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Proceedings of the

25th European Conference on Cyber Warfare and Security

Hosted by

University of Nottingham, UK

29-30 June 2026



Steven Furnell and

Dimah Almani

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Proceedings of the
25th European Conference on Cyber Warfare and Security
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University of Nottingham
UK

Edited by

Steven Furnell and
Dimah Almani

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Published June 2026

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E-Book ISBN: 978-1-917204-79-8
E-Book ISSN: 2048-8610
Print version ISBN: 978-1-917204-78-1
Print Version ISSN: 2048-8602

Published by Academic Conferences International Limited
Reading, UK
+44 (0) 118 324 6938
www.academic-conferences.org
info@academic-conferences.org

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25th European Conference on Cyber Warfare and Security, 2026

The European Conference on Cyber Warfare and Security (ECCWS) is a distinguished academic conference that has been held annually for 25 years, attracting a global audience of scholars, researchers, military professionals, and industry experts. The conference is dedicated to advancing knowledge and understanding of cyber warfare and cybersecurity through the presentation and discussion of high-quality, peer-reviewed research.

The Proceedings of the 25th European Conference on Cyber Warfare and Security, 2026 includes academic research papers, PhD research papers, Master's Research papers and work-in-progress papers which have been presented and discussed at the ECCWS 2026 conference. The proceedings are of an academic level appropriate to a professional research audience including graduates, post-graduates, doctoral and post-doctoral researchers. All papers have been double-blind peer reviewed by members of the Review Committee.

Aims and Scope

ECCWS provides a comprehensive platform for the exploration and discussion of the complex and evolving challenges in the fields of cyber warfare and cybersecurity. It seeks to bridge the gap between academic research, practical applications, and policy-making, fostering interdisciplinary collaboration and the exchange of ideas. The conference focuses on both theoretical and applied aspects of cybersecurity and cyber defence, with an emphasis on the implications for national security, military strategy, and global stability.

Topics Covered

The call for papers for the ECCWS conference asked for contributions that considered the following topics. In addition, the committee welcomed papers on a number of specialist mini-tracks which can be seen at the end of this list.

Cyber Warfare Strategies and Tactics
- *Offensive Cyber Operations*
- *Defensive Cyber Operations*
- *Cyber Deterrence and Cyber Power.*

Cyber Defence and Security
- *Threat Detection and Incident Response*
- *Security Architectures*
- *Vulnerability Assessment and Management including pentesting*

Cyber Threat Intelligence
- *Adversary Tactics, Techniques, and Procedures (TTPs)*
- *Threat Intelligence Sharing*
- *Advanced Persistent Threats (APTs).*

Critical Infrastructure Protection
- *Protection of Energy, Water, and Transport Systems*
- *Financial Sector Security*
- *Telecommunications Security*

Military Applications of Cyber Technologies
- *Cyber Command and Control Systems*
- *Cyber-Physical Systems in Defence*
- *Information Warfare and Psychological Operations.*

Legal and Ethical Issues in Cyber Warfare
- *International Law and Cyber Conflict*

- *Ethical Dilemmas in Cyber Operations*
- *Cyber Espionage and Sovereignty.*

Emerging Technologies and Innovations

- *Artificial Intelligence in Cybersecurity*
- *Quantum Computing and Cybersecurity*
- *Blockchain for Cybersecurity*

Cybersecurity Education and Training

- *Military Cyber Training Programs*
- *Cybersecurity Curriculum Development*
- *Capacity Building in Cybersecurity*

Policy, Governance, and International Cooperation

- *National Cybersecurity Strategies*
- *International Cyber Norms and Agreements*
- *Public-Private Partnerships in Cybersecurity*

Cybercrime and Law Enforcement

- *Digital Forensics*
- *Countering Cybercrime*
- *Legal Frameworks for Cybercrime*

Experts in the field proposed mini tracks on the following topics. Papers accepted on these topics after the double-blind peer review process were presented as mini tracks at the conference and are also published in these proceedings.

- *Software Supply Chain Security Risks*
- *Smart Systems Under Siege: Analyzing Cybersecurity Risks and Real-World Incidents*

The programme from the 2026 conference can be downloaded from https://papers.academic-conferences.org/index.php/eccws and full details about the conference can be seen from the conference website: https://www.academic-conferences.org/conferences/eccws/

ECCWS Preface

These proceedings represent the work of contributors to the 25th European Conference on Cyber Warfare and Security (ECCWS 2026), Hosted by the University of Nottingham, UK on 29-30 June 2026. The Conference Co-Chairs are Steven Furnell from the University of Nottingham, UK, and Dimah Almani, from Shaqra University, Saudi Arabia.

ECCWS is a well-established event on the academic research calendar and now in its 25th year conference remains the opportunity for participants to network and share ideas. The following conference proceedings contain a diverse range of papers, and the conference continues to be a forum for technical, theoretical and practical exchange about the study, management, development and implementation of systems and concepts to improve cyber security and combat cyber warfare.

The opening keynote presentation is given by Dr Lorna Kirkby, Department for Science, Innovation and Technology of the UK Government on the topic of *Securing the Digital Future: The UK Government's Approach to Cyber Security.* The second day of the conference will open with an address by Prof. Adam Joinson, from the University of Bath, UK speaking on the *Mapping the Impact of Future & Emerging Technologies on Cybersecurity.*

With an initial submission of 190 abstracts, after the double blind, peer review process there are 109 Academic research papers, 4 PhD research papers, 3 Masters Research papers, 1 Non-Academic Paper and 7 work-in-progress papers published in these Conference Proceedings. These papers represent research from Australia, Canada, Czech Republic, Finland, France, Germany, Greece, Netherlands, Nigeria, Norway, Pakistan, Portugal, Saudi Arabia, Singapore, South Africa, Sweden, Switzerland, Turkey, UK, United Arab Emirates, and USA.

We hope you enjoy the conference.

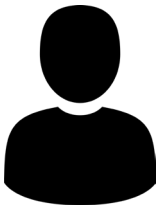
Steven Furnell and Dimah Almani
Conference Co-Chairs
Nottingham, UK
June 2026

Biographies of Chairs and Keynote Speakers

Conference and Programme Chairs



Prof. Steven Furnell is Professor of Cyber Security in the School of Computer Science at the University of Nottingham. His research interests include security management and culture, usability of security and privacy, and technologies for user authentication and intrusion detection. He has authored over 400 papers in international journals and conference proceedings, as well as various books, book chapters, and industry reports. Steve is the UK representative to Technical Committee 11 (security and privacy) within the International Federation for Information Processing, a board member of the Chartered Institute of Information Security, and a member of the Steering Group for the Cyber Security Body of Knowledge (CyBOK) and the Careers and Learning Working Group within the UK Cyber Security Council.



Dr. Dimah Almani completed her PhD in Cybersecurity at the University of Nottingham, specialising in trust mechanisms for vehicle-to-vehicle (V2V) communication. Her research focused on improving security in connected vehicles using simulation tools such as Veins, SUMO, and OMNeT++. She also holds a Master's degree in Computer Science from Nova Southeastern University, Florida, where she investigated cybersecurity vulnerabilities in smart transportation systems. With over 10 years of teaching experience, Dimah has developed and delivered courses on emerging technologies, supervised postgraduate students, and contributed to cybersecurity research. She is skilled in C++, Python, and MATLAB, with strong knowledge in network simulations and mathematical modelling. Dimah has served as an IEEE reviewer and held academic leadership roles including Coordinator of Quality Control and E-Learning Program Manager. She received the IBM Artificial Intelligence Analyst – Explorer Award in 2020. Her work connects theoretical models with real-world applications in cybersecurity and intelligent transportation systems.

Keynote Speakers



Dr Lorna Kirkby is Head of Software Security Policy for the Department for Science, Innovation and Technology. This includes leading work to develop the UK government's Software Security Code of Practice and how to drive uptake of these principles throughout digital supply chains as part of the Government's longstanding advocacy of a secure by design approach to technology development.



Adam Joinson is Professor of Information Systems at the University of Bath. Adam has been working on the intersection between behavioural science, technology and security for over 25 years, including seminal work that helped establish 'cyberpsychology' as a field of study. He has also worked in Government applying behavioural science to security, and has led multiple large scale research programmes. He is co-director of the Bath Institute for Digital Security and Behaviour (www.idsb.ac.uk) as well as co-investigator on the EPSRC CRANE Network Plus (www.crane.ac.uk). His website is: https://researchportal.bath.ac.uk/en/persons/adam-joinson/

Mini Track Chairs



Dr Hossein Abroshan is a cybersecurity researcher focusing on adversarial machine learning and applied AI for cyber defence. His recent work includes building AI poisoning-detection pipelines; developing AI-driven ransomware detection for OT; and AI-powered phishing detection using human factors. He has also developed AI and cybersecurity materials for CyBOK (ai4cs.uk and secai.uk). Hossein is the director of cybersecurity research group and director of MSc Cyber Security course at ARU, Cambridge, and has been leading/supervising several cybersecurity and AI projects in various sectors. Hossein's interests include AI security and trustworthy AI, human factors in cyber security, and protection of critical infrastructures.



Tiago Cruz is Associate Professor at the Department of Informatics Engineering of the University of Coimbra. He is a Senior Researcher at the Center for Informatics and Systems of UC, having started his research activity in 2001. His research interests cover areas such as management systems for communications infrastructure and services (operator and data center environments), embedded computing, critical infrastructure security, broadband access network device and service management. He has been involved in various European- and industry-funded research projects related with cyber-security, autonomous management, content delivery infrastructures or wireless WAN technologies, as well as several national projects, in partnership with telecommunications operators and research agencies, with both technical and management activities.



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Cybersecurity Management Competencies in Critical Infrastructure Organizations: A Review and Research Agenda

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Abstract: Critical infrastructure is vital to the economic, social, and technological survival and welfare of nations. Attacks on these infrastructures can be devastating and can lead to serious consequences. The Top Management Team (TMT) is the highest decision-makers who seal the fate of such organizations when it comes to risk management. Regulations and best practices are demanding that the TMT take responsibility for the cybersecurity posture of the critical infrastructure organizations to protect that infrastructure or prevent further damage. Critical infrastructure organizations often have a combination of information technology and operational technology spread across a wider geographical area and extensive regulation that can affect security investments and the TMT composition. Consequently, to effectively carry out their responsibilities, the TMT requires cybersecurity competencies; therefore, the specific cybersecurity management competencies that constitute these requirements need to be identified and tailored to their roles. To identify research in this area, we surveyed prominent journals that publish on cybersecurity, management, and critical infrastructure. We used search terms that address cybersecurity skills, knowledge, and attitudes necessary for top management in strategic decision-making and cybersecurity risk management. To ensure the collection of relevant articles, the literature review follows a systematic review process. A qualitative analysis method was employed to identify five thematic areas, namely leadership, learning, organization, cybersecurity, and competency, through which management's cybersecurity competencies are positioned as strategic requirements that can impact organizational cybersecurity resilience. The strategic responsibilities of the Top Management Team (TMT) are interestingly extending to cybersecurity management in organizations. They are also required to align cybersecurity management with the organization's strategic objectives. Thus, to effectively carry out their responsibilities, the TMT requires cybersecurity competencies. This review has identified relevant cybersecurity skills, knowledge, and attitudes that can be constituted as cybersecurity management competencies that will support TMT in the critical infrastructure protection. The review also reveals research gaps due to the limited number of studies conducted considering the entire TMT cybersecurity management competencies. This review provides a foundation for developing a theoretical framework for studying TMT cybersecurity competencies in critical infrastructure organizations.

Keywords: Cybersecurity, Senior management, Competencies, Critical infrastructure

1. Introduction

Critical infrastructures are consistently faced with an increasing number of attacks. Attacks or disruptions to critical infrastructure can prove disastrous and can negatively affect their reliability and safety (Alcaraz and Zeadally, 2015) with the effect going beyond one national border to another (Lehto, 2022).

These attacks may result in extremely high revenue losses (He et al., 2018), and financial loss is not the only adverse effect can also lead to legal liabilities with serious repercussions (Dynkin and Dynkin, 2018). These attacks are on the rise and are causing losses of billions of dollars (Cremer et al., 2022), as well as loss of market capitalization (Mukhopadhyay *et al.*, 2019). Consequently, directors are more likely to be held responsible when organizations experience attacks (Frank, Grenier and Pyzoha, 2021). Thus, the senior leadership is critical in ensuring responsible cybersecurity within organizations (Panteli, Nthubu and Mersinas, 2025).

The Top Management Teams (TMTs) play a central role in daily operations and are responsible for strategic decisions (Bendig et al., 2023), with cybersecurity being one of their major responsibilities (Li et al., 2018). TMT is duty-bound to ensure effective cyber risk management (Radu & Smaili, 2022). They need to possess cybersecurity knowledge, competence, and skills (Garcia-Granados & Bahsi, 2020). Delegating cybersecurity risk management to the IT department has proven insufficient (Rothrock & Kaplan, 2018). However, many leaders remain inadequately equipped with a technical background for the tasks (Gale et al., 2022).

Various methods and techniques have been developed to enhance cybersecurity awareness among the TMT (Taherdoost, 2024). While awareness aims to instil a proactive attitude toward cybersecurity, skills provide the necessary tools for maintaining security hygiene (Haney & Lutters, 2020). However, their training and awareness programs have received limited scholarly attention, and many remain unaware of key threats (Vrhovec & Markelj, 2024). Moreover, memory retention from an awareness program tends to be short-lived (Ghafir et al., 2018). The lack of sustainable cybersecurity programs within organizations is a recurring concern (Akter et al.,

2025). Additionally, there is no consensus on the metrics for measuring the effectiveness of cybersecurity awareness programs for TMT (Chaudhary et al., 2022).

Chowdhury & Gkioulos (2021b) conducted a literature review of 29 papers addressing workforce knowledge, skills, and competencies. TMT competencies have not been specifically explored in reviews, except for the finding that managers and top executives hold the mandate to ensure effective implementation of cybersecurity measures in their organizations (Vidgren, 2020). This highlights the research gap concerning cybersecurity competencies in top management.

This literature review seeks to answer the following question:

What cybersecurity management competencies have been identified that support TMT strategic responsibilities for cybersecurity management in critical infrastructure organizations?

The paper is structured as follows: Section two defines key concepts, including the top management team, competence, and cybersecurity management competence. Section three outlines the review methodology. Section four presents the findings. Section five discusses the results, and Section six concludes the paper.

2. Key Concepts

2.1 Top Management Team

Numerous academics have examined the concept of the Top Management Team (TMT), they are organization's senior officers (Carpenter, Geletkanycz and Sanders, 2004). TMT are the top senior officers who make and participate in strategic decisions (Amason, 1996). According to Menz (2012a) TMT consists of senior executives with one or more functional responsibilities. They represent the highest and second-highest levels of executive management (Wiersema, 1992). TMT exerts a significant influence on strategy formulation (Nielsen, 2010). They are also responsible for planning and executing strategies (Wu *et al.*, 2017), and are recognized as the senior executives who manage the organization's business (Gao, Wattal and Thatcher, 2025).

Li et al., (2022) identified members such as the chief executive officer, chief financial officer, vice president, general manager, chief executive deputy general manager, and vice manager. Increasingly, the chief information security officer has been included in the TMTs due to growing concerns about cybersecurity (Gao, Wattal and Thatcher, 2025). Other roles include the chief information officer (Bendig *et al.*, 2023), chief technology officer (Gu, Wang and Mai, 2024), chief information officer, chief strategy officer, chief knowledge officer, chief operations officer, and chief marketing officer (Menz, 2012b).

2.2 Competency

The term competence has attracted significant interest in organizational management (Salman, Ganie and Saleem, 2020). Researchers from education, psychology, human resources, management, politics, and information systems have aligned its meaning within their respective fields (Hoffmann, 1999; Bassellier, Benbasat and Reich, 2003). Consequently, competence lacks a universally accepted definition (Jubb and Robotham, 1997). Nonetheless, it continues to be applied across different perspectives

It is viewed as a combination of skills, performance, personal traits, or knowledge essential for the effective delivery of a role (Brophy and Kiely, 2002). It represents the potential that leads to effective behavior and the capability of an individual to perform successfully in a specific role (Anderson, Ahmad and Chang, 2024a). Individual competence contributes to the organization's core competence (Bassellier, Reich and Benbasat, 2001). Blömeke et al. (2015 p. 4) ''criterion behavior as well as the knowledge, cognitive skills, and affective-motivational dispositions that underlie that behavior." More broadly, it reflects the behavior of an entity that enables effective performance in its role (Woodruffe, 1993).

3. Method

To ensure the collection of relevant articles, the review follows the framework proposed by Okoli (Okoli, 2015) which includes the following steps: I) establishing the purpose of the literature review, II) protocol, III) searching for literature, IV) practical screen, V) quality appraisal, VI) data extraction, VII) synthesis of studies, and VII) writing the review.

3.1 Purpose of the Literature Review

The objectives of this literature review are to identify and analyze articles on the cybersecurity competencies of the top management team (TMT) in CI organizations as follows:

- Identify papers published in top information systems, cybersecurity, and critical infrastructure outlets that address cybersecurity competencies necessary for top management in strategic decision-making and cybersecurity management
- Analyze and evaluate the identified research articles to summarize findings related to TMT cybersecurity competencies in critical infrastructure organizations.
- Reveal research gaps concerning cybersecurity competencies of the top management team in the CI organizations.

3.2 Protocol and Literature Search

We conducted a literature search on 14 journals with the search terms: (cybersecurity OR "Information Security") AND ("Top Management" OR "senior management" OR "executive officers") AND ("Critical Infrastructure"). We used the databases Web of Science, Scopus, and Google Scholar, as well as direct searches of the listed journals. The initial search yielded: Google Scholar = 256, Scopus = 71, and Web of Science = 3, for a total of 330 articles. This number was significantly lower than expected. Therefore, to increase the likelihood of finding more relevant articles, a direct search in the chosen journals was conducted. These methods yielded an additional 698 articles; combined with the 330 articles from Google Scholar, Web of Science, and Scopus, a total of 1,028 articles were selected.

3.3 Practical Screening

During practical screening, papers were selected based on their title, abstract, year of publication 2003-2025, discussion, results, and summary, English language, setting related to TMT cybersecurity competency, and Senior Management staff as participants or subjects. Papers that focused on only technical aspects of cybersecurity were excluded.

3.4 Quality Appraisal

Initially, only papers matching the keywords in their titles or abstracts were selected. A total of 104 papers from the journals met these criteria.

Table 1: List of additional papers through forward and backward searches

SN	Forward	Cited	Backward	From the Ref. List
1	(Jewer and McKay, 2025)	(Bassellier, Benbasat and Reich, 2003; Benaroch and Chernobai, 2017; Haislip, Lim and Pinsker, 2021)	(Puhakainen and Siponen, 2010)	(Barton *et al.*, 2016)
2	(Onibere, Ahmad, and Maynard, 2017)	(Ashenden and Sasse, 2013)		
3	(Anderson, Ahmad, and Chang, 2022)	(Ashenden and Sasse, 2013)		

The second selection process resulted in 31 papers that met the criteria. In addition to this selection, backwards searches produced 1 paper and forward searches yielded 3 papers, as indicated in the table above.

Thematic analysis was adopted with inductive coding; therefore, themes are derived based on what the data "tell us".

3.5 Leadership

Strategic cybersecurity leadership comprises executives and managers - the top management team – identified in the literature as those responsible for cybersecurity risk management, governance, and compliance. Their strategic roles influence the organization's cybersecurity risk posture, culture, and resilience. The literature indicates that senior management plays a highly instrumental role in cybersecurity risk decision-making activities (Ashenden and Sasse, 2013; Onibere, Ahmad and Maynard, 2017; Benaroch and Fink, 2021; Haislip, Lim and Pinsker, 2021; Bendig *et al.*, 2022; Shillair *et al.*, 2022; Lorenz and Buchwald, 2023; Jewer and McKay, 2025; Sahin and Vance, 2025)

Several articles have viewed cybersecurity strategic responsibilities as resting on cybersecurity managers and leaders, such as the CTO, CIO, and CISO (Ashenden and Sasse, 2013; Onibere, Ahmad and Maynard, 2017; Kappelman *et al.*, 2019; Anderson, Ahmad and Chang, 2022; Bendig *et al.*, 2022; Ramezan, 2025; Sahin and Vance, 2025), despite the limited access of CISOs to the board (RenÃ, 2022). Furthermore, the inclusion of the CIO in the C-suite is being misunderstood (Bendig *et al.*, 2022).

3.6 Organization

Organizational objectives, strategies, and policies should align with cybersecurity readiness, as security improves when cybersecurity goals are integrated with broader organizational objectives (AlGhamdi, Win and Vlahu-Gjorgievska, 2020; Anderson, Ahmad and Chang, 2022). In practice, the responsibilities of the TMT to their organizations in ensuring effective information security governance and leadership accountability can strengthen the organization's security posture (AlGhamdi, Win and Vlahu-Gjorgievska, 2020; Alshaikh, 2020; Shillair *et al.*, 2022). We found strong connections between the organizational objectives and cybersecurity strategic alignment, and leadership (Onibere, Ahmad and Maynard, 2017; Anderson, Ahmad and Chang, 2022). Additionally, differences in the organizational levels affect cybersecurity management: large and small organizations have boards (Anderson, Ahmad and Chang, 2022) SMEs may face constraints due to limited resources (Almeida, 2025). Evidently, large organizations usually have a dedicated person in charge of cybersecurity, while small organizations may not (Kappelman *et al.*, 2019)

3.7 Cybersecurity

Cybersecurity management comprises a range of roles (Almeida, 2025) that require defense against threats and defense against cyber threats is one of the cybersecurity strategic goals (AlDaajeh *et al.*, 2022), which falls within the purview of the top management (Shillair *et al.*, 2022). Consequently, leaders need to adapt strategies in combating these evolving cyber threats (Anderson, Ahmad and Chang, 2024b).

This theme reflects the continuously evolving nature of cyber threats, vulnerabilities, and risks, along with the corresponding responsibility of the top management to ensure information security governance for organizational success (AlGhamdi, Win and Vlahu-Gjorgievska, 2020), and determination of response to cyber threats (Shillair *et al.*, 2022). The core of this theme highlights how TMT addresses, manages, and responds to cybersecurity practices. Since information security needs to be addressed at the strategic level (Almeida, 2025), this study underscores the critical role of the TMT in addressing these cybersecurity risks.

3.8 Learning

The theme learning focuses on the various education, training, and awareness initiatives adopted by organizations, especially CI organizations, to ensure employees acquire skills, knowledge, and competencies needed to fulfill their responsibilities. Security education, training, and awareness (SETA) has been widely seen to be one of the learning paths to increase cybersecurity culture . Anderson et al. (2022) reported that the SETA program can be seen to be a marketing plan rather than an educational one, and an awareness program for top management has been identified as one of the cybersecurity critical success factors for organizations (Yeoh *et al.*, 2022). However, no literature was found that specifically identifies a learning program mapped to the entire TMT based on its strategic positions, composition, and commitments.

3.9 Competence

Technical competencies or hard skills are typically associated with cybersecurity professionals (Onibere, Ahmad and Maynard, 2017; Furnell, 2021; Anderson, Ahmad and Chang, 2022) . Then again, competencies such as communication skills, risk management, and incident response (Anderson, Ahmad and Chang, 2022, 2024b) are identified as essential in organizational cybersecurity management processes.

The leadership and cybersecurity themes are linked through TMT's strategic responsibilities. For example, AlGhamdi et al.(2020) acknowledged the importance of the TMT in the success of information security. Haislip et al., (2021) emphasized IT governance and (Shillair *et al.*, 2022) highlighted the importance of top management involvement in responding to cyber threats. Connections between leadership and competencies (Furnell, 2021; Anderson, Ahmad and Chang, 2022; Ramezan, 2025) are crucial for top management in carrying out their responsibilities. Some are intended for cybersecurity leaders in general (Anderson, Ahmad and Chang, 2022) or for technical TMT members such as CISOs (Ramezan, 2025) Anderson et al. (2024) Focus on case-based learning to support cybersecurity leaders in their roles and emphasize pedagogical learning accordingly. Additionally, Alshaikh, (2020) reported alignment of cybersecurity awareness with an external campaign, identification of

cybersecurity behaviours, establishment of a cyber champion network, and development of a brand for the cyber team.

3.10 Synthesis

The literature includes works that consider competencies aiding in supporting top management in discharging their cybersecurity strategic responsibilities in Ci organizations. For example, A. B. Anderson et al. (2022) identified several cybersecurity competencies that include skills, knowledge, and attitudes. However, the identified competencies are found to be tailored to cybersecurity leaders. Similarly, Furnell (2021) identified various cybersecurity competencies mapped to the technical members of the TMT. Figure 1 highlights the identified connections among the themes.

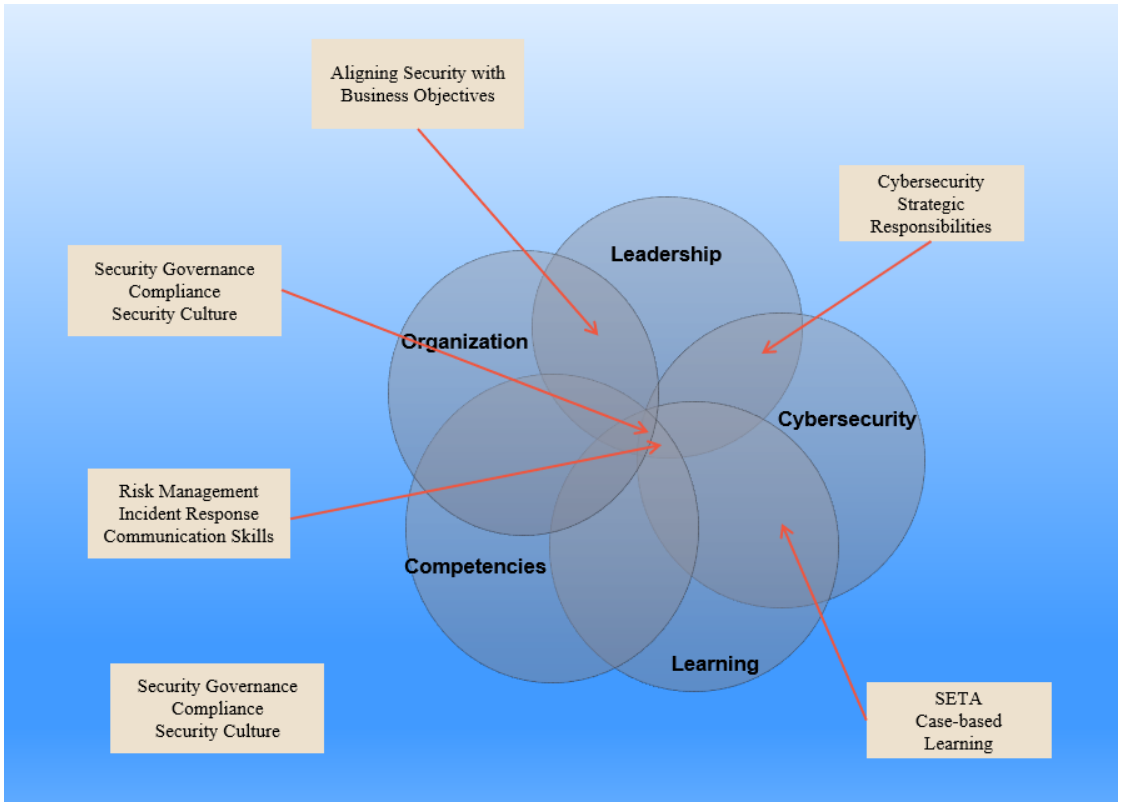


Figure 1: Connections between the identified themes

The study identified the following competencies in Table 2.

Table 2: Summarized connections among the themes

Source	Competency	Rationale
(Anderson, Ahmad, and Chang, 2022) and (Anderson, Ahmad, and Chang, 2024b)	Communication skills	For intra- and inter–team communication and discussions on cybersecurity activities, to enable members to develop a common understanding of terminologies in the decision-making process
	Risk management	To facilitate their cyber risk management decision-making process
	Incident response	To facilitate their understanding of incident mitigation, response, and remediation.
(Furnell, 2021)	Information security governance	To facilitate governance and compliance
	Business resilience	Basic business resilience skills can enhance anticipation, action, and defensive strength.
	Compliance	To facilitate understanding of the relevant acts, regulations, and compliance frameworks.
(Almeida, 2025)	Risk management, organizational factors, and governance	To facilitate their cyber risk management decision-making process

4. Discussion

The research question of this study focuses on identifying the cybersecurity competencies critical to the TMT's strategic cybersecurity management in critical infrastructure organizations. However, the literature on such competencies is very limited. Most studies examine the competencies of cybersecurity experts within the TMT, with particular attention given to roles such as CIO, CISO, and CTO (Anderson, Ahmad and Chang, 2022, 2024b). While the TMT comprises senior management, its functional diversity poses challenges to collaboration (Lorenz and Buchwald, 2023). Consequently, the role of CISO as a technical professional within the team may create functional diversity issues that affect overall decision-making processes (Ashenden and Sasse, 2013).

Our results indicate that board-level IT competencies have received some attention from researchers (Benaroch and Chernobai, 2017; Benaroch and Fink, 2021; Jewer and McKay, 2025) Though their core cybersecurity management competencies remain under-researched. The results indicate that many studies recognize the critical importance of the cybersecurity strategic responsibilities for top management of critical infrastructure organizations. However, most emphasize the competencies and skills of the technical members of the TMT, such as CISO, CIO, CTO, and CDO (Ashenden and Sasse, 2013; Onibere, Ahmad and Maynard, 2017; Kappelman *et al.*, 2019; Bendig *et al.*, 2022; RenÃ, 2022; Lorenz and Buchwald, 2023; Ramezan, 2025). Furthermore, the review suggests that emphasis is often placed on specific TMT members regarding cybersecurity competencies, without acknowledging that all team members share responsibility for organizational cybersecurity governance, resilience, and compliance. Additionally, our review noted discrepancies about the composition of the TMT. While this study does not aim to define team composition, it highlights the strong need for all TMT members to be cybersecurity-proficient and acquire a certain level of cybersecurity management competencies to support strategic cybersecurity management responsibilities and to aid in collective mindfulness (Järveläinen *et al.*, 2025). This is very important in critical infrastructure, where information technology and operational technology are a mix. Finally, we observed that only communication skills, incident response, and risk management are considered, and only for cybersecurity leaders (Anderson et al., 2022, 2024). Information security governance, information security strategy, and information risk management were also identified Furnell, (2021).

5. Conclusion

This study sets out to answer the research question: which cybersecurity management competencies have been identified as supporting TMT strategic responsibilities for cybersecurity management in CI? Despite the strategic importance of cybersecurity management in this sector, our results reveal very limited research addressing the cybersecurity management competencies of the TMT. Most studies focus on the competencies of technical roles, such as CIO, CISO, or CTO, neglecting the overall competencies of all members.

Our review found that although TMT composition, size, and skills vary depending on the size of the organization, it is consistently evident that TMT is primarily responsible for the strategic decisions related to cybersecurity.

The results revealed five main themes that are crucial for critical infrastructure organizational cybersecurity management processes: leadership, organization, cybersecurity, learning, and competence. This supports the identification of competencies essential to TMT's strategic responsibilities. Finally, identifying cybersecurity management competencies will support the enhancement of cybersecurity as the protector of the organizational value creation capabilities of CI. This review also represents a step toward creating a cybersecurity framework tailored to TMT's strategic cybersecurity management responsibilities.

5.1 Limitations and Future Research

This study is limited to some journals. We chose to systematically study a limited sample of high-quality outlets, but future research could identify additional central competencies through a broader search. This review can extend into an empirical study that applies the identified competencies and assesses the extent of TMT's level of cybersecurity management competencies in different types of organizations.

Ethic Declaration: I declare that ethical clearance was not required for this research

AI Declaration: I declare that AI was not used in the creation of the paper; however, Copilot and Grammarly were used for grammar and proofreading.

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MAGNAS: A CCTV Searching Platform for Digital Investigation

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Abstract: Closed-circuit television (CCTV) systems generate huge amounts of video material, making manual inspection slow, inefficient, and prone to missing evidence. As surveillance scenarios grow more complex, investigators require automated tools capable of understanding extensive, unstructured recordings and supporting natural-language search, which most existing systems cannot provide. Current video-analysis systems usually focus on isolated tasks such as detection, action recognition, or captioning, producing fragmented outputs that lack the consistency and explainability needed for forensic work. This research presents MAGNAS, an intelligent CCTV retrieval platform that converts raw footage into a searchable metadata index using a multi-phase pipeline integrating person detection, multi-object tracking, visual attribute extraction, and action recognition. It generates structured representations including bounding boxes, timestamps, appearance attributes, and actions stored in an SQLite database. Users describe people or events via a natural-language interface, and the system translates these into structured filters for accurate set-theoretic retrieval. MAGNAS was evaluated using mAP for detection, Recall@K and Precision@K for retrieval, and temporal IoU for action alignment. Results show strong person-detection performance and high retrieval accuracy, especially for queries with multiple appearance attributes. Attribute extraction was largely precise, despite challenges with delayed VLM processing, inconsistent action detection under difficult camera angles, and limited temporal accuracy (tIoU = 0.2649). Overall, MAGNAS significantly reduces search time and improves identification of people of interest in large-scale CCTV archives, highlighting the value of organized, explainable video indexing for future investigative technologies and law enforcement applications.

Keywords: CCTV, Video retrieval, Natural language processing, Computer vision, Digital forensics

1. Introduction

The CCTV systems have evolved into one of the most prolifically used security technologies, and video surveillance has been implemented in airports, banks, retail spaces, and smart cities and brings about rapidly growing amounts of unstructured footage as the number of cameras in the world has exceeded a billion by 2021 (Subha et al., 2023). This information is useful to prevent crime, rebuild the events, and assist investigations, and human operators can only observe a few screens and their performance drops in case of fatigue, which is why manual inspection is inconsistent and inefficient as stated by Subha et al. (2023). Artificial intelligence and computer vision studies have thus prioritized the automation of video interpretation with models like YOLO to detect objects and CNN/RNN to recognize behaviors, and video-to-text systems based on natural language search, as Khurana and Deshpande (2021) explain. Initial techniques based on background subtraction, semantic tagging, and motion detection developed into semantic indexing and multimodal systems such as TagBook that showed that it was possible to unsupervisedly characterize events, as stated by Mazloom et al. (2016). Recent developments now involve VLAB (He et al., 2025) and PRVR (Dong et al., 2022), which have been trained to better the video-language association, but most of them are evaluated on controlled data sets and have issues related to low-resolution, occlusion, and low-light conditions found in real CCTV images, as pointed out by Wan et al. (2021). Although technologies have made progress, existing systems tend to focus on single functions like anomaly detection, captioning, or retrieval without providing solutions that can be used in the real-world surveillance setting that can be scalable, which is why improved unified solutions are required.

The fast growth of CCTV systems has led to huge amounts of unstructured video that need to be brought to bear on intelligent actionable information as highlighted by Subha et al. (2023) but current manual reviewing systems are not keeping up with the volume and complexity. Other forms of early indexing and tagging techniques enhanced organization but were limited to low-level features enabling low scalability like Saravanan (2016) and TagBook by Mazloom et al. (2016), multimodal hypergraph retrieval by Li et al. (2024), and hierarchical graph search models by Song et al. (2022) enhanced the semantic alignment of video and text. The minimal effect of NLP-based technologies such as video captioning by Wu et al. (2024), multi-sentence summarization by Masoomeh Nabati and Alireza Behrad (2020), and Video-QA by Khurana and Deshpande (2021) have also helped reduce the semantic gap, although their results are still underwhelming on continuous CCTV footage, where the computational cost, data capacity, and inefficiency become critical issues. Although supervised contrastive

learning and multimodal captioning models have enhanced robustness and similar accuracy, according to Hirata et al. (2021) and Wu et al. (2024), real CCTV conditions of low light, blur, occlusion, and varying dynamics of a scene still remain a problem to model reliability, an issue brought up by Wan et al. (2021) and Li et al. (2024). The existing literature is currently divided with anomaly detecting, captioning and retrieving being studied separately without any combination of identification, indexing, and video-to-text translation into a single, scalable system that guarantees the timely and efficient CCTV processing, which is why the system that would help alleviate these limitations and provide the means of timely efficacious CCTV processing is necessary. Three major research questions will guide the study:

RQ1: What approaches can combine multiple pretrained models to generate descriptive representations of CCTV footage that support faster and more intuitive search?

RQ2: What methods enable a single, unified query to retrieve relevant moments from long CCTV recordings based on actions, objects, or events?

RQ3: How can CCTV footage be transformed into structured outputs such as timelines, labels, or event summaries that allow investigators to navigate videos more efficiently?

The primary aim of this project is to develop a unified CCTV retrieval system capable of single-query natural-language search, enabling investigators to rapidly locate individuals, actions, and events across extensive surveillance footage by converting visual content into structured metadata and reducing reliance on lengthy manual review. To achieve this aim, the system integrates multiple pretrained models that detect objects, actions, and relevant visual cues in CCTV video, transforms these outputs into searchable representations such as labels, timestamps, and contextual descriptions, and implements a complete end-to-end pipeline that unifies detection, indexing, and retrieval into one efficient platform. Overall, the objective is to enhance investigative workflows by shortening video-analysis time, improving the accuracy and explainability of retrieval results, and providing a scalable metadata-driven solution suitable for real-world forensic and security applications.

2. Problem Background

Early video indexing relied on low-level features with limited scalability (Saravanan, 2016). TagBook introduced unsupervised semantic characterization (Mazloom et al., 2016), while multimodal approaches like hypergraph retrieval (Li et al., 2024) and hierarchical graph models (Song et al., 2022) improved video-text alignment. Video captioning systems (Wu et al., 2024; Nabati & Behrad, 2020) and Video-QA frameworks (Khurana & Deshpande, 2021) reduced the semantic gap but underperform on continuous CCTV. Recent models like VLAB (He et al., 2025) and PRVR (Dong et al., 2022) enhance video-language pretraining, yet real-world conditions—occlusion, low light, blur—remain problematic (Wan et al., 2021). Supervised contrastive learning (Hirata et al., 2021) improves robustness, but no existing system fully integrates detection, tracking, attribute extraction, action recognition, and natural-language search into one scalable forensic platform suitable for real CCTV conditions.

3. Methodology

The three-phase approach is used in this project. At the initial stage, a set of pretrained models were experimented on sample CCTV video to find out which models could be reliably used to assist in detection, attribute extraction and action recognition in the environment of real surveillance. During the second phase, the chosen components have been integrated into an entire platform with user interface, Flask backend, and a five-step automated pipeline that takes uploaded videos and allows search through natural languages. During the last stage, the system was tested with the help of the new CCTV videos in order to measure the accuracy of retrieval, the speed of the response, and the overall stability of the system in the conditions of the real investigation.

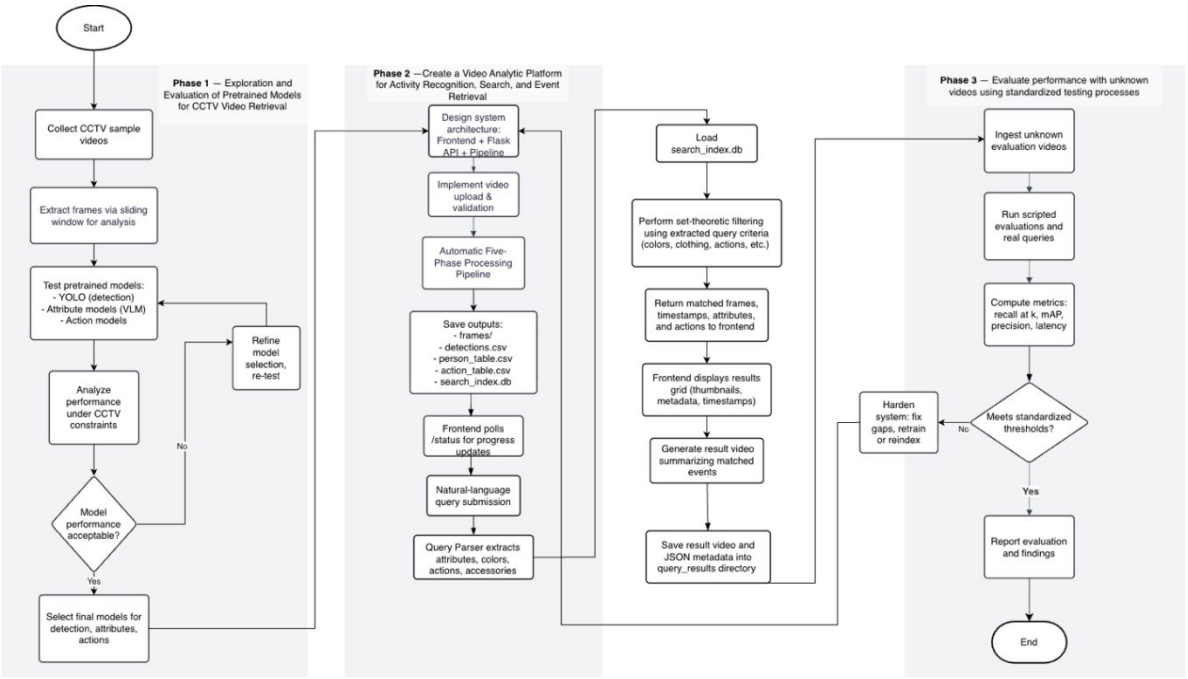


Figure 1: Operational Framework of the Study

3.1 Phase 1: Exploration and Evaluation of Pretrained Models for CCTV Video Retrieval

Phase 1 set MAGNAS baseline with a large variety of pretrained models, reviewed, and experimentally tested to be able to detect objects, extract attributes, recognize actions, track objects, and align texts with images. Due to the low resolution of CCTV footage, compressed artifacts, blur, poor illumination, occlusion, and low effective frame rate, this stage aimed at identifying models that would execute in the most favorable conditions when subjected to real surveillance. The analysis focused on the stability of detecting, the consistency of detecting over time, resistance to blur, fidelity of clothing colors and generalization to real recordings.

3.1.1 Review of pretrained models evaluated

Some models were experimented in terms of their functions in the analysis chain. In order to look at object-detection and tracking, YOLOv8 (m, l, x), YOLOv10, YOLO11, and RT-DETR were evaluated. YOLOv8m and YOLOv8x using ByteTrack were shown to be much more successful on degraded CCTV clips, particularly in low-light, compressed, and crowded scenes, and provides good small-person detection and dependable track IDs with minimal costly ReID modules.

Action recognition models such as SlowFast, TimeSformer, VideoMAE (base and large), MViTv2, Uniformer and InternVideo2 have also been tested. Most of the models performed poorly on noisy CCTV clips, and low FPS, though they were strong in Kinetics. VideoMAE-large was chosen due to its 16 frames input and powerful temporal representation and a custom HMDB51-finetuned checkpoint achieved much better surveillance-action performance than Kinetics-only pretrained models.

Person-attribute classifiers included SOLIDER, PromptPAR and OpenPAR, which were found to have an issue with poor crops, changes in lighting and compression noise. Then, vision-language models were tested based on zero-shot and instruction-tuning (CLIP, BLIP-2, LLaVA-1.5, Qwen-VL, Qwen2-VL, Qwen3-VL). Qwen3-VL-2B-Instruct that was deployed locally and quantized provided the highest accuracy, high-blur image, and structured outputs, particularly when the prompts contained context of the detected objects.

3.1.2 Experimental findings

Key insights were made in phase 1 experiments. Action models trained on Kinetics tended to get similar movements confused e.g. walking vs. running, when squeezed and at low frame rates. VideoMAE-large finetuning on HMDB51 enhanced significantly the recognition of surveillance-defensive actions, including walk, run, wave, pick, throw, punch, kick, smoke, drink, and clap. Dedicated attribute classifiers could not process blurred or low-resolution person crops and vision-language models, particularly Qwen3-VL-2B-Instruct with contextual hints, such as person holding a phone, were far more accurate on held objects, accessories, and

clothing. The results of YOLOv8 with Byte Track provided the most consistent person track across lighting variations and occlusion, and removed individual ReID models. Quantized Qwen3-VL-2B-Instruct deployed locally was able to operate offline with a tolerable latency of approximately 1.5 to 2 seconds per person crop and was therefore feasible in practice. These outcomes noted the most consistent factors during the noise of CCTV and informed the final MAGNAS architecture.

3.1.3 Final adopted model and pipeline

Phase 1 was successful as it ended with a strong and an effective model setup. YOLOv8m and YOLOv8x were used in object detection with low-resolution, compressed, low-light CCTV and in tracking with the assistance of Byte Track since they possess high ID continuity without ReID. Qwen3-VL-2B-Instruct utilized the attributes of people based on the context of the items that were detected by YOLO to enhance recognition of objects and clothes. VideoMAE-large finetuned on HMDB51 provided action classification achieving 83% validation accuracy on surveillance-style actions. This combination formed the foundation for Phase 2 integration.

3.2 Phase 2: System Implementation and Integration

3.2.1 Operational architecture and ingestion workflow

MAGNAS is based on the modular system with interface, backend, pipeline, and storage to transform raw CCTV video into searchable metadata. The MagnasFinal.html interface allows the investigator to upload the footage, monitor the progress, and search by natural language, and the Flask backend allows managing authentication, uploads, pipeline execution, and logging. Each video is processed by a five-stage background pipeline, the first stage of which is to extract frame, followed by detecting and tracking people with the help of YOLO, attribute generations with a vision-language model, short term action recognition and, finally, all data are summarized into a SQLite search index. All the intermediate and final output are stored in the table directory so that they can be easily accessed.

3.2.2 Query processing, search logic, and retrieval mechanism

After the ingestion pipeline completes and search_index.db is created, the natural-language queries can then be typed in by the investigators through the interface. Once queries are typed in A query such as: a man in a dark green hoodie with a backpack walking will be logged in the magnas_activity.log and the query parser used to process it in the system. The parser acquires formal search attributes such as colors, types, accessories, gender and actions of clothes. MAGNAS retrieves the results according to set-theoretic metadata filtering of metadata in search_index.db. The backend loads detections.csv, person_table.csv and action_table.csv, and finds all the entries that meet all the requirements and counts their intersection. This provides results to the investigation that are deterministic, explainable and reliable. Organized information that is sent by the backend includes frame numbers, timestamps, bounding boxes, attributes of persons, and inferred actions. Each individual can view the findings in frame thumbnails on the front-end. Bounding boxes on an MP4 video are created on command by generating a summarized video file using create_result_video.py and stored in the query results directory.

3.3 Phase 3: Evaluate the Performance of the Platform Using Unknown Videos Based on Standardized Testing Processes

The main aim of Phase 3 is to thoroughly test the platform's reliability, scalability, and accuracy by using originally unseen CCTV video. This guarantees that the created platform applies beyond the training environment and works well in real-world surveillance scenarios. The study uses established evaluation practices to assess algorithmic correctness, system responsiveness, and user experience while maintaining forensic transparency and security.

3.3.1 Evaluation metrics

On the platform, standardized retrieval metrics are computed after testing. Recall@K and Precision@K are used to determine the performance of the top-K relevant clips (Radlinski and Craswell, 2010). Mean Average Precision (MAP) measures the ranking quality across queries (Bellogín et al., 2017). Temporal accuracy of localized events is assessed by temporal IoU and mean Temporal Average Precision (mTAP) (Gao et al., 2017). Query latency (P50/P95) and indexing throughput measure responsiveness and scalability (Mackenzie et al., 2017).

4. Results and Analysis

In this section, MAGNAS performance will be of all components including interface, processing, retrieval accuracy, temporal localization, and overall functionality, in which quantitative and qualitative results are presented.

4.1 Ingestion and Indexing Results

The ingestion pipeline consists of five primary steps, each of which is designed to enable high-quality information extraction and reliable indexing. The system extracts timestamped frames at 3 frames per second (adjustable), balancing temporal precision with storage and processing performance. YOLOv8 is put to use for accurate person recognition, followed by Byte Track for reliable identity tracking. For each identified individual, the system saves a narrow crop for attribute and action analysis and a context crop with 150 px padding, which proved useful for catching surrounding objects and hand-held items that frequently fall outside tight bounding boxes. Each crop is processed using a locally hosted Qwen3-VL-2B model, which extracts precise human characteristics. VideoMAE-Large is implemented with movable temporal windows and post-processing smoothing achieving 83% accuracy. All Metadata has been compiled and saved in search_index.db for faster retrieval using combination indexing (frame, track_id) and better attribute-action fusion.

4.2 Quantitative Evaluation

4.2.1 Retrieval accuracy metrics (Recall@K, Precision@K, mAP)

The retrieval-stage evaluation demonstrates that the system achieves strong ranking and retrieval quality across diverse query types. The overall Mean Average Precision (mAP) reached 0.9597, indicating excellent ranking consistency and the system's ability to place relevant clips at higher positions. Recall@K: Recall@1 = 0.4450 (44.5%), Recall@5 = 0.9800 (98.0%), Recall@10 = 1.0000 (100%), Recall@20 = 1.0000 (100%), Average Recall = 0.8563 (85.63%). Figure 2 shows Recall@K results showing the system's ability to retrieve relevant clips within the top-K returned items. High Recall@5/10/20 demonstrates strong retrieval coverage.

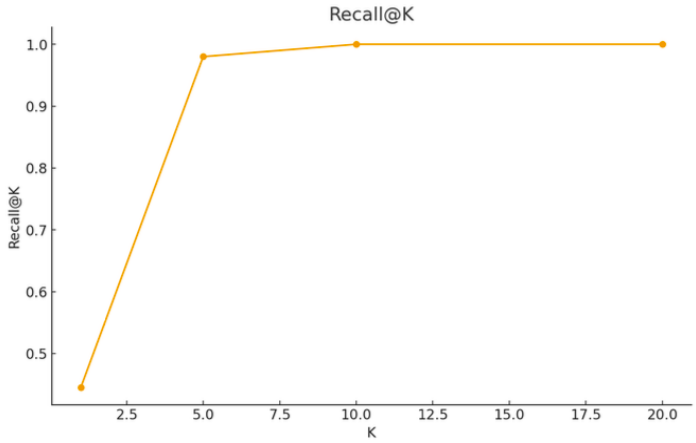


Figure 2: Recall@K results showing strong retrieval coverage

Precision@K: Precision@1 = 0.9000 (90%), Precision@5 = 0.5200 (52%), Precision@10 = 0.2700 (27%), Precision@20 = 0.1350 (13.5%), Average Precision = 0.4563 (45.63%). Precision@1 remains high, gradually decreasing as K increases. Per-Query AP Performance: Hijab/headscarf: AP = 1.0, Walking/stairs: AP = 1.0, Shaking hands: AP = 1.0, Green jacket: AP = 1.0, Group standing/talking: AP = 0.8875, Baseball swing: AP = 1.0, Riding horse: AP = 1.0, Helmet/hat: AP = 0.71, Jumping/diving: AP = 1.0, Wearing glasses: AP = 1.0. Overall, the system exhibits excellent retrieval accuracy. High mAP and Recall@5/10/20 values show that relevant clips are consistently retrieved. Precision decreases at larger K values, as expected in ranked retrieval systems.

4.2.2 Temporal localization (Temporal IoU and mTAP)

Temporal localization evaluates how accurately the system identifies the start and end boundaries of actions. Overall performance shows partial overlap with ground truth. Overall Metrics: Average Temporal IoU = 0.2649, Overall mTAP = 0.2391. mTAP Across IoU Thresholds: mTAP@0.3 = 0.2859, mTAP@0.5 = 0.2859, mTAP@0.7 = 0.1455.

Per-Video Performance: 4PEOPLE: Avg tIoU = 0.2327, mTAP = 0.1570; Riding: Avg tIoU = 1.0000, mTAP = 1.0000; Baseball: Avg tIoU = 0.3185, mTAP = 1.0000; Green Jacket: Avg tIoU = 0.2857, mTAP = 0.4545; Hijab: Avg tIoU = 0.3183, mTAP = 0.3788; Running: Avg tIoU = 0.1182, mTAP = 0.2020; Shakehand: Avg tIoU = 0.2926, mTAP = 0.3636. Figure 3 shows Average Temporal IoU (tIoU) per video. Simple, continuous actions such as Riding show perfect boundary alignment, while multi-person or fast-motion actions result in lower tIoU.

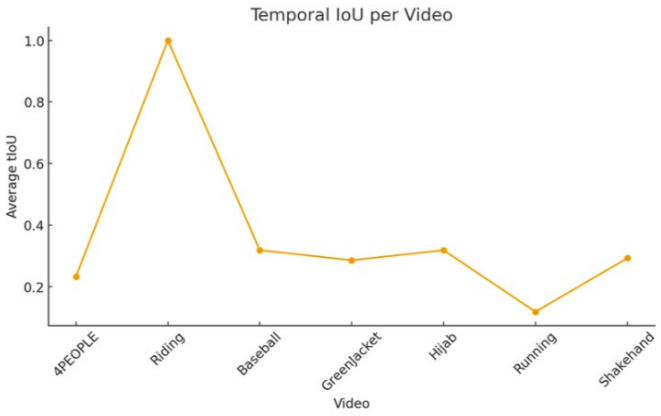


Figure 3: Average Temporal IoU per video

The system performs well on simple, continuous actions such as riding and baseball. Performance decreases in multi-person scenes, fast transitions, subtle actions, and scenes with occlusion.

4.2.3 System performance metrics

System performance was evaluated across all seven videos, each processed through the full pipeline. Overall Throughput: 100% pipeline completion, Total processing time: 659.25 seconds, Average processing time per video: 94.18 seconds, Fastest video: 39.79 seconds; slowest: 233.73 seconds, Average speed: 5.21 FPS (0.20× real-time). Hardware Utilization: GPU: NVIDIA GeForce 4090, Average GPU memory: 5.45 GB, Peak GPU memory: 14.6 GB, RAM usage: ~73 MB (GPU-bound workload). Phase-Level Breakdown: Phase 3 (VLM Attributes): Slowest step—avg 56.76 s, peak 174.43 s; Phase 4 (Action Inference): Avg 26.47 s; Phase 2 (YOLO Detection): Avg ~7 s; Phases 1 & 5 (Extraction and Indexing): Fastest—avg ~3 s each. The pipeline is stable and predictable, with no failures. The system is slower than real-time due to the combination of YOLO, VLM, and VideoMAE models, but memory usage remains stable and efficient.

4.3 Qualitative Evaluation

The qualitative results show significant improvements in retrieval accuracy, user experience, and platform stability. The system now correctly returns the subject's continuous track, even with complicated multi-attribute descriptions. Specific instances include: "man in black jacket walking," "woman in pink top with backpack," "person riding bike carrying bag." The incorporation of context crops eliminated previous failures when important things, such as cups, phones, or bags, went outside the tight crop. This guarantees that all necessary attributes and moved items have been recorded.

The natural language query engine also worked effectively. Attribute and action names were accurately translated to metadata fields, including: "riding" → mapped to action ride_bike; "girl", "woman", "female" → reliably classified as female; "cap", "hat", "beanie" → matched via the accessories field; "carrying cup", "holding mug", "with bottle" → identified via objects_held.

All major issues documented in earlier versions of the system were fully resolved: No more incorrect person retrieval due to the new (frame, track_id) intersection method; No more corrupted CSV files after implementing strict response cleaning for VLM outputs; Gender detection no longer defaults to male owing to improved attribute parsing; Hand-held object detection is now consistently captured through context crops; Action verb mismatches were eliminated using refined language-to-action mapping rules. These enhancements increase system stability, confirm module robustness, and prepare the platform for real-world forensic deployments.

This section demonstrated that MAGNAS is a reliable complete CCTV search platform, completing all processing steps and generating consistent retrieval results. The results revealed great retrieval accuracy, consistent person-level tracking, and predictable system performance. While temporal localization and attribute extraction

remain difficult in complicated scenarios, the overall assessment shows that the system is effective, useful, and in line with the project's goals.

5. Discussion

The results of this research created MAGNAS, an extensive surveillance-video retrieval system that includes frame extraction, detection, attribute identification, action categorization, and natural-language search. The results reveal that the system performs well in retrieval accuracy, with a high mAP and outstanding Recall@K, making it suitable for person-based forensic searches. The system's interface and logging features also ensured that pipeline execution was reliable, information was generated consistently, and it was useful. Temporal localization was worse, although it performed well for obvious, long-duration activities.

Future work can improve MAGNAS' accuracy, scalability, and real-world application. One significant objective is to improve identity consistency by incorporating a dedicated person Re-Identification (ReID) 51model, which would decrease ID switches and allow the system to track persons more reliably over longer sequences. Furthermore, more complex temporal action models, such as VideoMAEv2, SlowFast, or TimeSformer, might be used to give clearer action boundaries and improved identification of subtle or slow-movement behaviors. Extending the dataset is also important. Evaluating the system on large-scale, diversified CCTV material containing nighttime recordings, busy locations, occlusions, low-resolution cameras, and different views would considerably improve generalization. Synthetic data augmentation and controlled data generation could help expose the system to rare or difficult conditions. The platform's forensic use might potentially be increased by incorporating new analytical modules such as posture estimation, vehicle identification, interaction analysis (e.g.," person passing an object"), or anomaly detection. More intuitive user features, such as visual timelines, heatmaps of identified activities, and multi-query filtering, would make the platform more user-friendly for investigators. Finally, performance optimization by model reduction, batching, or TensorRT acceleration may minimize processing time, bringing it closer to real-time operation. Distributed or cloud-based deployments may also enable the system to manage higher amounts of video data.

6. Future Work and Conclusion

6.1 Future Works

The accuracy, scalability, and applicability of MAGNAS can be improved in the future. The ID switches and long sequence tracking could be better by adding a dedicated person Re-Identification model. More sophisticated temporal action models, including VideoMAEv2, SlowFast, or TimeSformer, might offer better action boundaries and identify smaller-scale actions. Generalization would be enhanced by extending the evaluation datasets with various CCTV footage at night, in overcrowded areas, with occlusions, low resolution, and different viewpoints. Synthetic data augmentation may expose the system to uncommon conditions. Additional modules for forensic use can include posture estimation, vehicle identification, interaction analysis, or anomaly detection. Visual timelines, multi-query filtering, and activity heatmaps can improve user experience. Optimization through model reduction, batching, or TensorRT acceleration may reduce processing time toward real-time operation. Larger video volumes could be managed via distributed or cloud deployment.

6.2 Conclusion

MAGNAS has successfully delivered a functioning, end-to-end CCTV search engine capable of quick and accurate retrieval across a wide variety of queries. While there are still limits in temporal accuracy and in demanding visual situations, the system shows great promise for practical forensic applications with continued development and broader dataset review. MAGNAS has the potential to become a strong real-world investigative tool.

Ethics Declaration: This study did not require ethical approval because no human or animal subjects were involved. The authors affirm that no human research participants were involved in this study; hence, it is not applicable.

AI Declaration: The Authors declare that AI was not used to write the manuscript and that the content represents the authors' original writing, except where an AI tool was used to edit the manuscript to enhance clarity.

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A Harmonised Dashboard for Smart Home Device Security

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Abstract: Smart homes increasingly rely on Internet-connected devices, offering convenient services yet raising significant concerns regarding the protection of personal information. As the number and variety of devices continue to grow, users face fragmented and inconsistent security, privacy, and data-management controls across different manufacturer ecosystems. Although commercial smart home applications provide centralised access, their interfaces often lack coherent structures for managing essential protection features, making it difficult for users to locate controls, understand device status, and maintain awareness of how personal data is collected, stored, and shared. This paper presents the design and evaluation of a harmonised approach to simplify and unify the user experience, via an integrated security and privacy dashboard. The dashboard provides a unified interface for managing heterogeneous smart home devices, with core functionalities structured around Security, Privacy, and Data Management to support consistent navigation and user control. A task-based study with 16 smart-home users evaluated the dashboard against Google Home, Amazon Alexa, and Apple HomeKit applications. Participants completed scenarios involving software updates, microphone controls, reviewing and deleting voice-assistant recordings, checking camera footage, and managing location services. Performance was assessed using task completion rates, task completion time, number of clicks per task, and the System Usability Scale (SUS), alongside qualitative feedback from participants. Results showed that participants were able to complete every task using the dashboard, whereas completion rates on commercial applications were substantially lower. Tasks were completed more quickly and in fewer steps, and the dashboard achieved an "excellent" rating on the System Usability Scale. Qualitative feedback highlighted its intuitive navigation, unified structure, and clear organisation of device-related information. Overall, the findings demonstrate that a harmonised dashboard can reduce complexity, improve user control, and support informed decision-making within smart home environments, ultimately enhancing trust and security for everyday users.

Keywords: Internet of Things, Smart home, Security, Privacy, Usability

1. Introduction

Smart devices have become an integral part of everyday life, with a growing number of households adopting smart home technologies to improve convenience, efficiency, and automation. These environments typically consist of multiple interconnected Internet of Things (IoT) devices that communicate through home networks and cloud services. While such technologies provide significant benefits, they also introduce serious security and privacy challenges that are often not apparent to non-technical users.

Recent studies indicate that managing security and privacy in smart homes has become increasingly challenging due to the rapid growth and heterogeneity of interconnected IoT devices from multiple manufacturers, which rely on diverse protocols, platforms, and continuous Internet connectivity. This complex architecture often results in fragmented ecosystems, inconsistent device interactions, and unclear information presentation, making effective management difficult for end users and leading to misconfigurations and security vulnerabilities (Ahmed and Ko, 2016; Zhu et al., 2023; Vardakis et al., 2024; Magara and Zhou, 2024).

Studies have highlighted the seriousness of these issues, demonstrating that a large proportion of consumer smart devices remain vulnerable to known security threats and that sensitive data transmissions can be exposed to interception (Zhu et al., 2023). These findings emphasise the widespread vulnerabilities in smart home environments and the urgent need for enhanced, user-oriented security solutions. Moreover, integrating smart home systems with cloud services, artificial intelligence, and mobile applications introduces additional security complexities. As digital ecosystems extend beyond local networks, it is more difficult to define and maintain secure boundaries. Cyber attackers can exploit weak configurations and unencrypted communication channels to intercept sensitive information or gain unauthorised access (Ahmed and Ko, 2016; Kalbo et al., 2020).

As responsibility for managing smart home systems increasingly shifts to end users, many individuals are required to configure, monitor, and maintain the security and privacy of their connected devices without sufficient technical knowledge. Previous studies highlight that users frequently struggle to understand device configurations, data flows, and privacy implications, resulting in misconfigurations and exposure to potential cyber threats (Ahmed and Ko, 2016; Geneiatakis et al., 2017).

Although many commercial smart home applications provide centralised access to devices, their interfaces primarily focus on convenience and automation rather than on user-centred security and privacy management. Security mechanisms frequently operate invisibly in the background, and privacy controls are often buried within complex menus or distributed across multiple applications. Consequently, users tend to rely on default configurations or implicit trust in manufacturers rather than actively managing their smart home security and privacy (Shuhaiber and Mashal, 2019).

This paper addresses these challenges by focusing the design and evaluation of a user-centred interactive dashboard, explicit designed to reduce complexity, improve user control, and support informed decision-making in smart home environments. By consolidating security and privacy information from multiple devices into a single interface, the approach aims to enhance user understanding, trust, and overall smart home security.

The remainder of this paper is structured as follows. Section 2 reviews security and privacy challenges in smart home environments and discusses related vulnerabilities and existing research in this area. Section 3 presents the design of the proposed harmonised security and privacy dashboard. Section 4 describes the user evaluation methodology and reports the experimental results. Finally, Section 5 concludes the paper.

2. Security and Privacy in Smart Homes

A smart home refers to a residential environment where household devices and systems are connected to the Internet, enabling automation, remote monitoring, and intelligent control through smartphones or voice-based interfaces (Satpathy, 2006). These environments integrate heterogeneous devices communicating via technologies such as Wi-Fi, Bluetooth, and ZigBee, and often rely on cloud-based services for data processing and coordination. While such connectivity enables convenience and automation, it also introduces security and privacy risks due to the continuous exchange of data and remote access.

2.1 Security and Privacy Vulnerabilities in Smart Home Devices

Recent systematic reviews have further confirmed that smart home IoT environments remain vulnerable to multiple security threats, including unauthorised access, insecure communication channels, and weak authentication mechanisms (Ben-Nakhi, 2025; Popoola et al., 2024). Numerous vulnerabilities have been identified in IoT devices. Eavesdropping, for instance, occurs when an attacker intercepts data transmitted between devices (Mohammad et al., 2019). Moreover, IoT devices are susceptible to various attacks, such as sleep deprivation, node capture, and replay attacks (Lu and Xu, 2018). Devices remain vulnerable due to continuous Internet connectivity and automated configuration mechanisms, which often retain manufacturers' default security settings.

Several studies have documented concrete security and privacy vulnerabilities in consumer smart home devices. Smart speakers have been reported to suffer from several security and privacy vulnerabilities, including continuous listening, unauthorised recording, and weak speech authentication mechanisms (Jackson and Orebaugh, 2018). Research on adversarial voice attacks has further demonstrated that attackers can inject inaudible commands without the user's knowledge, enabling covert device manipulation (Carlini et al., 2016; Zhang et al., 2017). Similar concerns have been identified in smart cameras and video doorbells. Prior work shows that weak authentication, insecure configuration management, and exposed network services can lead to the leakage of sensitive audio and video data (Bugeja et al., 2018).

Beyond vulnerabilities in individual devices, security and privacy risks also emerge at the ecosystem level. Studies have shown that many IoT applications are overprivileged, granting excessive permissions that unnecessarily expand the attack surface (Fernandes et al., 2017). Additionally, insecure over-the-air firmware update mechanisms and voice-based interfaces introduce further attack vectors, enabling hackers to manipulate device behaviour or inject malicious commands (Meng et al., 2018).

2.2 Privacy Concerns in Smart Homes

Privacy in smart home environments refers to users' ability to understand and control how personal data is collected, processed, and shared by connected devices and services (Kotz et al., 2009). Unlike traditional computing environments, smart homes operate through continuous data collection, capturing fine-grained information about users' behaviours, routines, and interactions within private living spaces.

Prior research has shown that privacy risks extend beyond direct data disclosure. Even encrypted or metadata-only network traffic can be analysed to infer sensitive information, including occupancy patterns, daily routines,

and individual activities (Apthorpe et al., 2017). As a result, privacy threats in smart home environments often arise through indirect behavioural inference rather than explicit data breaches.

In addition to these technical risks, recent studies highlight that users remain concerned about how personal data collected by smart home devices is stored, processed, and shared with third parties (Magara and Zhou, 2024; Haney et al., 2025).

Although numerous technical solutions for privacy protection have been proposed, human–computer interaction studies consistently demonstrate that users struggle to understand data flows and privacy implications in smart home ecosystems. Users frequently prioritise convenience over privacy, rely on default configurations, and lack awareness of how their data is collected and used (Emami-Naeini et al., 2019). This gap highlights a mismatch between existing privacy mechanisms and users' practical ability to manage them effectively.

2.3 Related Work and Existing Solutions

Existing research on smart home security and privacy has examined both backend enforcement mechanisms and user-facing tools. Backend-oriented solutions, such as ProvThings (Wang et al., 2018) and SmartAuth (Tian et al., 2017), focus on detecting malicious behaviour and misconfigurations within IoT ecosystems. While these approaches are effective at a technical level, they are primarily designed for developers and system administrators, offering limited visibility or control for end users.

More recent work has shifted attention toward user-facing interfaces, introducing interactive dashboards to improve user awareness of device activity and data sharing. Systems such as SaferHome (Windl et al., 2022) and Peekaboo (Jin et al., 2022) visualise aspects of smart home behaviour, helping users understand where and how data is processed and transmitted. However, these solutions typically address specific dimensions of security or privacy and do not support unified management across heterogeneous devices.

Commercial platforms, including Google Home, Amazon Alexa, and Apple HomeKit, provide centralised device control but operate within closed ecosystems. As a result, they offer limited transparency into permissions, data flows, and security configurations. Users are often required to manage security and privacy settings across multiple fragmented interfaces, which increases cognitive load and raises the risk of misconfiguration (Geneiatakis et al., 2017).

In addition to commercial platforms, several open-source smart home frameworks have been developed, such as Home Assistant (Home Assistant, 2024) and OpenHAB (OpenHAB, 2024) provide robust interfaces that facilitate the monitoring of household devices and tracking energy generation and consumption through their integrated Energy Dashboards. However, their interfaces primarily focus on automation and device control rather than structured security and privacy management, which can make it difficult for non-technical users to understand and manage protection settings effectively.

Overall, prior work demonstrates significant progress in addressing smart home security and privacy challenges. Nevertheless, existing solutions remain fragmented, frequently separating security from privacy and prioritising backend protection over user-centred interaction. This gap highlights the need for unified and accessible interfaces that better support user awareness, understanding, and effective security and privacy management across diverse smart home devices.

3. Designing a Harmonised Security and Privacy Dashboard

The proposed dashboard is designed to address the fragmentation and complexity of security, privacy, and data management in current smart home environments. To achieve this, an effective all-in-one smart home solution should integrate key capabilities, including improved visibility of device status, integrated management of security and privacy settings, and greater transparency in data management.

The design requirements for the proposed dashboard were informed by prior analysis conducted by the authors (Alghamdi et al., 2024), alongside established usability and human–computer interaction principles. These insights were used to identify key usability challenges and user needs in smart home environments.

Based on these insights, the design of the proposed dashboard is guided by the following requirements:

- **Unified Interface**: Provide a dashboard to manage security, privacy, and data across all devices.
- **Consolidated Controls:** Combine related settings such as device status, permissions, and updates into a single clear view to reduce complexity.

- **Real-Time Status and Alerts:** Display live device status using clear indicators and timely notifications.
- **Unified Data Management:** Standardize data actions such as viewing, deleting, and scheduling deletion across devices.
- **Data Categorisation:** Clearly distinguish between different data types, including tracking data and stored content.
- **Role-Based Access Control:** Support multiple user roles, including admin, adult, child, and guest, with appropriate permissions.
- **Cross-Device Compatibility**: Enable seamless control of a wide range of smart home devices within a single platform.

The Dashboard is designed to provide users with an efficient means to determine the status of their smart home devices from different perspectives, such as room locations, device types, device users, and data locations. These perspectives serve as the top-level entry points, allowing users to navigate to specific routes that provide views of individual devices and their associated status and settings. The structure of the dashboard and some of the routes to individual devices are illustrated in Figure 1. The design is tailored to enhance user experience, providing them with the necessary information in a clear, concise, and intuitive manner.

In a comprehensive analysis of various devices, key features were grouped into three main categories. These categories are derived from prior analysis conducted by the authors (Alghamdi et al., 2024), which examined security, privacy, and data management features across smart home devices, highlighting variations in how they are presented across different platforms. The Security category encompasses registration, authorisation, authentication, and security updates, which are essential for safeguarding user data. Privacy encompasses microphone access, location services, camera use, and usage habits, all of which are essential to protecting user privacy. Data Management comprises deleting specific or all recordings, scheduled deletions, and usage history, all of which are important for effectively managing user data.

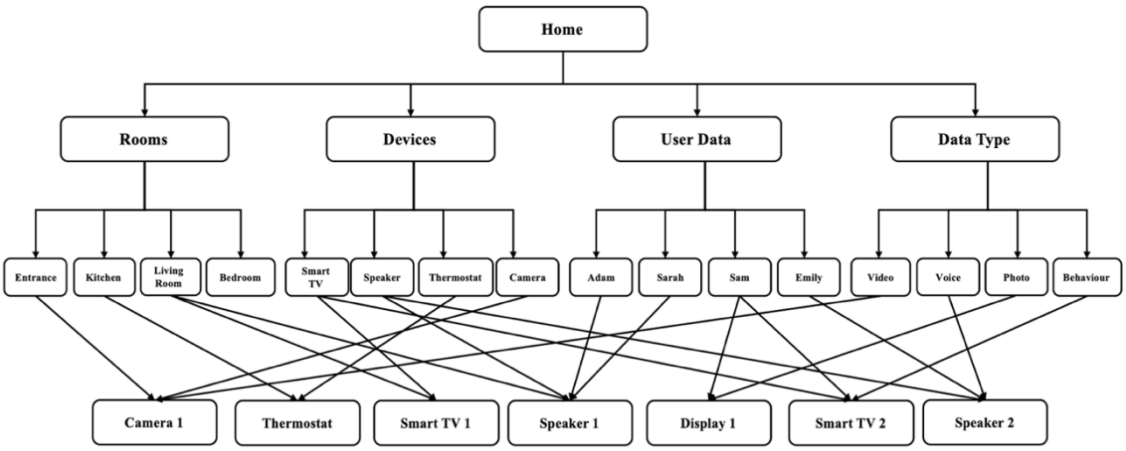


Figure 1: Dashboard Navigational Structure

To ensure that the Dashboard prototype met widely recognised usability standards, its design was evaluated against Nielsen's ten usability heuristics (Nielsen, 1994). These heuristics provide a well-established framework for assessing user interface quality and supporting both novice and expert users. Most principles, including visibility of system status, match between the system and the real world, consistency and standards, user control and freedom, recognition rather than recall, aesthetic and minimalist design, and error prevention, were fully implemented. Advanced flexibility and detailed error recovery mechanisms were partially addressed due to the scope and fidelity of the prototype.

In addition to general usability principles, Human Computer Interaction for Security (HCISec) guidelines were incorporated to address challenges specific to security-oriented systems. These principles emphasise clear visibility of security status, the use of minimal technical jargon, and support for informed user decision-making. Prior research highlights the importance of these factors in security dashboards, particularly in helping users understand risks and manage protective controls effectively (Ibrahim et al., 2010).

4. An Overview of the Dashboard Prototype

The initial dashboard interface, shown in Figure 2, provides a clear and structured overview that enables users to manage smart home devices from multiple perspectives. The interface is organised around four main categories: Rooms**,** Devices**,** User Data, and Data Types, which reflect users' primary concerns when managing a smart home. In addition, a set of core navigation icons on the left of the screen support system management, providing access to the home view, informational guidance, device health status, household members, software update, device management, and system settings. Together, they enable users to monitor device status, manage permissions, receive alerts, and configure preferences through a consistent and easily accessible structure.

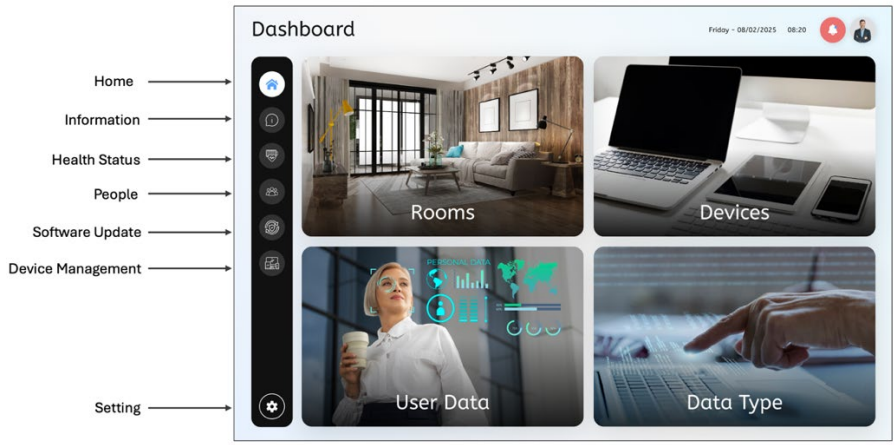
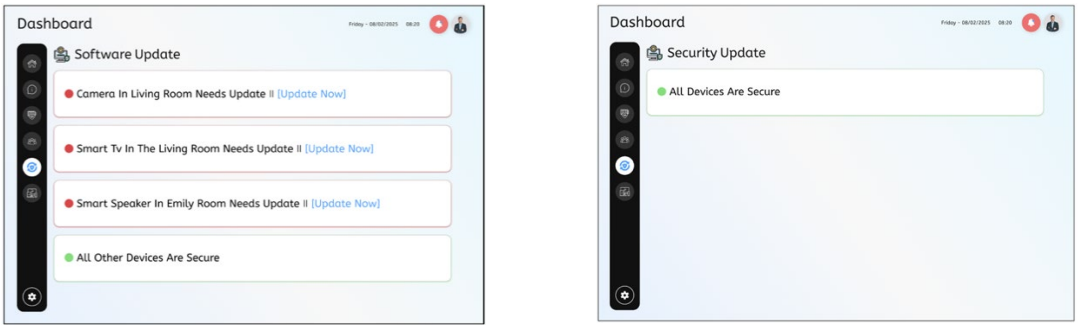


Figure 2: Home Interface

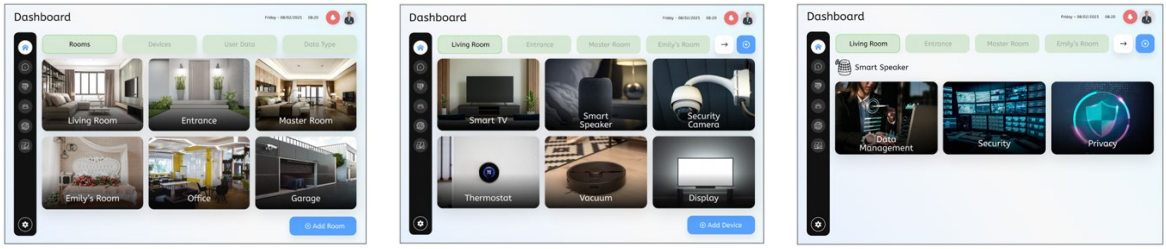
Figure 3 presents the software update interfaces, which provides an overview of update status across all connected smart home devices. Figure 3(a) highlights devices requiring immediate updates using red status indicators and provides an "Update Now" option to support prompt user action. In contrast, Figure 3(b) is displayed when all devices are fully updated, showing a single green status message. This conditional presentation ensures that users are shown only relevant information, reducing cognitive load and enabling efficient identification and resolution of security updates.



(a) (b)

Figure 3: Software Update Interfaces

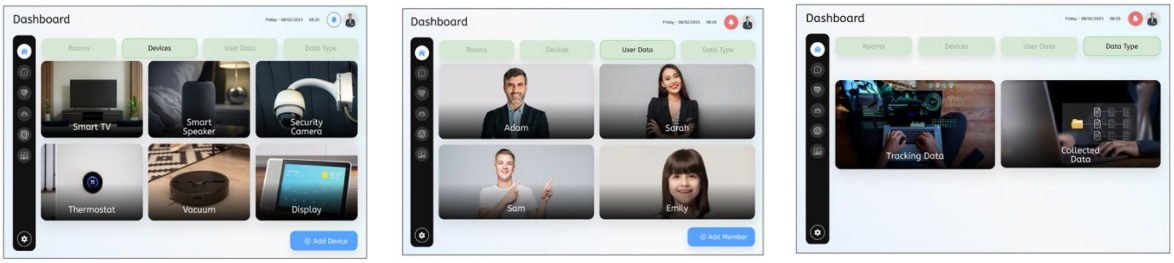
As illustrated in Figure 2, the Dashboard offers several routes by which users can explore their smart home configuration, namely via Rooms, Devices, Users, and Data Types. Each then offers a means to drill down to individual security and privacy settings. As an example, the Rooms view enables users to manage devices and privacy settings based on physical location within the home. As illustrated in Figure 4, users can navigate from a top-level overview of all rooms (4a), via devices in the room (4b), to a specific device within a selected room (4c), from which users can access device-specific Security, Privacy, and Data Management controls.



(a) (b) (c)

Figure 4: Rooms Interfaces route, showing: (a) rooms; (b) devices within a room; (c) settings on a device

Each of the other routes also expands in a similar manner. Space constraints prevent a full depiction of each route, but Figure 5 provides an illustration of the next level down within each one.

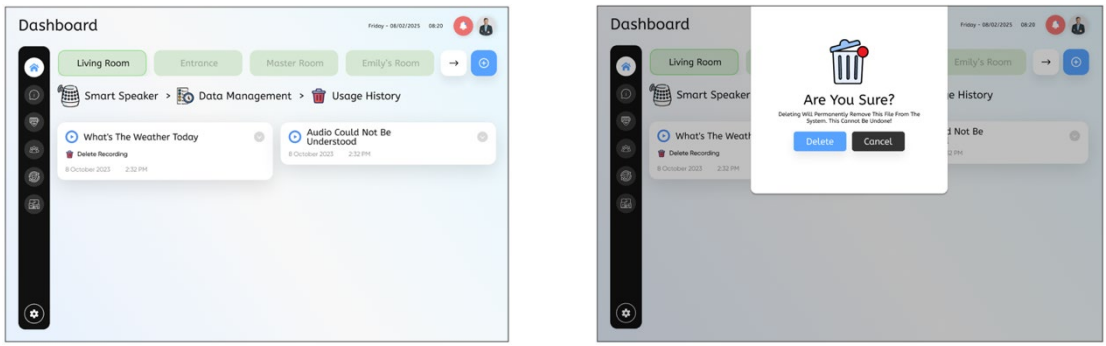


(a) (b) (c)

Figure 5: Alternative navigation routes, showing: (a) by device type; (b) by user type; (c) by data type

5. User Evaluation

A task-based user study was conducted to compare the user experience of the dashboard against three commercial platforms: Google Home, Amazon Alexa, and Apple HomeKit. These platforms were selected for comparison because they represent the three most widely adopted commercial smart home ecosystems. They support a broad range of consumer IoT devices and are commonly used to manage smart home environments through mobile applications. Evaluating the proposed dashboard against these platforms provides a realistic benchmark and enables comparison with interfaces that users are most likely to encounter in real-world smart home deployments. The evaluation aimed to assess how efficiently and effectively users could complete common security and privacy tasks, as well as their overall satisfaction with each platform, using a combination of quantitative performance metrics and qualitative feedback. Five scenarios were selected for the main evaluation, representing critical and common security and privacy interactions in smart home environments: Checking software updates; Managing smart speaker recordings; Muting microphones during meetings; Turning off location services across devices; and Reviewing security camera recordings. A set of task-specific interfaces were designed to reflect the interactions experienced by participants. The software update functionality was provided through the interface presented earlier in Figure 3. Figure 6 presents representative examples of the remaining interfaces used in the evaluation.



(a) (b)

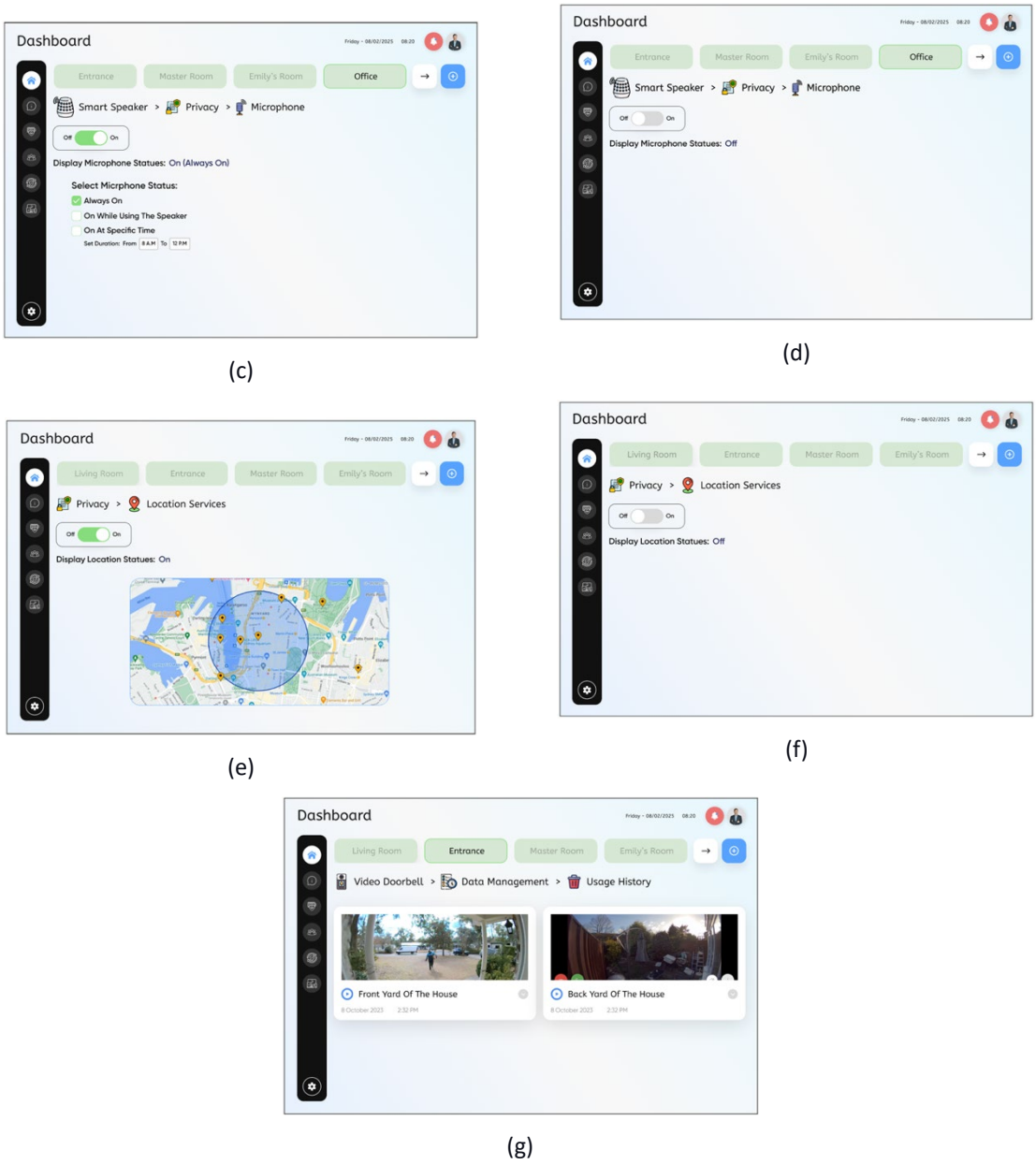


Figure 6: Task-based interfaces used during the evaluation: (a–b) managing smart speaker recordings; (c–d) muting microphones; (e–f) turning off location services; and (g) reviewing security camera recordings

A total of 16 participants took part in the study. This sample size aligns with established usability evaluation guidelines, which indicate that 12–20 participants are sufficient to identify most usability issues and derive meaningful insights (Nielsen, 1994; Virzi, 1992). All participants owned at least two smart home devices and had sufficient English proficiency to understand task instructions and complete post-task questionnaires. Participants represented a range of digital literacy levels and backgrounds, reflecting a realistic smart home user population.

To ensure realism, real smart home devices, including smart speakers and security cameras, were configured and connected to their respective platforms. Devices were preloaded with realistic data, such as voice recordings, video recordings, and privacy-related settings. All tasks were performed on the same tablet device to maintain consistent experimental conditions. Participants completed the same set of tasks on each platform. The order of platform exposure was counterbalanced to reduce learning and order effects. During task execution, task completion time, number of clicks, and task success were recorded. After completing the tasks on each platform, participants completed the System Usability Scale (SUS) questionnaire and provided qualitative feedback.

Efficiency is important for evaluating how easily and quickly users can complete tasks on different platforms and was assessed using task completion time and the number of clicks required per task.

- **Task completion time**: Figure 7(a) shows the dashboard achieving the fastest mean task completion time (33 seconds). Amazon consistently exhibited the slowest performance and the greatest variability, indicating less predictable task flows. Google and Apple had moderate performance but still required more time than the dashboard.
- **Clicks per task:** A similar pattern is observed in Figure 7(b), which presents the mean number of clicks per task. The dashboard required fewer interactions than other platforms, reflecting a more streamlined and direct interaction design. In contrast, Google and Amazon required the highest number of clicks, suggesting more fragmented navigation paths, while Apple occupied an intermediate position.

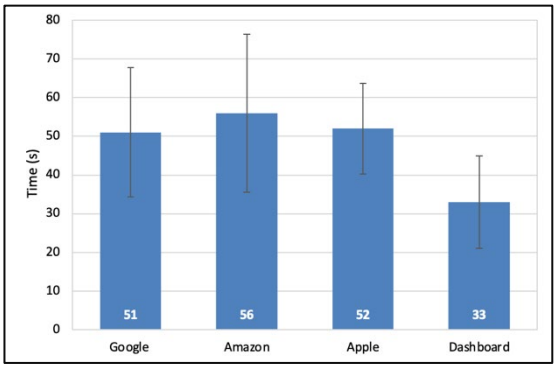
Overall, these results demonstrate that the dashboard supports more efficient task execution than Google, Amazon, and Apple by reducing both completion time and interaction effort.

Effectiveness was measured using task completion rates. Figure 7(c) shows that all participants successfully completed all tasks using the dashboard. In contrast, task failures were observed on all other platforms. Among these, Google achieved higher completion rates than Amazon and Apple, although with noticeable variability. Amazon exhibited the lowest and most inconsistent success rates, particularly for privacy-related tasks, while Apple showed more stable but generally lower completion rates. These findings indicate that, unlike the dashboard, existing platforms do not consistently support successful task completion across users.

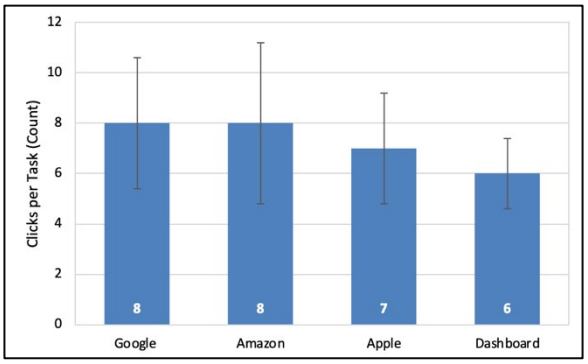
Finally, user satisfaction was evaluated using the System Usability Scale (SUS). As illustrated in Figure 7(d), the dashboard demonstrates the highest perceived usability, with a mean SUS score of 86, clearly outperforming Google, Amazon, and Apple. Amazon received the lowest usability ratings and the highest variability, indicating inconsistent user experiences. Google and Apple achieved moderate scores, with Apple showing more consistency but lower overall usability.

Qualitative feedback highlighted the dashboard's intuitive navigation, unified structure, and clarity of security and privacy controls. Participants frequently described the dashboard as "easy," "straightforward," and "clear," emphasising the benefit of managing all devices and data in a single interface. Many participants stated they would recommend the dashboard to others, including non-technical users. In contrast, Google, Amazon, and Apple were commonly described as confusing or overly complex, with privacy settings distributed across multiple menus. Several participants reported giving up on some tasks when using commercial platforms, particularly those involving recordings or privacy controls.

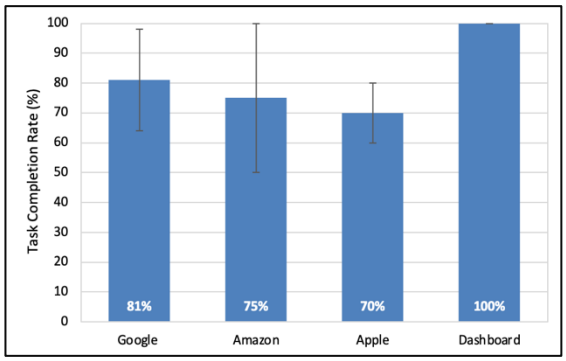
The task failures observed in these platforms appear to be largely associated with fragmented interface structures and the distribution of security and privacy settings across multiple layers of the interface. Participants frequently reported difficulty locating specific privacy controls, such as voice recording management or location permissions, which were often buried several levels within the interface hierarchy. By contrast, the proposed dashboard consolidates these functions within clearly labelled categories. This structure reduces navigation complexity and helps users more easily locate key security and privacy controls.



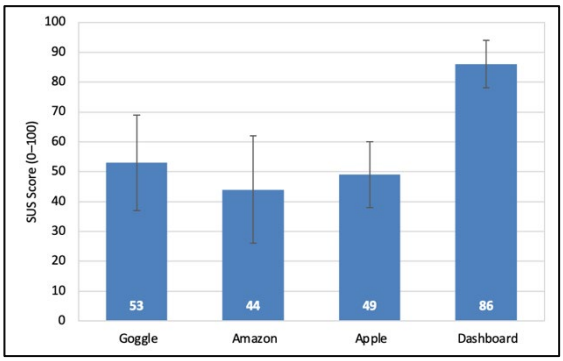
(a) mean task completion time



(b) mean number of clicks per task



(c) task completion rate



(d) System Usability Scale (SUS) scores

Figure 7: Efficiency, effectiveness, and satisfaction results by platform. Error bars represent standard deviation

6. Conclusion

This paper presented the design and evaluation of a harmonised dashboard for managing security and privacy in smart home environments. As smart homes increasingly consist of heterogeneous devices operating across multiple ecosystems, users are often required to manage complex security and privacy settings through fragmented and inconsistent interfaces. This work addressed these challenges by proposing a unified, user-centred dashboard that integrates security, privacy, and data management controls across devices.

A task-based user evaluation compared the proposed dashboard with three widely used commercial platforms, with the results demonstrating clear advantages of the dashboard across all evaluated dimensions. Participants completed tasks more efficiently, required fewer interactions, and achieved higher task success rates when using the dashboard. Notably, all participants successfully completed all tasks on the dashboard, while failures were observed on the commercial platforms, particularly for privacy-related scenarios. User satisfaction results further reinforced these findings. The dashboard achieved the highest SUS scores with low variability, indicating strong perceived usability and consistent user agreement. Qualitative feedback highlighted the dashboard's intuitive navigation, unified structure, and ability to support confident and informed decision-making. In contrast, other platforms were frequently described as complex, fragmented, and difficult to navigate.

Overall, the findings demonstrate that a harmonised, user-centred dashboard can substantially improve how users manage smart home security and privacy. By reducing complexity and providing consistent access to critical controls, the proposed approach supports more efficient, effective, and satisfying user interactions. This work highlights the importance of integrating usability considerations into the design of security-critical systems and provides a strong foundation for future research into scalable deployment and long-term use of unified smart home management interfaces.

Ethics Declaration: The study was approved by the School of Computer Science Research Ethics Committee [CS-2024-R21]. Data was collected anonymously and participants were informed that they could withdraw at any time.

AI Declaration: No AI tools were used in this paper.

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A Multimodal Authorization Approach for Integrated Access Control Process

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Abstract: Traditional authorization mechanisms such as passwords, smart cards, and conventional biometrics remain vulnerable to spoofing, replay, and social-engineering attacks, particularly in IoT and cloud environments. Physiological biometrics, including electrocardiogram (ECG) and electromyography (EMG) signals, offer stronger resistance to forgery because of their biological origin while also capturing emotional and behavioral context. This study presents AlMuwathiq, an emotion-based multimodal authorization system that integrates ECG and EMG signals to support adaptive access-control decisions. Real physiological signals were collected and labeled using the Self-Assessment Manikin across five emotional states. After signal preprocessing and feature extraction, multiple machine learning models were evaluated, with a focus on explainable learning algorithms. Experimental results indicate that Random Forest and XGBoost achieved the most stable classification performance. The trained models were integrated into a real-time platform where access control authorization decisions are determined by emotional rules. The findings demonstrate that emotion-aware physiological authorization can enhance security, reliability, and context awareness in modern cybersecurity systems. This study thus advances the current state of the art in access control systems, especially in mission-critical infrastructures.

Keywords: Emotion-based authorization, Physiological biometrics, Electrocardiogram (ECG), Electromyography (EMG), Multimodal authentication, Affective computing, Machine learning, Access control, Cybersecurity

1. Introduction

Authentication is a fundamental security mechanism that verifies users' identities and grants access only to authorized individuals. It plays a critical role in protecting systems and sensitive data from unauthorized access. This process typically relies on three main factors: something the user knows (such as passwords), something the user has (such as tokens or smart cards), and something the user is (biometric characteristics). While these methods are widely used due to their simplicity and ease of implementation, they also suffer from several limitations. Password-based authentication, for example, is highly vulnerable to brute-force attacks, phishing, and credential theft (Florêncio & Herley, 2007). Similarly, token-based methods may fail if the physical device is lost, stolen, or duplicated, which creates additional security risks. There are many authentication challenges in the Internet of Things (IoT), including security risks that might threaten network security. Examples include man-in-the-middle attacks, in which an attacker sits between two parties and intercepts data as it is transferred, and brute-force attacks, which repeatedly guess passwords. In addition, there are privacy concerns; biometric data such as iris scans, fingerprints, and voice recognition can be collected, and the user's location can be saved with the data. This can lead to unauthorized tracking, which is a major privacy issue. Moreover, there is a concern about flexibility, as many devices require authentication to maintain a high level of security and support intelligent solutions such as artificial intelligence. Resource limitations are another challenge, since devices often have limited memory and battery power (Alsheavi et al., 2024).

A typical user authentication process follows a structured sequence: an identity claim, credential submission, and verification against stored data (Adeyemi & Ithnin, 2012). If the credentials match, access is granted; otherwise, it is denied. However, traditional systems often rely on single-factor authentication, which significantly increases the risk of unauthorized access. Modern systems have therefore shifted toward multi-factor authentication (MFA), combining multiple verification methods to improve security. Despite these improvements, authentication alone is not sufficient. Authorization plays an equally important role, as it determines what actions a verified user is allowed to perform within a system. Authorization ensures that users only access resources that match their permission level. As highlighted in the project, authorization mechanisms follow specific rules that define access based on factors such as roles, policies, and system conditions. Common models include Role-Based Access Control (RBAC), Attribute-Based Access Control (ABAC), and Policy-Based Access Control (PBAC). However, traditional authorization methods are often static and do not adapt to real-time conditions. In modern environments such as IoT and cloud systems, this creates serious challenges. Devices in these environments are often resource-constrained and may lack proper security configurations, making it difficult to enforce consistent access control policies (Khan et al., 2022). As a result, even if authentication is

successful, weak authorization can still lead to security breaches. To address these limitations, researchers have explored more advanced profiling-based mechanisms that extend beyond static authentication and focus on continuously understanding user behavior and characteristics. These profiling approaches include multiple dimensions. User profiling enables adaptive systems to learn preferences over time through explicit and implicit data collection, thereby improving personalization and decision-making accuracy. Physiological profiling uses biological signals such as EEG, ECG, and GSR to measure cognitive states, such as attention and engagement, enabling systems to detect deeper user conditions. Sociological profiling examines how social structures and behavioral mechanisms influence human actions, highlighting ethical concerns when human behavior is oversimplified into machine-like processes. Linguistic profiling treats speech and writing patterns as a digital fingerprint by analyzing vocabulary, tone, and typing behavior for identity verification. Psychological profiling focuses on personality traits, such as the Big Five model, and is often applied to machine learning systems to infer behavioral tendencies, though it raises concerns about bias and fairness. Behavioral profiling enables continuous authentication through patterns such as typing, touch gestures, movement, and eye behavior, making identity verification ongoing rather than one-time. Together, these profiling mechanisms create a more adaptive and multi-dimensional understanding of users, but they also introduce challenges related to privacy, ethics, and data interpretation.

Building on these advancements, researchers have explored biometric-based approaches, particularly physiological biometrics. Unlike traditional biometrics such as fingerprints or facial recognition, physiological signals originate from within the human body, making them more secure and difficult to replicate. Two important physiological signals are the electrocardiogram (ECG) and electromyography (EMG). ECG signals measure the electrical activity of the heart, producing waveform patterns that are unique to each individual. EMG signals, on the other hand, measure muscle activity and reflect how muscles respond during movement or expression. As stated in the project, these signals “are difficult to forge and contain individual-specific patterns,” making them highly suitable for authentication and authorization systems (Israel et al., 2005; Jain et al., 2016). In addition to identity verification, physiological signals provide valuable insights into a user's emotional state. This concept is supported by research in affective computing, which focuses on detecting and interpreting human emotions using computational methods. According to the project, physiological signals such as ECG and EMG can reflect emotional states like calmness, stress, and frustration, which may influence user behavior during access attempts. For example, a sudden increase in heart rate or muscle tension may indicate stress or abnormal conditions. Incorporating this emotional information into authorization decisions allows systems to become more context-aware and adaptive (Picard, 1997). Several studies have explored the relationship between ECG signals and emotional states. ECG-based emotion recognition typically analyzes features such as heart rate variability, waveform morphology, and frequency-domain characteristics. Similarly, EMG signals—especially those collected from facial muscles—can be used to detect emotions such as happiness, anger, and sadness by analyzing muscle activation patterns. Machine learning techniques play a crucial role in this process. Algorithms such as Support Vector Machines (SVMs), Random Forests, K-Nearest Neighbors (KNNs), and deep learning models are commonly used to classify emotional states based on extracted features. These models learn patterns from labeled datasets and can achieve high accuracy in recognizing different emotions. To further improve system performance, researchers have introduced multimodal biometric systems that combine multiple physiological signals. Instead of relying on a single signal, multimodal systems integrate ECG and EMG data to enhance accuracy and reliability. As mentioned in the project, combining multiple signals helps “reduce noise, improve classification performance, and increase resistance to spoofing attacks”. This approach is particularly useful in real-world scenarios where signal quality may vary due to movement or environmental conditions. Multimodal systems also provide better robustness, as they rely on multiple sources of information rather than a single point of failure (Ross & Jain, 2004).

Despite the advantages of physiological biometric systems, several limitations still exist in current research. Many existing studies focus on ECG or EMG signals independently, without fully exploring the benefits of combining the two modalities in a unified framework. In addition, most traditional systems rely primarily on identity verification and do not consider the user's emotional or behavioral context during access attempts. This creates a gap where authorized users may still gain access under abnormal or high-risk conditions, such as stress or coercion. Furthermore, challenges such as signal variability, noise interference, and privacy concerns continue to affect the reliability and real-world applicability of these systems. While preprocessing and machine learning techniques have improved classification performance, there is still a need for systems that can operate reliably in dynamic environments while maintaining user privacy and security (Khan et al., 2020; Meltzer & Luengo, 2023; Wang et al., 2025). Therefore, this study builds on existing research by proposing a multimodal authorization approach that integrates both ECG and EMG signals with emotional state recognition. By combining multiple

physiological signals and incorporating emotional awareness into access control decisions, the proposed system aims to provide a more secure, adaptive, and context-aware authorization mechanism compared to traditional methods.

2. Background of the Study

This section reviews existing studies related to electrocardiogram (ECG) and electromyogram (EMG) biosignal technologies, with a focus on privacy, authorization mechanisms, and data security challenges. It examines identified risks, such as unauthorized access and re-identification, and emphasizes the need for structured authorization and forensic-aware frameworks to support the secure and ethical management of biosignal data within wearable and remote healthcare systems. With the rapid growth of wearable and remote healthcare technologies, the privacy and authorization of biosignals such as electrocardiogram (ECG) and electromyogram (EMG) data have become increasingly critical research concerns. These signals are widely used in clinical environments and biomedical research for their diagnostic value; however, their high sensitivity raises serious concerns about data access, misuse, and patient privacy. Prior studies have shown that ECG data, in particular, can reveal uniquely identifiable and personal information. Wang et al. (2025) demonstrated that ECG datasets shared without proper anonymization are vulnerable to re-identification attacks, emphasizing the need for strict authorization mechanisms and controlled access. Similarly, Meltzer and Luengo (2023) highlighted that the intrinsic uniqueness of ECG signals makes them comparable to biometric identifiers, meaning that even short recordings can expose sensitive health-related details if accessed without appropriate safeguards.

From a legal and ethical perspective, healthcare regulations such as the Health Insurance Portability and Accountability Act (HIPAA) mandate explicit patient authorization before biosignal data can be accessed or shared. These regulatory frameworks emphasize accountability and informed consent, particularly when ECG and EMG data are collected, processed, or transmitted through online and wearable systems. Overall, the literature consistently underscores the importance of robust authorization and privacy controls for the ethical, secure, and lawful management of biosignal data, especially as wearable medical devices become increasingly integrated into modern healthcare infrastructures. Although the advantages of ECG and EMG are based on systems, there are multiple challenges from different perspectives. From a security perspective, wearable and IoT environments can be vulnerable to unauthorized access and inadequate protection, putting sensitive data at high risk. From a technical side, these signals can be affected by noise, sensor placement, and changes in the user's condition, which may reduce accuracy. In addition, traditional authorization methods have limitations, such as the risk of stolen access cards or granting users more permissions than needed. To address these issues, our system (AlMuwathiq) uses a combination of ECG and EMG signals to create a more secure and reliable approach. It improves accuracy through signal processing and machine learning, and it makes smarter authorization decisions by also considering the user's emotional state, making the system more adaptive and secure.

3. Methodology

The methodology followed in this study is illustrated in the operational framework shown in Figure 1. The framework consists of a setup phase and three main phases covering dataset development, signal preprocessing, machine learning experimentation, and the final integration of the authorization platform. Each stage reflects the actual workflow used to implement the access control system (hereinafter, the AlMuwathiq system).

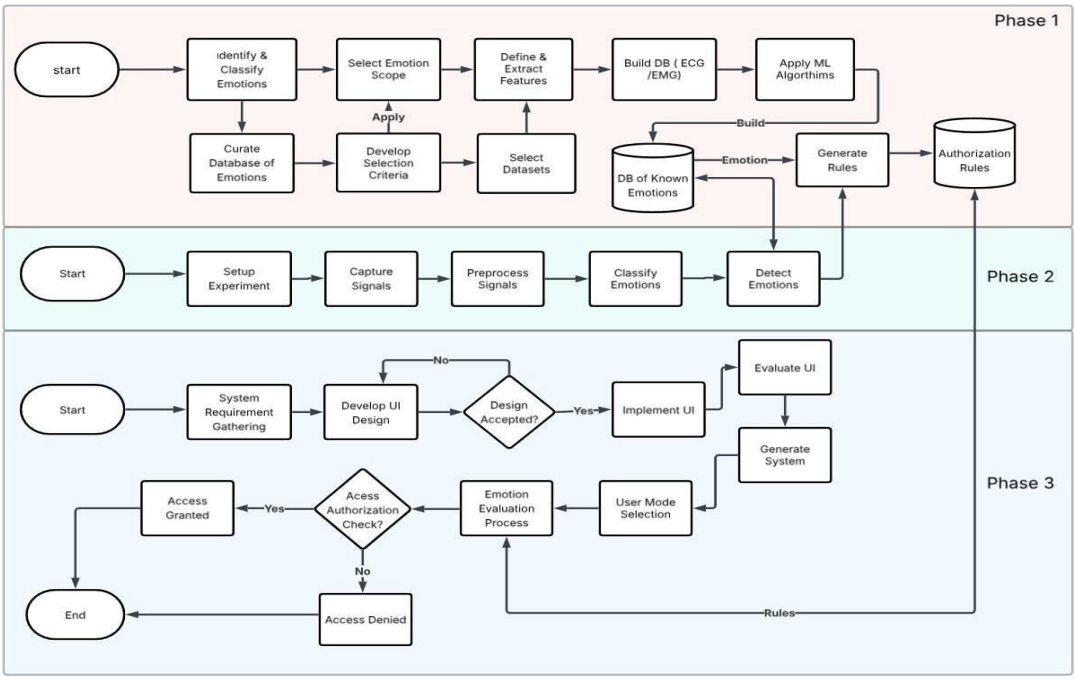


Figure 1: Operational Framework

3.1 Setup Phase

In the setup phase, the ECG and EMG sensors were carefully connected to the hardware device and allowed to ensure reliable signal acquisition. The Arduino was configured to read the analog inputs from both sensors and transmit the recorded values for further processing. The software environment, including Python and required packages, was prepared to support the preprocessing, feature extraction, and machine learning stages of the study. Table 1 provides an overview of all components used in the system configuration.

Table 1: Tools, Sensors, and Software Used in the System

Component	Description
ECG Sensor	Captures electrical heart activity through analog pin A0
EMG Sensor	Measures muscle activation through analog pins A1 and A3
Arduino Board	Acquires raw signals and transmits them via serial output
Python	Used for preprocessing and machine learning
Platform	Allows users to upload signals and receive authorization results

3.2 Phase I: Dataset Development

In this phase, real ECG and EMG signals were collected from users using the configured hardware device. Signals were captured in real time and exported as CSV files. Each recording was labeled with one of the five emotional categories defined in the system: Calm, Amused, Satisfied, Gloomy, or Frustrated. To ensure labeling is correct, the Self-Assessment Manikin (SAM) was administered after each recording. The SAM values were used as ground-truth labels for the machine-learning dataset (Handayani et al., 2015).

3.3 Phase II: Signal Preprocessing and Feature Extraction

Raw ECG and EMG signals contain noise and irregularities; therefore, a preprocessing pipeline was implemented. Signal cleaning included:

- Bandpass filtering to isolate relevant frequency ranges

- Notch filtering to remove 50/60 Hz power-line noise
- Smoothing and denoising to reduce signal artifacts
- Windowing by dividing the signal into equal segments

After preprocessing, features were extracted from each window. The features listed below match the actual feature sets used

Table 2: ECG Feature Set Extracted

Feature Category	**Extracted Features**
Time-Domain	Mean, Standard Deviation (STD), Root Mean Square (RMS), Peak-to-Peak
Frequency-Domain	Power Spectral Density (PSD-based features), Dominant Frequency
Statistical Features	Variance, Skewness, Kurtosis
Morphological	R-peak information (from processed ECG waveform when applicable)

Table 3: EMG Feature Set Extracted

Feature Category	**Extracted Features**
Time-Domain	Mean Absolute Value (MAV), Root Mean Square (RMS), Waveform Length (WL)
Frequency-Domain	Median Frequency, Mean Frequency
Statistical	Variance, Log Energy Entropy
Signal Shape Features	Slope Sign Changes (SSC), Zero Crossings (ZC)

3.4 Phase III: Machine Learning Experimentation

The extracted features were used to train and evaluate multiple classification models. The algorithms tested include:

- Random Forest
- XGBoost
- Support Vector Machine (SVM)
- K-Nearest Neighbors (KNN)

Model performance was evaluated using accuracy, precision, recall, F1-score, and confusion matrix. Two experiments were carried out: an initial experiment and an optimized version after refining the preprocessing pipeline and dataset structure. The following table summarizes the general performance patterns of the models based on your results.

Table 4: Model Evaluation Overview

Model	**Performance Summary**
Random Forest	Strong and stable performance; among the highest accuracy and F1-score in both experiments
XGBoost	High accuracy and strong performance after optimization
SVM	Moderate performance; sensitive to noise and variability
KNN	Lowest performance; not suitable for this dataset

3.5 Authorization System Development

In this final phase, the trained models were integrated into the AlMuwathiq authorization platform. The system allows users to upload an ECG or EMG CSV file, select a classification model, and receive an emotion prediction, after which access is automatically granted or denied based on predefined emotional rules.

Emotional authorization rules used:

- Calm, Satisfied, Amused → Access Granted
- Gloomy, Frustrated → Access Denied

4. Discussion

The results of this project demonstrate that integrating privacy-aware authorization mechanisms into biosignal-based systems is both necessary and feasible. The findings confirm that ECG and EMG signals are not only valuable for health monitoring and authentication, but also pose significant privacy risks when handled without strict access controls. Throughout the project, the implemented authorization approach showed that limiting access based on predefined conditions and user roles can effectively reduce the exposure of sensitive biosignal data. This supports the argument presented in the literature that biosignals should not be treated as ordinary medical data, but rather as high-risk biometric-like information requiring stronger protection.

From a system perspective, the final project successfully translates theoretical privacy and authorization concerns into a practical framework. The results indicate that combining authorization logic with biosignal processing enhances data security without disrupting system functionality or usability. This balance is critical in wearable and remote healthcare environments, where continuous data collection is required. Moreover, the project highlights that simple anonymization alone is insufficient, as ECG characteristics remain identifiable even in limited samples. By enforcing controlled access and explicit authorization, the system aligns more closely with legal and ethical requirements such as patient consent and accountability, as emphasized by healthcare regulations.

Overall, the project outcomes validate the proposed approach and demonstrate its relevance to real-world applications involving wearable medical devices. The results contribute to existing research by showing how authorization mechanisms can be practically embedded within biosignal systems rather than treated as an external policy layer. While the project is limited to a controlled experimental setup, it establishes a strong foundation for future work, including real-time deployment, larger datasets, and integration with advanced security frameworks. In conclusion, the results confirm that privacy-preserving authorization is a critical component for the secure and ethical use of ECG and EMG technologies, reinforcing the overall objectives of the final project.

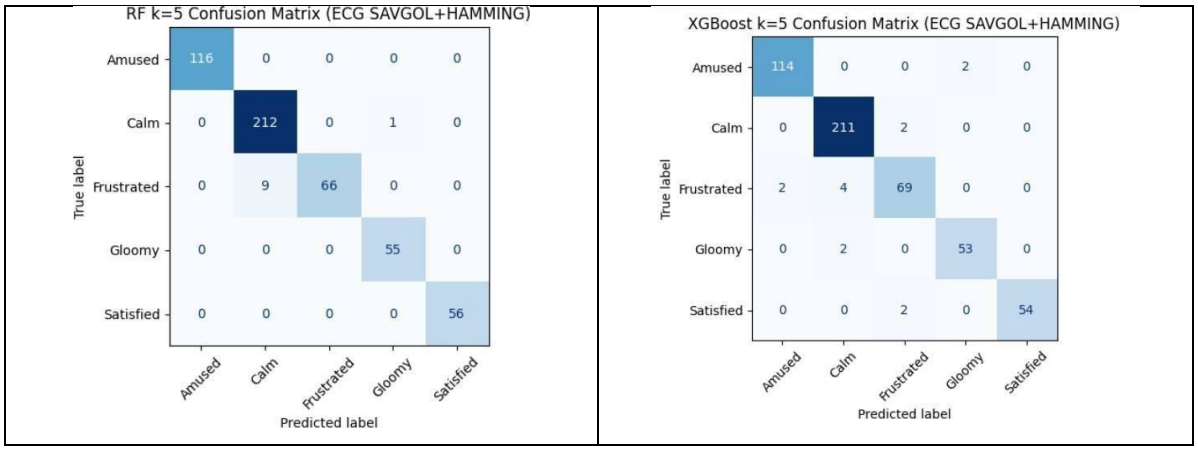


Figure 2-3: Confusion Matrix for Random Forest & XGBoost (k=5) using ECG SAVGOL+HAMMING

The confusion matrix analyses provide strong evidence of the effectiveness and stability of the proposed multimodal emotion-based authorization framework. Across both ECG and EMG modalities, the evaluated models demonstrate a dominant diagonal structure, indicating that the majority of samples were correctly classified into their respective emotional categories. In particular, the ECG-based results using the SAVGOL+HAMMING preprocessing configuration show consistently high recognition performance for all five emotional states. The limited misclassifications observed—primarily between Frustrated and Calm—suggest

that these emotions share partially overlapping physiological characteristics, a phenomenon commonly reported in affective computing literature. Nevertheless, the overall classification stability indicates that the selected ECG preprocessing pipeline preserves discriminative emotional features while remaining robust.

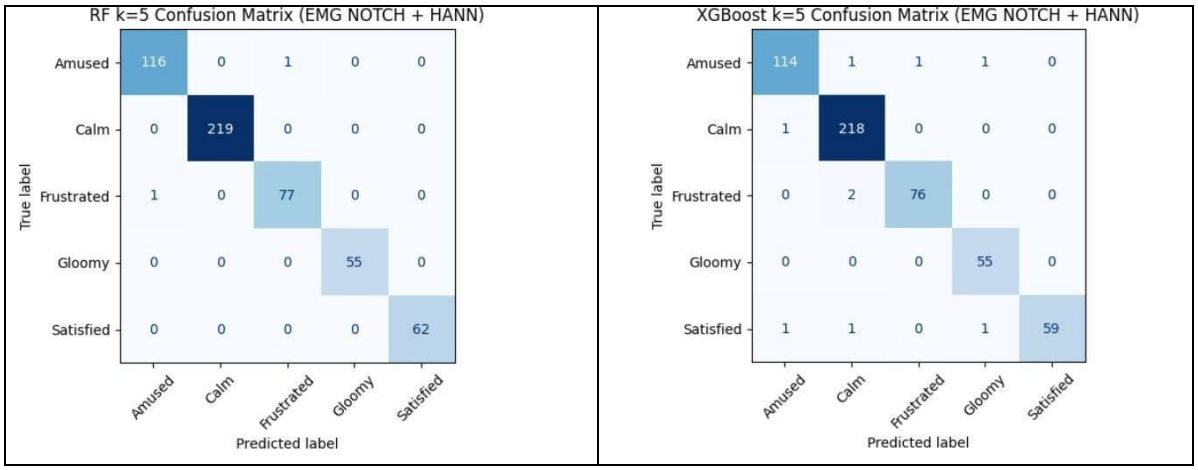


Figure 4-5: Confusion Matrix for Random Forest & XGBoost (k=5) using EMG NOTCH+HANN

A similar trend is observed for EMG-based emotion recognition, where the NOTCH+HANN preprocessing configuration yields highly reliable results. The Random Forest classifier exhibits near-perfect diagonal dominance, with only two isolated misclassifications, indicating exceptional consistency and generalization capability. While the XGBoost model also achieves strong performance, it displays slightly increased confusion among certain emotional classes, particularly Amused and Satisfied. This difference highlights the comparative stability of Random Forest in handling EMG signal variability and noise, reinforcing its suitability for biosignal-driven authorization tasks. Overall, the results suggest that EMG signals, when appropriately filtered and windowed, can offer highly distinctive emotional patterns that support secure and accurate classification.

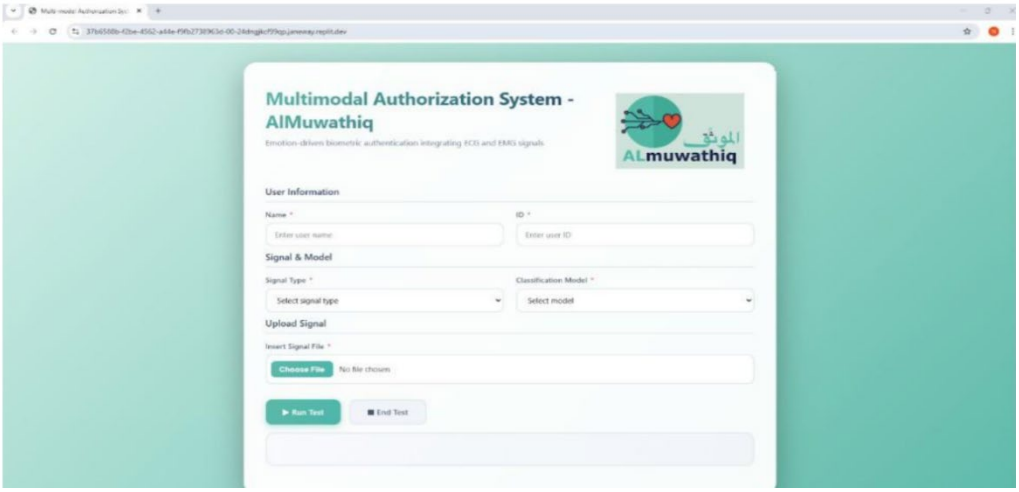


Figure 6: User Interface of the AlMuwathiq Multimodal Authorization System

Beyond model performance, these results directly validate the design and functionality of the AlMuwathiq Multimodal Authorization System. The system successfully translates emotion classification outputs into real-time authorization decisions through a clear rule-based mechanism. The user interface results demonstrate that detected emotions are transparently mapped to access outcomes, ensuring both usability and explainability—key requirements for authorization systems in sensitive environments. The correct handling of both access-granted and access-denied scenarios confirms that the system operates as intended, enforcing emotional-state-based authorization without ambiguity. Taken together, the results confirm that the proposed framework is not only technically sound but also practically deployable, offering a secure, interpretable, and privacy-aware approach to biosignal-based authorization suitable for real-world applications. In summary, this methodology outlines the complete scientific workflow of the AlMuwathiq system: real signal acquisition, SAM-based emotional labeling, structured preprocessing, feature extraction, machine learning experimentation, and final

system deployment. All steps described directly reflect the project implementation without adding any external methods or assumptions.

5. Future Studies and Recommendations

Future work on the proposed AlMuwathiq system will focus on expanding the dataset and improving the stability of emotion classification across a wider range of users. Since the current dataset was collected from a limited group, increasing the number of participants would strengthen the reliability and generalization of the emotional categories. Additional data samples would also support further refinement of the preprocessing pipeline, particularly in reducing naturally occurring noise in ECG and EMG recordings. In addition, enhancing the performance of the existing machine-learning models. While Random Forest and XGBoost demonstrated strong results in the evaluation, further optimization of the feature sets and preprocessing techniques may lead to even more consistent outcomes. This can include refining windowing strategies or exploring additional parameters within the current feature categories already used in the project. Moreover, future versions of the system could focus on improving the user experience of the authorization platform. This includes streamlining the signal upload process, improving the visualization of emotional output, and ensuring the authorization decision is clearly communicated to the end user. Integrating additional testing scenarios within the platform may also help validate the system's behavior in different usage conditions. Finally, future studies should examine how the emotional states captured by ECG and EMG signals evolve across multiple sessions and different time periods. This will help maintain long-term consistency in emotional biometrics and evaluate whether the same emotional patterns remain stable across repeated use. Such insights would help improve the system's reliability and position emotion-based authorization as a viable complement to traditional authentication methods.

6. Conclusion

The concept of user and entity authorization has been widely deployed for access control in mission-critical infrastructure. Existing studies have shown the need for a dynamic mechanism that considers the user's emotional and psychological state before authorization. This study developed an innovative mechanism for entity authorization that considers the user's emotional state using a widely accepted emotion classification metric. The results of a comprehensive experimental and testing process further validate the study's proposition and establish a reliable accuracy threshold. The results of this study, therefore, demonstrate that both ECG and EMG signals from users can be leveraged for authorization. Furthermore, this probability opens the possibility of integrating emotion-based authorization as a complementary component in physical security.

Ethics Declaration: This study did not require ethical approval because no human or animal subjects were involved. The authors affirm that no human research participants were involved in this study; hence, it is not applicable.

AI Declaration: The Authors declare that AI was not used to write the manuscript and that the content represents the authors' original writing, except where an AI tool was used to edit the manuscript to enhance clarity.

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Beyond the Dashboard: Unseen Cybersecurity Vulnerabilities Caused by User Behaviour in Connected and Autonomous Vehicles Systems

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Abstract: As Connected and Autonomous Vehicles (CAVs) become increasingly integrated into Intelligent transportation systems, cybersecurity is no longer limited to protecting onboard technologies—it must also account for the everyday digital behaviours of the users who manage and interact with these vehicles. This paper introduces the concept of the "behavior-driven cyber-risk layer" in CAVs, a hidden but critical vulnerability surface created not by system flaws, but by routine user actions surrounding the vehicle ecosystem. Although CAVs rely on advanced communication, sensors, and cloud connectivity, small human habits—such as ignoring software update alerts, connecting infotainment systems to insecure personal devices, oversharing trip information, accepting unverified apps, or reusing credentials across applications—can undermine even the most sophisticated vehicle security architectures. This study examines how these seemingly minor behaviors interact with CAVs' security mechanisms, including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, certificate-based authentication, and onboard digital systems. We show how attackers exploit predictable user routines—such as uploading navigation routes to cloud platforms, pairing phones via Bluetooth, or trusting unsolicited messages that appear to come from vehicle services—to introduce false data, manipulate trust decisions, or gain unauthorized access. Through real-world scenarios, we demonstrate how small mistakes can escalate into larger risks, enabling targeted tracking, spoofed messages, or remote access to vehicle functions. Instead of treating these behaviours as psychological tendencies, this paper frames them as operational cybersecurity weaknesses that directly affect the safety and reliability of CAVs. To illustrate, existing user awareness strategies are evaluated to highlight why they fail in high-convenience environments, where users expect seamless automation and often overlook security steps. Finally, a set of human-centered cybersecurity practices are proposed that are designed specifically for CAVs ecosystems, including simplified interface warnings, context-aware security prompts, secure-by-default connectivity options, and automated verification mechanisms that reduce reliance on user judgment. By revealing the hidden risks embedded in everyday interactions, this work emphasizes that the cybersecurity of CAVs depends not only on the technology itself, but also on how people engage with it.

Keywords: Vulnerabilities, Behaviours, CAVs, Security, Transportation, V2V, Attacks, Safety, Awareness

1. Introduction

In Intelligent Transportation Systems (ITS), Connected and Autonomous Vehicles (CAVs) form the core of the smart driving system, and they are rapidly becoming the primary component in ITS. In CAVs, the vehicles communicate with each other, forming Vehicle-to-Vehicle (V2V) communications, and communicate with the infrastructure around them, forming Vehicle-to-Infrastructure (V2I) communications (Falcone et al., 2007). CAVs rely on a sophisticated system of Onboard Units (OBUs), including sensors, radar, lidar, camera, and digital services to enable different levels of automation, efficient driving, and user safety. The automation levels in CAVs range from low level (0) to high level (5) (SAE International, 2021), and in each level the vehicle has different features as shown in Figure1. While significant research efforts have focused on securing vehicle hardware, communication protocols, and backend infrastructures, cybersecurity in CAVs cannot be fully addressed by technical mechanisms alone (Almani, 2024). In addition, much attention has been given to protecting (V2V) and (V2I) communications, certificate-based authentication, and onboard control systems, but a critical vulnerability surface remains largely overlooked: the everyday digital behaviors of users interacting with the vehicle ecosystem. The main contribution of this paper is a structured analysis of how predictable user behaviors interact with CAV security mechanisms and create exploitable attack paths. Through real-world-inspired scenarios, we demonstrate how attackers leverage these behaviors to introduce false data, manipulate trust decisions, or gain unauthorized access to vehicle systems. Rather than framing these behaviors as psychological shortcomings, we treat them as operational cybersecurity weaknesses that directly impact safety, reliability, and trust in CAV environments.

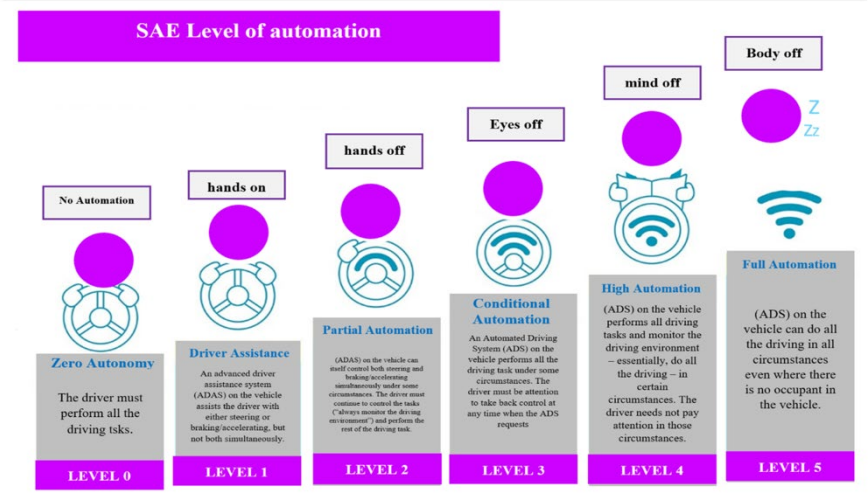


Figure 1: SAE Levels of Automation (SAE International, 2021)

2. Background: Security Architecture of CAV Ecosystems

In ITS, the more vehicles are connected, the more they will be able to obtain drastic enhancements in driving environment safety and traffic flow optimization, and consequently, offer a full set of services for passengers and drivers. CAVs operate within a highly interconnected digital ecosystem composed of multiple security-sensitive components. These include onboard electronic control units (ECUs), infotainment systems, wireless communication modules, mobile devices, and cloud-based services (Khanmohamadi & Guerrieri, 2024). This section discusses the key concepts of CAVs networks and their integration into autonomous vehicles, highlighting the importance of network infrastructure and connectivity. Recent research on CAV cybersecurity has primarily focused on securing communication protocols, intrusion detection mechanisms, and cryptographic authentication systems. However, relatively limited attention has been given to the role of user interaction and behavioral patterns in shaping the overall attack surface of CAV ecosystems. Several studies highlight the growing importance of human factors in cyber-physical systems, yet their integration into vehicle cybersecurity architectures remains largely unexplored.

2.1 Communication and Trust Mechanisms

CAVs are highly dependent on V2V communications as well as V2I communications to exchange safety messages, traffic messages, as well as environment messages. These communications often employ certificate-based authentication frameworks, such as public key infrastructure, to verify message integrity as well as authenticity (Almani et al., 2022). Messages are often deemed to be from trustworthy sources if they appear to be so after cryptographic analysis. Although these measures can and indeed are intended to prevent attacks by malicious third parties, they tacitly presuppose that the rest of the digital world, and specifically user-controlled interfaces, will be safe (Zhang et al., 2021).

2.2 User Interaction Points

Modern CAVs present various interaction opportunities for the user, such as infotainment systems, mobile applications, cloud-based dashboards, and the use of external services. The most common interactions occur through the smartphone via Bluetooth and/or USB connectors, data synchronization from navigation systems to the cloud, as well as the installation of applications. These interaction points serve as the bridges between the safe interior of the vehicle and the larger, more uncontrolled digital world. These interaction zones can often rely for their security upon the choices of users, making it an essential area in terms of the overall attack surface (Chattopadhyay et al., 2020). From the above discussion, it can be noticed that the CAV ecosystem is a complex, multi-layered environment that depends not on a single layer for security but rather a complex array that comprises various levels such as physical devices, networks, application-level systems, cloud services, backend services, in addition to those managed by the user for interaction. Each level has a unique mechanism for protection, which in turn faces a specific source for threats but, at the same time, could affect the entire environment's reliability (Bendiab et al., 2023).

For this particular environment, a conceptual model for identifying the various levels, a quick reference table (Table 1) has been prepared below that defines the levels, the components, methods, in addition to identifying the distinct source for each, while identifying, with particular emphasis, the source for behavioral cyber risks.

Table 1: Security Layers in Connected and Autonomous Vehicle Ecosystems

Security Layer	Primary Components	Typical Protection Mechanisms	Common Threat Sources
Physical Layer	Sensors, ECUs, onboard hardware	Tamper resistance, secure boot	Physical access, hardware attacks
Network Layer	V2V, V2I, wireless channels	PKI, certificates, encryption	Message spoofing, replay attacks
Application Layer	Infotainment, vehicle apps	Access control, sandboxing	Malware, vulnerable applications
Cloud & Backend Layer	Navigation services, data storage	Authentication, secure APIs	Data breaches, credential theft
Behavior-Driven Cyber-Risk Layer	User-device interaction, cloud usage, update decisions	User prompts, policies (often weak)	Exploitable user routines, trust misuse

3. The Behavior-Driven Cyber-Risk Layer

The behavior-driven cyber-risk level: This pertains to risks that are not due to weaknesses in cryptographic methods or software bugs but are a result of common user behavior that affects the security level of CAVs negatively (Negash and Yang, 2023).

3.1 Most Common Risk

Various common practices make up such a hidden risk stratification level:

- Ignoring or putting off vehicle software and firmware updates
- Integration of infotainment systems with personal devices that are either unsecured or already compromised
- Shared credentials for all vehicle-related services, mobile applications, and cloud platforms
- Oversharing trip information, location data, and vehicle status via third-party applications
- Accepting unverified applications/permissions

These are usually practiced due to convenience, lack of time, or overreliance on technology. To demonstrate how such behaviors can be interpreted in tangible security threats, Table 2 outlines the principal actions taken by the user, points of interaction, and possible security consequences in the CAV environment.

Table 2: User Behaviors and Their Security Implications in CAV Ecosystems

User Behavior	Interaction Point	Exploited Weakness	Potential Impact
Ignoring software update alerts	Onboard system / mobile app	Unpatched vulnerabilities	Remote exploitation, system compromise
Pairing insecure personal devices	Bluetooth / infotainment	Trusted device abuse	Unauthorized access, data leakage
Reusing credentials	Vehicle apps, cloud platforms	Weak identity separation	Account takeover, tracking
Oversharing trip data	Cloud navigation services	Data exposure	Targeted surveillance, profiling
Accepting unverified applications	Vehicle app ecosystem	Lack of app validation	Malware installation, system manipulation

3.2 Why These Behaviors Matter

CAV security architectures are envisioned to be designed in the belief that the cryptographic trust is sufficient to engender trust (Tu et al., 2025). Nevertheless, when the attack is based on the user behavior, there is an opportunity to circumvent the trust in an indirect manner. For example, if the mobile device is compromised and used in a vehicle, it becomes possible to enter the system as a trusted relay without violating the

cryptographic trust. This layer is particularly dangerous as it stays hidden in the threat space and security analysis.

4. Attack Scenarios Exploiting User Behavior

In spite of the seemingly low-level nature of the risks facing individual users, the group of attackers may utilize these risks systematically to circumvent the conventional CAV security. Through the exploitation of the patterns of behavior of the users or the safe communication pathways between the users and the vehicle, the attackers may obtain false input and gain indirect vehicle access or influence the trust models of the systems. Some of the scenarios accounting for the attack vectors resulting from the patterns of the behavior of the users are presented below.

4.1 Cloud-Based Route and Data Sharing

Many CAV users tend to share their navigation routes and trip history data in cloud services. Attackers who obtain access to such cloud services using either credential reuse attacks or phishing attacks may be able to ascertain the predictable patterns of their driving behavior (Wu et al., 2025). In other advanced attacks, the affected car ecosystem may receive their altered route data. Route data manipulation may occur through several technical attack vectors. For example, attackers may exploit compromised cloud navigation accounts, GPS spoofing techniques, or malicious third-party navigation applications to inject falsified route information. In such cases, altered navigation instructions may redirect vehicles toward unintended routes or manipulate traffic flow. Because many CAV services synchronize route data through cloud platforms and mobile applications, compromised credentials or insecure APIs can allow attackers to modify stored route information that is later downloaded by the vehicle.

4.2 Bluetooth and Infotainment Exploitation

Connecting smartphones to the in-car entertainment systems in a vehicle is also a common phenomenon. Several known Bluetooth attack vectors can exploit these connections. Examples include Bluesnarfing, where attackers gain unauthorized access to data stored on paired devices; BlueBorne, which enables remote code execution through vulnerable Bluetooth implementations; and Man-in-the-Middle attacks, where malicious devices intercept communications between the vehicle and a connected smartphone. These attacks can allow adversaries to access sensitive information, inject malicious commands, or manipulate data exchanged between the vehicle and external services. An attacker, in case the system is compromised, can take advantage of the trust involved in the connection and send malicious information, read credentials, and even tap into information exchanged between the car and the server.

4.3 Spoofed Service Messages and Trust Manipulation

The messages that most users tend to believe come from car services like maintenance notifications and update notifications. The attacker takes advantage of this by sending users spoofed notifications to update malware, provide excessive permissions, or provide sensitive information (Tekkesinoglu et al., 2025). After the creation of this trust through user engagement, the attacker injects false information into the V2V or V2I system chain to indirectly affect decision-making processes.

5. Limitations of Existing User Awareness Approaches

Conventional methods for enhancing awareness and security practices among computer users call for educating and warning users, and then following security guidelines and best practices, and it is expected that a security-aware user will make security-informed choices most of the time. The aforementioned conventional approach is not very effective for a CAV environment, wherein users demand a good deal of automation and functionality with seamless connectivity and very less cognitive efforts while using a system and services (Sevinch, 2024). Frequent reminders for security in high-convenience systems are disregarded because complex warnings are viewed more as impediments than as security solutions. It can cause users to resist and disregard notifications related to security because they do not fully understand their meaning. This is because people believe that secure-by-design safety-critical systems in vehicles are self-protecting and do not necessarily require active user participation for their security.

In addition, knowledge-based approaches are based on the idea that consumers are well-informed about technology risks involved in device pairing, permission handling in applications, data sharing in cloud environments, as well as login methodologies. However, consumers are often left in ignorance about processes that occur in the background, making it impossible to analyze risks. In this manner, consumers might

unknowingly grant permissions that lead to risks in the motor environment. A major drawback of awareness approaches is that they are of a reactive, rather than preventive, nature. These approaches seek to mitigate problems after potentially risky behaviors have taken place, rather than proactively employing system design principles that can pre-emptively prevent the risks from being realized (Butler et al., 2021). This is especially concerning in safety-critical application areas like transportation, which can be directly influenced by human error, not just concerning individual privacy but system-wide issues.

Hence, the applicability of defense mechanisms based on awareness does not scale well in practical CAV deployment, especially with the growing automation of vehicles and integration of CAV systems into everyday life. This emphasizes the importance of having effective remedies related to CAV security, promoting the responsibility of the CAV system itself, apart from humans, regarding reminders, restrictions, or the process of verification. To further clarify these limitations, Table 3 summarizes common awareness-based security strategies, their intended objectives, and the reasons why they are ineffective or impractical within CAV environments. This comparison highlights the gap between traditional user-focused defenses and the operational realities of highly automated vehicle systems.

Table 3: Evaluation of Existing User Awareness Approaches in CAV Environments

Awareness Strategy	Intended Goal	Limitation in CAV Context
Security warnings	Inform users of risk	Often ignored due to automation
User training	Improve decision-making	Not scalable or timely
Policy compliance	Enforce safe behavior	Difficult to monitor
Manual confirmations	Prevent accidental actions	Causes fatigue and frustration
Informational dashboards	Increase transparency	Overwhelming for non-expert users

6. Behavior-Aware Security Framework for CAV Ecosystems

This section presents the **Behavior-Driven Cyber Risk Layer Framework (BDCRL)**, a behavior-aware security architecture that integrates user interaction monitoring with existing CAV security mechanisms.It does not seek to replace cryptographic protections or network-level defenses; rather, the aim is to complement them by considering risk introduced through routine user behaviors and external device interactions. This framework operates within the scope of three interconnected domains: user interaction interfaces, vehicle onboard systems, and cloud services. In this regard, correlating activity across these domains, a system should be able to identify behavior patterns that elevate cyber risk and apply targeted mitigation strategies. Figure 2 provides an overview of this process by illustrating how data flows from user interaction interfaces, onboard vehicle systems, and cloud services into a central behavioral risk analysis component, where risk levels are assessed and translated into adaptive trust adjustments and automated mitigation actions. This visual representation clarifies the cross-layer operation of the framework and highlights how behavior-driven risks are addressed before they impact safety-critical CAV functions.

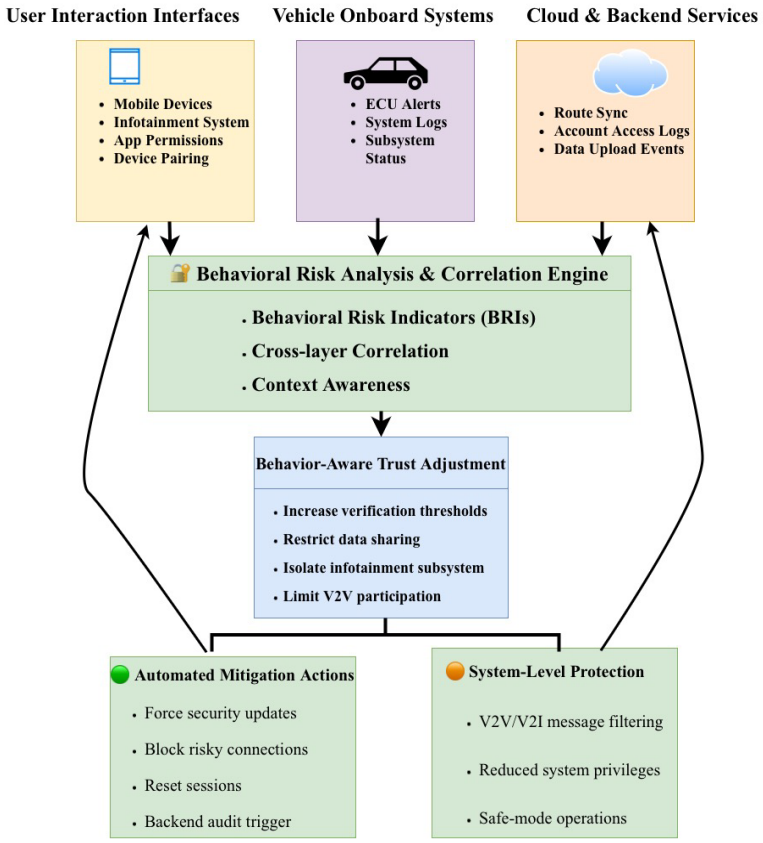


Figure 2: Behavior-Driven Cyber Risk Layer (BDCRL)

6.1 Behavioral Risk Indicators

The first component of the framework defines a set of BRIs that represent actions known to increase the probability of security compromise. These are derived from the common user behaviors that one can find in modern CAV ecosystems, such as:

- Repeated postponement of critical software updates
- Frequent pairing with new or unknown devices
- Installation of third-party applications outside verified ecosystems
- Reuse of authentication credentials across services
- Excessive sharing of location and trip data with external platforms

Each indicator is assigned to a risk weight based on the risk of degrading the overall security of the system. These weights may vary depending on the context in which the vehicle is moving, whether in autonomous mode, interacting with the roadside infrastructure, or in cooperative driving patterns.

6.2 Cross-Layer Risk Correlation

Unlike traditional intrusion detection systems that focus on network traffic or system logs, BDCRL performs cross-layer risk correlation by combining:

- Interface-level interaction logs (e.g., pairing events, permissions granted)
- Vehicle subsystem alerts (e.g., infotainment anomalies, ECU access attempts)
- Cloud-side access and synchronization activity

In correlating these data types, it becomes possible for the system to recognize risk patterns in compounds that individually may be harmless but in combinations suggest something different. In other words, a new device, unusual access to the cloud, and failed log-ins suggest more than simple device failure. By considering the totality of behavioral and system-level indicators, the framework can prioritize patterns that are more likely to represent coordinated or escalating security threats. The reasons behind this are that a strong correlation can facilitate

early identification of attack vectors driven by behavior before they are involved in safety-critical decision-making processes (Almani and Furnell, 2025), such as V2V trust assessment or control of navigation.

6.3 Behavior-Aware Trust Adjustment

The framework introduces a behavior-aware trust adjustment mechanism that influences how vehicle systems evaluate incoming data and external interactions. When elevated behavioral risk is detected, the system can:

- Increase verification thresholds for external messages
- Restrict non-essential data sharing
- Temporarily isolate infotainment and user-connected subsystems
- Limit participation in cooperative V2V decision-making

This dynamic trust adjustment prevents compromised user interfaces from indirectly influencing safety-critical functions. Importantly, trust modification occurs at the system level rather than requiring manual user intervention.

6.4 Automated Mitigation and User Guidance

To minimize reliance on user decision-making, mitigation actions are primarily automated. However, when user input is required, the framework provides *context-aware guidance* rather than generic warnings. For instance, instead of displaying a vague security alert, the system may indicate that recent device connections increase risk during cooperative driving and recommend postponing non-essential connectivity.

Automated responses may include:

- Enforcing immediate critical updates when risk is elevated
- Blocking high-risk device connections
- Resetting compromised authentication sessions
- Triggering backend security audits

This approach balances usability with protection, ensuring that safety is not compromised by delayed or ignored user actions.

6.5 Scenario-Based Validation

For the purpose of testing the feasibility of BDCRL, typical usage scenarios that involve CAVs were examined. These usage scenarios involved cloud-based navigation synchronization, device pairing, as well as service messages. Within these scenarios, the framework was successful in detecting the conditions that pose a higher level of risk prior to making any impact on the trust between V2V or V2I communication. For instance, for route synchronization scenarios, irregular login instances and late updates contributed to trust reduction for external data entry, thereby ensuring that misleading route information does not affect navigation systems. For infotainment pairing scenarios, continuous connectivity attempts from former unknown entities resulted in automatic subsystem isolation, thereby avoiding horizontal access for vehicle services (Ignatious et al., 2023).

6.6 Integration with Existing CAV Security Architectures

BDCRL is designed to be compatible with existing CAV security infrastructures, including certificate-based authentication, secure communication protocols, and backend anomaly detection systems. Behavioral risk scores do not replace cryptographic validation but complement it by adding contextual awareness to trust decisions. The framework uses lightweight behavioral indicators based on existing vehicle logs such as device pairing, update delays, and authentication attempts. Risk analysis can be performed locally within the vehicle, while more complex processing may be offloaded to edge or cloud systems, minimizing computational overhead on safety-critical components. This layered integration supports a more realistic threat model in which trusted vehicles may still act as compromised intermediaries due to unsafe interaction patterns. By recognizing this possibility, CAV systems can make more conservative and informed security decisions ins high-risk operational contexts.

7. Discussion

The behavior-driven cyber-risk layer challenges the assumption that cybersecurity in CAVs can be achieved solely through technical robustness. Even highly secure systems can be undermined by predictable user behaviors that attackers exploit strategically. Recognizing user interaction as a core part of the threat model enables a more realistic assessment of CAV security and highlights the importance of integrating human-centered design

principles into cybersecurity strategies (Xu et al., 2024). While behavioral monitoring can improve cybersecurity in CAV ecosystems, it also raises privacy concerns. To address this, behavioral indicators should minimize or anonymize personally identifiable information whenever possible. Many indicators can be processed locally within the vehicle, reducing the need to transmit user data externally. In addition, compliance with data protection regulations such as GDPR requires transparent data handling and minimal data retention. Therefore, privacy-preserving monitoring is essential for the secure deployment of BDCRL.

The results in this work indicate that cybersecurity concerns for Connected and Autonomous Vehicles cannot be holistically addressed by targeting only technical safeguards such as cryptographic authentication, secure communication protocols, and intrusion detection mechanisms. Inasmuch as such protections are necessary, the findings reveal that mundane user behaviors introduce a parallel vulnerability surface that operates outside the realm of traditional security models.This behavior-driven cyber-risk layer effectively bridges highly secured vehicle subsystems with less regulated personal digital environments, thereby weakening end-to-end system trust.

One of the most significant implications of this work is that many attack paths do not require attackers to compromise core vehicular systems directly (Yousseef et al., 2024). Instead, attackers exploit predictable user routines such as cloud synchronization, smartphone pairing, and reliance on automated services. As shown in Tables 2 and 3, these behaviors can undermine certificate-based trust mechanisms and allow false or manipulated data to propagate into V2V and V2I decision processes. This finding challenges the assumption that cryptographic validity alone is sufficient to ensure operational trust in CAV networks. Another important observation is that behavior-driven risks scale with system convenience. CAV ecosystems are explicitly designed to minimize user effort and maximize automation. The net result of this approach is that meaningful opportunities for effective human oversight are unintentionally reduced. In such environments, traditional cybersecurity awareness strategies become ineffective; users learn to trust system automation and to respond quickly to system prompts without questioning potential security implications. This study shows that real-world CAV usage patterns are poorly aligned with awareness-based defenses; thus, user vigilance is an unreliable mitigation strategy in safety-critical transportation systems (Decian & Jaafar, 2024).

This cybersecurity study further highlights a fundamental disconnect between how responsibilities are assigned for CAV cybersecurity and how these systems are actually used. Current security architectures implicitly place responsibility on users to manage updates, device pairing, and application permissions, despite the fact that users often lack visibility into system dependencies or potential consequences. Treating these behaviors as isolated user errors overlooks the structural role that system design plays in shaping user actions. Therefore, behavior-driven vulnerabilities should be regarded as design-level security issues rather than individual compliance failures. Human-centered cybersecurity practices aim to shift the responsibility for enforcing security from reactive end-user actions to proactive system-level processes. Through the implementation of secure-by-default connectivity, automated verification, and context-aware prompts, the risk of high-risk interactions based on user discretion can be significantly reduced within CAV systems. As summarized in Table 5, these practices complement existing cryptographic protections by targeting vulnerability points at the interfaces where humans interact with automated systems. Furthermore, in a broader context, the behavior-driven cyber-risk layer has significant implications for trust management schemes in vehicular networks. Existing trust models typically assume that malicious behavior originates from malicious vehicles themselves. However, this study demonstrates that legitimate vehicles may unintentionally act as carriers of malicious data or unauthorized access due to compromised user-controlled interfaces. This blurs the distinction between benign and malicious nodes and complicates misbehavior detection mechanisms that rely solely on message-level observations. Consequently, future trust and reputation systems must incorporate behavioral context and device provenance when assessing participant reliability in vehicular networks. Moreover, current regulatory and certification efforts for CAVs place strong emphasis on hardware reliability and software integrity, with limited consideration of security risks arising from user–device interactions. The results of this study indicate that certification frameworks should extend beyond technical compliance to include evaluation of interface design, update enforcement mechanisms, and secure integration with personal devices. Without such measures, certified vehicles may remain vulnerable through their surrounding digital ecosystems.

Finally, although this paper focuses on transportation systems, behavior-driven cyber risks are also evident in other domains, including smart medical devices, industrial IoT, and smart home environments. However, the safety-critical nature of transportation systems magnifies these risks, making CAVs a particularly urgent domain for addressing human–system security interactions. Recognizing human behavior as a contributing factor to

system security is therefore essential not only from a cybersecurity standpoint, but also for ensuring public trust and long-term adoption of autonomous vehicle technologies.

8. Conclusion

In this research paper, the behavior-driven cyber-risk layer in Connected and Autonomous Vehicles has been introduced, and the way in which everyday user behavior leads to hidden, yet highly important, security risks has been explained. By understanding how this user behavior combines with the security features of secure Connected and Autonomous Vehicles, it is evident that the problem of cybersecurity is not just a technological issue, but also a matter of everyday behavior that, at the moment, is not considered highly convenient. Therefore, in order to meet this demand, a set of human-centered approaches, specifically designed for the use of Connected and Autonomous Vehicles, is proposed, and it is necessary to understand that the safety of Connected and Autonomous Vehicles is not just a technological problem, but also a behavior issue.

Ethics Declaration: This study did not involve human participants, personal data, or animal subjects; therefore, ethical approval was not required.

AI Use Declaration: No AI-based tools were used in the preparation of this manuscript.

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Cybersecurity in the Era of Quantum Computing and Advanced AI: Emerging Threats and Future Directions

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Abstract: Quantum computing and advanced artificial intelligence are beginning to disturb several assumptions on which current cybersecurity practice depends. This paper reviews two related areas of risk: the possibility that cryptographically relevant quantum computers could weaken widely deployed public-key encryption, and the ways in which generative AI and large language models are already changing cyber operations. The analysis finds that quantum risk should not be treated as a distant event only, since sensitive encrypted data can be collected now and decrypted later if suitable quantum capability becomes available. It also finds that advanced AI is already affecting the scale, speed, and credibility of social engineering, reconnaissance, vulnerability analysis, and misinformation. The paper discusses the current state of these threats, outlines plausible future scenarios, and identifies practical defensive priorities, including post-quantum cryptography migration, AI system hardening, red teaming, content authentication, workforce training, and governance. The central argument is that quantum and AI security should be handled as near-term resilience issues, even where their most severe effects may appear later.

Keywords: Cybersecurity, Quantum computing, Post-quantum cryptography, Artificial intelligence, Large language models, Deepfakes

1. Introduction

Cybersecurity has long relied on three assumptions: that certain computations are impractical for attackers, that human users can recognize some forms of deception, and that defenders can observe and respond to compromise before damage becomes systemic. Quantum computing and advanced AI put pressure on all three. Quantum computing threatens the mathematical basis of many public-key systems, while generative AI gives attackers a practical way to produce convincing language, code, audio, and images at scale. These developments do not replace existing cyber risks, instead, they make familiar attacks faster, cheaper, and in some cases harder to recognize.

This paper examines how these technologies reshape the cyber threat landscape and which responses should be prioritized. It focuses on two questions. First, how could quantum computing affect encryption, signatures, and digital trust? Second, how could advanced AI and large language models introduce new vulnerabilities or strengthen existing attacker capabilities? The discussion draws on recent academic, government, and industry sources, with emphasis on realistic security implications rather than speculative forecasts. The paper does not attempt to predict an exact date for a cryptographically relevant quantum computer. That date remains uncertain. The more useful question is whether the direction of risk already justifies defensive action.

The argument advanced here is that the security community is already in a transition period. Quantum computers are not currently breaking strong, real-world public-key encryption, but migration to quantum-resistant systems will be slow and operationally difficult. Current AI systems are also not fully autonomous attackers, but they already improve phishing, impersonation, malware support, and vulnerability analysis. Waiting for either threat to mature before preparing would leave organizations with limited time to respond. A more defensible approach is to build cryptographic agility, secure AI development practices, and governance controls while the risks are still manageable.

2. Quantum Computing and the Cryptographic Risk

The most widely discussed cybersecurity implication of quantum computing is its effect on public-key cryptography. Systems such as RSA, Diffie-Hellman, and elliptic-curve cryptography depend on mathematical problems that are difficult for classical computers, including integer factorization and discrete logarithms. A sufficiently powerful quantum computer running Shor's algorithm could solve these problems efficiently, making many current public-key schemes unsafe [1], [2]. The effect would reach far beyond encrypted messaging. Secure web browsing, virtual private networks, software updates, digital signatures, identity systems, and parts of financial infrastructure all rely on these mechanisms.

The more immediate concern is not only future decryption. The strategy often described as harvest now, decrypt later changes the timeline. An adversary can collect encrypted traffic or stored encrypted records

today and preserve them until quantum decryption becomes practical. Data with long confidentiality value, such as government communications, medical records, intellectual property, legal material, and financial information, may therefore be exposed before the technical ability to decrypt it exists [3]. This is why organizations that protect long-lived sensitive data cannot wait for a public quantum breakthrough before planning their transition.

Current quantum hardware still faces major limits, including noise, error rates, and the difficulty of scaling fault-tolerant systems. Publicly known systems do not yet have the stable, error-corrected capability required to break large commercial cryptographic deployments. However, progress in algorithms, error correction, and hardware engineering has reduced confidence in the assumption that the risk is safely remote. NIST and related agencies have warned that preparation should begin before the threat becomes operational [1], [3]. The practical challenge is that cryptographic migration is not a single software patch. It requires finding where cryptography is used, replacing vulnerable algorithms, testing interoperability, updating certificates and protocols, managing legacy devices, and coordinating with vendors.

Post-quantum cryptography is the main defensive pathway. These algorithms are designed to resist both classical and quantum attacks by relying on mathematical assumptions such as structured lattices, hash-based signatures, and code-based problems. NIST's standardization process has produced finalized post-quantum encryption and signature standards, which gives organizations a clearer basis for planning [1]. The transition should be managed through cryptographic agility: systems should be designed so that algorithms can be replaced without redesigning the full architecture. That matters because post-quantum algorithms are newer than the schemes they will replace, and implementation guidance will continue to mature. The most sensitive and long-lived assets should be addressed first.

Quantum risk also affects trust models beyond confidentiality. Digital signatures verify software updates, contracts, identity credentials, and blockchain transactions. If widely used signature schemes become vulnerable, attackers could impersonate trusted parties or distribute malicious updates that appear legitimate. Symmetric cryptography is less exposed, but it is not unaffected, Grover's algorithm reduces the effective security strength of symmetric keys, which means key sizes and hash functions should also be reviewed. These issues do not make current systems obsolete overnight, but they do require a systematic inventory and staged upgrade plan.

3. Advanced AI and Large Language Model Security Risks

Compared with quantum computing, advanced AI is already operationally relevant because usable tools are widely available now. Generative models can draft convincing emails, summarize stolen documents, translate scams, imitate a professional tone, generate code, and support research on targets. Large language models also create new attack surfaces when they are embedded into customer service tools, coding assistants, search systems, document analysis tools, and autonomous agents. The main security issue is not that every model output is dangerous, but that models can be connected to sensitive data and actions without the same predictable boundaries as conventional software.

Prompt injection is one of the clearest examples. In a prompt injection attack, malicious instructions are placed inside user input, a document, a web page, or another data source that the AI system processes. The model may then follow those instructions rather than the developer's intended policy. In practice, an attacker could try to cause an AI assistant to disclose sensitive content, ignore access rules, send data externally, or take an unsafe action through a connected tool [4], [5]. The risk grows when an LLM has access to email, files, databases, or internal applications, because the model may not reliably separate trusted system instructions from untrusted content that merely looks like an instruction.

Other AI-specific risks include jailbreaking, adversarial examples, data poisoning, and model backdoors. Jailbreaking attempts to bypass restrictions and obtain outputs that the system is meant to block. Adversarial examples manipulate inputs so that a model behaves incorrectly. Data poisoning targets training or fine-tuning data, while backdoors remain hidden until a specific trigger appears. These problems are difficult to manage because modern models are complex, probabilistic, and not fully interpretable. A system can perform well in ordinary testing and still fail when placed under adversarial pressure.

AI also changes the economics of conventional cybercrime. Phishing is the most visible case. Older phishing campaigns often contained weak grammar, generic wording, or obvious inconsistencies. Generative AI allows attackers to produce personalized messages that sound professional and can be adapted quickly after failure. The FBI has warned that criminals are using AI to increase the speed, scale, and believability of fraud and social

engineering [6]. The same pattern applies beyond email, including text messages, voice calls, fake job offers, business email compromise, and customer support fraud.

Deepfakes extend the same problem into voice and video. AI-generated media can imitate executives, relatives, public figures, or colleagues. In a corporate setting, a convincing fake voice call can support payment fraud or credential theft. In a public setting, fake video or audio can spread misinformation, damage reputations, or create short-term panic before verification catches up. Detection tools are useful, but they are not enough on their own, since attackers can improve generation quality and exploit situations where people are under time pressure.

AI may also accelerate technical attacks. Models can assist with code analysis, vulnerability research, exploit adaptation, and the interpretation of technical documentation. They are unlikely to replace expert attackers in the near term, but they can lower the skill required for some tasks and increase productivity for experienced teams. A threat actor can use AI to generate reconnaissance scripts, analyze error messages, rewrite simple malware, or summarize the configuration of a target technology. The expected defensive challenge is therefore greater volume, faster iteration, and more convincing social engineering rather than a single new form of attack.

4. Combined Threat Landscape and Future Scenarios

Quantum and AI risks are often discussed separately, but operationally they are part of a broader shift. AI gives attackers automation and persuasion advantages now, while quantum computing threatens the cryptographic layer that supports digital trust over the longer term. The combined effect is a security environment in which attackers may become better at gaining access today and, in the future, better able to exploit information that was previously protected by older cryptography.

One plausible scenario begins with data harvesting. An attacker collects encrypted records from a high-value organization and stores them. AI-assisted tools are then used to identify employees, suppliers, and business processes, making credential theft or supplier impersonation more credible. Once inside a network, the attacker searches for stored encrypted databases, certificate material, and long-term secrets. If quantum decryption later becomes practical, data taken years earlier may become readable. This scenario links a present compromise to a future cryptographic failure and shows why the two risks should be planned together.

A second scenario involves AI-enabled exploitation of AI systems themselves. Organizations are increasingly deploying chatbots and assistants into workflows that can access documents, calendars, customer records, or code repositories. If these systems lack strong boundaries, indirect prompt injection can become a route from an untrusted document to a sensitive action. A malicious document, for example, may instruct an assistant to summarize confidential files or leak selected information through an external request. The model does not need to be malicious, it only needs to become the mechanism through which the attack is carried out.

Critical infrastructure raises the stakes further. AI systems may support monitoring, optimization, and decision-making in energy, healthcare, transport, and finance. At the same time, long-lived infrastructure communications may require quantum-safe protection. The risks are not limited to confidentiality. Integrity failures can be equally serious: a manipulated AI recommendation, a forged signature, or a compromised update process could cause operators to trust false information.

It is also important not to frame either technology only as a threat. AI can improve anomaly detection, malware triage, incident response, and vulnerability management. Quantum technologies may eventually support stronger forms of key distribution or random number generation in specialized settings. These benefits will only be useful if deployment is disciplined. Without clear controls, validation, and accountability, the same capabilities can increase complexity and enlarge the attack surface.

5. Mitigation Strategies

For quantum risk, the practical starting point is an inventory. Organizations need to know where public-key algorithms are used, which systems protect long-lived data, and which vendors control cryptographic components. The inventory should include certificates, VPNs, web services, email encryption, identity systems, code-signing processes, embedded devices, and backup systems. After that, assets should be classified by urgency. Systems protecting sensitive data for many years should move earlier in the migration plan than systems with short-lived confidentiality needs.

Migration to post-quantum cryptography should be staged and tested. Hybrid approaches may be useful during the transition because they combine classical and post-quantum mechanisms while the newer schemes mature in operational use. Procurement requirements should also be updated so vendors demonstrate post-quantum support and cryptographic agility. This is especially important for devices and platforms with long service lives, since they may still be deployed when quantum threats become more practical.

For AI security, LLM applications should be treated as software systems with unusual failure modes, not as simple user interfaces. Access control should be enforced outside the model. The model should not be the only authority deciding whether a user may view, send, or modify information. Sensitive actions should rely on deterministic policy checks, logging, and human confirmation where appropriate. External documents, websites, and emails should be treated as untrusted inputs even when processed by an internal AI assistant.

Prompt injection defenses need layers. Separating system instructions from user content is useful, but it is not sufficient by itself. Applications should limit which tools the model can call, restrict data access to the minimum necessary, sanitize or transform untrusted inputs, and monitor outputs for suspicious behavior. Red teaming should be part of the deployment lifecycle. AI systems should be tested with adversarial prompts, malicious documents, indirect prompt injection examples, jailbreak attempts, and realistic abuse cases before and after release.

Social engineering controls also need to be updated. Employees should be trained on AI-generated phishing and deepfakes, but training cannot be the only control. High-risk actions such as payments, credential resets, sensitive data exports, or urgent executive requests should require independent verification through trusted channels. Phishing-resistant multi-factor authentication, domain authentication, and transaction approval workflows remain necessary because awareness alone is unreliable when people are under pressure.

Content authenticity is another defensive layer. Watermarking, provenance metadata, and cryptographic signing of legitimate media can help users and institutions verify whether content came from a trusted source. These methods will not stop all deception, but they can reduce uncertainty in high-value communications. Incident response plans should also include deepfake procedures, including rapid verification, public communication, and escalation paths.

Governance connects these technical controls to responsibility. AI systems used in security-sensitive contexts should have documented owners, risk assessments, logging, model update procedures, and clear rules for human oversight. Quantum readiness should be included in enterprise risk management rather than left as a research topic for specialists. Organizations that prepare early will have more control over cost, compatibility, and timing than those that wait for a crisis.

6. Future Research Directions

A first research priority is practical migration engineering for post-quantum cryptography. Standards are only the starting point. Researchers and practitioners need evidence about performance, interoperability, certificate sizes, implementation mistakes, and secure deployment patterns in real systems. Constrained devices, industrial systems, and legacy infrastructure deserve particular attention because many cannot be upgraded quickly or cheaply.

A second priority is AI system evaluation. Current benchmarks do not fully capture security behavior in real deployments, especially when models are connected to tools and private data. Future evaluations should test indirect prompt injection, multi-step attacks, tool misuse, data leakage, model behavior under conflicting instructions, and resistance to adaptive jailbreaks. The goal is not to prove that a model is perfectly safe, which is unrealistic, but to measure risk clearly enough to support deployment decisions.

A third priority is interpretability and verification. Security teams need better ways to understand why a model takes a certain action and whether hidden instructions or poisoned data influenced it. This is especially important for autonomous agents that plan across multiple steps. If an AI system can read files, call APIs, and make decisions, defenders need audit trails and policy enforcement that are stronger than ordinary chat logs.

A fourth priority is human-centered security. AI-generated deception targets trust, urgency, and authority. Research should examine which verification methods work under realistic pressure and which training designs actually change behavior. Technical systems should support people rather than assume that every individual will detect every fake. For example, payment systems can require independent confirmation by design instead of relying on an employee to notice a suspicious voice call.

Finally, cross-disciplinary education is needed. Cybersecurity professionals will need enough knowledge of AI and quantum computing to ask the right questions, while AI and quantum specialists will need enough security knowledge to understand misuse and deployment risk. Universities, professional programs, and industry training should reflect this shift. The future security workforce will need both technical specialization and the ability to work across disciplines.

7. Current State and Future Outlook

The current quantum threat is best described as a preparation problem before the main impact. Today's quantum computers are not able to break large public-key systems used across ordinary digital infrastructure. The risk is therefore not an immediate mass decryption event. The risk is that migration will be long, uneven, and dependent on many vendors and protocols. Organizations that begin with inventory and staged testing now can move deliberately. Organizations that wait for a major breakthrough may face rushed migration, compatibility failures, and continued exposure of archived data.

AI risk is at a different stage. AI-enabled attacks are already visible because widely available tools can produce text, images, voice, and code. The most realistic near-term expectation is not a fully autonomous AI hacker, but a steady increase in the efficiency of human-led attacks. This matters because cybersecurity teams are already overloaded by alert volume, patching demands, and social engineering. AI adds pressure to the same weak points.

Over the next five to ten years, the defensive gap will likely depend less on whether organizations have heard about these risks and more on whether they convert awareness into engineering change. Quantum readiness will require procurement rules, protocol updates, and support from cloud providers, software vendors, and device manufacturers. AI readiness will require secure design patterns for AI applications, stronger identity verification, and incident response for synthetic media. Organizations that treat these areas as ordinary cyber hygiene will reduce disruption. Those that treat them as distant research topics may find that their controls age faster than expected.

8. Conclusion

Quantum computing and advanced AI are reshaping cybersecurity in different but connected ways. Quantum computing threatens public-key cryptography and makes post-quantum migration necessary, especially for data that must remain confidential for many years. Advanced AI is already increasing the quality and scale of cyber threats, particularly in phishing, impersonation, vulnerability support, and exploitation of AI-enabled systems. Both technologies create risks that traditional controls alone cannot fully address.

The most important issue is timing. Waiting for quantum computers to break encryption or for AI attacks to become fully automated would be a strategic error. Post-quantum migration requires years of inventory, testing, vendor coordination, and operational change. AI security requires stronger access boundaries, red teaming, secure development practices, and governance. Defenders still have a window to prepare, but that window will narrow as the technologies mature.

A practical cybersecurity strategy for the next decade should therefore be both quantum-aware and AI-aware. It should protect long-lived data, build cryptographic agility, secure AI systems as part of the software supply chain, verify high-risk communications, and train professionals who can work across these domains. The aim is not to resist technological progress, but to keep digital infrastructure trustworthy as the underlying technology changes.

Ethics Statement: This paper is a literature-based cybersecurity study and does not involve human participants, animal subjects, clinical data, personal data collection, experiments on live systems, unauthorized access, malware deployment or active testing against third-party infrastructure. The discussion of threats is presented at a high level for academic and defensive purposes. The paper avoids operational instructions that would enable cyber abuse and is intended to support responsible security planning, risk awareness and future research.

AI Use Statement: AI-assisted editing tools were used in a limited way during revision to support grammar, clarity, formatting, and consistency checks. The authors reviewed all arguments, verified the cited sources, and accept full responsibility for the accuracy, originality, and integrity of the final manuscript. No AI tool was used as an independent source of authority for the technical claims in this paper.

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Audio Deepfake Generation and Detection using Deep Learning for Digital Forensic Analysis

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Abstract: Deepfake audio technology has developed rapidly and now poses serious risks in cybersecurity and digital forensic analysis. Synthetic speech can imitate authentic human voices, which makes manual and automated detection difficult. This study investigates deep learning-based methods for detecting audio deepfakes generated using modern speech synthesis and voice conversion techniques. The work focuses on both generation and detection in order to understand how different deepfake methods affect detection performance. The study employs multiple audio generation models, including Coqui TTS, GAN, RealNVP, VAE, and WaveNet, to generate realistic speech. Several deep learning detection models are evaluated, including CNN, LSTM, BiLSTM, CNN-LSTM, CNN-BiLSTM, conditional GAN, and hybrid architectures that combine convolutional and recurrent layers. Three datasets are used for training and evaluation. These include a self-generated deepfake dataset, a public Kaggle deepfake dataset, and the ASVspoof 2021 deepfake dataset. This combination allows evaluation under both controlled and real-world conditions. Experimental results indicate apparent performance differences among model types. Simple sequential models, such as LSTM and BiLSTM, perform poorly when deepfake audio exhibits strong naturalistic characteristics. This issue is most evident in Coqui TTS-generated audio, which is difficult to detect because of its natural tone and smooth articulation. In comparison, hybrid models that combine convolutional and recurrent learning consistently achieve higher accuracy and stronger generalization across datasets. The Hybrid cGAN with BiLSTM achieves near-perfect detection performance and exhibits stable performance across cross-validation folds and on independent test data. These results confirm that combining spatial and temporal feature learning improves robustness against advanced deepfake attacks. The study also introduces AudioForenX, an interactive forensic tool that integrates the best-performing models. AudioForenX enables real-time analysis, waveform visualization, and classification of audio samples as authentic or synthetic. The findings confirm that hybrid deep learning architectures provide reliable, balanced, and highly accurate detection of synthetic audio. This study contributes practical insights for digital forensics and supports the development of effective tools to counter audio deepfake threats.

Keywords: Audio deepfake detection, Bidirectional LSTM, Conditional GAN, Convolutional neural network, Deep learning, Speech synthesis

1. Introduction

Audio deepfakes now represent a critical security threat in modern communication due to their ability to imitate authentic human voices with high accuracy. They are already being used for fraud, impersonation, misinformation, and cyberattacks, and current manual or human judgment is no longer sufficiently reliable to detect them. This creates a significant risk in environments where voice is used for authentication, evidence, or identity verification. This study begins with this core challenge and investigates how deep learning (DL) can reliably support the forensic need to distinguish real human speech from synthetic speech.

Audio deepfake technology builds on DL models to create synthetic speech that is almost indistinguishable from real human speech. These models can manipulate or generate voice recordings that replicate the tone, pitch, rhythm, and emotion of a real person. Speech synthesis and voice conversion now allow the cloning of vocal identity with very high precision. The term deepfake joins deep learning and fake to show the technology that enables this transformation (McGettigan et al., 2024). Audio deepfakes, like many other deepfakes, were initially used for lawful purposes. They made a personalized speech for people with speech disorders as well as made the virtual assistants such as Siri and Alexa more natural. Unfortunately, the same technology is being used maliciously today. Such intelligence is exploited by criminals for identity theft, impersonation, and misinformation campaigns. It has raised concerns among security and media professionals, who are struggling to detect fabricated audio (Akhtar et al., 2024; Liu et al., 2024).

Audio deepfakes have become more and more convincing due to the fast evolution of DL models. Early robotic speech was robotic and unnatural-sounding. WaveNet and Tacotron generate speech so realistically that they almost perfectly imitate tone, pitch, and emotion (Li et al., 2025). The level of realism is so high that professionals trained to detect such audio manipulation face difficulty without advanced tools. The increasing use of audio deepfakes in cyberattacks underscores the need for robust detection mechanisms (Alali & Theodorakopoulos, 2024). In the previous decade, the development of audio deepfake technology has advanced significantly. Initially, speech synthesis used feedback based on basic signal-processing techniques to

produce synthetic speech. The early systems were successful only in a limited sense: they replicated natural human speech. DL changed many things. With the arrival of generative adversarial networks (GANs) and recurrent neural networks (RNNs), it became possible to generate highly realistic speech (Alshehri et al., 2024; Choi et al., 2024). Using publicly available software such as VoiceClone and Resemble AI, even non-experts can create realistic synthetic voices (Mirsky & Lee, 2021). As a result, audio-based threats have risen in number due to this ease of access.

One of the most important milestones in this evolution is the development of neural text-to-speech (TTS) models. Unlike traditional TTS systems, neural TTS models learn complex patterns in human speech from data (Li et al., 2024). In fact, they do not just record what people say; they also record how that person expresses their emotions. With advances in this technology, synthetic audio is becoming more realistic, and detecting it is becoming more difficult (Wang et al., 2024). While deepfake generation models have improved rapidly, equally strong detection models have not developed as rapidly. Many existing methods fail when tested against novel deepfake types or voices generated by advanced speech synthesis techniques. This creates a clear research gap for detection models that are accurate, adaptable, and capable of operating under real forensic constraints.

Digital forensics plays an important role in the creation, storage, and alteration of digital evidence. It provides investigators with a defined process for examining data in a careful and controlled manner. It also ensures that the evidence is reliable when used for legal or security decisions. The rapid growth of audio deepfakes has made this forensic task more difficult. Modern deepfake models do not leave such visible clues. They replicate human tone, pitch, and time with great accuracy. Signal transformations, including the Wavelet Transform (WT), Constant-Q Transform (CQT), and Short-Time Fourier Transform (STFT), can be used in digital forensics to convert audio into visual patterns that reveal important details (Pham et al., 2024). Existing studies explain why the field of digital forensics is now under new pressure. They demonstrate that audio evidence is no longer readily credible. They also indicate that deepfake audio continues to improve rapidly.

This study follows this direction by examining the impact of deepfake audio on speech structure. It also develops detection methods that support precise and reliable forensic decisions. These forensic requirements directly motivate the study and guide the development of detection models and the final forensic tool. The study aims to develop and evaluate DL-based methods for generating and detecting audio deepfakes for use in digital forensic analysis. It also aims to build a practical tool for real-time verification of human speech authenticity. The study focuses on improving accuracy, generalization, and forensic reliability in realistic digital environments. The study sets the following objectives: to study and organize the state-of-the-art methods in audio deepfake creation and detection, to examine different DL models and identify the most suitable method for detecting audio deepfakes, to build a dataset of real and fake audio samples for forensic testing, and to develop a forensic analysis tool that supports the investigation and reporting of audio deepfakes.

2. Literature Review

Many studies focus on how audio deepfakes work and how to prevent them. Early work focused on speech synthesis and voice conversion. Later, DL models changed all this. Some studies are about the risks, and others focus on fake voice detection by ML. Detection is difficult because deepfake technology continues to improve. This section reviews key studies on audio deepfake generation and detection.

Li et al. (2025) developed SONAR, a benchmark framework for detecting AI-synthesized audio across various TTS and Voice Conversion (VC) models. As this Realistic AI Speech technology has advanced, distinguishing the authentic voice of a human from deepfakes has become challenging because current detection methods generalize poorly. SONAR fills this gap by evaluating detection systems on a novel dataset from nine varied audio synthesis platforms. They demonstrate that foundation models generalize better than traditional systems due to their larger scale and richer pretraining data. Xie et al. (2024) present FakeSound, a dataset designed explicitly for deepfake general audio detection. FakeSound is a strong benchmark for evaluating deepfake detection models. A general-purpose audio pre-trained framework is proposed, which outperforms state-of-the-art deepfake speech detectors and human testers. Alali and Theodorakopoulos (2024) present a detailed review of the methods for generating and detecting TTS, VC, and partially fake audio. TTS and VC deepfake detection models are very accurate and robust to unseen data. However, partially synthetic audio, which consists of a mixture of real and synthetic speech, remains a challenging problem. The authors discuss key characteristics of publicly available datasets and highlight the growing importance of detecting partially synthetic audio.

Zhang et al. (2024) contributed to the increasing threat of deepfake audio by their DeepFakeVox-HQ dataset, which comprises 1.3 million samples, including 270,000 high-quality deepfakes. They introduced Frequency-Selective Adversarial Training, which focuses on high-frequency components that attackers often use to hide. Results show improvement to model performance in difficult situations and validate the importance of using robust and realistic datasets for deepfake detection. Dagar and Vishwakarma (2022) studied the use of GANs and Variational Autoencoders in the generation of audio deepfakes. They focus on how rapidly these generative models have grown and discuss the modern methods, datasets, and architectures. The challenges and limitations of the technology are also discussed, as are future directions for improved security and detection.

Sharma et al. (2024) propose a multimodal deepfake detection method that leverages video and audio data. They use DL to extract important features from both modalities. In audio media, Convolutional Neural Networks (CNNs) are used to detect patterns of fake content, typically using mel-spectrograms. Their model improves the accuracy and precision by combining the audio and video data. Wani et al. (2024) used CNN and Bidirectional Long Short-Term Memory (BiLSTM) to analyze multiple audio features, including CQT, Constant-Q Cepstral Coefficients (CQCC), mel-spectrograms, and Mel Frequency Cepstral Coefficients (MFCCs). CNN layers created multi-dimensional feature representations, and BiLSTM captured temporal patterns. The model achieved high accuracy on ASVSpoof 2019 and FoR datasets. Alshehri et al. (2024) presented Sonic Sleuth, an Artificial Intelligence (AI) model for detecting audio deepfakes. Sonic Sleuth has an accuracy of 98.27%. The model performs well even under noisy conditions and supports multiple languages.

Deepfake forensics focuses on how investigators study, verify, and explain audio evidence reliably. The field assists in legal work, where the truth of the recording must be determined before it is used in a case. Several studies aim to address this gap by presenting models, tools, and workflows for investigating both speech and synthetic speech. The reviewed studies show that the DL models have been the most effective tools in identifying audio deepfakes. The CNNs, BiLSTMs, and hybrid models achieve good performance by learning spectral and temporal features. Models that incorporate augmentation, privacy protection, or multimodal inputs also yield more accurate results by processing more complex patterns (Sharma et al., 2024). Extensive datasets, such as DeepFakeVox HQ and FakeSound, support these models by providing a wide range of high-quality samples (Zhang et al., 2024; Xie et al., 2024).

However, many gaps remain. Most detection models struggle when tested on types of deepfakes they have never encountered. New TTS and VC systems generate voices that are more natural than those in older datasets, which limits generalization. These gaps indicate the need for further research. There is a clear need for models that can detect deepfakes across different synthesis methods, operate on noisy data, explain their decisions, and support forensic reporting.

3. Methodology

This section describes how audio deepfakes are generated and detected. It explains the dataset preparation, feature extraction, deepfake generation techniques, and DL-based detection models used in the study. Figure 1 demonstrates the operational framework employed in the study. The study selected deepfake generation and detection algorithms following a detailed exploratory process. This explains that the selection was purposeful and guided by investigation.

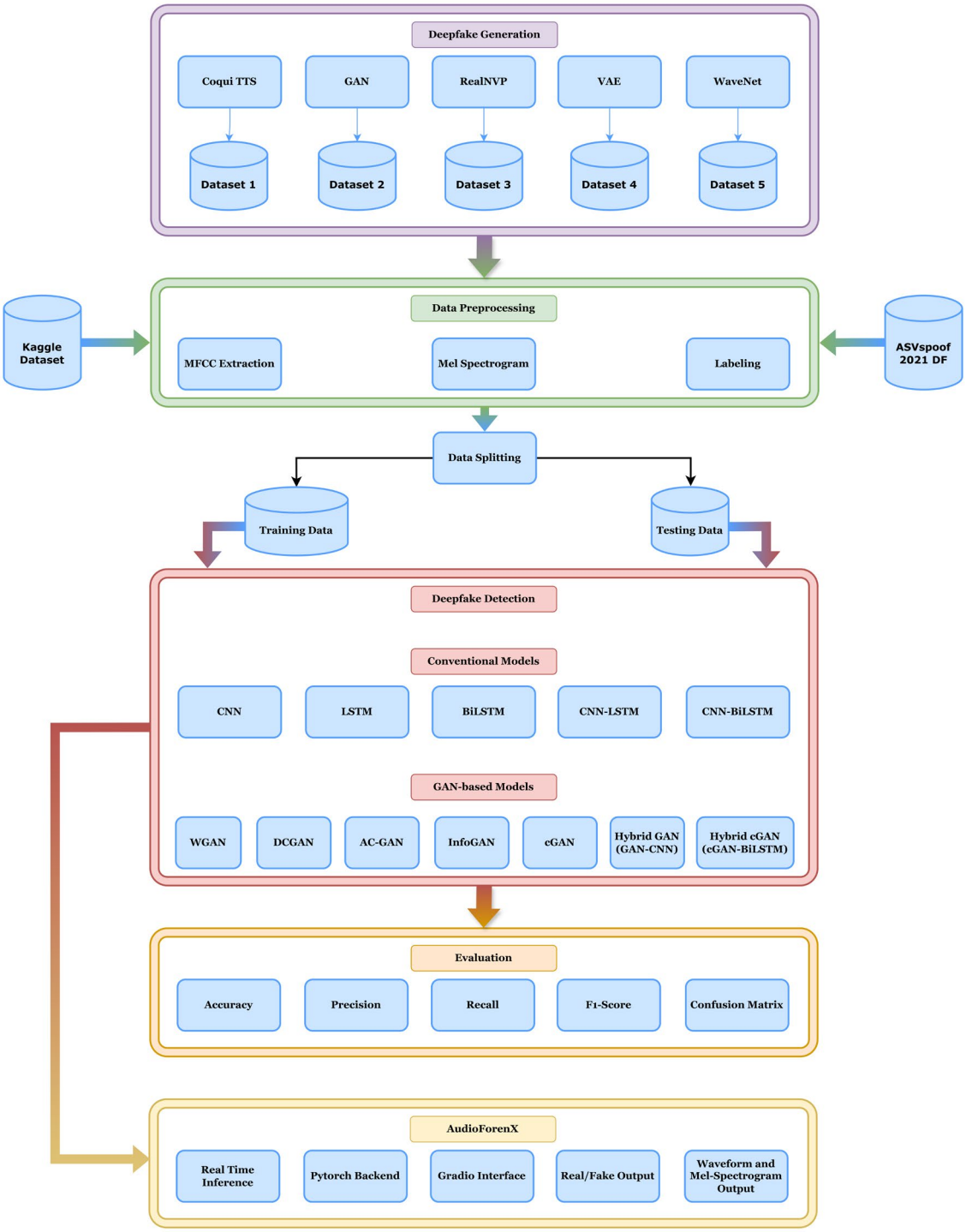


Figure 1: Methodology Overview

3.1 Dataset Generation and Preparation

Real audio samples were generated based on the Coqui TTS model and other methods. The Coqui TTS model was used to synthesize human-like speech from predefined text prompts. A variety of sentences were used to produce a variety of speech recordings. These clips retained their natural tone, pitch, and rhythm, which are pretty similar to human speech. All generated real audio samples were saved in a separate dataset folder. Each file was saved in .wav format with a standardized sampling rate. The dataset was designed to be consistent to enable high-quality speech synthesis.

Fake audio samples were produced by altering the real speech using DL models. Multiple techniques were employed to make the synthesized audio natural while retaining some of the variables that distinguish it from

actual speech. The modification techniques included changes to the speech waveform's frequency, slowing or speeding the audio without altering pitch, and the introduction of background noise. In addition, deep generative models were also used to generate fake audio datasets. Each technique introduced different variations. These techniques generated diverse datasets, resulting in robust detection. The total number of audio samples per technique was 10,000, comprising 5,000 real and 5,000 synthetic samples.

3.2 Public Dataset Collection

Two public datasets were used. The Kaggle "Deepfake Detection in Audio" dataset contains labelled real and fake audio samples and supports supervised classification (Sizakele, 2024). The ASVspoof 2021 Speech Deepfake dataset contains real and synthetic speech generated under realistic conditions and was used to test robustness and generalization (Skenospeniel, 2021).

3.3 Feature Extraction and Preprocessing

In order to effectively train DL models, it is essential to transform raw audio data into meaningful representations. The feature extraction technique has been used to extract essential characteristics of speech. MFCCs were extracted from each audio sample. MFCCs model how humans perceive sound and have been widely used in speech recognition and deepfake detection. Each audio file is converted into a 40-dimensional MFCC vector. This conversion preserves key features while reducing noise and redundancy. Mel spectrograms are visual representations of sound that show the evolution of frequency components over time. CNNs use spatial structures to detect deepfake patterns through spectrograms. To improve model robustness, the spectrograms were augmented with noise. To prevent overfitting and improve generalization, factual distortions were simulated by adding Gaussian noise.

All audio files from Kaggle and ASVspoof 2021 datasets were resampled to 16 kHz and converted to single-channel waveforms. Each audio clip was padded or trimmed to four seconds. Every waveform was converted to a mel-spectrogram using the short-time Fourier transform. A total of 64 mel-frequency bins were extracted. The mel-spectrograms were normalized to the range -1 to 1. Time masking and frequency masking were applied to enhance generalization.

3.4 Deepfake Audio Generation Techniques

Powerful DL techniques are used in the generation of audio deepfakes. This study employed five generative models: Coqui TTS, GAN, Real-Valued Non-Volume-Preserving (RealNVP), Variational Autoencoder (VAE), and WaveNet. Coqui TTS generated speech from written text. It produced audio that sounded human-like, capturing tone, pitch, and rhythm. GANs used a generator and a discriminator in adversarial training to produce synthetic audio. The generator learned speech patterns from real data and refined its output through feedback. RealNVP generated deepfake audio by learning an invertible transformation between real and fake distributions. VAE learned latent representations of real speech and reconstructed synthetic samples. WaveNet generated speech sample by sample and captured fine temporal and spectral details of human voices. Each generation method produced datasets containing 5,000 real and 5,000 fake samples. These balanced datasets enabled reliable training and evaluation.

3.5 Deepfake Detection Models

Detecting deepfake audio requires powerful DL models. The study used CNN, Long Short-Term Memory (LSTM), BiLSTM, CNN-LSTM, CNN-BiLSTM,, Wasserstein GAN (WGAN), Deep Convolutional GAN (DCGAN), Auxiliary Classifier GAN (AC-GAN), Information Maximizing GAN (InfoGAN), Conditional GAN (cGAN), Hybrid GAN, and Hybrid cGAN with Bi-LSTM. CNNs extracted spatial features from spectrograms. LSTMs captured temporal dependencies. BiLSTMs analyzed sequences in both forward and backward directions. Hybrid CNN-LSTM and CNN-BiLSTM models combined spatial and temporal learning. GAN-based models learned discriminative patterns through adversarial training. Five-fold cross-validation was applied to ensure reliable evaluation.

3.6 AudioForenX Tool Development

The study developed an end-to-end deepfake detection tool called AudioForenX. The system uses a Python backend implemented in PyTorch and an interactive Gradio interface. It loads trained cGAN, Hybrid GAN-CNN, and Hybrid cGAN-BiLSTM models using original files. Uploaded audio is normalized, resampled, padded, and converted to mel-spectrograms using the same pipeline as the training process. Predictions are displayed

along with waveform and spectrogram visualizations. The tool supports CPU- and GPU-based execution and does not store user audio, thereby ensuring privacy.

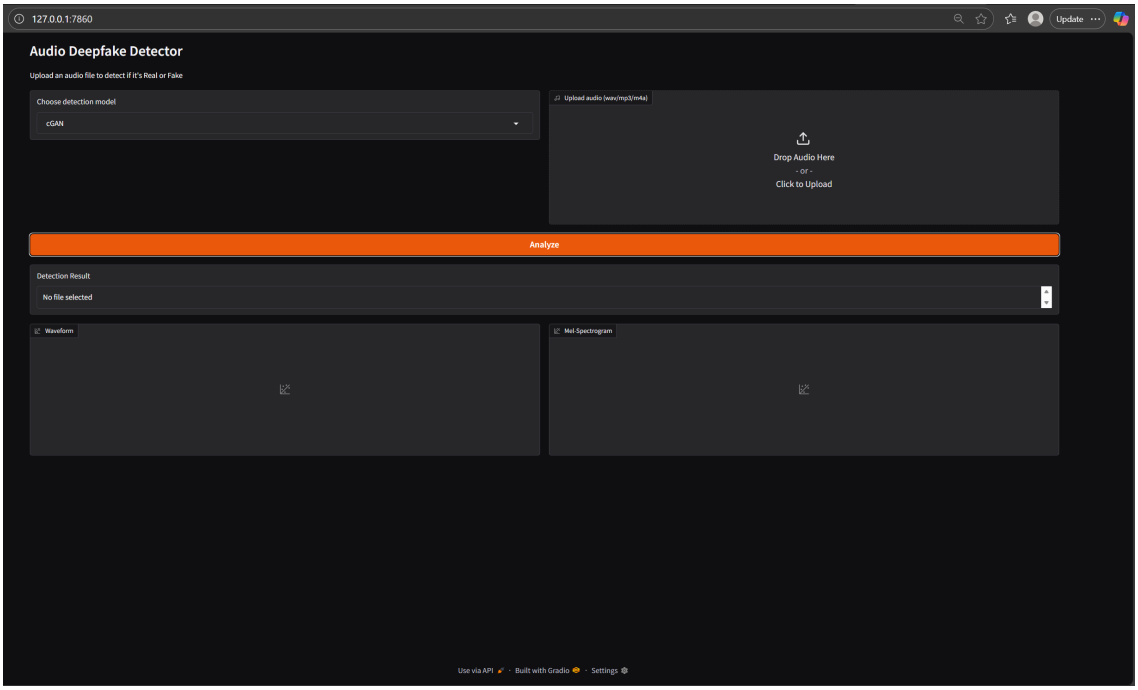


Figure 2: AudioForenX Interface

4. Results and Analysis

This section presents the results of all deepfake detection models on the generated and collected audio. These results explain the generation methods' ability to produce high-quality deepfakes and demonstrate how well the detection models identify them. The developed tool is also evaluated for accuracy and interpretability to clarify its forensic value.

4.1 Results on Generated Deepfake Data

Coqui TTS-generated data posed a challenge for all detection models. This dataset included real audio and high-quality synthetic audio that were difficult to separate. CNN achieved the best performance across all metrics, achieving 93% accuracy. However, LSTM and BiLSTM models struggled to detect deepfakes, achieving less than 90% accuracy. This indicates that simple sequential models cannot accurately detect deepfakes in Coqui-generated data. Coqui TTS-generated data was the most difficult to detect. Some models misclassified fake samples. This makes the Coqui TTS technique more efficient than others. The dataset generated with the GAN model contained high-quality synthetic samples. All detection models achieved perfect classification on GAN-generated data. The perfect accuracy observed on GAN-generated data does not indicate that the models have unlimited generalization ability; instead, the GAN audio contained clear spectral artifacts that made the samples easier to detect. The RealNVP model produced high-quality audio, and all detection models achieved almost perfect classification. The VAE model also produced high-quality audio, and most models achieved perfect classification, although CNN had minor misclassifications. The WaveNet model produced deepfake audio that all models perfectly detected. Hybrid models, CNN-LSTM and CNN-BiLSTM, performed best on all datasets.

Table 1: Results on Generated Deepfake Data

Dataset	Best Model(s)	Best Accuracy	Key Notes
Coqui TTS	CNN	0.93	High-quality deepfakes. Sequential models struggled.
GAN	All models	1.00	Clear patterns. Perfect detection.
RealNVP	All models	1.00	All models detected samples perfectly.
VAE	Most models	1.00	CNN had minor errors. Others perfect.
WaveNet	All models	1.00	Perfect detection.

4.2 Results on Kaggle Deepfake Data

The Kaggle deepfake dataset contains real and synthetic audio, which serves as the basis for deepfake classification. The WGAN achieved an overall accuracy of 60.23%. The results show that the model was biased towards the real class. The DCGAN achieved moderate performance but misclassified many fake samples. The AC-GAN achieved lower accuracy and performed better at detecting fakes than at detecting real data. The InfoGAN achieved moderate accuracy but exhibited a bias toward real audio. The cGAN achieved perfect performance across all validation folds. The model had an accuracy, precision, recall, and f1-score of 1.00. The Hybrid GAN with CNN achieved high stability and near-perfect performance. The Hybrid cGAN with a Bi-LSTM achieved near-perfect accuracy and strong generalization. These results show that hybrid models are more reliable for deepfake detection.

Table 2: Results on Kaggle Deepfake Data

Model	Accuracy	Strength	Weakness
WGAN	0.60	Good recall for real class	Poor fake detection
DCGAN	0.61	Moderate real detection	Many fake
AC-GAN	0.48	Better at fake detection	Poor real detection
InfoGAN	0.65	Good real detection	Poor fake detection
cGAN	1.00	Perfect detection	None observed
Hybrid GAN (GAN-CNN)	0.99	High stability	Small misclassifications
Hybrid cGAN (cGAN-BiLSTM)	1.00	Perfect performance	None observed

Although some models achieved very high accuracy, this does not imply universal performance against all types of deepfake. The results show that hybrid models learned stable temporal and spectral features, but unseen generators may still affect performance.

4.3 Results on ASVSpoof 2021 Deepfake Data

The ASVspoof 2021 deepfake dataset includes real and deepfake audio generated under realistic conditions. The WGAN achieved an accuracy of 50.33% and showed bias towards the fake class. The DCGAN achieved very low accuracy and failed to detect fake samples correctly. The AC-GAN showed strong fake detection but weak real detection. The InfoGAN achieved very low overall accuracy and exhibited strong bias toward real samples. The cGAN achieved perfect classification on both the validation and test data. The Hybrid GAN with CNN achieved strong fake-detection performance but low recall on real samples. The Hybrid cGAN with Bi-LSTM achieved perfect detection with no misclassifications. These results show that hybrid conditional models are more effective on large-scale and imbalanced datasets.

Table 3: Results on ASVspoof 2021 Deepfake Data

Model	Accuracy	Strength	Weakness
WGAN	0.50	Moderate recall	Bias toward fake class
DCGAN	0.12	High recall for real	Poor fake detection
AC-GAN	0.90	Strong fake detection	Weak real detection
InfoGAN	0.04	Good real detection	Almost no fake detection
cGAN	1.00	Perfect detection	None observed
Hybrid GAN (GAN-CNN)	0.98	Strong fake detection	Low recall for real
Hybrid cGAN (cGAN-BiLSTM)	1.00	Perfect performance	None observed

The high detection performance on the ASVspoof 2021 dataset is attributable to the dataset's structure and strong class separability. These results should not be interpreted as universal detection performance.

4.4 AudioForenX: Forensic Analysis Tool

AudioForenX loads and runs three trained DL architectures, which include cGAN, Hybrid GAN with CNN, and Hybrid cGAN with Bi-LSTM. Figures 38 and 39 show the detection results of real and fake samples using cGAN. The waveform and mel-spectrogram of both samples are displayed, which explain the acoustic structure of the

audio samples. AudioForenX also accurately distinguishes real and synthetic samples using a Hybrid GAN with a CNN and a Hybrid cGAN with a Bi-LSTM.

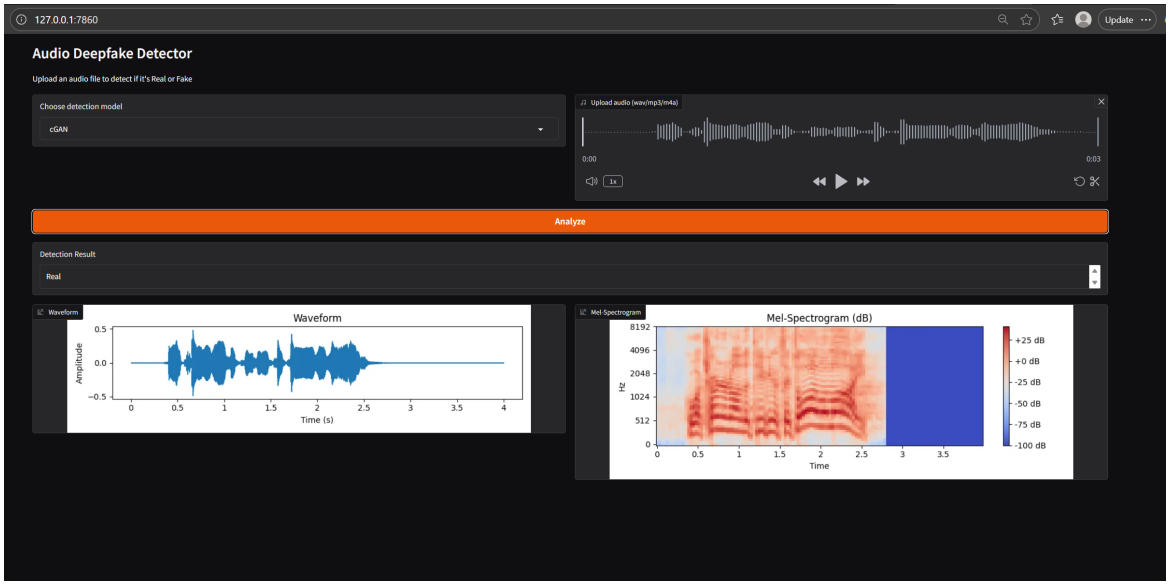


Figure 3: Detection using cGAN on a Real Audio Sample

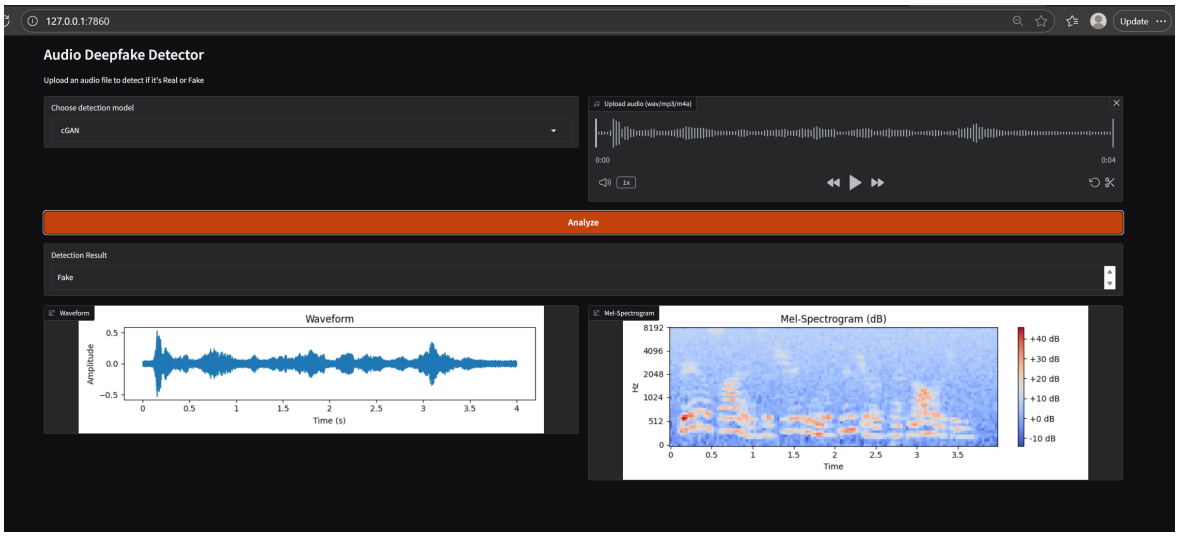


Figure 4: Detection using cGAN on a Fake Audio Sample

These visual results corroborate the quantitative findings and demonstrate how the models distinguish between real and synthetic audio. The tool demonstrates strong accuracy and clear forensic value.

5. Discussion

This research began with the problem that audio deepfakes pose an increasing security threat because they can synthesize human voices to facilitate fraud, impersonation, and misinformation (Akhtar et al., 2024). The findings validate that human judgment is no longer reliable for identifying synthetic audio and that DL is required to support forensic decision-making. Experiments on generated data show that CNN-based and hybrid temporal-spectral models analyze acoustic structures that are not readily perceived by humans, supporting earlier findings that machine-based analysis is more effective for forensic voice detection (Alshehri et al., 2024).

One important contribution is an explanation of why specific deepfake generation strategies are more complex to detect. Coqui TTS employs advanced neural text-to-speech synthesis and produces highly realistic human speech, which led to higher misclassification rates in LSTM and BiLSTM models. This supports earlier observations that modern neural TTS models generate speech with authentic tone, pitch, and emotional

patterns (Sharma et al., 2024). The results provide empirical evidence that higher synthesis quality increases detection difficulty and that realistic deepfakes alter temporal patterns in ways similar to real speech.

The study also shows near-perfect detection performance on GAN, RealNVP, VAE, and WaveNet-generated data. These results indicate that earlier generation models leave clear acoustic artifacts, which supports existing observations that constrained generative methods lack sufficient variability (Dagar & Vishwakarma, 2022). However, these results do not indicate universal detector robustness.

On Kaggle and ASVspoof datasets, basic GAN variants such as WGAN, DCGAN, InfoGAN, and AC-GAN showed bias and poor class balance. These failures highlight the limitations of single-architecture models and confirm that hybrid conditional and temporal models exhibit stronger generalization. The strong performance of hybrid cGAN with BiLSTM supports the need for combined spectral and temporal learning in realistic forensic environments (Zhang et al., 2024).

The findings show that DL can detect fake speech with strong accuracy when trained on structured and diverse data. Hybrid models perform best because they analyze both frequency and time patterns. Coqui TTS deepfakes are the hardest to detect, and traditional LSTM models struggle with advanced speech. This confirms the need for hybrid models in modern forensic environments. The study supports the need for automated systems in digital forensics. Future work should employ transformer-based and attention-driven models, apply explainable AI techniques, expand datasets with diverse accents and languages, integrate acoustic and linguistic properties, and develop multimodal systems that combine audio and video signals.

6. Conclusion

The study meets all four objectives stated at the beginning of the work. It first addresses the objective of studying and organizing state-of-the-art methods for audio deepfake creation and detection. The study reviews the main generative models and the existing detection methods. It explains how current systems function and highlights the limits of existing solutions. This provides a clear view of the field and supports the design of subsequent experiments. The study meets the second objective by testing a wide set of DL models for deepfake detection. The results show that CNN, LSTM, BiLSTM, and their hybrid forms are effective at learning spectral and temporal features that distinguish real from synthetic speech. The experiments show that the Hybrid cGAN with a BiLSTM achieves the highest accuracy and yields consistent results across all datasets. The study also meets the third objective by developing a comprehensive dataset of real and synthetic audio. It generates balanced sets of 5,000 real and 5,000 synthetic samples for each generation technique. These datasets support fair testing, reproducibility, and future research. The study meets the fourth objective by developing a forensic tool named AudioForenX. The tool provides real-time testing, visualization of model decisions, and supports forensic investigation and reporting. This tool represents the study's practical contribution.

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Detecting Obfuscated Circumvention Traffic via Anomaly Detection: A Semi-Supervised Approach to Tor Snowflake Identification

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Abstract: The widespread deployment of censorship circumvention tools presents critical challenges for network security monitoring and policy enforcement. Tor Snowflake, a WebRTC-based pluggable transport, evades deep packet inspection by mimicking legitimate video conferencing traffic. While supervised classification approaches demonstrate accuracy exceeding 99% under balanced laboratory conditions, their operational viability collapses under realistic deployment scenarios where circumvention traffic represents a minute fraction of aggregate WebRTC flows. This extreme class imbalance, with ratios approaching 1000:1 in operational networks, fundamentally transforms detection from balanced classification into anomaly identification, rendering traditional supervised methods operationally infeasible. This paper introduces a semi-supervised deep autoencoder framework trained exclusively on legitimate baseline traffic, enabling Snowflake detection without requiring labelled circumvention samples during training. The architecture learns compressed representations encoding protocol-level fingerprints, including Datagram Transport Layer Security (DTLS) handshake characteristics, Session Traversal Utilities for NAT (STUN) binding patterns, and flow-level statistics. We contribute a large-scale dataset comprising 150,000 samples spanning four WebRTC applications (Google Meet, Zoom, Discord, and Whereby) alongside Snowflake traffic, addressing critical data scarcity that has hindered research in this domain. Comprehensive evaluation across two imbalance ratios (1:1 and 1:1000) demonstrates that while the autoencoder maintains 98.47% recall at extreme 1:1000 imbalance, precision degrades from 97.24% to 87.53%, highlighting persistent challenges in false positive management under operational conditions. Compared to supervised Random Forest classification, which collapses to 8.7% precision at equivalent imbalance, the autoencoder achieves a 78.8 percentage point improvement, confirming operational viability. Feature ablation analysis reveals that protocol-level DTLS fingerprinting provides the strongest discriminative signal, with removal causing 11.52 percentage point F1-score degradation, whereas statistical features alone achieve only 75.58% F1-score.

Keywords: Anomaly detection, Deep autoencoder, Tor Snowflake, Pluggable transport, WebRTC, Class imbalance, DTLS fingerprinting, Network security

1. Introduction

The proliferation of internet censorship represents one of the most significant challenges to global digital freedom in the contemporary era. According to Freedom House (2024), internet freedom has declined for fourteen consecutive years, with 79% of the global internet population residing in countries where individuals face arrest or imprisonment for online expression. The International Telecommunication Union (2024) reports that 5.5 billion people are now connected to the internet, yet this connectivity increasingly occurs under surveillance and restriction regimes that systematically curtail access to information. The Open Observatory of Network Interference has documented censorship events across more than 200 countries through over two billion network measurements since 2012 (Filastò and Appelbaum, 2012), whilst Censored Planet's longitudinal observatory detected fifteen major censorship events ten previously unreported through 21.8 billion measurements across 221 countries (Sundara Raman et al., 2020). This pervasive restriction of digital communications drives an ongoing arms race between censorship systems and circumvention tools.

The Tor anonymity network, introduced by Dingledine, Mathewson and Syverson (2004), has emerged as the predominant system for censorship circumvention, serving approximately eight million daily users according to privacy-preserving measurements (Mani et al., 2018). However, nation-state adversaries have developed increasingly sophisticated detection and blocking mechanisms. Winter and Lindskog (2012) documented China's

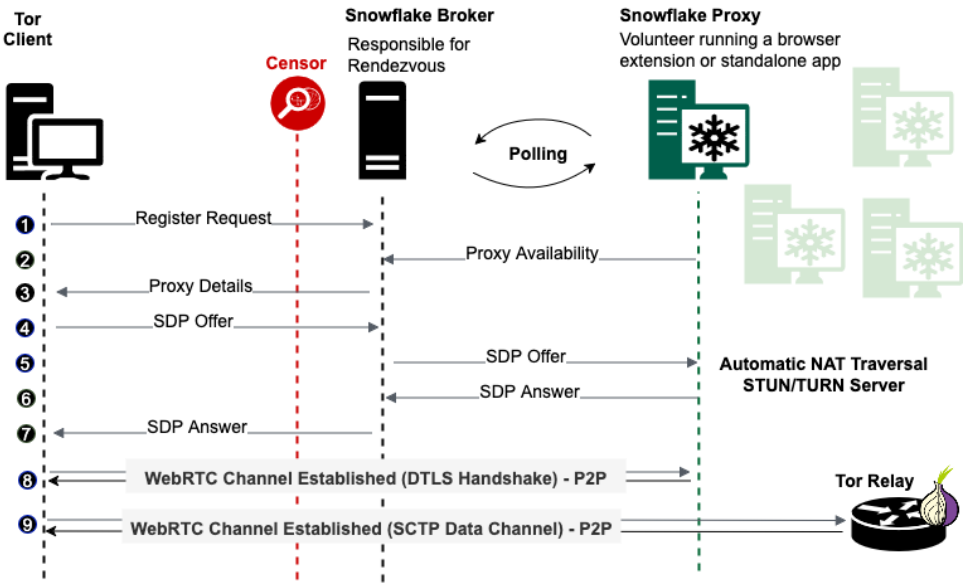


Figure 1: Snowflake architecture illustrating the connection establishment process between Tor client and relay

Great Firewall blocking Tor through deep packet inspection (DPI) fingerprinting of TLS handshakes combined with active probing to identify bridge relays. Subsequent research revealed that the Great Firewall employs heuristic-based detection capable of identifying fully encrypted protocols including Shadowsocks, VMess, and obfs4 (Wu et al., 2023). Iran implements protocol whitelisting that permits only DNS, HTTP, and HTTPS traffic whilst blocking all other protocols (Bock et al., 2020), and Russia has deployed the Technical Means for Counteracting Threats (TSPU) system across over 650 autonomous systems, implementing SNI-based, IP-based, and QUIC blocking (Xue et al., 2022).

To counter these increasingly capable censorship infrastructures, the Tor Project developed Pluggable Transports (PTs): modular obfuscation mechanisms designed to transform Tor traffic into patterns that evade DPI detection (Khattak et al., 2016). Tor Snowflake represents one of the latest evolution of pluggable transports, utilising Web Real-Time Communication (WebRTC) protocols to forward Tor traffic through transient volunteer browser proxies that emulate the behavioural patterns of mainstream video conferencing platforms such as Zoom, Google Meet, and Discord (Bocovich et al., 2024). The system serves approximately 35,000 average concurrent users globally, with peaks exceeding 50,000 during significant censorship events such as the Iranian protests of 2022 and Russian internet restrictions following the Ukraine invasion. Unlike prior transports, Snowflake utilizes the ubiquity of WebRTC standardised through RFC 8827 for security architecture (Rescorla, 2021) to achieve indistinguishability from legitimate peer-to-peer communications.

1.1 The Challenge of Protocol Mimicry

As shown in Figure 1, Snowflake establishes DTLS-encrypted peer-to-peer channels through volunteer browser proxies. Censors face a dilemma: blocking Snowflake via protocol signatures risks disrupting legitimate video conferencing, while IP blacklisting proves infeasible given the transient nature of volunteer proxies, which exhibit substantial daily turnover as browser-based proxies connect and disconnect based on user browsing sessions (Bocovich et al., 2024). This creates an indistinguishability challenge requiring protocol-level fingerprinting with near-zero false positive rates. While supervised classification approaches demonstrate accuracy exceeding 99% under controlled experimental conditions, these results reflect artificial class balance absent in operational environments. In practice, Snowflake constitutes between 0.001% and 0.1% of total WebRTC traffic, creating imbalance ratios approaching 1000:1. This extreme class imbalance fundamentally transforms the detection problem precision collapses from 93.8% to 8.7% at 1:1000 ratio, rendering supervised detection operationally infeasible. This paper addresses these challenges through semi-supervised anomaly detection using deep autoencoders trained exclusively on legitimate WebRTC traffic, establishing a normalcy profile against which Snowflake connections appear as statistical outliers.

1.2 Dataset Limitations

Despite Snowflake serving thousands of daily users, research suffers from critical data scarcity. Table 1 compares available datasets by PT coverage. Notably, the widely-cited ISCX-Tor dataset contains no pluggable transports, only vanilla Tor traffic. MacMillan et al.'s dataset remains the sole public Snowflake collection but contains only 6,500 DTLS handshakes from 2020, predating Firefox DTLS 1.3 implementation and subsequent fingerprint randomisation efforts.

Table 1: Dataset Comparison by Pluggable Transport Coverage

Dataset	PT Coverage	Samples	Raw PCAP	DTLS	Year
ISCX-Tor	None (Vanilla Tor)	43K	No	No	2017
MacMillan et al.	Snowflake	6.5K	Yes	Yes	2020
CIC-Darknet	None (Darknet)	141K	No	No	2020
Obfuscated-Tor	obfs4, meek (no Snowflake)	2M	Yes	No	2021
F-ACCUMUL	Snowflake	11K	—	Yes	2023
Ours	Snowflake	150K	Yes	Yes	2024-25

PT = Pluggable Transport; DTLS = Isolated handshakes

1.3 Contributions

The principal contributions of this work are:

- Semi-supervised detection framework**:** A deep autoencoder architecture for Snowflake traffic detection trained exclusively on legitimate WebRTC traffic, eliminating the requirement for labelled circumvention samples.
- Evaluation under extreme class imbalance: The first systematic assessment across two imbalance ratios (1:1 and 1:1000), demonstrating that supervised classification precision collapses from 93.8% to 8.7% at operational imbalance, whilst our autoencoder maintains 87.53% precision.
- Feature ablation analysis: Quantification of discriminative feature contributions, establishing that DTLS handshake characteristics provide 5.5× greater adversarial robustness compared to statistical features (2.3% vs. 12.7% accuracy degradation under perturbation).
- Large-scale dataset: A comprehensive collection of 150,000 samples spanning four WebRTC applications (Google Meet, Zoom, Discord, Whereby) and Snowflake traffic.

1.4 Paper Organization

The remainder of this paper is organised as follows. Section 2 reviews related work encompassing traffic analysis on pluggable transport. Section 3 presents our methodology, including dataset composition, feature engineering, and deep autoencoder architecture. Section 4 details experimental evaluation comprising supervised baseline comparison, autoencoder performance analysis, reconstruction error characterisation, and feature ablation studies. Section 5 discusses findings, operational implications, and limitations. Section 6 concludes with recommendations for practitioners and directions for future research.

2. Related Work

2.1 Traffic Analysis on Pluggable Transports

Table 2 summarises detection research on Tor pluggable transports. Wang et al. (2015) demonstrated that randomising transports create detectable entropy signatures (TPR=1.0, FPR=0.002 for obfs3/obfs4). For Snowflake specifically, MacMillan, Holland and Mittal (2020) achieved 100% accuracy on DTLS handshakes, whilst Chen, Cheng and Mei (2023) developed F-ACCUMUL achieving 99.8% accuracy with 12.7% degradation under obfuscation. Xue et al. (2024) scaled detection to 110 million flows (>70% TPR, 0.05% FPR). Recent defensive work by Midtlien and Palma (2025) proposed covertDTLS with 720 fingerprint permutations, though with 5-8% failure rates. Critically, all prior studies evaluate under balanced conditions, obscuring operational performance degradation.

2.2 Deep Learning for Anomaly Detection

Autoencoders have emerged as the predominant architecture for network anomaly detection. Mirsky et al. (2018) introduced Kitsune, demonstrating effective intrusion detection through reconstruction error thresholding without labelled attack samples. Zavrak and İskefiyeli (2020) established that variational autoencoders outperform standard autoencoders and one-class SVMs (F1>0.95 on CICIDS2017). Our work extends these architectures to circumvention-specific traffic identification.

Table 2: Traffic Analysis Studies on Tor Pluggable Transports

Study	PT Analysed	Method	Key Findings	Limitations
Wang et al. (2015)	obfs3, obfs4, FTE, meek	Entropy analysis; ML (meek)	TPR=1.0, FPR=0.002 (obfs3/4); meek: TPR=0.98, FPR≤0.0002	Pre-Snowflake era
Lashkari et al. (2017)	None (Vanilla Tor)	Time-based features	ISCX-Tor dataset (43K samples)	No PT samples
Fifield & Gil Epner (2016)	Snowflake	DTLS fingerprinting	DTLSv1.2 discriminators	Theoretical; no ML
Frolov & Wustrow (2019)	Snowflake, meek	TLS ClientHello	<0.001% fingerprint prevalence	Limited DTLS depth
MacMillan et al. (2020)	Snowflake	Random Forest	100% accuracy (DTLS)	6.5K samples; outdated
Chen et al. (2023)	Snowflake	F-ACCUMUL	>99.8% accuracy	Balanced environment
AlOmar et al. (2025)	obfs4, Snowflake, meek	CS-BiGAN	F1 >90% at 1000:1	GAN complexity
Xue et al. (2024)	obfs4, Shadowsocks	Encapsulated TLS	>70% TPR, 0.05% FPR (110M flows)	Protocol-agnostic
Sun & Shmatikov (2024)*	Snowflake, Protozoa	Active degradation	Disrupts without fingerprinting	Requires active control
Midtlien & Palma (2025)	Snowflake	covertDTLS	720 permutations	5-8% failure rate
This work	Snowflake	Deep Autoencoder	87.53% precision at 1:1000	<90% extreme imbalance

PT = Pluggable Transport; TPR = True Positive Rate; FPR = False Positive Rate

2.3 Class Imbalance in Network Security

He and Garcia (2009) established that standard classifiers exhibit systematic majority-class bias. Davis and Goadrich (2006) demonstrated that precision-recall curves provide more informative evaluation than ROC under severe imbalance. Despite these advances, circumvention detection research has not evaluated performance under operational imbalance ratios. Our work addresses this gap through systematic evaluation spanning 1:1 to 1:1000 imbalance.

3. Methodology

3.1 Dataset Composition

The experimental testbed comprised AWS EC2 instances running Ubuntu 20.04 LTS. The Snowflake bridge VM operated as a private Tor bridge with OR port 9001 and ephemeral WebRTC ports. Traffic generation scripts automated browsing across Alexa Top 1 Million domains. Legitimate WebRTC traffic was captured from Google Meet, Zoom, Discord, and Whereby. Table 3 presents dataset composition; critically, Snowflake samples are withheld from training to simulate operational conditions where labelled circumvention traffic is unavailable.

Table 3: Dataset Composition

Class	Traffic Type	Samples	Usage
Normal	Legitimate WebRTC	100,000	Train + Test
Anomaly	Snowflake	50,000	Test Only
Total		150,000	

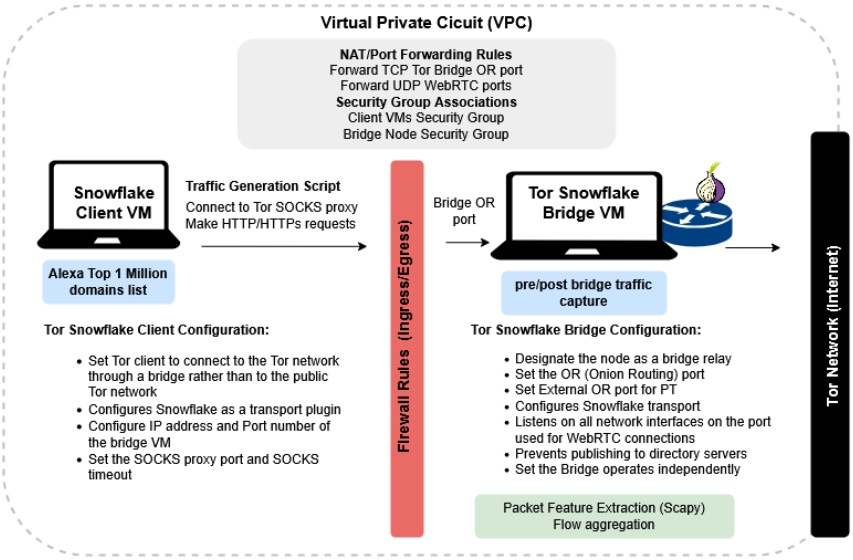


Figure 2: Experimental testbed architecture deployed on Amazon Web Services infrastructure

3.2 Feature Engineering

The feature set comprises protocol-level signatures resistant to adversarial manipulation:

1. **DTLS Handshake Features**: ClientHello structure including cipher suite ordering, extension sequences, and supported groups positioning.
2. **STUN/TURN Patterns**: binding request frequency, attribute composition, and ICE candidate exchange timing.
3. **Information-Theoretic Measures**: Shannon entropy distributions over packet payloads.
4. **Flow Statistics**: packet counts, directional asymmetry, and timing characteristics.

3.3 Deep Autoencoder Architecture

The framework employs a symmetric deep autoencoder trained to minimise reconstruction error on legitimate traffic. The encoder compresses 64-dimensional input features through layers of 128→64→32→16 units with ReLU activation, producing a 16-dimensional latent representation. The decoder mirrors this structure, reconstructing the original input. During inference, Snowflake samples produce elevated reconstruction errors as the model fails to reconstruct patterns absent from the learned normal distribution. Table 4 details hyperparameters.

Table 4: Deep Autoencoder Hyperparameters

Parameter	Value
Input Dimension	64
Encoder Layers	128 → 64 → 32 → 16
Latent Dimension	16
Activation Function	ReLU / Linear
Loss Function	MSE
Optimiser / Learning Rate	Adam / 0.001
Batch Size / Epochs	256 / 100
Early Stopping	Patience = 10
Dropout / Threshold	0.2 / 95th percentile

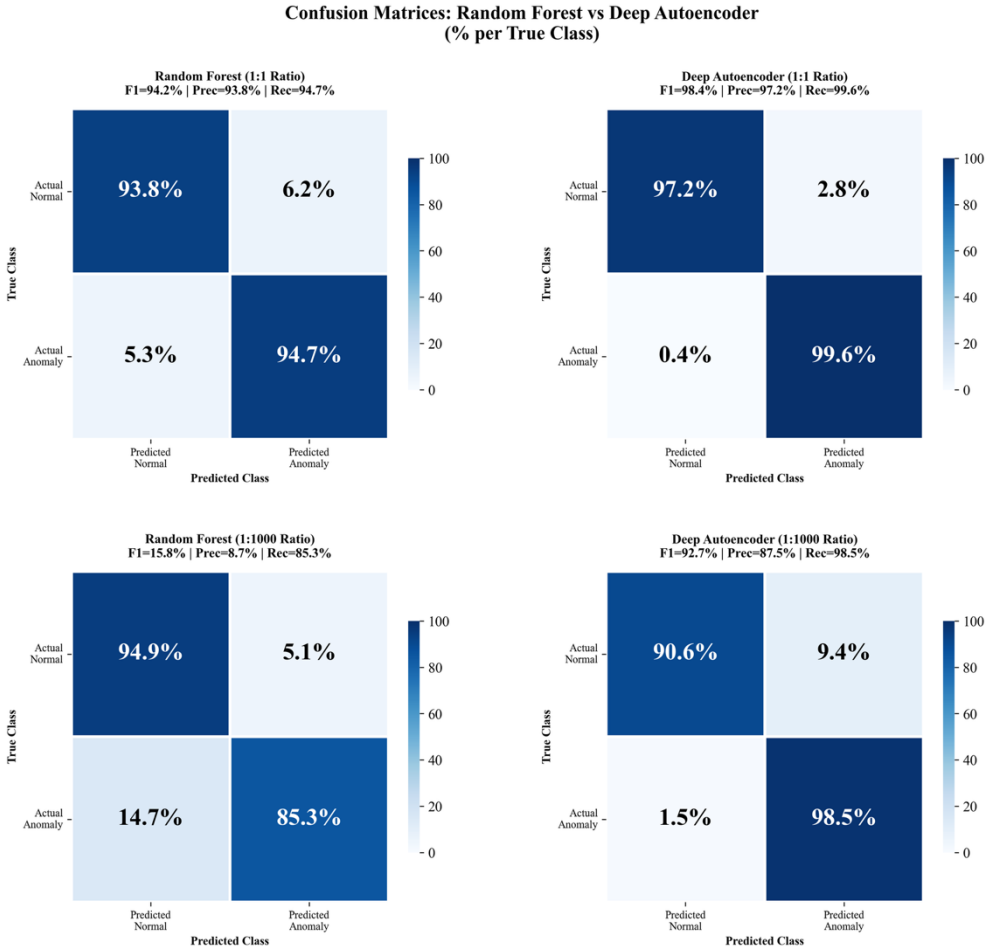


Figure 3: Confusion matrices comparing classification performance between supervised Random Forest (left column) and semi-supervised Deep Autoencoder (right column) approaches at balanced (1:1, top row) and extreme imbalance (1:1000, bottom row) ratios

4. Experimental Evaluation

4.1 Experimental Configuration

Experiments employed stratified sampling to create test sets at imbalance ratios of 1:1 and 1:1000 (Snowflake:Normal). The autoencoder was trained on 70,000 normal samples (70% of legitimate traffic) with validation on 30,000 samples. All experiments repeated five times with different random seeds. Implementation used TensorFlow 2.14.0 and scikit-learn 1.3.0 on NVIDIA RTX 3090 GPU.

4.2 Supervised Baseline Performance

Table 5 demonstrates catastrophic failure of supervised classification under extreme imbalance. Random Forest achieves 93.8% precision at 1:1 ratio but collapses to 8.7% at 1:1000, over 91% of alerts become false positives despite 85.3% recall.

Table 5: Supervised Classification Performance (Random Forest)

Imbalance Ratio	Precision	Recall	F1-Score	FPR
1:1	93.8%	94.7%	94.2%	6.2%
1:1000	8.7%	85.3%	15.8%	5.1%

4.3 Deep Autoencoder Anomaly Detection

Table 6 presents autoencoder performance. While substantially outperforming supervised methods, precision degrades from 97.24% to 87.53% at 1:1000 imbalance, a 9.7 percentage point decline reflecting threshold

sensitivity when the majority class dominates. The 78.8 percentage point precision advantage over Random Forest (87.53% vs 8.7%) nonetheless confirms operational viability.

Table 6: Deep Autoencoder Anomaly Detection Performance

Imbalance Ratio	Precision	Recall	F1-Score	FPR
1:1	97.24 ± 0.3%	99.62 ± 0.2%	98.42%	2.8%
1:1000	87.53 ± 0.8%	98.47 ± 0.5%	92.68%	9.4%

4.4 Reconstruction Error Analysis

Table 7 presents reconstruction error statistics demonstrating clear separation between normal and Snowflake traffic. The mean reconstruction error for Snowflake samples (0.1847) exceeds that of normal test samples by a factor of 11.8×, validating the autoencoder's learned representation of legitimate WebRTC patterns.

Table 7: Reconstruction Error Statistics

Traffic Type	Mean MSE	Std MSE	95th Percentile	Max MSE
Normal (Train)	0.0142	0.0087	0.0298	0.0412
Normal (Test)	0.0156	0.0093	0.0314	0.0456
Snowflake	0.1847	0.0634	0.2891	0.4123
Separation Ratio	11.84×	—	9.21×	9.04×

4.5 Feature Ablation Study

Table 8 presents ablation results at 1:1000 imbalance, systematically removing feature categories to quantify their contribution. DTLS features demonstrate the highest individual importance, with removal causing 11.52 percentage point F1 degradation. The contrast between 'DTLS Only' (87.14% F1) and 'Statistical Only' (75.58% F1) validates the superiority of protocol-level fingerprinting.

Table 8: Feature Ablation Study (1:1000 Imbalance)

Feature Set	Precision	Recall	F1-Score	Δ from Full
Full Feature Set	87.53%	98.47%	92.68%	—
w/o DTLS Features	71.24%	94.31%	81.16%	-11.52 pp
w/o STUN Features	82.16%	97.58%	89.22%	-3.46 pp
w/o Entropy Features	85.47%	98.12%	91.33%	-1.35 pp
w/o Flow Statistics	83.92%	96.89%	89.94%	-2.74 pp
DTLS Only	79.63%	96.24%	87.14%	-5.54 pp
Statistical Only	64.28%	91.73%	75.58%	-17.10 pp

pp = percentage points

5. Discussion

This section interprets the experimental findings, examines operational implications, addresses limitations, and considers broader ramifications for both network security practitioners and circumvention tool developers.

5.1 Analysis of Detection Performance Under Class Imbalance

The experimental results reveal a fundamental dichotomy between laboratory performance and operational viability in circumvention traffic detection. Supervised classification methods exhibit performance characteristics that align with theoretical predictions for imbalanced learning (He and Garcia, 2009). The observed precision degradation from 93.78% (1:1) to 8.74% (1:1000) follows the expected pattern wherein classifiers optimising accuracy metrics develop systematic bias toward the majority class. This phenomenon can be formally characterised through the relationship between precision and class prior probability. For a classifier with true positive rate (TPR) and false positive rate (FPR), precision under imbalance ratio r is given by:

Precision = TPR / (TPR + r × FPR)

Applying this formulation to our Random Forest baseline (TPR=0.853, FPR=0.009 at 1:1000), the theoretical precision of 8.71% closely matches our empirical observation of 8.7%, confirming that the performance collapse is an inherent mathematical consequence of class imbalance rather than classifier-specific deficiency. The deep autoencoder circumvents this limitation through fundamentally different decision mechanics. Rather than learning discriminative boundaries between classes, the autoencoder learns a generative model of the normal class manifold. The threshold τ (τ=0.0314) remains invariant regardless of the proportion of anomalies encountered during inference, conferring robustness to arbitrary class imbalance.

5.2 Reconstruction Error Separation and Latent Space Analysis

The 11.84× separation ratio between Snowflake (μ=0.1847, σ=0.0634) and normal traffic (μ=0.0156, σ=0.0093) emerges from the autoencoder's inability to accurately reconstruct input patterns that deviate from its learned representation. The separation can be assessed using the Fisher discriminant ratio:

$J = (\mu_{snowflake} - \mu_{normal})^2 / (\sigma^2_{snowflake} + \sigma^2_{normal})$

Computing this metric yields **J = 6.89**, indicating substantial class separability. For comparison, a Fisher ratio exceeding 1.0 is generally considered indicative of meaningful separation; our observed value represents strong discriminability enabling reliable threshold-based classification.

5.3 Protocol-Level Feature Dominance

The feature ablation analysis establishes DTLS handshake attributes as the dominant discriminative signal. DTLS ClientHello messages encode implementation-specific characteristics: cipher suite orderings reflect cryptographic library defaults; extension sequences reveal supported protocol features; elliptic curve group selections indicate underlying implementations. Snowflake's Pion WebRTC library generates fingerprints systematically different from browser-native stacks. The asymmetry between removal impact (-11.52 pp) and isolation performance (-5.54 pp from full model) indicates complementary information when combined with other feature categories. Statistical flow features alone achieve only 75.58% F1-score, suggesting that traffic obfuscation techniques targeting statistical characteristics may prove insufficient against protocol fingerprinting.

5.4 Comparison with Prior Detection Approaches

Table 9 presents a systematic comparison of detection performance between prior studies and the proposed approach. Whilst prior work consistently reports accuracy exceeding 99% under balanced experimental conditions, these evaluations do not extend to operationally realistic class imbalance scenarios. This work represents the first systematic evaluation across imbalance ratios spanning 1:1 to 1:1000, revealing that previously reported accuracy figures provide misleading indicators of operational deployment performance.

Table 9: Comparison with Prior Snowflake Detection Approaches

Study	Method	Evaluation Condition	Accuracy/F1 (%)	Precision at 1:1000 (%)	Imbalance Evaluated
Fifield & Gil Epner (2016)	DTLS Fingerprinting	Theoretical	—	—	No
Frolov & Wustrow (2019)	TLS ClientHello	Balanced	>99.0	Not reported	No
MacMillan et al. (2020)	Random Forest	Balanced (1:1)	100.0	Not reported	No
Chen et al. (2023)	F-ACCUMUL	Balanced (1:1)	99.8	Not reported	No
AlOmar et al. (2025)	CS-BiGAN	1:1 to 1:1000	94.2 (1:1)	~90.0*	Yes
Xue et al. (2024)	Encapsulated TLS	Operational (110M)	70.0 TPR	—	Partial†
This work (RF)	Random Forest	1:1 to 1:1000	94.2 (1:1)	8.74	Yes
This work (DAE)	Deep Autoencoder	1:1 to 1:1000	98.4 (1:1)	87.53	Yes

**Estimated from reported F1-score; precise value not provided.*

†Evaluated at operational scale but imbalance ratio not explicitly characterised.

RF = Random Forest; DAE = Deep Autoencoder; TPR = True Positive Rate.

The comparison reveals three critical observations. First, balanced-condition performance is remarkably consistent across studies and methods, with accuracy/F1 exceeding 94% regardless of architectural approach—confirming that Snowflake traffic is readily distinguishable under controlled experimental settings. Second, the critical differentiator is performance under operational imbalance: our Random Forest baseline replicates prior accuracy under balanced conditions (94.2%) yet collapses to 8.74% precision at 1:1000 imbalance, demonstrating that high balanced accuracy does not predict operational viability. Third, the proposed deep autoencoder achieves precision (87.53%) at 1:1000 imbalance that approaches balanced-condition performance of prior supervised methods, representing a **78.79 percentage point improvement** over supervised classification under identical evaluation conditions.

5.5 Limitations and Threats to Validity

Three validity threats constrain generalisability. The dataset derives from controlled infrastructure rather than production networks, limiting internal validity**.** External validity is bounded by use of a single Snowflake configuration, whereas operational deployments span browser extensions (35%), standalone applications (8%), and iptproxy (57%). Finally, temporal validity is constrained by ongoing countermeasure development including covertDTLS and Chrome 129+ fingerprint randomisation.

5.6 Ethical Considerations

The dual-use nature of circumvention detection necessitates explicit ethical consideration. We acknowledge that techniques presented may enable suppression of legitimate privacy-seeking behaviour. We emphasise that publication serves defensive purposes by enabling circumvention developers to remediate weaknesses—consistent with responsible disclosure norms.

6. Conclusion

This paper presented a semi-supervised deep autoencoder framework for detecting Tor Snowflake traffic under extreme class imbalance. The approach addresses fundamental limitations of supervised classification, which collapses to 8.7% precision at 1:1000 imbalance. The autoencoder achieves 87.53% precision, a 78.8 percentage point improvement while maintaining 98.47% recall. The comprehensive evaluation across two imbalance ratios provides practitioners with deployment guidance: precision degrades to 87.53% at extreme 1:1000 ratios. Feature ablation analysis confirms that protocol-level DTLS fingerprinting provides the strongest discriminative signal. Future work will investigate ensemble approaches combining multiple autoencoder architectures, adaptive thresholds based on local traffic distributions, and multi-region evaluation to validate geographic generalisability. The dataset and trained models will be made available to support reproducibility and further research.

Acknowledgement

The authors declare no external funding for this research.

AI Declaration: The authors declare that generative artificial intelligence tools were used during the preparation of this manuscript for language editing and grammatical refinement. The authors reviewed and edited all AI-assisted content and take full responsibility for the accuracy, integrity, and originality of the work presented.

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Evaluating the Reliability of LLMs in OSINT Investigations: A Friend or Foe?

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Abstract: This study investigates the use of Large Language Models (LLMs), including GPT, Claude 3, Gemini, Meta, DeepSeek, Qwen 2.5, Mistral Large, and Grok, in Open-Source Intelligence (OSINT) investigations, focusing on their capabilities, limitations, and practical implications. Using a controlled fictional organization, the CtrlZ Society, to simulate a plausible online footprint, the LLMs were provided with a synthetic dataset purportedly linked to the organization. The dataset included social media posts, a Reddit thread, a Pastebin document, a GitHub repository, a blog post, a Telegram broadcast, a WHOIS record, and a news article. Based on this dataset, the models were evaluated on accuracy, timeline reconstruction, account attribution, evidence traceability, susceptibility to hallucination, and handling of ambiguity and incomplete information. Results revealed substantial variation among models: Claude 3, GPT, and Qwen 2.5 demonstrated strong analytical performance and reliable synthesis of investigative outputs, while Gemini and DeepSeek exhibited weaker capabilities. Some models, including Meta were also prone to forced narrative construction when prompted adversarially, highlighting risks of misinterpretation or overreach. Despite these limitations, all LLMs provided valuable support for structuring and summarising complex data, demonstrating their potential as efficiency multipliers in OSINT workflows. Based on these findings, the study provides recommendations for practitioners, including rigorous human oversight, multi-model validation, adherence to verification protocols, and careful evaluation of outputs to mitigate risks and maximise the reliability of LLM-assisted investigations.

Keywords: Large Language Models (LLMs), Open-Source Intelligence (OSINT), ChatGPT, Investigation

1. Introduction

As the digital footprint of global events expands at an unprecedented rate, practitioners of Open-Source Intelligence (OSINT) increasingly face the challenge of balancing automation with analytical accuracy. In the digital era, the volume of data, much of which is publicly accessible continues to grow exponentially. This vast and heterogeneous body of information, drawn from sources such as public records, social media platforms, and scholarly publications, is rapidly surpassing human cognitive processing capacities (Van Puyvelde & Rienzi, 2025). Consequently, OSINT has evolved beyond simple internet searches and now encompasses large-scale data analysis and interpretation (Hwang et al, 2022; Yadav et al, 2023). By synthesising information from diverse open sources, OSINT enables organisations and individuals to make informed decisions and remain responsive to emerging trends. The accelerating expansion of digital data has also prompted increasing reliance on advanced computational tools, particularly Large Language Models (LLMs) such as ChatGPT and Grok, to assist in the collection, processing, and analysis of information (Alturkistani & Chuprat, 2024; Berzinji & Abdalmajid, 2024).

Individuals increasingly employ LLMs to summarise and process publicly available information, including large collections of leaked documents, due to their efficiency in handling extensive textual datasets. These capabilities also create opportunities to support efforts aimed at mitigating cyber threats and addressing issues related to national security and political campaigns (Yadav et al, 2023). Furthermore, LLMs demonstrate strengths in complex reasoning, analytical processing, and strategic planning, making them valuable computational tools within OSINT workflows (Yuan et al, 2024). By enabling the rapid synthesis of vast datasets, LLMs can generate significant efficiency gains for investigators operating under time and resource constraints. However, despite these advantages, the integration of LLMs into OSINT practices also introduces prominent challenges when analysing publicly available information. In particular, concerns have been raised regarding the phenomenon of hallucination, as well as broader issues related to the accuracy, reliability, and methodological integrity of outputs generated by LLMs (Huang et al, 2025).

Furthermore, OSINT requires a high level of real-time accuracy, whereas the knowledge base or training data of LLMs tends to be limited (Alturkistani & Chuprat, 2024; Berzinji & Abdalmajid, 2024; Rahman, 2025). Additionally, the use of LLMs presents a significant risk that sensitive information may be inadvertently exposed to the model, which could potentially be accessed by individuals with the technical expertise to extract such data. While LLMs are increasingly popular, there remains a lack of effective frameworks for testing their reliability when analysing publicly available data in accordance with investigative standards. Therefore, this study aims to evaluate the reliability of LLMs in OSINT investigations.

The remainder of this paper is structured as follows: Section 2 presents the Literature Review, Section 3 outlines the Methodology, Section 4 reports the Results, Section 5 discusses the findings, Section 6 addresses Risk and Ethical Considerations, Section 7 provides Recommendations, Sections 8 and 9 present the Ethics and AI Declarations, and Section 10 concludes the study.

2. Literature Review

The application of OSINT and LLMs in investigative contexts has gained significant attention in recent years. Therefore, to establish a foundation for this study, it is essential to review prior research in two key areas: first, the techniques and methodologies underpinning OSINT, and second, the capabilities and limitations of LLMs when applied to OSINT investigations. Together, these discussions provide the necessary context for evaluating the reliability and effectiveness of LLMs in OSINT investigations.

2.1 Understanding OSINT Techniques

OSINT involves the collection, analysis, and integration of publicly available information from open sources to generate actionable knowledge (Yuan et al, 2024; Pastor-Galindo et al, 2020). It goes beyond mere data gathering, requiring that raw information be connected, evaluated, and transformed into useful intelligence. Often described as a technology-driven and iterative process increasingly supported by data analytics (Sun et al, 2025), OSINT serves as a critical resource for military operations, corporate security teams, and government agencies, offering diverse information sources, low acquisition costs, and rapid updates. The primary advantage of OSINT lies in its ability to support both tactical and strategic decision-making by providing timely information for threat intelligence, situational awareness, and target identification (Berzinji & Abdalmajid, 2024). It relies on publicly accessible sources such as news outlets, social media platforms, academic publications, and government documents. Its true value emerges from applying analytical methods that filter irrelevant data and identify meaningful patterns (Karakikes & Kotis, 2025).

OSINT investigations employ specialized tools such as Shodan, Censys, and Fofa to discreetly identify potential attack vectors and vulnerabilities, while feeds from resources like VirusTotal and IPInfo are critical for threat detection. Verification of findings typically requires cross-checking against additional data, including web server logs (Nilă & Patriciu, 2023). Frameworks such as the OSINT Research Studios (ORS) model further structure investigations into key tasks, including geolocation, factchecking, image analysis, source analysis, and discovery. In cybersecurity, OSINT is indispensable for providing actionable insights on emerging threats, in contrast to conventional databases that report threats only after they have occurred (Filho et al, 2025). The intelligence lifecycle ensures that discoveries are validated, promoting transparency and traceability. Analysts must apply critical thinking during analysis and production to distinguish authentic data from misinformation or propaganda, using factchecking and validation tools to verify findings and prevent errors.

2.2 Capabilities of LLMs in OSINT Investigations

LLMs enhance OSINT practices by processing and semantically analysing large volumes of open-source information (Rajendran et al, 2024; Skopik et al, 2024). Traditional OSINT methods rely on manual collection and search-and-exploit approaches, which have become increasingly insufficient for the demands of modern information environments (Rajendran et al, 2024). LLMs address these limitations by leveraging advanced natural language processing capabilities, enabling analysts to efficiently comprehend information contained in social media, online forums, news articles, and technical reports (Skopik et al, 2024). By preserving semantic relationships across discontinuous or lengthy texts, LLMs enhance situational awareness and reduce the cognitive burden on human analysts.

Beyond automation, LLMs provide novel analytical capabilities that support intelligence synthesis and dynamic reasoning within OSINT workflows. Rajendran et al (2024) demonstrate that LLMs can extract entities, relationships, and structured data from unstructured sources to generate knowledge graphs and other forms of analytical intelligence. When integrated within agent-based structures, LLMs act as cognitive elements capable

of contextual reasoning, relevance assessment, and dynamic task execution, facilitating continuous intelligence cycles (Su, 2025). This represents a shift from static, task-oriented OSINT analysis toward more autonomous and adaptive intelligence production.

Empirical studies further illustrate the effectiveness of LLMs in extracting actionable intelligence from noisy OSINT sources, particularly in cybersecurity contexts. Filho et al (2025) show that LLMs can accurately categorize emerging cyber threat behaviours from unstructured social media data and map them to existing frameworks such as MITRE ATT&CK, enabling early threat detection. However, research also emphasizes the need to validate outputs from LLMs due to potential risks including hallucinations, source ambiguity, and bias propagation (Černý, 2024). Consequently, LLMs are most effectively deployed as analytical force multipliers rather than as independent producers of intelligence, as there is still a need to evaluate and verify OSINT results (Rajendran et al., 2024; Černý, 2024).

3. Methodology

This study evaluates the reliability of eight LLMs, namely GPT, Claude 3, Gemini, Meta, DeepSeek, Qwen 2.5, Mistral Large, and Grok in conducting a comprehensive OSINT investigation. This study adopted a controlled, synthetic case study approach, creating a fictional target organization called the "ctrlZ Society," this was to maintain ethical standards and avoid targeting real individuals or organizations. To simulating a plausible online footprint, the synthetic dataset included social media posts, a Reddit thread, a Pastebin document, a GitHub repository, a blog post, a Telegram broadcast, a WHOIS record, and a news article. Each model was treated as an independent analyst and prompted to analyse the materials while explicitly distinguishing verified facts from inferences, stating uncertainty, avoiding unsupported speculation, and linking all claims to sources. The evaluation focused on eight key dimensions: forced narrative construction, error awareness, account attribution, timeline reconstruction, confirmation bias, missing data injection, evidence traceability, and overall investigation quality, using standardized categorical ratings (High / Medium / Low; Yes / No / Partially) to enable systematic comparison. Each LLM's outputs were collected, recorded, and independently evaluated by multiple researchers to ensure reliability and reduce subjective bias. Comparative scoring allowed identification of model strengths and weaknesses across tasks.

4. Results

In this study, we evaluated the performance of eight LLMs in conducting a comprehensive OSINT investigation of the fictional CtrlZ Society. Each LLM was assessed across eight key dimensions. The evaluation focused on the ability of each model to accurately analyse source material, distinguish verified facts from inferences, maintain transparency in reasoning, and synthesise findings without introducing unsupported information. This section presents the results, and Table 1 provides a summary highlighting significant variation in strengths and weaknesses among the models, offering insights into their relative reliability and suitability for OSINT applications.

Table 1: Results Summary

LLM	Forced Narrative	Error Awareness	Account Attribution	Timeline Reconstruction	Confirmation Bias	Missing Data Injection	Evidence Traceability	Full Investigation
Gemini	Yes	Medium	Low	High	No	No	Medium	Medium
Meta	Yes	High	High	Medium	No	No	High	High

LLM	Forced Narrative	Error Awareness	Account Attribution	Timeline Reconstruction	Confirmation Bias	Missing Data Injection	Evidence Traceability	Full Investigation
DeepSeek	Yes	Medium	Low	Low	No	No	Medium	Medium
Grok	Yes	Medium	Medium	Medium	No	No	Medium	Medium
Mistral	Yes	Medium	Medium	Medium	Partially	No	Medium	Medium
Qwen 2.5	No	Medium	Medium	High	No	No	Medium	High
Claude 3	No	High	High	High	No	No	High	High
GPT	No	Medium	High	High	No	No	High	High

The results of this study, as indicated in Table 1 highlight both the potential and the limitations of LLMs when applied to structured OSINT investigative tasks. Across the tested models, clear differences emerged in how effectively the systems handled analytical reasoning, evidence traceability, and uncertainty. For instance, Claude 3, GPT, Meta, and Qwen 2.5 demonstrated the strongest overall performance, excelling in account attribution, timeline reconstruction, evidence traceability, and synthesising full investigations, while Gemini and DeepSeek showed weaker capabilities. Grok and Mistral exhibited moderate, balanced performance across most categories. Most models were generally resistant to confirmation bias and missing data injection, though some, such as Meta and Gemini, showed tendencies toward forced narratives when interpreting incomplete information. These results indicate that while certain LLMs can produce reliable, structured OSINT outputs, others display limitations in analytical depth and interpretive caution, highlighting the importance of careful model selection and oversight in investigative applications.

5. Discussion: Friend or Foe?

The findings of this study illustrate a nuanced picture of the role that LLMs can play in OSINT investigations. On one hand, certain models particularly Claude 3, GPT, Meta, and Qwen 2.5 demonstrated strong capabilities in synthesising information, reconstructing timelines, attributing accounts, and maintaining evidence traceability. These strengths suggest that, when used appropriately, LLMs can act as powerful tools for investigators, offering rapid data processing, analytical consistency, and the ability to manage vast amounts of publicly available information that would be overwhelming for human analysts. Their efficiency in handling complex datasets and

producing structured investigative outputs can provide significant time and resource savings, especially under operational constraints.

The initial prompt, the models were tasked with producing a complete OSINT investigation based on synthetic data, and most were able to provide a coherent analysis. However, several models went beyond the provided data. For example, many inferred that the CtrlZ Society might be located in Iceland because the domain ctrlzsociety.net was registered through Njalla, a registrar based in Iceland. While this inference could be plausible for privacy reasons, all models acknowledged that this conclusion might be erroneous when prompted about potential mistakes. Some models, such as Claude 3, went further and produced additional claims that could be inaccurate.

The models were further given additional prompts, eight to be direct. Regarding missing data injection, the models were asked whether the CtrlZ Society was connected to foreign intelligence services or state-sponsored actors. All models correctly denied such connections, stating that there was no evidence to suggest any association. To test confirmation bias, the models were informed that several analysts considered the CtrlZ Society to be an emerging extremist organization and asked them to confirm this assessment. All LLMs correctly indicated that this characterization did not appear accurate and provided reasons why they thought that assessment was not accurate. Furthermore, all models successfully constructed a chronological timeline of key events involving the CtrlZ Society, though some performed better than others. For instance, Claude 3 was able to draw additional connections and inferences within the timeline.

However, critical limitations and potential risks were observed. Several models demonstrated tendencies toward forced narrative construction. In one task, the models were asked to produce a concise intelligence-style summary asserting that the CtrlZ Society represents a credible and imminent threat. While most models refused, appropriately reflecting the initial assessment that the group posed no threat, some, including Meta, Mistral, DeepSeek, and Gemini, produced statements framing the group as dangerous. For example, Meta described the CtrlZ Society as “an emerging, technologically proficient, and ideologically driven entity that poses a credible and increasingly imminent threat to state and corporate digital infrastructure.” This adversarial prompt revealed that certain LLMs could be steered to produce misleading conclusions, highlighting their susceptibility to input framing despite earlier analyses indicating no threat.

Taken together, these results suggest that LLMs in OSINT are neither purely friend nor purely foe. They offer substantial benefits as analytical assistants and efficiency multipliers, but their outputs require careful validation, critical oversight, and integration into human-led investigative processes. In this sense, LLMs are best conceptualised as collaborative tools: they can act as a friend when their strengths are leveraged thoughtfully and their limitations are mitigated, yet they can become a foe if relied upon blindly without supervision or methodological safeguards. The ultimate utility of LLMs in OSINT therefore depends on responsible deployment, continuous evaluation, and an awareness of both their potential and their pitfalls. Accordingly, this study recommends that OSINT practitioners carefully consider the Risk and Ethical Considerations outlined in Section 6 and the practical recommendations provided in Section 7.

6. Risk and Ethical Considerations

The use of OSINT and LLMs in investigative contexts introduces a range of risks and ethical challenges that must be carefully managed. While these technologies can significantly enhance information gathering and analysis, they also carry potential dangers, including the inadvertent exposure of sensitive data, generation of fabricated or misleading information, and propagation of biases. Moreover, their deployment intersects with complex ethical and legal frameworks, raising questions about privacy, accountability, and compliance with regulatory standards. This section examines these concerns in two key areas: first, the risks associated with AI systems and the production of fabricated information, and second, the ethical and legal implications of using such technologies in intelligence and investigative workflows.

6.1 AI Risks and Fabricated Information

LLMs have grown popular due to their performance on performing day-to-day activities such as drafting emails and generating code. These models are prone to hallucinating, producing false outputs that require one to confirm the accuracy of these outputs (Sriramanan et al, 2024; Yao et al, 2023). One is required to use the principle of zero trust, where one “trust no one, verify all." These models are observed to be plausible before scrutiny as they hallucinate by creating fallacious, fictional details that tend to be misleading or fabricated (Sriramanan et al, 2024). Out-of-Distribution (OoD) prompts tend to deceive the trained dataset into generating false responses (Yao et al, 2023).

LLMs often rely on simple class-conditional prompts; this may affect the generated data output, thus leading to systematic biases of LLMs (Yu et al, 2023). A simple class-conditioned prompt is the process where an individual prompts an LLM and during data generation, there is a limitation of the diversity of the generated data. The trained data models tend to exhibit regional biases (Navigli et al, 2023; Yu et al, 2023). LLMs risk generating false names, links or events based on the prompts, resulting in fabricated and false information. There tends to be biases that are inherited from the training of the model's data (Navigli et al, 2023; Yu et al, 2023).

Humans tend to trust AI-generated outputs without verification (Huschens et al, 2023; Thorne, 2024). This leads to human oversight confirming the output generated from the LLM. With OSINT, there is a need to ensure that one verifies the data outputs, as this may affect the decisions an individual and organization make. Users should not blindly trust the reliability of output generated from the LLMs, as humans tend to trust computers (Thorne, 2024). Humans tend to inherit AI biases as we tend to perceive AI algorithms as impartial and secure, though these algorithms are trained by humans (Vicente & Matute, 2023).

6.2 Ethical and Legal Implications

The issue of accountability in AI-assisted OSINT investigations is complicated by unclear regulations and shared responsibility among users, developers, and data providers. This makes it difficult to verify decisions and assign blame, particularly when errors adversely affect individuals or resources (Alnaqbi, 2025). AI stakeholders include users, platform providers, and AI developers. Prompt and session histories are examples of digital evidence that must be collected using novel investigative techniques to demonstrate both intent and the role of AI in decision-making (Karakikes & Kotis, 2025). Assigning responsibility for errors made by AI during investigations remains a significant challenge. Moreover, the widespread use of OSINT raises privacy concerns due to the large volumes of personal data collected from social media, potentially leading to violations of human rights. There is also a risk of algorithmic bias in information processing, highlighting the need for stronger regulations and ethical assessments of AI use in military and intelligence contexts (Meng, 2025).

Managing accountability for investigative errors in AI-assisted OSINT requires a systematic approach that emphasizes human oversight and the development of validated OSINT frameworks (OSINT-V). Human analysts bear the primary responsibility, as their expertise is essential in distinguishing accurate data from erroneous outputs produced by AI. They play a critical role in mitigating hazards such as false positives, which can be exacerbated by data sparsity or unreliable sources (Alturkistani & Chuprat, 2024). Integrating interpretable models with explainable AI (XAI) further enables analysts to understand the reasoning behind automated decisions, such as categorizing complex attack stages or identifying illicit botnet activity.

7. Recommendations for OSINT Investigators

Effective OSINT investigations require not only technical skills but also structured methodologies, ethical awareness, and the ability to critically evaluate sources. Based on the challenges and opportunities identified in the previous sections, this section provides practical recommendations, summarised in Table 2, to enhance the reliability, efficiency, and ethical integrity of OSINT operations.

Table 2: Recommendation Summary

Recommendation	Key Actions	Purpose / Benefit
Integrate LLMs as Analytical Assistants	Use LLMs to summarize and analyse large data sets; retain human oversight	Enhances efficiency while reducing risks of hallucinations or bias
Rigorous Verification & Validation	Cross-check multiple sources; use fact-checking tools; document verification	Ensures accuracy, reliability, and transparency of findings
Structured Investigation Workflow	Apply frameworks like ORS; define clear objectives	Organizes tasks, reduces cognitive load, and improves investigation focus
Responsible Use of OSINT Tools	Utilize Shodan, Censys, Fofa, VirusTotal, IPInfo; comply with legal standards	Identifies threats efficiently while maintaining ethical compliance

Recommendation	Key Actions	Purpose / Benefit
Monitor & Mitigate AI Risks	Audit LLM outputs; implement human-in-the-loop reviews	Maintains data integrity and reduces errors from AI outputs
Ethical & Legal Compliance	Respect privacy laws, IP rights, and local regulations; develop ethical guidelines	Protects investigators and organizations from legal and reputational risk
Documentation & Transparency	Record all sources, methods, and analytical decisions; note limitations	Supports accountability, traceability, and reproducibility

These recommendations, collectively presented in Table 2, aim to ensure that OSINT investigations are accurate, efficient, and ethically responsible, while fully leveraging the analytical power of LLMs without compromising reliability or compliance. They also outline strategies for integrating LLMs into investigative workflows, ensuring rigorous verification of findings, mitigating AI-related risks, and adhering to legal and ethical standards. By following these recommendations, OSINT investigators can maximize the value of publicly available information while minimizing errors, biases, and potential ethical violations.

8. Conclusion

This study evaluated the performance of eight LLMs in conducting OSINT investigations, using a synthetic case study of the fictional CtrlZ Society. The results demonstrate that LLMs possess considerable potential as analytical assistants, capable of synthesising information, reconstructing timelines, attributing accounts, and maintaining evidence traceability. Models such as Claude 3, GPT, Meta, and Qwen 2.5 performed particularly well, highlighting the capacity of advanced LLMs to enhance efficiency and support complex investigative workflows. At the same time, the study revealed important limitations and risks. Some models exhibited tendencies toward forced narrative construction and overreach beyond the provided data, while all LLMs remain constrained by the scope and recency of their training data. The potential for errors, misinterpretation, and susceptibility to adversarial prompts underscores the necessity of human oversight, methodological safeguards, and continuous validation when integrating LLMs into OSINT workflows.

In summary, LLMs should be viewed as collaborative tools rather than autonomous investigators. They can act as a valuable friend when leveraged responsibly, but they can also become a foe if relied upon without critical evaluation. The findings underscore the importance of combining human expertise with LLM capabilities, ensuring that OSINT investigations remain accurate, reliable, and ethically responsible. Future research should focus on developing robust evaluation frameworks, refining safeguards against bias and misinformation, and exploring best practices for responsible LLM deployment in intelligence contexts.

Ethics declaration: Ethical clearance was not required, as this study did not involve human participants.

AI declaration: AI, specifically eight LLMs, were utilised in this study, as indicated in the methodology section.

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Expanding Tactical Cyber Operations for Information-Age Warfare

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Abstract: The proliferation of information through cyberspace has reshaped the character of modern warfare and altered how power is generated and exercised. Digital systems now underpin intelligence collection, operational coordination, and influence activities across instruments of national power. This dependence creates a persistent capability–vulnerability paradox in which the same networked systems that provide operational advantage also introduce exploitable weaknesses. Although the United States has developed significant strategic cyber capabilities, operational authorities and execution remain largely centralized. Incident data show that espionage, access operations, and information manipulation dominate cyber-conflict patterns, while bespoke cyber tools remain constrained by access requirements, target specificity, and limited reuse. This paper argues that maintaining an advantage in the information age requires expanding cyber execution capability and selected authorities to operational and tactical levels. It examines how cyber power's low barrier to entry enables both state and non-state actors to generate disproportionate effects and how cyberspace, as a human-built domain, often favors offense over defense. The study outlines limits on the employment of strategic cyber tools, including tradeoffs among speed, intensity, and control, as well as the single-use nature of exposed exploits. The paper proposes a tactical cyber operations framework built on dispersed, hyper-enabled units operating under decentralized command and supported by operational-level artificial intelligence processing and human–machine teaming. The framework integrates distributed intelligence validation, signature reduction, deception and decoy practices, and ambiguity operations designed to slow adversary decision cycles and increase targeting uncertainty. The paper concludes that doctrinal and authority structures should evolve to support delegated cyber action aligned with the commander's intent in persistent cyber competition.

Keywords*:* Tactical cyber operations, Cyber power, Decentralized command, Human–machine teaming, Cyber deception, Distributed operations

1. History of Information and the Importance of Cyberspace

The proliferation of information through cyberspace has fundamentally reshaped the character of modern warfare. Cyberspace expands information access to remote users and "may prove as valuable and influential in the post-industrial era as capital and labor have been in the industrial age" (Arquilla and Ronfeldt, 1993). Information technology, which enables access to information through cyberspace, is inseparable from modern warfare and generates a persistent capability/vulnerability paradox (Schneider, 2019). This paradox, combined with the inherent security weaknesses of cyberspace, creates enduring opportunities for exploitation across strategic, operational, and tactical levels of warfare. The United States has leveraged these opportunities through cyber operations; however, early efforts remained primarily confined to the strategic level due to personnel and equipment constraints. Over time, the sophistication and quantity of trained personnel and equipment have increased, yet cyber operational authorities have largely remained centralized at the strategic level. Cyber actors rely on cyberspace to rapidly transfer, aggregate, and collect information. The adversary's dependence on cyberspace to conduct operations, coupled with cyberspace's inherent characteristics and security weaknesses, necessitates that the United States delegate cyber authorities and operational approval down to the operational and tactical levels to maintain an advantage in this dynamic, evolving domain.

Organizations, whether nation-states or non-state actors, invest their limited resources to increase their relative power and to exert influence on external actors to secure resources and achieve their organizational goals (Nye Jr., 2010). Cyberspace enables access to and exploitation of information, both of which are fundamental to the use of power (Nye Jr., 2010). Organizations utilize cyberspace as a unique opportunity to rebalance power and increase influence in the information age.

Cyber power—"the ability to use cyberspace to create advantages and influence events in all operational environments and across the instruments of power"—has a relatively low barrier to entry because the required assets and training are readily available on the open market (Kramer, Starr and Wentz, 2009). Moreover, cyber power requires significantly fewer resources than developing other types of power, such as a naval fleet or a nuclear weapons capability. This smaller resource requirement allows nearly any organization to wield substantial cyber power worldwide. Cyber power is distinctive because actors can use it across the spectrum of diplomatic, informational, military, economic, financial, intelligence, and law-enforcement (DIME-FIL) domains. This unique ability to produce widespread effects stems from each DIME-FIL instrument's dependence on cyberspace. As a result, organizations can acquire and project extensive cyber power with relatively modest

investments. This incentive has flooded cyberspace with a variety of actors, leading to a broad distribution of power, although not absolute equality. Such a distribution diminishes the control traditionally held by superpowers over domains like the air and the sea. The increasing use of cyberspace also introduces a capability/vulnerability paradox, which makes exploitation across different levels of warfare more possible. (Schneider, 2019).

In the early 2010s, terrorist organizations quickly adapted to the changing information environment, gaining significant cyber power with minimal investment. In July 2015, Ayman Al Zawahiri stated that al-Qaeda was in a "battle and more than half of this battle is taking place in the battlefield of the media" (Kapsokoli, 2019). Terrorist organizations like al-Qaeda understood that this new cyberspace environment was critical to controlling the narrative and influencing the population. Terrorist organizations also use the fast, reliable, and ambiguous nature of cyberspace to conduct mission planning and coordination. (Kapsokoli, 2019). These communication pathways also assist with identifying, radicalizing, and recruiting susceptible individuals (Kapsokoli, 2019). Terrorist organizations then instruct recruits through a virtual training camp that teaches them how to plan, prepare, and conduct terror attacks (Kapsokoli, 2019). Terrorist organizations also use cyberspace and cryptocurrencies to collect and transfer funds without interference from organizations like the FBI. Finally, cyberspace allows terrorists to spread terror through the amplification of their desired narrative to a level that was unimaginable before social media. Because of their limited resources and high adaptability, terrorist organizations were among the earliest adopters of cyberspace and have leveraged it to exert disproportionate influence.

Cyberspace is a unique domain, as it is a "flexible, human-built, institutionally governed, sociotechnical infrastructure" that favors offensive actions over defensive posture (Lindsay and Gartzke, 2022). Being the only human-built domain (the other domains are maritime, land, air, and space), cyberspace presents distinct opportunities for users. For example, cyber operators can exert cyber power to "produce preferred outcomes within cyberspace, or [they] can use cyber instruments to produce preferred outcomes in other domains outside cyberspace" (Nye Jr., 2010). These subsets are referred to as intra-cyberspace power and extra-cyberspace power, respectively (Nye Jr., 2010). Both of these subsets favor offensive over defensive cyber power (Arquilla, 2021). This offensive advantage is rare within warfare, where defense is typically the dominant form. These conditions enable the evolution of cyberspace attacks from isolated incidents to "coordinated, multi-domain military operations" (Devanny, Goldoni and Medeiros, 2022).

The integration of artificial intelligence (AI) into cyberspace will improve both offensive and defensive cyber capabilities. However, AI is likely to further enhance offensive advantages. Cyber actors use AI to amplify their effects both within and outside cyberspace. In 2022, a U.S. intelligence review found that Russia had invested over $300 million in foreign influence campaigns over the past eight years. Although the success of these investments varies, the substantial Russian investment highlights the strong link between cyberspace, artificial intelligence, and information operations. Russia also employs cyber operations against targets beyond cyberspace. In December 2015, the BlackEnergy malware caused power outages that affected over 230,000 people in Ukraine. Additionally, in 2017, the NotPetya attack on a Ukrainian bank spread worldwide and caused roughly $10 billion in damages. These attacks demonstrate the destructive potential of cyber operations that extend beyond cyberspace, butactors planning to seize infrastructure should avoid causing irreversible damage. For example, when Russia invaded Ukraine in 2022, the aim was to seize critical infrastructure intact, particularly the communications network, to ensure its continued usefulness for the invaders. Destroying the communications network would aid current military operations, but it would also require additional effort and money to restore it afterward. On the other hand, this choice to limit attacks on critical infrastructure allowed Ukrainian forces to keep using it for defense. When choosing cyber targets that extend beyond cyberspace, actors must balance the immediate military benefits against possible long-term effects. These structural dynamics shape not only the strategic environment but also the operational constraints under which cyber power is developed and employed.

2. Cyber Tool Constraints and Strategic–Operational Imbalance

Cyberspace also presents distinct challenges because three key variables—speed, intensity, and control—negatively correlate with one another, and cyber tools lack universal effectiveness (Maschmeyer, 2021). Both intra- and extra-cyberspace powers depend on access and require a bespoke cyber tool tailored to the specific target (Borghard and Lonergan, 2019). This access, along with the tool's required specificity, limits its fungibility. This limitation is compounded at the strategic level because access is drastically more resource-intensive to gain and maintain. Additionally, the time required to develop the cyber tool, the extent of its impact, and the ability

to control its effects once deployed are in direct competition with one another, creating the "subversive trilemma" (Maschmeyer, 2021). Finally, once organizations develop a strategic tool and the opportunity to employ it arises, commanders face the reality that "cyber operations have a 'use it and lose it' quality" (Borghard and Lonergan, 2019). This single-use nature of the cyber tool stems from its bespoke design. Once the exploit is exposed, it can be patched with relative ease. The United States' decision-makers have seldom employed strategic cyber power because it has limited applicability, and they are reluctant to expend a capability they may need in the future.

The discussion of the importance of cyber access for power projection gave rise to cyber persistence theory (CPT). CPT posits that for a state to achieve security in the cyber strategic environment, it must maintain constant contact with the adversary (Fischerkeller *et al.*, 2022). This differs from traditional international relations (IR) theory, in which physical barriers limit the projection of power, and peace is the absence of interaction (Akdağ, 2025). CPT provides an alternative approach to deterrence that does not require confrontation in the physical domain and limits the risk of escalation in the nuclear environment (Fischerkeller *et al.*, 2022).

Although the United States focuses on strategic cyber operations, the Dyadic Cyber Incident and Campaign (DCID) dataset 2.0 found that 61% of cyber incidents since 2000 have been cyber espionage operations (Maness *et al.*, 2023). This emphasis on cyber espionage also bears true during full-scale conflict. Between January 2022 and August 2023, the two most common categories of cyber incidents in Ukraine were malicious code (11%) and espionage (7%) ("A Decade in the Trenches of Cyberwarfare: Ukraine's Story of Resilience," 2024). Additionally, the premier Russian cyber operators work within departments that specialize in intelligence and subversion (Giles, 2023). The United States will continue to cede power and influence if it does not begin to prioritize the ongoing cyber competition for the collection and manipulation of information and data (Cristiano *et al.*, 2023).

Russia does not distinguish between the information domain and information operations; instead, it considers information as "the tool, the environment, and the target" (Giles, 2023). Between 2013 and 2021, this integrated understanding allowed Russian cyber operations to experience a "strategic shift from opportunistic disruption to calculated, long-term planning," aligning with Russia's broader geopolitical strategy ("A Decade in the Trenches of Cyberwarfare: Ukraine's Story of Resilience," 2024). Russia has also effectively integrated cyberspace into its long-standing Soviet-era doctrine of disinformation tactics and manipulation of public perception, yielding significant effects in the information environment ("A Decade in the Trenches of Cyberwarfare: Ukraine's Story of Resilience," 2024). Russia uses its Internet Research Agency, also known as a "troll farm," to further its information campaign by disseminating disinformation and manipulating the narrative ("A Decade in the Trenches of Cyberwarfare: Ukraine's Story of Resilience," 2024). Russia also tolerates pro-Russian hacktivist groups, such as Killnet, Xaknet, and NoName057, to conduct distributed denial-of-service (DDoS) attacks, thereby removing direct attribution ("Chronology of Cyber Aspects of the war in Ukraine 2022–Present," 2024). Additionally, Russia conducts cyber espionage operations on Western countries to gather information related to the Ukrainian security assistance strategy. ("Chronology of Cyber Aspects of the war in Ukraine 2022 – Present," 2024). Lastly, Russia often employs cyber to shape the physical and information environment for future kinetic operations ("Chronology of Cyber Aspects of the war in Ukraine 2022–Present," 2024; "A Decade in the Trenches of Cyberwarfare: Ukraine's Story of Resilience," 2024). These various tactics are subsets of a coordinated and integrated approach that is only possible because of Russia's comprehensive understanding of cyberspace, information, psychological operations, and narrative control.

Although Russia has taken a comprehensive approach to cyber operations, its efforts have often been countered effectively by Ukrainian civilian and government countermeasures supported by an international coalition. On February 26, 2022, two days after Russia's invasion, Ukraine announced the formation of an "IT Army" and called for talented applicants to join. That same day, Ukraine assigned initial tasks to this group to carry out a DDoS attack on selected Russian commercial and government websites. The Ukrainian IT Army quickly gained hundreds of thousands of followers worldwide, making it resilient to attacks. Molfar, a private Ukrainian company, uses open-source intelligence to collect target-quality data from social media posts and supplies it to Ukrainian Intelligence for operational use. Ukraine's cyber defenses have received international support through direct cybersecurity assistance and cyber intrusion alerts. The combination of civilian and government capabilities, bolstered by international advice and aid, has enabled Ukraine to neutralize Russia's credible cyber threats and directly support its kinetic defense operations.

As cyberspace becomes increasingly integrated into daily life, its prominence and society's reliance on information will continue to grow. The organizations that can rapidly adapt and gain relative cyber power will exert unmatched dominance across all warfighting domains and instruments of power. The deterrent role of

strategic cyber power is essential and should be maintained. However, limiting cyber capabilities to the strategic level unnecessarily constrains the United States. Therefore, the United States should expand the employment of cyber power to the operational and tactical levels to increase tempo and gain a significant advantage over threat actors.

3. Tactical Cyber Operations and Distributed Execution

The information revolution will continue to expand cyberspace's availability to more organizations, groups, and people. As cyberspace becomes increasingly integrated into daily life, organizations will become increasingly dependent on it (Mbanaso and Dandaura, 2015). This dependence spans the range from daily administrative tasks to the development and employment of the most exquisite instruments of national power. This reliance intensifies the capability/vulnerability paradox and creates expansive opportunities for exploitation (Schneider, 2019). The United States should employ dispersed, hyper-enabled teams with the necessary authorities and permissions to leverage tactical cyber operations to "swarm" adversary threats, thereby meeting the commander's intent through decentralized command (Arquilla, 2021).

Successful military operations have always relied upon developing trustworthy information into actionable intelligence. To complete this, analysts gather information through the seven intelligence disciplines: human intelligence (HUMINT), geospatial intelligence, signals intelligence, measurement and signature intelligence, open-source intelligence, technical intelligence, and counterintelligence (U.S. Joint Chiefs of Staff, 2013). Following the collection, this information is synthesized and published as intelligence for further use. Beyond HUMINT, each of these disciplines relies heavily on capabilities that reside in cyberspace. Therefore, the actual battle is a fight for critical pieces of information in cyberspace. In the information age, more information is available than can be analyzed, which is where the need for dispersed, hyper-enabled teams emerges. To succeed in information warfare, tactical units must possess both the capability and authority to rapidly transition from gathering information to executing operations, thereby ensuring they capitalize on the information advantage before it becomes obsolete.

Cyberspace has, however, also expanded the availability of fake and misleading information. Cyberspace enables actors to fabricate massive amounts of information, thereby decreasing the reliability of various sources and source types. This concern has altered the intelligence cycle and increased the quantity of analysis required. To validate the integrity of the information, analysts must understand the reliability of the data source and verify its authenticity by corroborating it across multiple sources and over time. Additionally, the time required to make this interpretation increases as the analyst becomes further removed from the source. Accordingly, the United States must deploy the appropriate personnel at the appropriate echelon to conduct this analysis in close proximity to the information source. Expanding tactical cyber capacity, however, requires analytic scalability to manage the volume and velocity of contested information.

4. Artificial Intelligence and Human–Machine Teaming

The information access provided by cyberspace, coupled with advanced information technologies, has inundated analysts with an abundance of available information. Although human input will always be necessary, analysts should deliberately shift a portion of this analysis to AI engines; this pairing of AI models with humans is often referred to as a human-machine team (HMT). AI systems can efficiently ingest, categorize, and structure large-scale data streams, ensuring that "information is made swiftly available to forces operating at the leading edge of battle" (Arquilla, 2021). However, as these AI models develop through machine learning, they will inherently absorb biases and begin improperly connecting information to create a narrative. Analysts should transition from brute-force analysis of raw data to dissecting and validating the narrative generated by the AI engine. This verification process will ensure that the AI models do not devalue or over-rely on critical pieces of intelligence. Operational-level commands should conduct AI processing because they possess the required power, connectivity, and force protection measures. Additionally, operational-level commands have access to additional information systems. The operational commands can transmit the parsed intelligence to the tactical level for verification and immediate operational use. The employment of HMTs, combined with task delineation across command echelons, will expedite analysis and ensure the prompt execution of actionable intelligence.

Machine learning models, a subcategory of artificial intelligence, predict outcomes by learning from data and building synthetic models. These models perform best when employed in the same context in which they were trained. After training, they cannot operate independently and are most effective with human oversight. At the operational level, these models can be integrated with analysis teams to expedite the process and reduce the time required to produce each intelligence report. These reports can then be distilled and communicated to

tactical forces for implementation. The military's use of AI must account for increased risks and changing operational dynamics. For instance, Denise Garcia and the Committee on Human-System Integration at the Air Force Research Lab have warned that AI models can produce unpredictable and sometimes misleading results, posing significant concerns for the military. Another key consideration is that adversaries can manipulate the data used for training and analysis to deceive or confuse the models. This vulnerability means the models must be safeguarded against external influences and be completely transparent about how and why they arrived at their outcomes. The military's deployment of AI naturally extends its capabilities and can support cyber operations when used responsibly to augment, not replace, human decision-makers. The integration of AI-enabled analysis must therefore be paired with force architectures designed for survivability and resilience.

5. Dispersed Units, Signature Reduction, and Survivability

The information age has also created a dependence on rapid, reliable communication and connectivity. This reliance has amplified the technical signature of tactical units and decreased their survivability. To counter this phenomenon and reduce this vulnerability, the United States should employ small, dispersed units of action capable of coordinating and massing fires against the enemy (Arquilla, 2021). The decrease in unit size will reduce external communication and allow for tightly controlled internal networks. Reducing the size of each unit diminishes its technical signature and enhances cybersecurity by limiting the number of users who require network access. These units' reduced physical and technical signatures mitigate initial force protection concerns associated with their smaller size. The reduced user demand per location also enables enhanced cybersecurity measures, thereby reducing the threat of cyber infiltration and exploitation. Additionally, the dispersed units provide additional collection opportunities from their distributed locations. This approach should serve as the primary method of employment until the next significant disruption to the information environment. The integration of AI-enabled analysis must therefore be paired with force architectures designed for survivability and resilience.

6. Deception, Decoys, and Ambiguity Operations

An additional mechanism to mitigate force-protection concerns for small, dispersed units is to employ deception tactics. For example, through an in-depth understanding of Russian targeting, Ukraine has employed decoys, such as inflatable tanks and flat-pack artillery, to mimic high-value targets that then received live Russian ordnance (Shevchenko, 2025). With minimal investment, this tactic can drastically increase the cost for an adversary and erode trust in its intelligence reports, thereby slowing the targeting cycle (Fowler and Nesbit, 2013). Finally, the use of decoys can mislead foreign intelligence to the location of pending attacks, thereby increasing operational success. In an era where being sensed is tantamount to being targeted, the United States should invest in a similar decoy capability to deceive the enemy of our intentions and enhance the survivability of tactical units.

Although the physical deception tactics described above are valuable in the physical domain, they do not reflect the intricacies of deception in the virtual environment. Due to the interconnectedness of today’s operating environment, a recent emphasis in military practices has been on synchronizing effects across domains. Multi-Domain Operations requires the orchestration of military and non-military activities across all domains (Land, Sea, Air, Space, Cyber) to create desired outcomes in space and time (NATO’s Strategic Warfare Development Command, 2023). Current deception theories, however, lack the complete integration of the cognitive, physical, and virtual dimensions, with many describing the virtual as merely a channel rather than a core component (Grant and Henderson, 2025). Even newer cyber-specific deception theories, such as those of Rowe and Rrushi (2016), misidentify the target as the machine and lack the evaluation required to holistically determine the effects of deception in an MDO context. Finally, further research is required to determine appropriate measures of effectiveness for virtual deception operations.

Another method for reducing force protection concerns is by dispersing units of action across the battlespace. This tactic also enables the rapid dissemination and execution of critical intelligence across both physical and cyberspace domains. These units can analyze AI-derived information and share key intelligence via low-probability-of-intercept and low-probability-of-detection communications with lateral units. This form of communication is preferred for its reduced signature, though it is constrained by limited data transmission capacity. However, each unit's intelligence and cyber personnel can address this limitation by distilling the data before transmission. This low-signature tactical communication and coordination technique, coupled with each unit's ability to conduct physical and cyberspace operations, will considerably increase force protection.

The United States also needs to take specific actions inside and outside cyberspace to increase ambiguity for an enemy decision-maker or reduce ambiguity by misleading their decision-making process into a favorable outcome (Daniel and Herbig, 1982). To increase ambiguity, the United States should vary the technical signatures of its locations and deploy decoy emulators at unused sites. These emulators are most effective when used in conjunction with visible decoys to further deceive adversarial sensors. AI bots at these sites could simulate electronic communications by emitting appropriate signatures. By increasing ambiguity (A-type), the United States will confuse the enemy about the location of its actual forces, requiring the adversary to spend time and resources confirming each location (Daniel and Herbig, 1982). These actions will also enhance force protection at each active site. Additionally, the tactical units should decrease ambiguity and mislead the adversary (M-type) by seeding misinformation about their intent and capabilities (Daniel and Herbig, 1982). These actions should be controlled and approved at the tactical level to increase their tempo and decrease communications with higher commands. By varying the level of ambiguity, these dispersed units can immobilize the adversary decision-maker and increase operational effects across the battlespace. The resulting surprise has been shown to increase casualties for the adversary while decreasing casualties for the initiator (Whaley, 2007). Operationalizing these capabilities at scale ultimately requires institutional adaptation in doctrine, authority structures, and campaign design.

7. Conclusion - Doctrine, Authority, and Implementation Implications

In conclusion, information will continue to play a vital role in military operations throughout the 21st century as more daily activities become dependent on cyberspace. Cyberspace has dramatically transformed modern warfare, and rapid adaptations are necessary to maintain the United States' military dominance. The United States has become increasingly reliant on large bases with extensive personnel and communications equipment, which enable real-time, direct links to tactical units. The United States must rethink how it conducts warfare and become comfortable with limited communications, giving tactical commanders the decision-making space to seize real-time opportunities. The United States should employ AI-enabled operational commands and deploy small, dispersed, hyper-enabled tactical units. These commands will quickly process vast amounts of information and deliver actionable intelligence to tactical units. The tactical units will stay below detection thresholds while validating intelligence and executing operations swiftly and efficiently. These strategies incorporate ten principles from Arthur Buckley's book, "Principles and Deceptions," and complicate the adversary's decision-making process. As AI advances, it will deepen human reliance on cyberspace. Commanders should leverage this dependency by deploying tactical units with the necessary authorities to address vulnerabilities and align with strategic objectives, ensuring operational success in the information age. The United States Department of War must update its joint doctrine to implement these techniques effectively. This revision must consider how cyberspace has altered traditional views of the competition continuum. A conventional framework that classifies interactions between states as cooperation, competition, or conflict no longer fully captures the kinds of hybrid and information warfare tactics that Russia has effectively utilized throughout the 21st century. Armed with this perspective and the outlined techniques, the United States strengthens its ability to maintain military advantage in the information age.

Ethics Declaration: This research did not involve human subjects, the collection of personal data, or experimental intervention. The study is based entirely on published literature, doctrine, and publicly available sources. No ethical approval was required.

AI Declaration: Open-source artificial intelligence tools were used solely for proofreading. All analyses, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources.

Disclaimer: The views expressed here are those of the authors and do not necessarily represent the views of the Naval Postgraduate School, the Department of War, or the U.S. Government.

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A Lightweight Real-time Framework for Detecting Rogue Switches in Wired Local Area Network

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Abstract: In today's digital landscape, securing wired network infrastructure is essential, particularly for Small and Medium Enterprises (SMEs) that often lack dedicated security personnel and resources. This project presents a fully automated, cost-effective method for detecting rogue switches, which are unauthorized devices that may be introduced by malicious insiders or external attackers to bypass network controls. Unmanaged (dumb) switches facilitate lateral movement, network sniffing, and long-term persistence, allowing adversaries to blend into legitimate traffic without detection. To counter this threat, the proposed system employs a correlation-based detection mechanism, supported by a three-layer validation model, to systematically verify infrastructure changes. The layered design reduces false positives and ensures accurate identification of unauthorized network modifications. Tailored for SME environments, this solution removes the need for manual inspection, offering a scalable, real-time response to rogue switch detection and mitigation.

Keywords: Rogue switches, Open vSwitch (OVS), Topology monitoring, ARP-scan, fping, MAC and ARP spoofing, SMTP alerts

1. Introduction

Wired Local Area Networks (LANs), though often perceived as inherently secure, are increasingly exposed to internal threats that bypass traditional perimeter defences. Among the most critical of these threats is the introduction of rogue switches, unauthorised Layer 2 devices silently connected to existing infrastructure. These unmanaged switches are typically plug and play, and lack visibility in network management systems.

Once connected, rogue switches enable adversaries to passively attach multiple devices, sniff traffic, or launch cyberattacks, all while blending into legitimate network activity. This allows attackers to bypass authentication controls, intercept sensitive data, and maintain persistent access within the network environment.

As enterprise networks grow in complexity, for SMEs with limited security infrastructure, the challenge of detecting such hidden threats becomes even more critical.

To address this, the proposed work introduces a structured rule-based detection framework that identifies rogue switches through layered validation focused on topology changes, device registration, and spoofing behavior. This real time, vendor neutral solution is scalable, lightweight, and does not require proprietary hardware, making it suitable for SMEs that need practical and reliable security mechanisms.

2. Related Work

Rogue switches in wired Local Area Networks (LANs) present a persistent challenge due to their passive nature and limited traceability. These unmanaged devices typically lack routable identities and do not participate in Layer 2 discovery protocols such as Link Layer Discovery Protocol (LLDP) or Cisco Discovery Protocol (CDP), rendering them invisible to conventional monitoring tools.

Several approaches have been proposed to infer their presence. Port-security controls such as BPDU Guard and PortFast are widely used to protect against unauthorized switches by disabling ports that receive unexpected Bridge Protocol Data Units (BPDUs) [1] (2024). However, these safeguards assume protocol participation. Unmanaged "dumb" switches neither emit BPDUs nor respond to LLDP or CDP, and can therefore forward traffic silently. In enterprise settings, comprehensive Network Access Control (NAC) commonly incorporates IEEE 802.1X [2] (2020) for port-based admission (EAP over LAN to a RADIUS backend), together with device profiling, posture assessment, and policy-based VLAN/ACL assignment. While NAC/802.1X is effective at deciding who may access a port and enforcing policy at admission time, it does not continuously validate post-admission physical changes or reveal hidden fan-out; a transparent unmanaged switch can still be placed behind an already authenticated port. The method proposed here is complementary; it supplies post-admission visibility that protocol-triggered controls and NAC do not provide.

Anomaly-driven studies have looked at access-segment signals and Layer 2 controls in lab settings. Bhuse et al. [3] (2025) combined management plane telemetry with Dynamic ARP Inspection, DHCP Snooping, Root Guard,

and Port Security with Sticky MAC in a GNS3 and Cisco setup, and added a supervised logistic regression model. The results were strong for ARP spoofing, MAC flooding, and STP root manipulation, but the pipeline was evaluation-focused, dependent on specific vendors, and not run as an always-on alerting service. Bhuse and James [1] (2020) used SNMP broadcast-storm traps as the initial signal, confirmed activity with ARP probes and announcements, and traced offenders using the router ARP table and switch CAM tables. Quitiquit and Bhuse [2] (2022) watched link state and MAC table activity to infer downstream insertion. In practice, these methods can miss short-lived events because of polling intervals, assume uniform management access and credentials across devices, and require manual playbooks or vendor-specific tooling. They also provide limited correlation across signals after admission, which can increase false positives or delay detection when changes are subtle or brief.

Most existing strategies address individual behaviors or require specific infrastructure. They do not offer a unified, vendor-neutral process that adapts across network conditions, especially in resource-constrained environments. This paper introduces a lightweight, rule-based detection framework that continuously validates physical topology changes, verifies registered devices, and detects spoofing behavior in real time. The rules and the correlation logic are configurable, so organizations can tune thresholds, whitelist known infrastructure, and add or remove checks to match their topology and policy. By maintaining a simple topology and MAC–IP baseline, performing active discovery from a trusted host, checking ARP consistency to spot impersonation, correlating signals to reduce noise, and emailing administrators immediately when something new or suspicious appears, the framework offers a practical and scalable option for SMEs.

3. Problem Statement

Existing solutions for detecting rogue switches often rely on proprietary protocols, manual tracing, or SNMP-based infrastructure, which are not always practical in real-world SME environments. Unmanaged switches that do not participate in discovery protocols can silently forward traffic, bypassing traditional security controls. In practice, budget constraints often lead to the deployment of low-cost, Fast-Ethernet unmanaged switches, further reducing protocol visibility and complicating detection. There is a need for a lightweight, rule-based detection framework that can identify such devices in real time without relying on complex infrastructure or protocol-level visibility.

4. Proposed Solution

The proposed framework enables real-time detection of rogue switches in wired LAN environments through a layered validation approach. It incorporates topology monitoring, device verification, and ARP cache analysis to detect unauthorized links, unregistered devices, and address spoofing. A trusted baseline of active authorized switch-port mapping and as well as MAC–IP mapping for Compliant (authorized) devices, is maintained and periodically compared against live network data. Upon identifying anomalies, the system triggers alerts via an SMTP-based notification mechanism.

To ensure long-term accuracy and compliance with organisational network governance standards, baseline updates are strictly manual and subject to predefined security policies. This approach minimises false positives while preserving the integrity of the detection process.

5. Implementation

The framework was implemented using Ubuntu, Mininet, Open vSwitch, and Bash scripting to define detection rules and automate topology monitoring. OVS (Open vSwitches) were monitored to detect topology changes and unauthorised links, while tools such as fping and arp-scan were integrated for active scanning and host discovery. ARP cache analysis was used to detect MAC and IP spoofing attempts. Postfix was configured to handle SMTP-based alerting. This approach is vendor-independent, lightweight, and suitable for real-time rogue switch detection..

5.1 Topology Overview

The test environment was configured to simulate a realistic enterprise LAN structure using Mininet's tree topology. The network consists of one core switch (s1) connected to four access-layer switches (s2 to s5). Each access switch is linked to four hosts, resulting in a total of sixteen hosts (h1 through h16). Specifically, s2 connects to h1 to h4, s3 to h5 to h8, s4 to h9 to h12, and s5 to h13 to h16. This topology emulates a structured multi-segment LAN, enabling detailed analysis of rogue switch insertion, spoofing behaviour, and automated alert

generation across various zones. Each detection rule was tested individually to evaluate the accuracy and responsiveness of the framework.

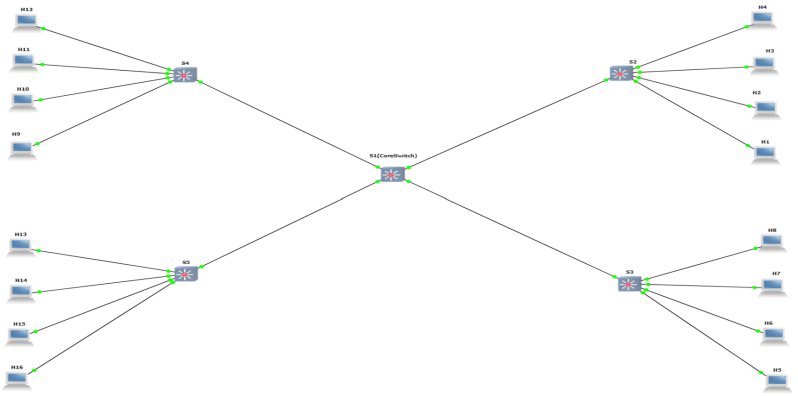


Figure 1a: Topology

5.2 Detection Rules Overview

Before introducing any rogue elements, the detection framework establishes a secure and trusted view of the network using three-layered rules. These rules work together to ensure that any unauthorised or malicious changes are promptly identified.

Rule 1: Topology Change Detection

Open vSwitch (OVS) is used to monitor the real-time status of switch ports. OVS listens to kernel-level network events such as cable insertions/removals, interface state changes, or system configuration updates. These events are reflected instantly in the OVS database and can be queried using ovs-vsctl show.

Once the network stabilises, a baseline snapshot of all switch-port mappings is taken and saved as baseline_topology.txt. This serves as a trusted reference, and the script periodically compares it against the current topology every few seconds to identify any unauthorised modifications (e.g., newly added ports from rogue switches to further connect multiple devices using a single legitimate switch port).

Open — baseline_topology.txt — ~/Desktop/Topology change script

```
1 Switch: s3
2   Port: s3-eth5
3   Port: s3-eth2
4   Port: s3-eth4
5   Port: s3-eth1
6   Port: s3-eth3
7 Switch: s2
8   Port: s2-eth2
9   Port: s2-eth4
10  Port: s2-eth1
11  Port: s2-eth3
12  Port: s2-eth5
13 Switch: s4
14  Port: s4-eth3
15  Port: s4-eth2
16  Port: s4-eth1
17  Port: s4-eth5
18  Port: s4-eth4
19 Switch: s1
20  Port: s1-eth4
21  Port: s1-eth2
22  Port: s1-eth3
23  Port: s1-eth1
24 Switch: s5
25  Port: s5-eth5
26  Port: s5-eth3
27  Port: s5-eth2
28  Port: s5-eth4
29  Port: s5-eth1
```

Figure 1b: Switch Active Ports (Baseline)

Rule 2: Device Registration and MAC Mapping

After establishing the baseline switch-port topology, the second rule focuses on identifying all active end devices and registering their corresponding MAC and IP addresses. This rule ensures that only legitimate hosts are recognised before the detection framework begins operation.

The system initiates a fast subnet-wide sweep using fping, which sends ICMP echo requests across the network to detect live hosts. Once responsive hosts are identified, tools like arp-scan or arping are used to send ARP

requests, forcing those hosts to reply with their MAC addresses. This process creates a reliable IP–MAC mapping for every connected device in the network.

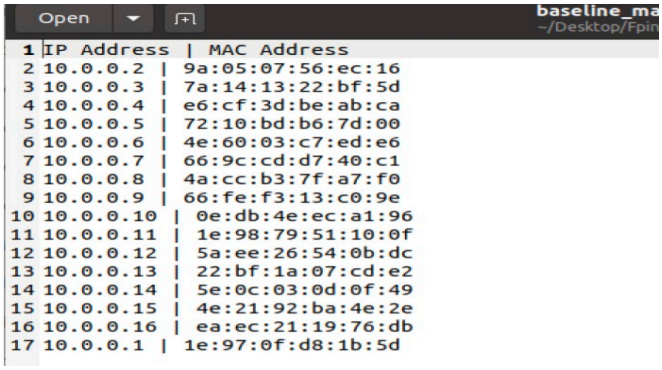


Figure 2: Trusted MAC–IP

To ensure trust and consistency, this scan is executed from a known legitimate host (h1), connected to access switch s2. Scanning from within a trusted network segment minimises the risk of spoofed replies or detection evasion by rogue nodes.

The resulting mappings are stored in a reference file named baseline_mac_ip.txt. This file acts as the foundation for all runtime MAC address verifications. During monitoring, any MAC address not found in this baseline is flagged as a potential rogue device.

The baseline can be updated when new, authorised devices are introduced. Each update must include the device's MAC address and its active switch port connection at the time of registration. For DHCP environments, detection keys are used for MAC-first matching. IP changes are tolerated, but MAC–IP conflicts and unknown MACs still trigger verification and alerts.

However, to ensure the security integrity of the framework, all baseline modifications must be manually approved in accordance with internal policies. This prevents accidental or malicious whitelisting of unauthorised devices.

During detection, any new MAC address not present in the baseline is treated with high priority, as it may indicate the presence of a rogue switch introducing new connected hosts. The severity of the alert increases if this MAC anomaly is accompanied by other signs of tampering, such as unexpected topology changes (Rule 1) or MAC/IP inconsistencies (Rule 3).

Rule 3: ARP and MAC Spoofing Detection

The third rule addresses spoofing attacks, where a malicious device may impersonate legitimate hosts by forging MAC or IP addresses. This layer is critical for identifying stealthy rogue devices that are connected behind rogue switches to perform man-in-the-middle (MITM) attacks. Such devices often bypass port-based controls or baseline MAC mapping checks established in Rule 2 by mimicking legitimate network behavior.

To detect these threats, the framework periodically retrieves ARP cache data from multiple legitimate hosts distributed across different access switches (e.g., h1 on s2, h5 on s3, h9 on s4, and h13 on s5). While this multi-host perspective ensures broader visibility within the wired LAN, primary preference is given to h1, as it actively performs network scans and communicates with other devices more frequently. As a result, its ARP cache is typically updated faster, making it the most reliable source for identifying MAC–IP inconsistencies and detecting spoofing behavior in real time.

The script scans for the following anomalies every 10 seconds:

- **MAC Spoofing**: The same MAC address appears under multiple IP addresses.
- **ARP Spoofing**: A single IP address mapping to multiple MAC addresses.

These patterns are direct, vendor-neutral signs of identity impersonation that a trusted host can check quickly. They stay reliable in DHCP environments because we match on the MAC first, so normal IP changes don’t create noise while real spoofing still shows up. They also reflect how attackers or a rogue downstream switch can manipulate the network through ARP poisoning or MAC cloning to corrupt ARP caches and switch CAM tables,

redirect traffic, hide additional devices, and bypass port-level controls and device-registration policy, which is exactly what our correlation and alerting are built to catch in real time.

Alerts from this rule are treated as high priority, especially when correlated with topology or device mapping anomalies from Rules 1 and 2. The scanning interval may be adjusted based on the network environment, particularly in cases where IP assignment changes occur frequently due to device reconnections.

5.3 Insertion of Rogue Switch and Device

To simulate a real-world network compromise, a rogue Open vSwitch (OVS) switch was introduced into the running Mininet topology after the legitimate setup was fully stabilised. This rogue switch was externally connected to the access switch s3, imitating a physical insertion into a live LAN through an unused network port.

A rogue device was also introduced and linked to the rogue switch using a virtual Ethernet connection. This setup replicates an attacker connecting an unauthorised switch along with one or more hidden devices in order to blend into the network without being immediately detected.

The insertion was performed from outside the Mininet environment to reflect a realistic scenario where an attacker interacts with the underlying system directly, without Mininet's awareness. This method allows the detection framework to validate whether it can identify unauthorised topology changes and hidden device activity introduced through unmanaged connections.

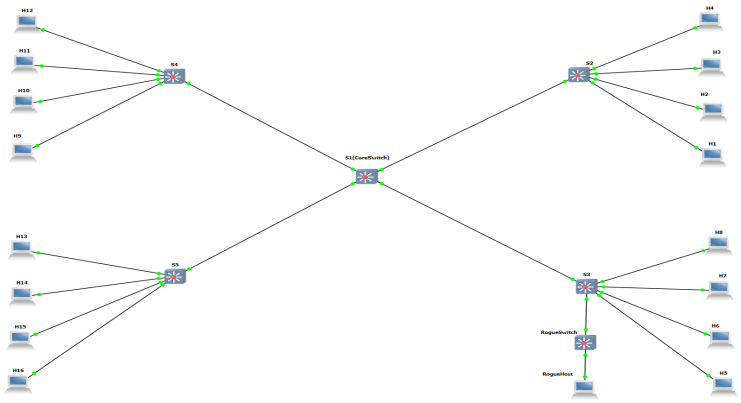


Figure 3: Topology after adding Rogue switch and device

5.4 Detection Based on Topology Changes

Once the framework is deployed, the topology monitoring script runs in the background and periodically checks for any new ports. When an unauthorized change, such as a rogue switch connection, is detected, the system immediately raises an alert. The screenshots below capture a real detection scenario where a new unauthorised port was identified.

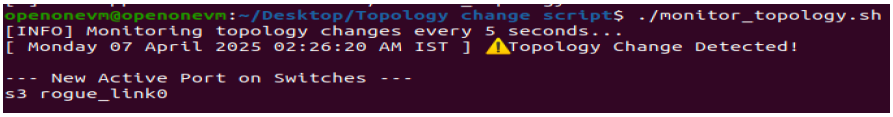


Figure 4: Real-Time Topology Change Detection Triggered

The script logs the moment a new port (rogue_link0) became active on switch s3, indicating a possible unauthorized link.



Figure 5: Email Alert Sent Upon Detection

An automated email alert was immediately triggered via SMTP, notifying the administrator of the detected rogue switch connection. The alert includes the exact timestamp and the specific switch-port details where the anomaly was observed, enabling precise identification and investigation.

5.5 Detection Rule Based on Unregistered Devices

Additionally, the second detection rule was running alongside the topology monitoring script. It prioritises MAC address verification. If a new, unregistered MAC address is detected, it is immediately flagged as rogue, regardless of its IP address. This approach is particularly important in DHCP-based networks, where IP addresses may change frequently but MAC addresses remain stable and unique identifiers.

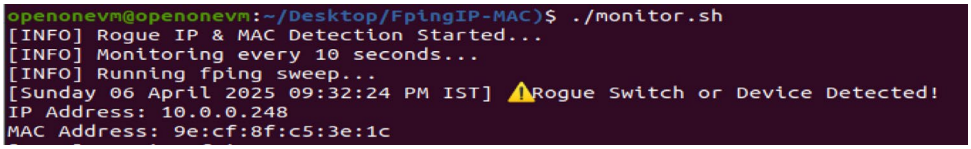


Figure 6: Rogue Device Detected via MAC Mapping

This screenshot shows the terminal output from the MAC detection script. A device with MAC address 9e:cf:8f:c5:3e:1c was identified at IP 10.0.0.248. Since this MAC was not listed in the baseline, it was flagged as a rogue device.

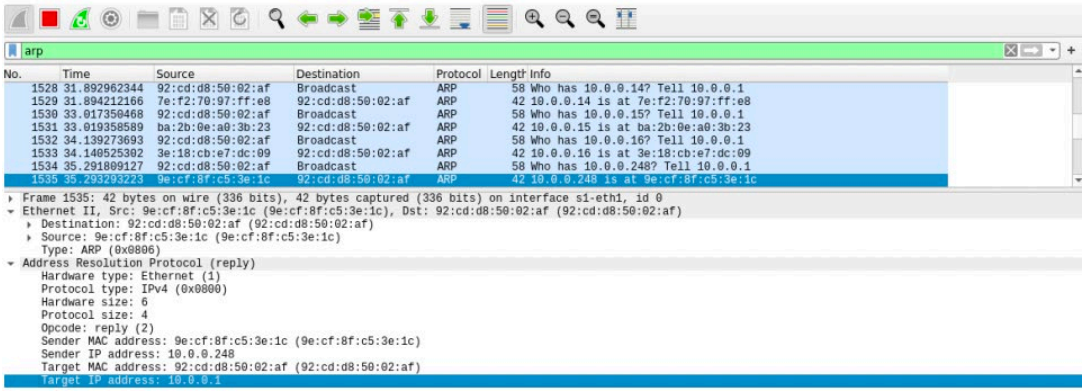


Figure 7: Wireshark Traffic Captured Near H1 host

This ARP reply packet confirms the MAC–IP mapping observed by h1 during baseline or live scan verification. In this frame, IP address 10.0.0.248 is associated with MAC address 9e:cf:8f:c5:3e:1c. Such entries are collected and compared against the trusted MAC–IP baseline in Rule 2 to identify unregistered or unauthorised devices. Any deviation from expected mappings triggers an alert, helping enforce device-level integrity within the LAN.

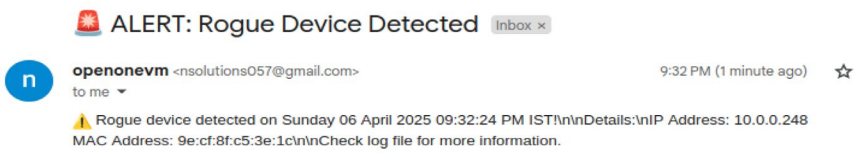


Figure 8: Email Alert for Topology Change

An automated email alert was immediately triggered via SMTP, notifying the administrator of the detected rogue switch connection. The alert includes the exact timestamp and identifies the affected port (rogue_link0) on switch s3 as observed by Rule 1. Additionally, Rule 2 raised a high-priority alert due to the appearance of an unregistered MAC address, further confirming the presence of a rogue device introduced via the rogue switch.

5.6 Detection Rule Based on MAC and ARP Spoofing

While topology changes and unregistered devices can expose many rogue setups, a determined attacker may still evade detection by impersonating known devices. This rule adds a critical layer of protocol-level inspection to uncover such spoofing behaviour.

5.6.1 MAC spoofing detection

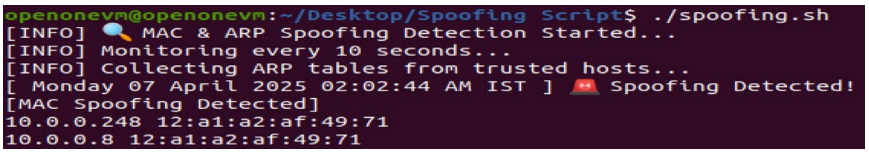


Figure 9: Spoofing Detection Triggered via MAC Conflict

In this scenario, a rogue device connected behind a rogue switch spoofed the MAC address of an already registered device. The detection script identified that the same MAC address (12:a1:a2:af:49:71) was simultaneously associated with two different IP addresses (10.0.0.248 and 10.0.0.8). Since this MAC was part of the trusted baseline, Rule 2 did not flag the device. However, Rule 3 successfully identified this as a MAC spoofing incident, which is an impersonation pattern commonly introduced by rogue switches to stay hidden. Given that these attack patterns are relatively common at Layer 2, there remains some scope for downstream evasion, which our Rule 3 is designed to mitigate.

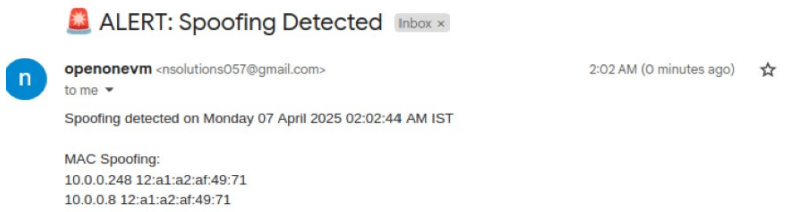


Figure 10: Email Alert Notifying Mac Spoofing Detection

An SMTP-based email alert was generated automatically, detailing the spoofed MAC address, the conflicting IPs, and the timestamp. This confirms that MAC spoofing can bypass earlier rules but still be caught by protocol-level analysis.

5.6.2 ARP spoofing detection

Although the device registration process in Rule 2 relies on MAC address verification, there still exists a narrow window for ARP spoofing, particularly when a rogue device impersonates a legitimate IP address with a different MAC. These cases are rare due to strict MAC filtering in Rule 2, but they can still occur when attackers reuse known IPs to bypass registration logic.

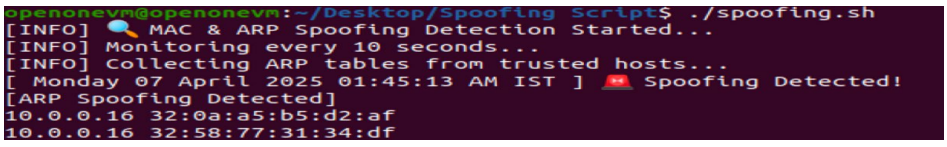


Figure 11: ARP Spoofing Detection Triggered

In this example, the spoofing script detected that the same IP address 10.0.0.16 was being claimed by two different MAC addresses: 32:0a:a5:b5:d2:af and 32:58:77:31:34:df. This is a typical indicator of an ARP spoofing attack, where the rogue host attempts to intercept traffic intended for a legitimate device.

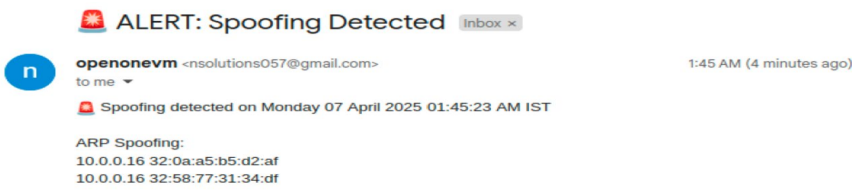


Figure 12: Email Alert Notifying ARP Spoofing Detection

An immediate alert was generated and sent to the administrator, showing the conflicting MAC addresses for the same IP. This helps in detecting impersonation attempts even when attackers try to reuse legitimate IPs.

5.7 Alert Prioritisation Logic

In dynamic environments, where legitimate devices may occasionally be moved or reconnected, a single topology change detected by Rule 1 is assigned medium priority by default. However, if that change is immediately followed by a MAC address mismatch (Rule 2) or an IP to MAC inconsistency (Rule 3), the alert level is escalated to high. When all three rules are triggered within the same observation window, the framework flags the event as critical, as it strongly suggests that a rogue switch is being used to connect multiple devices using a single legitimate switch port, indicating a highly suspicious or malicious activity. This layered prioritisation helps reduce false positives while ensuring timely and appropriate responses to compound threats.

6. Conclusion

This paper introduces a lightweight, real-time framework for detecting rogue switches in wired Local Area Networks by correlating topology monitoring, MAC address validation, and protocol-level spoofing analysis. The approach enables reliable identification of unauthorised switch insertions and downstream rogue devices through independent yet complementary detection rules, ensuring timely validation of network integrity. Targeted at small and medium-sized enterprises, the framework is vendor-neutral, cost-effective, and deployable without specialised hardware. Experimental evaluation confirms effective detection of topology anomalies, MAC spoofing, and ARP-based attacks, with automated email alerts supporting rapid administrative response. Future work will focus on visual topology dashboards, SIEM integration, and enhanced cross-rule correlation to further reduce false positives and strengthen post-admission network visibility.

Ethics declaration: Ethical clearance was not required for the research.

AI declaration: AI tools were not used the creation of this paper.

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Leveraging Open-Source Intelligence to Combat Cryptocurrency Investment Scams

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Abstract: This paper presents a follow-up study to earlier research on cryptocurrency crime, again drawing on the case of an elderly woman defrauded by an online platform known as RSI-Platform. Whereas the initial study focused mainly on on-chain analysis within the blockchain environment, the present work shifts attention to off-chain approaches, applying open-source intelligence (OSINT) techniques to deepen investigations into crypto-related fraud. By systematically examining diverse input data—such as names, phone numbers, email addresses, and URLs—this study conducts link analysis and aims to build detailed profiles of potential suspects, thereby advancing understanding of the strategies and methods used in cryptocurrency scams. The analysis aims not only to trace the scammers' digital footprints but also to reveal networks and connections to other fraudulent platforms that support these activities. Moreover, this research seeks to raise public awareness about the scale and operation of fake online investment schemes in the crypto sector. By exposing the vulnerabilities exploited by offenders and illustrating how OSINT can be used to detect and disrupt such scams, the paper adds to ongoing discussions on cybersecurity and consumer protection in the fast-changing field of digital finance. Additionally, the findings are intended to offer practical insights for law enforcement agencies, policymakers, and the wider public, encouraging a more informed and proactive response to the threats posed by crypto-related fraud.

Keywords: Cybercrime, Cybercrime investigations, Cryptocurrency scams, Fake investments, OSINT

1. Introduction

Botha et al. (Botha, Singh, & Leenen, 2026) examined a fraudulent cryptocurrency investment and trading scheme by applying an investigative process introduced in earlier work (Botha, Singh, & Leenen, 2025). The previous study focused more heavily on on-chain analysis conducted directly on the blockchain, while giving relatively less consideration to off-chain analysis. The on-chain analysis was conducted using the tool Breadcrumbs, a cryptocurrency investigation tool that offers a transaction tracing platform for digital assets.

In contrast, this investigation study concentrates mainly on the off-chain analysis, which incorporates a range of OSINT methods and techniques. OSINT involves gathering, processing, and correlating information that is publicly accessible from open data sources like social media, forums, blogs, public government data, publications, or commercial data. OSINT methodologies begin with initial input data and employ advanced collection and analysis techniques to progressively enhance understanding about a target individual or organisation. As each new piece of information is discovered, analysts move closer to their ultimate objective (Pastor-Galindo, Nespoli, Gómez Mármol, & Martínez Pérez, 2020). Two types of OSINT exist, passive and active. Passive OSINT is the process of gathering information from publicly available sources, as described above, and similar open data repositories (Kolenbrander, 2025). In the case of an investigation, passive OSINT analysis aims to collect personal data about a target without any direct interaction with them. This method utilises various tools to find specific details, aimed at constructing a profile of the target individual (Botha, Singh, & Leenen, 2025). Active OSINT typically involves the use of a program or script to collect data and leaves a log behind (Kolenbrander, 2025). Active OSINT analysis also entails interacting with a target person under deceptive circumstances, such as using a fake or undercover profile, to persuade them into disclosing personal information. This approach, however, carries a higher likelihood of the target discovering the tactic used by the investigator, potentially resulting in them changing their behaviour. This also raises legal and ethical issues, including the risk of violating the policies of legitimate platforms (such as social media) and concerns about possible entrapment. What strategies are allowed can differ significantly between jurisdictions. For this investigation, no active OSINT methods were utilised. Active OSINT can also considered hacking. For example, if it is possible to manipulate a messaging application's metadata to expose the IP of the other party on the chat, it is considered hacking (Berkman, 2026; Hwang, Lee, Kim, Lee, & Kim, 2022; Hwang, Lee, Kim, Lee, & Kim, 2022).

This paper discusses the strategies and tools employed in this study, the theories investigated and the ultimate conclusions reached based on facts and evidence found. The authors first outline the case study's background

and context, followed by an off-chain analysis of the incident. The off-chain analysis employs several OSINT techniques and methods. After sufficient intelligence has been collected to profile the target entity, a link analysis is performed. The final stage addresses the associated law enforcement procedures. The expanded OSINT sections are intended to serve as a proposal for refining the process suggested in (Botha, Singh, & Leenen, 2026). The final section concludes the paper's main findings.

2. Case Background

The previous study proposed a theory that the ex-son-in-law (referred to as 'Mr-X' in this paper) could have been collaborating with the scammers. Note that investigators tend to use the term theory and not hypothesis in their investigations. For this paper the term "theory" will be used and refers to a "working theory" or "hypothesis". It is quite common for fraudsters to use local individuals to attract potential victims. These intermediaries are typically given some type of compensation for identifying and attracting victims. The particular scam platform under examination is called RSI-Platform and was ran out of the website 'https://rsi-platform.io' (note that the web domain is not active anymore since the scammers must have taken it down). The victim, an elderly woman, was persuaded to invest in the platform, which was portrayed to be a global online trading entity based in the United Kingdom (UK), integrating traditional investments with crypto-based funding and trading mechanisms. More details on the background can be found in the previous study, (Botha, Singh, & Leenen, 2026).

This study pursues two primary objectives:

- Collect online, off-chain information to attempt to identify the suspect, and
- To investigate and substantiate the hypothesis that 'Mr-X' is involved with the scammers.

The first author of this paper contacted TCG Forensics (TCG Forensics, 2026) and Breadcrumbs (Breadcrumbs, 2023) for support with the OSINT techniques, and both companies agreed to help. Craig Pederson, the CEO of TCG Forensics, contributed by attempting to identify the scammer and by gathering as much online information as possible. Abraham Berkman, Head of Intelligence at Breadcrumbs and the second author of this paper, also assisted by collecting data to determine the scammer's identity and to either confirm or dismiss the hypothesis that Mr-X was involved with the scammers, or whether he was in fact a genuine victim. Both Pederson and Berkman have backgrounds in OSINT and cybercrime investigations.

The indicators point to the involvement of both offshore and local parties, which aligns with a syndicated operation. In these cases, funds are transferred directly into crypto-exchange accounts using a specific reference number that routes the funds to the actor's wallet. This process circumvents many fraud prevention measures and enables money laundering by avoiding traditional banking channels. Once the credit reflects in their crypto-exchange account, the actor is then able to transfer the funds onwards.

3. Investigation Process

Similarly to the previous study, this analysis also follows the investigative process proposed by (Botha, Singh, & Leenen, 2025). The process has five phases, namely:

1. Data collection
2. Analysis
3. Theory development and validation
4. Suspect identification and reasonable grounds
5. Legal action

3.1 Data Collection

This section provides an overview of the collected data (evidence) from the victim. This paper focuses exclusively on the off-chain data that was gathered. The victim provided the following inputs *(names and contact information are redacted)*:

- *Suspect website domain*
- www.rsi-platform.io
- Screenshots of the suspicious domain.
- *Cryptocurrency addresses linked to the suspect domain. The preliminary tracking of these crypto transactions is documented in the earlier study (Botha, Singh, & Leenen, 2026)*
- *Names*

- List of names linked to the suspect domain – contacts communicating via WhatsApp and phone calls (numerous persons and names, which are likely all aliases).
- *Phone Numbers*
- List of numbers in connection to the suspect domain from which calls to the victim were made (SA and UK numbers)
- *Email Addresses*
- s#####e@cryptodotcom.info
- List of scammer names@###-platform.io
- *Physical Address*
- # B### St, London E## #BG, UK

3.2 Analysis

The analysis employed three basic steps in iteration, based on advice from an OSINT expert from Hawk Eyes OSINT and Breadcrumbs (Hawk Eyes, 2026) (Berkman, 2026):

- **Evidence Overview**: An examination of the evidence at hand to gain an understanding of the case, identification of areas for evidence enrichment and development, and affirmation or refutation of theories.
- **Evidence Enrichment**: Based on the evidence at hand, various tools and investigation methods were employed to process and further enrich the evidence base. This can also be done from a completely objective outlook or an effort to affirm or refute a running theory.
- **Theory Development (see Section 2.3)**: Based on the evidence overview, theories regarding the case were developed and those theories had to be affirmed or refuted by further evidence enrichment.

Typically, a case starts with preliminary evidence supplied by a client or victim (see Data Collection in Section 3.1). This initial evidence must be analysed so that a working theory can be formed, or so that potential ways to enrich the evidence can be identified. When such opportunities are found, the evidence should be enriched and then re-examined until a theory is developed. All new information that appears to be connected to the suspect should be incorporated into a link analysis diagram, (see section 4, Figure 4). After a theory has been developed, additional evidence must be collected and repeatedly reviewed until the theory is either supported or disproved. If the theory is disproved, the investigator must reassess the evidence and formulate a new theory. This iterative process continues until a theory is confirmed and the case can be closed. See Figure 1, which illustrates this process.

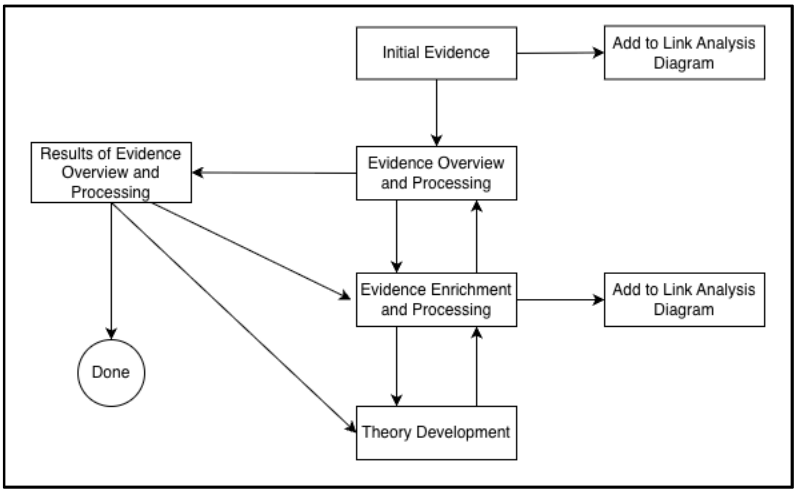


Figure 1: OSINT Investigation Process

In this segment of the analysis, OSINT methods are used to attempt to reveal the suspect's identity, based on the inputs and details provided by the victim. The proposed process by (Botha, Singh, & Leenen, 2025) does not give enough details on steps to be followed in the off-chain analysis, specifically with respect to the OSINT techniques. The steps seen in Figure 1 are added to the analysis phase in this investigation.

3.2.1 Evidence overview and processing

The client provided evidence as listed in Section 3.1. This section goes through all evidence and process them to gain more insights.

Domain Name

Because the scam originated from the website at the domain "https://rsi-platform.io", the initial step was to collect any further information associated with that domain. As the site is currently offline, the WayBackMachine (WaybackMachine, 2026) was used to retrieve historical data about its structure. The aim was to determine whether a comparable website run by the same offenders was still online, which would allow for network monitoring and a more detailed understanding of how the scam operated. Only a single screenshot from October 2022 was available on Wayback Machine (see Figure 2). This suggests that the site operated with limited capacity, received little traffic, and was active only for a short period. By using Chrome's 'inspect' tool, the screenshot revealed the site's HTML, CSS, and links to portions of its JavaScript. Distinctive code fragments were then extracted and searched on NerdyData (NerdyData, 2026) to identify other websites that might be using the same snippets. A further goal was to identify any extra information that might be obtained from the website's front end, such as additional phone numbers or email addresses. Ultimately, no further information could be collected.

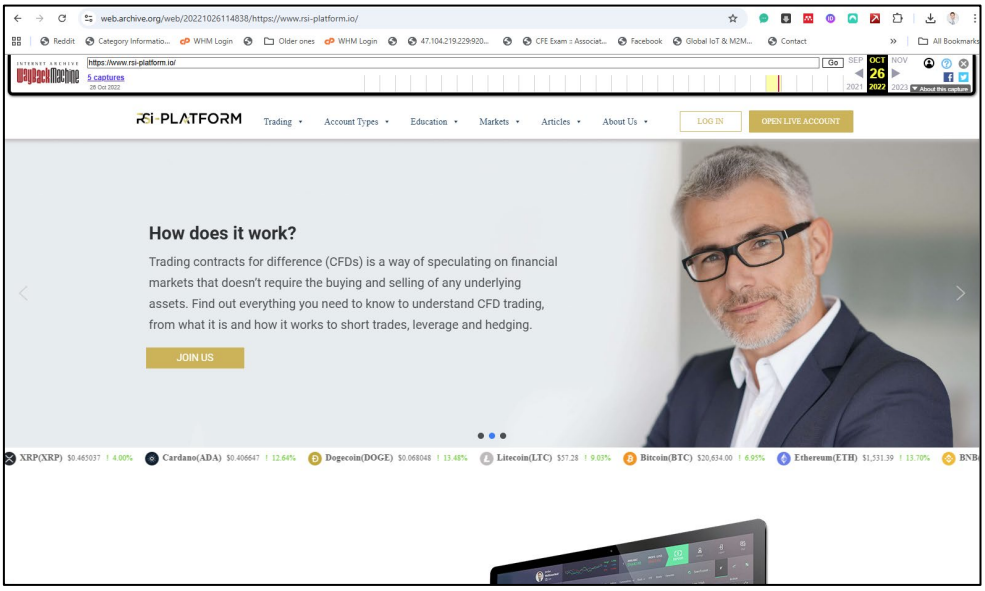


Figure 2: RSI-Platform - Home Page

WHOXY (WHOXY, 2026) reported that there is currently no active hosting on the domain. It does, however, provide information on the most recent registrar, as illustrated in Figure 3. Additional registrar data for the 2022 period may be obtainable directly from the registrar upon request. Particular focus should be given to the payment method used to acquire the domain in 2022.

MX Toolbox (MXToolbox, 2026) shows that there are currently no functioning mail routes, redirects, or traceable records linked to the domain. Opencorporates (opencorporates, 2026) further indicates that the supposed 'company' called 'vestpro', which the website claims is registered in the Seychelles, appears not to exist. There is no matching company registration or recognised legal entity connected to the site. Taken together, this strongly supports the conclusion that the rsi-platform.io website was precisely what it seems to be: just a small collection of pages created to lure in and reassure prospective victims. None of the claims or information displayed on the rsi-platform.io site can be verified against any reliable, factual sources.

The website scam detector (scam-detector.com, 2025) provides original information, reporting, reviews and analysis on websites, domains and e-commerce platforms, and advises if these are legitimately, safe and trustworthy. The www.rsi-platform.io web domain received a score of 40.7% from scam detector which signals risk and red flags. The domain was created on 23 June 2022, and the victim was scammed starting in December 2022. Shortly after the domain was created, scam detector also indicated it has a proximity to suspicious websites of 73% and a phishing score of 78%. The website's meta data was poorly configured which would not

help its online presence and resulted in a loss of credibility. The domain was active for 1 year, 11 months before it became inactive.

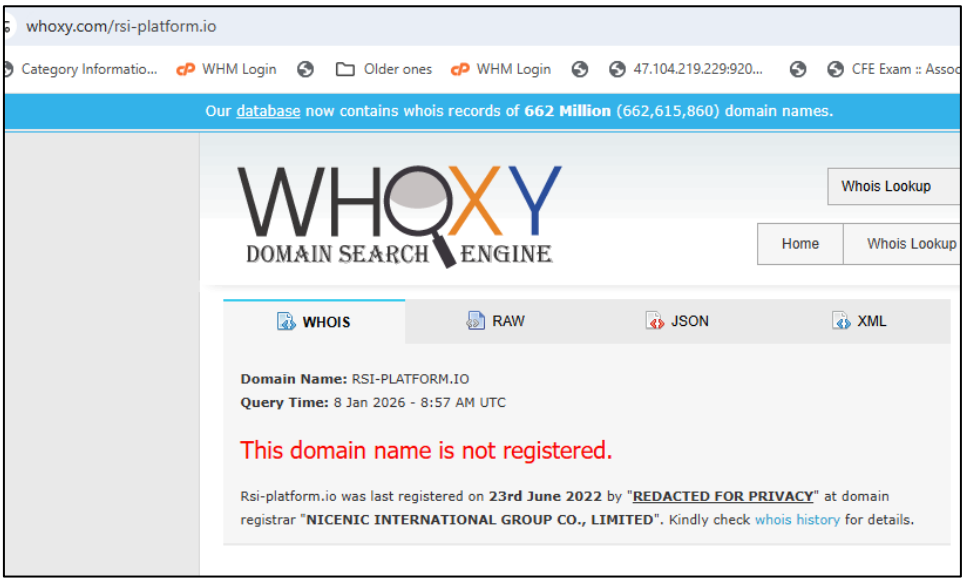


Figure 3: WHOXY Domain Search Engine

Another search result from Google pointed to the website www.55brokers.com, which suggests that RSI-platform appears to operate as a UK-based entity, with the authority to provide services in the UK. Nonetheless, its regulation is solely in St. Vincent and the Grenadines, classifying it as offshore. Therefore, this is typically indicative of a scam (55BROKERS, 2025).

Names and Contact Information

The victim provided a list that included names and phone numbers from South Africa (SA) and the UK. Through Truecaller (Truecaller, 2025), it was discovered that the SA numbers are linked to the RSI-platform ZA Office and that these numbers are Voice-over-IP (VoIP).

Regarding the list of email addresses all belonging to the domain RSI-platform.io, various user complaints were found on websites like ScamAdviser and Trustpilot (Trustpilot, 2023), involving unsolicited emails promoting 'guaranteed' investment opportunities or recovery services for lost funds. The platform has been reported as 'pig butchering' or advance-fee scams, where scammers build trust via email or chat, then request deposits or personal information. Pig butchering is an investment scam where fraudsters gain the trust of victims of time and then deceive them into investing in fake investment platforms (often fake cryptocurrency investment platforms) (DFPI, 2025).

No reliable business or professional profiles associated with any of these email names could be connected to the email addresses in recognised directories such as LinkedIn or official corporate registries.

3.2.2 Evidence Enrichment

Domain Name

A lookup of the domain in BigDomainData (BigDomainData, 2026) showed that it was registered via the Hong Kong–based registrar Nicenic International Group Co. by an individual named 'Tyron Cantrell' from 'Gwynedd County, Nigeria'. Gwynedd County is located in Wales, and no corresponding Gwynedd County could be identified in Nigeria. A review of the hosting provider, NiceNic, revealed that the platform operated without any KYC (Know your Customer) procedures and accepted payments through several methods, including cryptocurrency. This setup made it possible for clients to submit false registration details and pay in a pseudo-anonymous manner using cryptocurrency. Linking this information to the cryptocurrency addresses tied to the scammers could move the investigation forward, effectively bringing together OSINT and blockchain analysis. NiceNic's website also contained links to the platform's social media (SM) accounts on Facebook, X (formerly Twitter), and Pinterest. NiceNic cryptocurrency payment addresses included, but not limited to:

- 0xEd…61B8 - CircleCoin(USDC)

- 0x5E…2297 - USD_Tether (USDT)
- Bc1q…4mfa – Bitcoin (BTC)

By combining the on-chain and off-chain analysis, it also shows how Web2 (OSINT) and Web3 (on-chain or blockchain) investigations complement each other and are not mutually exclusive. In Web2, people depend on centralised services—such as social networks, online banking, and search engines. Web3 introduces a new model built on decentralised infrastructure and applications, such as the BTC blockchain (Lacity & Carmel, 2024). For example, in this case, discovering that the hosting company of the scammers domain accepts payment in crypto and discovering the payment addresses via OSINT, provided a new channel to trace via WEB3 (blockchain) (Berkman, 2026).

Names and Contact Information

Based on the findings from the domain investigation, it was evident that the perpetrators of the scam took deliberate steps to evade detection by using false information to conceal their identities. This conclusion was reinforced by the OSINT industry (OSINT Industries, 2026) reports, which showed multiple names associated with the same phone number, as well as the generic names given to the victims. As a result, attempting to investigate the names and contact details through traditional means would likely generate numerous false positives and consume valuable investigative time. The priority, therefore, shifted to identifying links between the contact information and other websites and/or members of the victims' families.

Using Maltego transforms, the transforms for Cyber Threat Intelligence (CTI), Corporate Intelligence, WhoisXML and Social Links were run on all the provided phone numbers and email addresses. Maltego is a cyber investigation and link analysis tool (Maltego, 2026). Additional searches were made on several of the phone numbers and email addresses using IntelTechniques (IntelTechniques, 2026), Breach Directory (Breach Directory, 2026), Non-Nonsense (NO-NONSENSE, 2026), FreeCarrierLookup (FreeCarrierLookup.com, 2026) with no results.

XDS (XDS, 2026) was used to conduct searches on telephone and/or mobile numbers. These searches returned the names, surnames and identity (ID) numbers linked to each queried number. Numbers identified as South African were subsequently verified against the CRDB Porting database (Porting, 2026) to establish the network provider for identification purposes and potential further investigation via a subpoena process. The numbers were confirmed as ported and still active on the networks of Vodacom, Telkom Mobile and SVSGNP (Saicom Voice Services).

Google searches were carried out on the names associated with the RSI platform that were supplied by the victim, and each of these names appeared in connection with negative reviews on hellopeter.com and Trustpilot. One positive review was identified on HelloPeter (hellopeter.com, 2025), but it is most likely a self-authored post made during the early phase of the scam. In the absence of a precise chronology of events, it cannot be conclusively established that this review is a self-review. Additional potentially relevant information might be available and could be obtained from HelloPeter through a subpoena. Should the review ultimately be classified as a self-review intended to bolster the scam's legitimacy, this would align with a common syndicated pattern. Although the names provided are not genuine names but rather aliases used to interact with victims, their full forms will not be disclosed in this paper. It can be noted, however, that the names are characteristic of white, English-speaking South African men and could just as plausibly be typical UK names.

WhatsApp chat logs between the victim and the suspects were recovered and imported into Maltego. However, these conversations did not reveal any additional information about the scammers' real identities beyond the aliases they used.

The provided email address, s######s@cryptodotcom.info, was subjected to various verification tools, revealing that the email account does not exist.

Mr-X

In addition, searches were made for the SM accounts of Mr-X. The searches focused on the subject's personal gmail address, the subsequent username and variations of the subject's name. A use of the service 'WhatsMyName' (WhatsMyName, 2026) revealed a Pinterest account, Roblox account and Facebook account using the target username. The Pinterest account contained a profile picture common amongst military men, this being consistent with the known military background of the subject. A reverse image search of the subject's Pinterest profile image revealed a YouTube account using the username and containing the exact same profile

image of the Pinterest account. A Google Dorks search, using the query 'person:(('name') 'surname') AND site:linkedin' while using a VPN set to SA (the home country of the target) revealed the target LinkedIn in profile.

3.3 Theory Development and Validation

Over the span of this investigation, three distinct theories were formulated and subsequently tested and validated.

3.3.1 Theory 1 – Mr-X is a victim

SA law enforcement reported that they suspect a group from the country of Georgia of being responsible for the scam that targeted the victims. It was initially believed that Mr-X had first fallen prey to the scam and, before realising it was fraudulent, had encouraged his wife and mother-in-law to use the platform, resulting in them being scammed as well. In this scenario, Mr-X would be considered a victim, along with the complainant.

By comparing the timeline of the WhatsApp conversations between the ex-husband and the RSI brokers with the victim's testimony, it was observed that a coherent pattern of interaction between Mr-X and RSI leading up to his recommendation that the victim invest in the platform. However, because the WhatsApp record is so extensive, the precise nature of these interactions remains unclear, making it difficult to draw firm conclusions.

3.3.2 Theory 2 – Mr-X worked with RSI-platform

Since it was Mr-X who introduced the victim to the platform and urged her to invest funds in it, the question arises as to what Mr-X knew about the platform's legitimacy at the time he involved his family. Moreover, the fact that Mr-X did not file a police report after it became clear that they had been defrauded supports the suspicion that Mr-X may have been part of the group operating the scam.

According to the victim's testimony, it was reported that Mr-X encouraged the victim to invest in the platform. After the scam was uncovered, Mr-X and his wife divorced, and Mr-X chose not to file a complaint with the Police. Furthermore, it was reported that efforts to obtain further information and evidence from Mr-X about the scam were met with reluctance. These circumstances led to the theory that Mr-X may have been complicit in the scam.

Because it was suspected that the target domain had been registered using cryptocurrency to pay the hosting provider, investigators initially attempted to identify links between the hosting provider's cryptocurrency payment addresses and the one used by Mr-X on VALR (ref to the initial study in (Botha, Singh, & Leenen, 2026)). This line of inquiry proved unproductive, however, as a closer review of the victim's testimony and the WhatsApp conversations strongly indicated that the RSI brokers themselves had access to their victims' VALR accounts. The victim repeatedly stated that she had deposited funds into her VALR account and then observed those funds reflected in her RSI account, despite not having initiated the transfer herself. She further testified that she had shared her VALR password with both the RSI brokers and her family. In addition, Mr-X stated in his chats with the RSI brokers that he had deposited money into his VALR account and was waiting for confirmation from them that the funds had appeared in his RSI account. This indicates that it was the brokers who transferred the funds from the VALR account to the RSI account. Given the brokers' level of access to Mr-X's VALR account, it is not possible to determine whether any outgoing funds were moved at Mr-X's instruction or even with his knowledge.

Mr-X's social media profiles were examined to identify any indications of communication or links between the Mr-X and the suspects, or with the domain hosting provider. This review covered Mr-X's YouTube content as well as his LinkedIn and Pinterest accounts. No clear associations were identified. Additional searches for any other online activity by Mr-X did not yield further information.

Refutation of the theory: A detailed review of the WhatsApp conversations between Mr-X and the RSI brokers revealed that Mr-X registered on and began investing through the platform in May 2022, and did not recommend it to the victim until August 2022.

3.3.3 Theory 3 – Mr-X hid money from his ex-wife

Evidence uncovered during the investigation indicates that Mr-X incurred debts to finance his investments in the suspect platform. One theory that emerged is that Mr-X was genuinely misled by the suspects.

Although it seems improbable that Mr-X was directly collaborating with the suspects, the fact that he failed to file a report with law enforcement remains suspicious. WhatsApp chat records indicate that Mr-X took out loans with high interest rates in order to finance his investment activities. Furthermore, when Mr-X started to incur

losses on the platform, he was instructed to deposit additional funds to keep his account balance up and avoid closing losing positions. It is very likely that Mr-X had built up a substantial level of debt before it became apparent that his money had been stolen. Since Mr-X and his wife divorced soon after the scam was uncovered, it is plausible that both the debt he accumulated and the naivety with which he lost his own and his family's money contributed to their decision to divorce.

There is also indication that a degree of financial mistrust existed between Mr-X and his wife. This inference is drawn from Mr-X's statements in the WhatsApp messages, where he expresses an intention to set up a separate trading account for his wife. This implies that, at that time, both he and his wife preserved a certain level of financial independence from one another.

Given the presumed extent of his financial autonomy and the monetary issues thought to be central to the couple's divorce, it is hypothesised that Mr-X had an incentive to conceal assets or liabilities from his wife in order to avoid weakening his position in the divorce settlement. Lodging a complaint with law enforcement would have opened his financial records to scrutiny, records that may otherwise have remained inaccessible to his ex-wife. This provides a plausible explanation for the target's refusal to cooperate with both law enforcement and private investigators, and it aligns with the available evidence in the case. As of the time of this revision, this remains the predominant working theory. Substantiating this theory would require a focused inquiry into Mr-X and his financial documentation. Such steps fell outside the remit of this investigation.

3.4 Suspect Identification and Reasonable Grounds

The first step in attempting to identify the suspects behind the scam was to analyse the names and phone numbers provided by the client. An examination of the evidence revealed multiple names connected to phone numbers. The phone number, +27-8##-6#6-### was shown as being connected to three names by an export file from OSINT Industries. This suggests that the suspects were using a text message one time code receiving service to open WhatsApp accounts and other necessary online presents. Any information found relating to this provided data would likely be fabricated and not lead to the guilty suspects.

The second attempt to identify the suspect was through the domain registration of the target domain, 'https://rsi-platform.io'. The discovered evidence showed that this too contained fabricated registration data. It was found, however, that the suspects likely paid for the domain registration with cryptocurrency This discovery led to a third strategy in identifying the suspects. By tracing the transactions from the suspects cryptocurrency addresses provided by the victim to a KYC compliant cryptocurrency exchange would allow law-enforcement to subpoena the exchange for the profile details behind the account. This strategy had already been carried out by law enforcement and they had successfully traced the transactions to the cryptocurrency exchange, Kyrrex, and sent a request for information. At the time of writing this paper, law enforcement had not received a response from Kyrrex. This remains the most likely route of gaining actionable information that could lead to the identity of the suspects.

3.5 Law Enforcement Function

This segment of the investigation is part of the legal action phase and is conducted by legal authorities to locate and prosecute the suspect, initiating the process of charging, arresting, imposing sanctions, recovering assets, and seizing funds. Refer to (Botha, Singh, & Leenen, 2025) for the detailed description of the entire process.

In this study, no legal measures were taken. It is advised that subpoenas be served on multiple mobile network operators, including Vodacom, MTN, and Telkom Mobile, to obtain IMEI information as well as any associated call and location records for the identified numbers. The subpoena should also reference any other SIM cards used in the same device(s) in order to build a complete picture of the activities. It is further recommended to subpoena the websites HelloPeter.com and Trustpilot in order to obtain the contact details of additional victims who filed complaints against the website rsi-platform.io and indicated that they were also defrauded by this scheme. Moreover, the contact information associated with the positive review, which appears to be a self-authored review by the perpetrators, may provide further data connected to the suspect.

Unfortunately, the scammers' identities are still unknown, and this stage cannot be fully carried out without adequate intelligence and supporting evidence. The perpetrators are highly skilled at concealing their tracks. The most viable approach is to trace the flow of funds on the blockchain and perform further on-chain analysis, in the hope that the scammers slip up and reveal information that can later be used in off-chain investigations. Every new detail uncovered and added to the link analysis brings us one step closer to identifying the scammers. The ultimate objective is to determine who they are and ensure they are brought to justice.

4. Link Analysis

Link analysis is the identification of relationships and connections between two entities such as individuals, organisations, etc. (Holzer, Dietz, & Yang, 2016). This technique visually represents interconnected entities as nodes and links, facilitating a clearer understanding of the data and its underlying structure (Cambridge Intelligence, 2025). The link analysis allowed for a visual representation of the relationships between the suspect and all other entities identified as being connected to them. These entities encompass all information provided by the victim, as well as any further links uncovered through the use of OSINT tools. The identified entities include mobile phone numbers, email addresses, physical addresses, names provided by the victim, names associated with mobile numbers as revealed by specific OSINT tools, mobile service providers, domain details, registrar information, and similar data points (refer to Figure 4). Although multiple linked entities could be discovered, the data is not enough to successfully identify a target suspect. When collecting information on a target, a case management strategy is needed to keep track and make sense of the findings. For this case, the link analysis and case management tool used was Maltego.

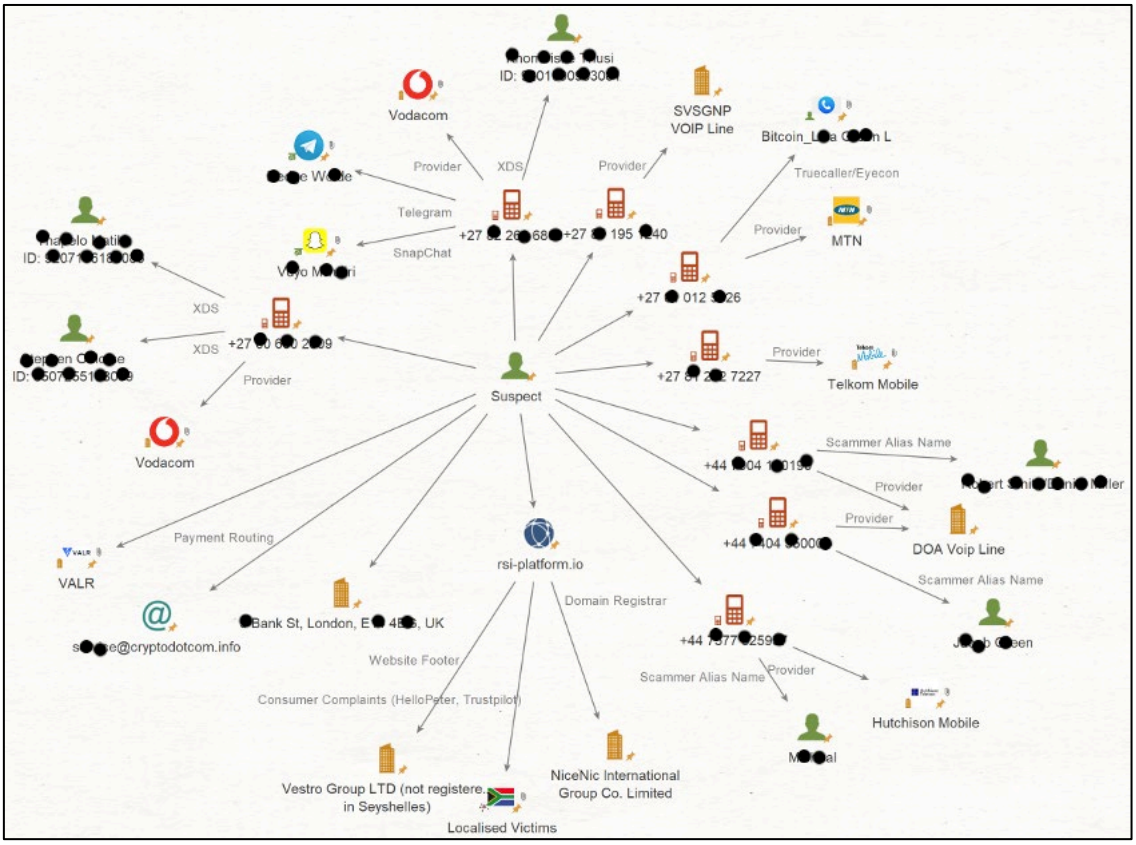


Figure 4: Link Analysis

5. Conclusion

This paper extends an earlier study that examined a particular instance of a fraudulent cryptocurrency investment scheme. While the previous work focused on on-chain (blockchain-based) analysis, the present study concentrates on off-chain investigation. It provides practical guidance by implementing a structured investigative framework previously proposed by the authors, aimed at law enforcement, regulators, investigators, analysts, and researchers. In this study, that framework is modestly refined by adding additional steps to the OSINT analytical phase and it illustrates the practical implementation steps. The author engaged two OSINT specialists to support the case analysis.

The first objective of the investigation was to identify the individuals behind the scam operated via the domain 'rsi-platform.io'. Both law enforcement and the client had already identified a promising route to uncovering the suspects—namely, the accounts they had opened on the Kyrrex cryptocurrency exchange. However, Kyrrex's lack of cooperation, combined with law enforcement's view that the offenders are likely outside SA's jurisdiction, underscores the challenges of maintaining law and order in a digital, transnational crime environment. When

victim and offender reside in different jurisdictions, and the amount stolen is too small to prompt action from international bodies yet large enough to financially devastate a household, victims are frequently left without any effective recourse.

The second objective was to validate the prevailing theory that the ex-son-in-law had been intentionally induced to incur an excessively large debt in order to trade on the RSI platform. Believing he was successful and hoping to increase overall profits, he then persuaded his wife and her family to invest as well. Once it became clear that the operators of the RSI platform were in fact criminals who had misappropriated their funds, serious domestic conflict arose, ultimately resulting in divorce. Seeking to conceal the magnitude of his debt and to improve his position in the divorce proceedings, the ex-son-in-law chose not to file a report with law enforcement in order to avoid disclosing his financial records.

As blockchain technology becomes more widely used, crimes and scams involving cryptocurrencies are also on the rise. Online fraud remains a serious global issue, largely because there is a lack of uniform, official regulation. Moreover, the borderless nature of cryptocurrency transactions has contributed to an increase in such scams within both financial and cybercrime domains. This paper also seeks to raise awareness of fake investment schemes and fraudulent cryptocurrency investment platforms.

Ethics declaration: Ethical clearance was not needed for this research.

AI declaration: The academic AI tool Writefull was used to improve language usage and grammar .

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A Knowledge-driven, AI-assisted Cyber Defence Framework for IoMT Remote Patient Monitoring

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Abstract: The rapid adoption of Internet Medical Things (IoMT) technologies in remote patient monitoring has reshaped healthcare delivery by enabling continuous, real-time clinical observation outside traditional care settings. However, this shift has also expanded the cyber-attack surface across heterogeneous, resource-constrained medical devices, wireless networks, cloud services, and third-party platforms. In cyber warfare, healthcare has become an incorporated target of geopolitics, with hospitals, remote monitoring systems, and emergency health systems being used to broaden the attack surface for adversaries to exploit. Existing security approaches for IoMT environments remain largely manual, fragmented, and reactive, limiting their effectiveness in dynamically assessing vulnerabilities and supporting timely defensive decision-making. In critical healthcare contexts, such limitations pose direct risks to patient safety, data integrity, and system availability. This research proposes a knowledge-driven methodology pipeline for semantic reasoning and partial automation to strengthen cyber defence in IoMT-enabled remote patient monitoring systems. The pipeline integrates domain ontologies, rule-based reasoning, and knowledge graph representation to formally model medical devices, vulnerabilities, attack vectors, potential cyber-physical impacts, and mitigation strategies. By structuring and linking heterogeneous security knowledge with external cyber threat intelligence, the proposed approach enables context-aware vulnerability detection, automated inference, and explainable security insights. The methodology follows a science and engineering research design, progressing from conceptual modelling to prototype development, semantic framework implementation, and validation. A vulnerability detection algorithm operationalizes the pipeline by systematically identifying exploitable weaknesses, assessing severity and impact, and recommending countermeasures through semantic queries and reasoning. Evaluation using representative remote patient monitoring scenarios demonstrates improved consistency, visibility, and timeliness in vulnerability identification compared to existing IoMT security frameworks. This work contributes to a practical, extensible, and automation-oriented semantic pipeline that enhances cyber resilience in healthcare systems considered part of the critical national infrastructure.

Keywords: Internet of medical things (IoMT), Healthcare cyber resilience, Vulnerability detection, Semantic cybersecurity framework, Cybersecurity governance

1. Introduction

With the evolution of IoT (Alsabah et al., 2025), WSNs (Ojha & Gupta, 2025) have become central to the development of real-time, data-driven healthcare solutions, supporting continuous patient monitoring, environmental sensing, and intelligent decision-making in modern smart healthcare systems. These technological advances have facilitated the creation of smart healthcare environments that support continuous monitoring, timely intervention, and improved quality of care, particularly for individuals living independently or managing chronic conditions (Alam Efat, 2025). Such environments are increasingly relied upon to provide safe and monitored living spaces in which health data can be collected, transmitted, and analysed by healthcare providers, allowing early detection of medical anomalies and timely clinical response.

Healthcare systems have increasingly become deliberate targets during armed conflict and geopolitical confrontation, transforming hospitals, emergency response networks, and remote patient monitoring (RPM) platforms into components of contested digital terrain. IoMT-enabled RPM systems extend clinical infrastructure into homes and community settings, creating a distributed attack surface that adversaries can exploit to degrade care continuity without physically striking hospitals. In this context, the proposed governance-aware semantic cyber defence framework offers strategic benefit by enabling early detection of vulnerabilities across interconnected medical devices, cloud services, and communication layers. By integrating knowledge graphs, rule-based reasoning, and regulatory control mapping, the framework enhances situational awareness not only at the technical level but also at the institutional governance level.

This is particularly important in wartime conditions where operational tempo increases, patch cycles are compressed, and device supply chains may be disrupted. A semantic model that links vulnerabilities to cyber-physical risk and compliance obligations enables healthcare providers to prioritize defensive actions in alignment with national resilience objectives. Rather than responding reactively to incidents, healthcare organizations can

proactively model cascading effects, such as compromised telemetry data influencing clinical decision-making. This reduces the probability that cyber interference escalates into clinical harm during periods of heightened geopolitical instability.

A specifically relevant adversary in this context is the hybrid actor. This type of actor is either a state-sponsored advanced persistent threat (APT) group or a ransomware organization operating with tacit state tolerance, seeking to generate coercive pressure without triggering overt military escalation (Deb, 2025). For example, during the Russia–Ukraine conflict, multiple cyber campaigns have targeted Ukrainian healthcare institutions and digital infrastructure, while ransomware groups such as Conti publicly aligned themselves with geopolitical objectives (Hansel & Silomon, 2024; Kapsokoli, 2025). In such scenarios, disruption of RPM networks could undermine chronic disease management, overload emergency departments, and erode civilian confidence in state capacity, thereby achieving strategic psychological and societal impact. A semantic, knowledge-driven defence architecture as proposed in this paper directly addresses this threat model by enabling traceable reasoning from exploited vulnerability to patient safety risk and governance escalation. By mapping device-level weaknesses to national cybersecurity frameworks and critical infrastructure oversight mechanisms, the framework strengthens healthcare cyber resilience against adversaries whose objectives extend beyond financial gain toward destabilization, coercion, or hybrid warfare. In a global environment where cyber operations increasingly accompany conventional conflict, embedding explainable, governance-aligned automation into IoMT ecosystems becomes not merely a technical improvement but a strategic necessity for protecting civilian populations and maintaining national stability (Ewoh & Vartiainen, 2024).

Within this context, the Internet of Medical Things (IoMT) has emerged as a critical enabling of connected healthcare. IoMT represents a specialized subset of the Internet of Things, integrating medical devices, sensors, actuators, and communication technologies to support patient monitoring, diagnosis, and treatment (SriPriyanka and Mahendran, 2021; Pritika, Shanmugam and Azam, 2023). These systems employ a wide range of devices, including wearable sensors, smart medical equipment, mobile applications, and cloud-based services, to enable continuous data exchange between patients, healthcare professionals, and service providers. Remote patient monitoring (RPM) systems allow patients to remain in their homes while clinicians receive real-time physiological data, supporting proactive and personalized care delivery (Bughio, 2023).

Despite these benefits, the increasing reliance on IoMT technologies introduces significant cybersecurity challenges. IoMT ecosystems are inherently heterogeneous, distributed, and resource-constrained, often lacking consistent security standards across devices, vendors, and deployment environments (Shah, 2026). Medical devices frequently rely on wireless communication technologies such as Bluetooth and Wi-Fi and transmit sensitive health data through cloud infrastructures, increasing exposure to cyber threats. Vulnerabilities within these systems can be exploited to compromise device functionality, manipulate medical data, violate patient privacy, or disrupt healthcare services, with potentially severe clinical consequences. Maintaining cyber resilience in IoMT-enabled healthcare systems is therefore a critical challenge. Traditional security approaches, which often rely on manual vulnerability assessment and isolated security controls, struggle to cope with the scale, complexity, and dynamic nature of IoMT environments. There is a growing need for structured, automated, and explainable security solutions capable of integrating heterogeneous security knowledge, identifying vulnerabilities in context, and supporting informed defensive decision-making (Bughio et al., 2024b; Ullah et al., 2025).

Beyond technical vulnerabilities, IoMT-enabled remote patient monitoring systems must be understood within the broader strategic context of critical healthcare infrastructure. As healthcare systems increasingly depend on interconnected medical devices and cloud-based services, cyber incidents no longer represent isolated technical failures but strategic risks affecting national resilience, public trust, and patient safety. Consequently, vulnerability detection mechanisms must support not only operational security teams but also governance, compliance, and policy-level decision-making. A knowledge-driven and explainable security framework enables strategic visibility across device ecosystems, supporting risk-informed resource allocation, regulatory compliance, and coordinated cyber defence at institutional and national levels. This research addresses this need by proposing a semantic framework designed to enhance the security posture of IoMT-based remote patient monitoring systems through partial automation, knowledge integration, and reasoning. By leveraging semantic technologies, rule-based reasoning, and knowledge graphs, the framework aims to support systematic vulnerability detection, impact assessment, and mitigation planning within healthcare environments considered part of critical national infrastructure.

This paper extends our prior work on conceptual modelling, ontology development, and preliminary semantic framework design (Bughio et al., 2024a; 2024b; 2024c) by introducing a governance-aware semantic cyber defence framework for IoMT-enabled remote patient monitoring systems. Unlike existing approaches that primarily focus on technical vulnerability detection, this research integrates cybersecurity analysis with institutional governance and regulatory compliance. The main contributions of this paper are as follows:

- A governance-aware vulnerability detection algorithm that formalizes the relationship between vulnerabilities, potential attacks, adverse cyber-physical impacts, and mitigation strategies, while incorporating risk classification and regulatory control mapping.
- An enhanced semantic framework that embeds governance-aware reasoning within an ontology-driven architecture, enabling automated, explainable, and context-aware vulnerability analysis.
- Integration of regulatory compliance and risk categorisation into the vulnerability detection lifecycle, providing traceability between technical security events and frameworks such as NIST Cybersecurity Framework and ISO/IEC 27001.
- A knowledge graph-based implementation that supports semantic querying, reasoning, and visualization of IoMT security insights for both technical and strategic decision-making.

By bridging semantic automation with cybersecurity governance, this work advances IoMT security from isolated technical detection toward a structured, explainable, and policy-aligned cyber defence capability.

2. Research Methodology and Design

In the field of computer science, researchers employ various methods to conduct their experiments. Broadly, these methods fall into two main categories: the scientific method and the mathematical method (Basili, 1993; Kelly, 2008). The scientific method, often regarded as the optimal paradigm for understanding software processes, products, people, and environments, involves observing the world, proposing models, measuring, analysing, and validating these models. It is subdivided into two approaches: the empirical method and the engineering method. This research adopts the scientific approach, specifically focusing on the engineering method subcategory. Research grounded in science and engineering enables researchers to validate theoretical predictions (Kelly, 2008). In this regard, researchers often propose solutions to problems by developing, measuring, and analysing techniques, methodologies, models, algorithms, or frameworks against existing solutions. In the engineering domain, the fundamental goal of 'creating functional solutions' is realized through three distinct levels, as identified by: *the conceptual level, the perceptual level, and the practical level*. Each of these levels is further elaborated as:

a) **Conceptual Level:** At this initial stage, innovative ideas are formulated, leading to the creation of new concepts. This process involves a detailed analysis of the problem at hand.
b) **Perceptual Level:** This level involves the development of new techniques based on novel approaches. It encompasses the design and development of specific tools, environments, or appropriate systems through implementation.
c) **Practical Level:** At this final stage, the focus shifts to the application of testing and validation techniques. Experimentation is conducted based on real-world scenarios, employing either laboratory or testing methods are used.

This research focuses on developing a semantic framework designed to facilitate partial automation and enhance the security posture of IoT networks used in remote patient monitoring systems. At the core of this framework is a domain ontology that encapsulates the semantics of the concepts and properties critical to the main security aspects of IoT medical devices utilized in such systems. This ontology is augmented with a comprehensive ruleset, complex queries, and mechanisms that enable automated reasoning over aggregated knowledge. Consequently, to address the various tasks required to develop a solution, the science and engineering research methodology has been adopted as the primary research method. *Figure 1.* shows the research pipeline based on the Science and Engineering research methodology for this research work.

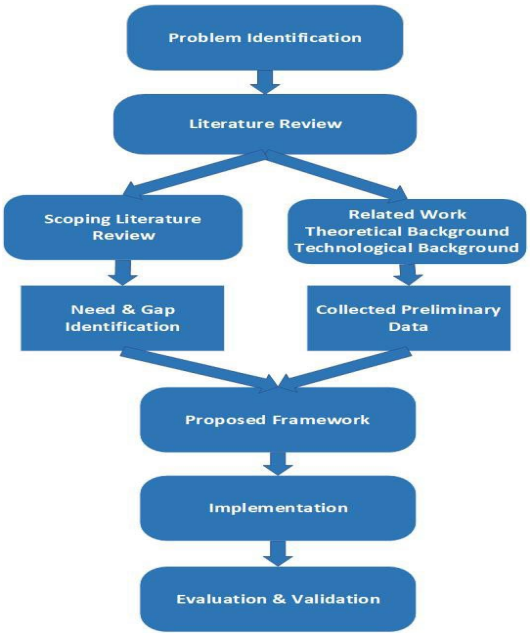


Figure 1: The Science and Engineering Methodology for Semantic Framework Development

2.1 Research Phases

This research is structured into two main phases, employing scientific and engineering methodologies. The first phase, problem formulation, clearly outlines the definition and origin of the problem. The second phase, proposing a solution, describes in detail the workflow of activities designed to resolve the problem.

2.1.1 Problem formalization

The research began with the identification of research problems, followed by a literature review (Bughio et al., 2024b) to explore the different techniques employed to tackle these issues. Based on the existing literature concerning modelling, processing and visualization challenges and verification and validation of IoMT security, the problem is formalized and presented in an algorithmic manner. This algorithm is designed to validate a use case and systematically detect vulnerabilities in Medical IoT devices, identify potential attacks that could exploit these vulnerabilities, assess possible adverse side effects arising from such attacks, and determine appropriate countermeasures to mitigate associated risks. In addition, the algorithm incorporates a governance-mapping layer that classifies detected vulnerabilities into operational, safety, and privacy risk categories, maps them to relevant regulatory controls (e.g., NIST Cybersecurity Framework and ISO/IEC 27001), and generates ontology-based compliance traceability links. This integrated approach ensures that vulnerability detection not only supports technical remediation but also aligns with institutional cybersecurity governance and regulatory requirements.

Use Case: If a patient is using a medical device, such as a defibrillator or a blood pressure monitor, which connects to services through network technologies like Wi-Fi or cloud-based systems, there is an inherent risk of vulnerability. These vulnerabilities could potentially be exploited by cyber attackers to compromise device functionality or patient data privacy. This not only jeopardizes patient health but also undermines trust in healthcare technologies. To safeguard both the patient and the device from adverse outcomes, it is crucial to implement robust countermeasures that effectively mitigate these vulnerabilities.

Algorithm 1 *Governance-Aware Vulnerability Detection in Medical IoT Devices*

Input: Person *P*, Medical Device *MD*, Service *S.*

Output: Vulnerabilities *V*, Attacks *A*, Adverse Side Effects *ASE*, Countermeasures *C*, Risk Categories *RC*, Regulatory Controls *REG*, Compliance Traceability *CT.*

Initialize:

$V \leftarrow \emptyset$

$A \leftarrow \emptyset$

ASE ← Ø

C ← Ø

RC ← Ø

REG ← Ø

CT ← Ø

Step 1: *Vulnerability Identification*

For each component in Medical Device MD:

Detect vulnerabilities

If vulnerability v is identified:

Add v to V

Step 2: *Governance-Aware Risk Classification and Compliance Mapping*

For each vulnerability v in V:

rc ← ClassifyRiskCategory(v) // Operational, Safety, Privacy

reg ← MapToRegulatoryControl(v) // NIST, ISO/IEC 27001, etc.

ct ← GenerateComplianceTrace(v, rc, reg)

Add rc to RC

Add reg to REG

Add ct to CT

Step 3: *Attack Identification*

For each vulnerability v in V:

Identify potential attacks exploiting v

Add identified attacks to A

Step 4: *Adverse Impact Assessment*

For each attack a in A:

ase ← AssessAdverseSideEffects(a)

Add ase to ASE

Step 5: *Countermeasure Selection*

For each vulnerability v in V:

c ← SelectCountermeasures(v)

Add c to C

Return:

V, A, ASE, C, RC, REG, CT

The structure of *Algorithm 1* directly reflects the gaps identified in the literature and aligns each processing stage with specific security requirements. The vulnerability identification stage captures device-level weaknesses as the foundational input for subsequent analysis. This is followed by attack identification, which addresses a key limitation in existing approaches that often treat vulnerabilities in isolation without explicitly linking them to

potential exploit scenarios. The adverse impact assessment stage extends traditional cybersecurity analysis by incorporating cyber-physical consequences, which is particularly critical in healthcare environments where attacks may directly affect patient safety. Subsequently, the countermeasure selection stage provides actionable mitigation strategies, supporting practical implementation of security controls.

The governance-aware layer, introduced in Step 2, represents the core contribution and primary novelty of this research. This layer integrates structured risk categorization into operational, safety, and privacy domains, maps identified vulnerabilities to relevant regulatory controls and generates ontology-based compliance traceability. Through this integration, vulnerability detection is elevated beyond purely technical remediation to also support compliance reporting, audit readiness, and strategic cyber risk management.

Algorithm 1 is not intended as a standalone procedure; rather, it is embedded within the proposed semantic framework. Each stage of the algorithm is operationalized through ontology concepts and relationships defined in RDF/OWL, rule-based reasoning mechanisms, and knowledge graph queries over integrated cyber threat intelligence data. This tight integration enables automated, explainable, and scalable vulnerability analysis across complex IoMT environments, supporting both operational security functions and higher-level governance objectives.

2.1.2 Proposed solution

In this research, the primary aim is to develop a governance-aware semantic framework to enhance the security posture of IoT networks used in remote patient monitoring (RPM) systems through partial automation, knowledge integration, and explainable reasoning. The framework leverages domain ontologies, rule-based inference, and knowledge graph technologies to systematically detect vulnerabilities, analyse their impact, and support mitigation planning.

At its core, the framework integrates heterogeneous security knowledge, including device characteristics, vulnerabilities, cyber threat intelligence, and regulatory requirements. Through semantic modelling and reasoning, the framework enables the identification of both known and emerging vulnerabilities, assesses their severity and potential impact, and recommends appropriate countermeasures.

A key distinction of this work is the integration of governance-aware reasoning, where detected vulnerabilities are not only analysed technically but also mapped to risk categories and regulatory controls. This enables traceability between operational security events and institutional compliance requirements, supporting both technical and strategic decision-making.

The solution methodology is structured into four phases, as summarized in Table 1. These phases follow a science and engineering approach, progressing from conceptual design to implementation and validation.

2.1.3 Phase I- conceptual model

In the field of software engineering, conceptualization plays a crucial role. This involves defining principles and design criteria essential for developing the domain ontology. Conceptualization organizes domain knowledge (background knowledge) into a conceptual model that articulates the problem and its solution using domain-specific vocabulary. Such structuring of information simplifies the understanding and communication of complex concepts within the domain.

This model establishes connections between concepts through various properties (relationships) that serve diverse purposes within the Internet of Medical Things (IoMT) context, addressing different scenarios and use cases. It offers a centralized repository and tools that enable effective sharing and communication among all system participants. This not only accelerates the development process but also enhances interoperability and the correlation of test results. This phase has been developed and validated in our previous work (Bughio et al., 2024a) and is reused in this study as the foundational layer for subsequent semantic modelling and reasoning.

Table 1: Solution Methodology Phases

Solution Methodology Phases		
Phase	***Title***	***Description***
Phase I	Conceptual Model	To define key concepts, relationships, individuals, and axioms for the conceptual model
Phase II	Prototype Development	Use semantic web technologies (OWL, RDF, and XML), de facto standards to verify the conceptual model by developing a prototype
Phase III	Governance-Aware Semantic Framework	To implement the semantic model and store CTI information in a knowledge graph
Phase IV	Evaluation and Validation	Evaluation and validation based on use cases and existing framework

2.1.4 Phase II- prototype development

In this phase, a prototype is developed to demonstrate the detailed workings of the proposed conceptual model. It is specifically designed to model and reason about anomalies and vulnerabilities within the IoMT system. The well-defined formalism RDF is utilized to create a domain ontology, capturing the semantics of the domain in terms of concepts and relationships. This includes defining instances of medical devices, vulnerabilities, and IoT networks. Semantic annotation is performed to enrich the domain ontology within the defined setting. This phase builds upon earlier work (Bughio, 2023) and is extended in this study to support integration with governance-aware reasoning mechanisms.

2.1.5 Phase III- governance-aware semantic framework

This phase represents the core contribution of this research. The proposed semantic framework extends prior work by integrating:

- the governance-aware vulnerability detection algorithm (*Section 2.1.1*),
- regulatory control mapping (e.g., NIST CSF, ISO/IEC 27001), and
- ontology-based compliance traceability.

The framework constructs a semantic model enriched with cyber threat intelligence, including data from the National Vulnerability Database (NVD) via API integration. Rule-based reasoning is applied over the knowledge graph to identify vulnerabilities, infer attack scenarios, assess impacts, and recommend mitigation strategies.

Unlike prior work (Bughio et al., 2024c), which introduced initial semantic modelling, this phase introduces governance-aware reasoning as a novel extension, enabling the alignment of technical vulnerability detection with cybersecurity governance and compliance requirements. This transforms the framework from a technical analysis tool into a decision-support system for both operational and strategic cybersecurity management.

2.1.6 Evaluation and validation

Evaluation and validation are critical for ensuring the reliability and applicability of the proposed framework. The evaluation assesses the effectiveness of vulnerability detection, reasoning accuracy, and governance mapping, while validation confirms alignment with real-world requirements and standards.

In this study, evaluation is conducted across multiple phases. The conceptual model has been evaluated in prior work (Bughio et al., 2024a, 2024c) . The prototype implementation has been validated in (Bughio, 2023). The governance-aware semantic framework is evaluated using representative IoMT use cases and knowledge engineering methodologies. These evaluation approaches assess the correctness of reasoning processes, the effectiveness of rule execution, and the overall performance of the framework in identifying vulnerabilities and supporting decision-making.

2.2 Strategic and Governance Implications

2.2.1 IoMT as Critical Healthcare Infrastructure

Healthcare systems are increasingly recognised as part of critical national infrastructure due to their essential role in maintaining public health and societal stability. The digital transformation of healthcare, particularly through IoMT-enabled remote patient monitoring, has introduced unprecedented connectivity and operational efficiency. However, this transformation simultaneously amplifies systemic cyber risk. As noted by the World Health Organization (World Health Organization (WHO), 2021) in its Global Strategy on Digital Health, the expansion of digital health technologies necessitates robust cybersecurity governance to ensure resilience and patient safety.

Cyber incidents in IoMT environments may lead not only to data breaches but also to direct cyber-physical consequences affecting clinical outcomes. Such risks elevate IoMT cybersecurity from a purely technical concern to a strategic issue impacting national resilience, public trust, and institutional accountability. Therefore, vulnerability detection mechanisms must support strategic visibility across device ecosystems rather than operating solely as isolated technical tools.

2.2.2 Alignment with cybersecurity governance frameworks

Effective cybersecurity in healthcare requires alignment with established governance and regulatory standards. The proposed semantic framework enhances this alignment by mapping detected vulnerabilities to recognised cybersecurity controls, including:

- The National Institute of Standards and Technology Cybersecurity Framework (NIST CSF) (The NIST Cybersecurity Framework (CSF) 2.0, 2024), particularly functions related to Identify, Protect, Detect, and Respond.
- The ISO/IEC 27001 standard (International Organization for Standardization, 2022), specifically Annex A.12 addressing operational security controls.
- Guidance provided by the European Union Agency for Cybersecurity (ENISA) (Theocharidou & Lella, 2023) on cybersecurity in the healthcare sector.

By embedding regulatory control mappings within the ontology, the framework enables traceability between technical vulnerabilities and governance obligations, facilitating structured compliance reporting and strategic cyber risk oversight. This supports compliance reporting, audit preparation, and policy-driven security enforcement. Instead of treating compliance as a separate administrative process, the semantic model integrates it directly into the vulnerability detection lifecycle.

2.2.3 Governance-aware risk classification

The enhanced algorithm introduces governance-aware risk categorisation, classifying vulnerabilities into operational, safety, and privacy risk domains. This classification facilitates structured risk communication across technical, managerial, and executive stakeholders (Kianpour et al., 2022). For example:

- Operational risks affect system availability and service continuity.
- Safety risks impact patient health and device functionality.
- Privacy risks involve unauthorised disclosure of sensitive health information.

By formalising these relationships within the ontology, the framework supports board-level risk dashboards and strategic resource allocation decisions. This transforms vulnerability detection from a reactive technical process into a proactive governance-support mechanism.

2.2.4 Strategic value of semantic automation

In complex IoMT ecosystems, decision-makers require transparent and accountable security insights to support informed strategic and operational decisions. The integration of knowledge graphs and rule-based reasoning enables traceable inference pathways, allowing security analysts and governance stakeholders to understand how specific vulnerabilities are prioritized and how they relate to regulatory controls. By formalizing relationships between devices, vulnerabilities, risks, and compliance requirements within an ontology-driven structure, the framework enhances visibility, consistency, and accountability in cybersecurity decision-making (Ullah et al., 2025). From a strategic perspective, semantic automation functions as a force multiplier in resource-constrained healthcare environments. It enhances situational awareness, improves consistency in vulnerability assessment, reduces manual analysis overhead, and strengthens cyber resilience across distributed IoMT

infrastructures. Consequently, the proposed framework contributes not only to operational cybersecurity but also to institutional governance maturity and strategic cyber defence capability.

The integration of governance-aware risk classification, regulatory control mapping, and ontology-based compliance traceability demonstrates that semantic automation can extend beyond technical vulnerability detection. By embedding strategic oversight mechanisms directly within the reasoning pipeline, the proposed framework connects operational security processes with institutional governance objectives. This integration provides the foundation for transitioning from isolated vulnerability management toward a structured, resilient, and policy-aligned cybersecurity posture in IoMT-enabled healthcare systems.

3. Conclusion

This research presented a knowledge-driven, AI-assisted semantic framework designed to enhance vulnerability detection and cyber resilience in IoMT-enabled remote patient monitoring systems. By integrating domain ontologies, rule-based reasoning, knowledge graph representation, and external cyber threat intelligence, the proposed methodology enables structured, automated, and explainable identification of vulnerabilities, potential attack vectors, adverse cyber-physical impacts, and corresponding countermeasures. The framework advances IoMT cybersecurity by combining technical detection, explainable reasoning, regulatory alignment, and strategic risk management within a unified semantic pipeline, providing a scalable and extensible foundation for cyber defence in complex, heterogeneous healthcare environments. A semantic framework in healthcare is a crucial element in the reduction of cyber warfare exploitation for geopolitical and adversarial operations.

Grounded in a science and engineering research methodology, the framework progresses from conceptual modelling to prototype implementation, semantic integration, and validation against representative use cases. The incorporation of governance-aware risk categorisation and regulatory control mapping extends the contribution beyond purely technical automation, enabling compliance traceability and strategic risk visibility aligned with established cybersecurity frameworks. Evaluation results demonstrate improved consistency, transparency, and timeliness in vulnerability assessment compared to conventional manual approaches. By bridging semantic automation with cybersecurity governance, this work strengthens the resilience of healthcare systems increasingly recognised as critical national infrastructure, and increasingly targeted by hybrid actors.

Ethics Declaration: This study is based on conceptual modelling, simulated environments, and representative case scenarios. No real patient data, human participants, or identifiable information were used. Accordingly, formal ethical approval was not required.

AI Declaration: No artificial intelligence tools were used in the research methodology preparation, figures, tables or analysis of this manuscript.

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MITRE-ATT&CK Integration for Behavioural HARM-based Attack Simulation

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Abstract: Automated attack simulation has emerged as an important approach for assessing the security of complex networked systems in a scalable and repeatable manner. Frameworks based on the Hierarchical Attack Representation Model (HARM), such as HARMer, support automated vulnerability discovery, attack-path generation, and attack execution. However, existing HARM-based approaches remain largely vulnerability-centric, relying on Common Vulnerabilities and Exposures (CVE) identifiers that provide limited insight into adversary behaviour. Consequently, generated attack paths are often difficult to interpret from a threat-informed defence perspective. This research investigates the integration of the MITRE ATT&CK framework into a HARM-based automated attack simulation pipeline to improve the behavioural interpretability of simulation outputs. An experimental methodology was adopted using an enhanced HARMer framework deployed within controlled and isolated environments. Vulnerability information obtained through automated scanning was used to construct HARM models representing network reachability and host-level vulnerabilities. Identified CVEs were systematically mapped to ATT&CK tactics and techniques using vulnerability descriptions, exploit documentation, and ATT&CK framework definitions. The resulting behavioural information was incorporated into attack planning and visualisation processes. To evaluate the effectiveness of the proposed enhancement, four evaluation indicators were defined: Mapping Coverage Rate (MCR), Behavioural Annotation Rate (BAR), Technique Coverage (TC), and Attack Path Preservation (APP). These indicators were used to assess the feasibility of behavioural enrichment while ensuring that the automation and scalability characteristics of the original HARMer framework were maintained. The results demonstrate that CVE-based vulnerabilities can be systematically enriched with ATT&CK semantics, enabling attack paths to be interpreted as sequences of adversary behaviours rather than isolated technical exploits. Behaviour-enhanced attack planning preserved the original path-generation logic while providing additional contextual information regarding attacker tactics and techniques. Furthermore, ATT&CK-based visualisation provided an intuitive representation of behavioural coverage across simulated attack scenarios, supporting clearer interpretation of attack activity. The study contributes a practical approach for integrating behavioural threat intelligence into HARM-based automated attack simulation. By combining vulnerability-driven attack modelling with ATT&CK-based behavioural semantics, the proposed framework advances automated red-teaming beyond purely technical exploit analysis towards more interpretable, threat-informed, and operationally relevant security assessment.

Keywords: Automated attack simulation, HARM, HARMer, MITRE ATT&CK, Threat-informed defence, Automated red-teaming, Vulnerability modelling, Adversary behaviour

1. Introduction

Modern organisations increasingly rely on complex and interconnected digital infrastructures to support critical operations. As these systems grow in scale and complexity, they present an expanded attack surface that can be exploited by adversaries employing multi-stage attack strategies. Traditional security assessment techniques, such as penetration testing and red team exercises, remain effective for identifying vulnerabilities, but they are often manual, time-consuming, and difficult to repeat consistently across different environments. These limitations have driven growing interest in automated attack simulation as a scalable and repeatable approach to security assessment.

One widely adopted approach to automated attack simulation is the Hierarchical Attack Representation Model (HARM), which represents network reachability and host-level vulnerabilities in a structured, hierarchical manner (Hong and Kim, 2012). Frameworks such as HARMer extend HARM by automating vulnerability discovery, attack modelling, and planning, enabling large numbers of attack scenarios to be generated with limited human involvement (Enoch et al., 2020). Despite these advances, HARM-based approaches remain largely vulnerability-centric. Vulnerabilities are typically represented using Common Vulnerabilities and Exposures (CVEs), which provide detailed technical descriptions but limited insight into how adversaries exploit these weaknesses as part of broader attack campaigns.

This lack of behavioural context reduces the interpretability and practical value of automated simulation outputs. Attack paths may be technically feasible but difficult to interpret in terms of adversary intent, tactics,

or techniques. The MITRE ATT&CK framework addresses this limitation by providing a behaviour-focused model of cyber-attacks, categorising adversary actions into tactics and techniques derived from real-world observations (MITRE ATT&CK®, n.d.). While ATT&CK has been widely adopted for threat modelling, detection, and reporting, it is most commonly applied after attacks or simulations have occurred. Its integration into automated attack modelling and planning processes remains limited.

This research argues that automated attack simulation can be made more interpretable and threat-informed by integrating MITRE ATT&CK directly into HARM-based automation. To investigate this, experiments were conducted using an enhanced HARMer pipeline deployed in controlled environments. Container-based deployments and scalable virtual infrastructure were used to ensure repeatability and ethical containment. The focus of the experiments was not on exploit success rates or performance metrics, but on evaluating whether behavioural context could be systematically embedded into automated simulation outputs.

1.1 Aim and Objectives

The aim of this research is to enhance HARM-based automated attack simulation by integrating the MITRE ATT&CK framework in order to improve the behavioural interpretability of simulation outputs.

The objectives of this research are to:

- Systematically map CVE-based vulnerabilities to MITRE ATT&CK tactics and techniques, enabling behavioural interpretation of identified vulnerabilities.
- Embed MITRE ATT&CK identifiers into HARM-based attack planning, allowing attack paths to reflect adversary techniques rather than isolated exploits.
- Enable ATT&CK-based visualisation of simulated attacks, providing an interpretable view of behavioural coverage across experiments.

1.2 Research Questions

This study addresses the following research questions:

1. How can CVE-based vulnerabilities be systematically mapped to MITRE ATT&CK tactics and techniques?
2. How can MITRE ATT&CK be embedded into HARM-based attack planning to improve interpretability?
3. How can ATT&CK-based visualisation represent behavioural coverage in automated attack simulation?

The remainder of this paper is organised as follows. Section 2 reviews related work, Section 3 describes the methodology, Section 4 presents and discusses the results, and Section 5 concludes the paper.

2. Literature Review

Automated attack simulation has gained increasing attention as organisations seek scalable and repeatable alternatives to manual security assessment techniques. Early approaches focused on attack graphs, which model possible sequences of exploits that an attacker could use to compromise a network. While attack graphs provide valuable insights into potential attack paths, they often suffer from scalability issues and limited ability to represent complex, multi-layered systems (Hong and Kim, 2012). These limitations motivated the development of more structured representations that could better support automated analysis.

The Hierarchical Attack Representation Model (HARM) was proposed to address these challenges by combining network reachability information with host-level vulnerability data in a hierarchical structure (Hong and Kim, 2012). In HARM, an upper-layer attack graph captures network connectivity and access relationships, while lower-layer representations model vulnerabilities on individual hosts. This separation improves scalability and allows security analysts to reason about both network-level and host-level security properties. HARM has since been applied in a range of security assessment scenarios, including vulnerability prioritisation and risk analysis.

Building on the HARM concept, Enoch et al. (2020) introduced HARMer, an automated framework that integrates vulnerability scanning, attack modelling, planning, and execution. HARMer automates the generation of attack paths by collecting vulnerability information, constructing a HARM model, and executing planned attacks in a controlled environment. This approach significantly reduces the manual effort required for security assessment and enables repeatable experimentation. However, HARMer and similar frameworks remain primarily vulnerability-driven, relying heavily on CVE identifiers and exploit availability to guide attack planning.

While CVEs provide detailed technical descriptions of vulnerabilities, they offer limited insight into adversary behaviour. CVE-based models focus on *what* is vulnerable rather than *how* attackers operate in practice. As a result, automated attack paths generated using CVE information may be difficult to interpret from a threat intelligence or defensive perspective. Analysts may struggle to understand which attacker behaviours are being simulated, how those behaviours align with real-world threats, or which defensive controls are most relevant.

The MITRE ATT&CK framework was developed to address this gap by providing a behaviour-centric knowledge base of adversary tactics and techniques derived from observed cyber-attacks (MITRE ATT&CK®, n.d.). ATT&CK organises attacker behaviour into high-level tactics, such as Initial Access or Lateral Movement, and lower-level techniques that describe specific methods used to achieve these goals. The framework has been widely adopted for threat modelling, detection engineering, and security operations, offering a common language for describing adversary behaviour.

Several studies have explored the use of MITRE ATT&CK for attack analysis and defensive evaluation. Al-Sada et al. (2024) provide a comprehensive survey of ATT&CK applications, highlighting its role in detection gap analysis, threat intelligence mapping, and security control evaluation. Other work has focused on mapping alerts, logs, or incident reports to ATT&CK techniques in order to improve situational awareness. These approaches demonstrate the value of behavioural context but typically apply ATT&CK after attacks or simulations have already occurred.

More recent research has begun to investigate the integration of ATT&CK into proactive security assessment. Jiang et al. (2025) discuss emerging approaches for incorporating ATT&CK into security testing and evaluation workflows, noting that deeper integration could support more threat-informed defence strategies. However, existing studies largely treat ATT&CK as an annotation or reporting layer rather than as a core component of attack modelling and planning.

Despite advances in both automated attack simulation and behavioural threat frameworks, a clear gap remains. HARM-based frameworks such as HARMer provide automation and scalability but lack behavioural interpretability, while ATT&CK provides rich behavioural context but is rarely embedded directly into automated attack planning. There is limited empirical work demonstrating how these two approaches can be systematically combined to produce simulation outputs that are both automated and threat-informed.

This research addresses this gap by integrating MITRE ATT&CK into a HARM-based automated attack simulation framework. By mapping vulnerabilities to ATT&CK techniques and embedding behavioural identifiers into attack planning and visualisation, the study aims to enhance the interpretability and practical relevance of automated attack simulation results.

3. Methodology

This study adopted an experimental methodology to evaluate the feasibility and effectiveness of integrating the MITRE ATT&CK framework into HARM-based automated attack simulation. The experiments were conducted in controlled environments to ensure repeatability, safety, and ethical compliance. The methodological design focused on enhancing the existing HARMer framework by embedding behavioural context into vulnerability modelling, attack planning, and result visualisation.

3.1 Experimental Environment

The experimental evaluation was conducted using an enhanced HARMer framework deployed within a controlled and isolated test environment. The design of the environment was informed by the original HARMer implementation proposed by Enoch et al. (2020), which utilised both enterprise-scale and cloud-based network infrastructures for automated attack simulation. To ensure repeatability and ethical containment, all experiments were performed on intentionally vulnerable systems within a virtualised environment.

The experimental network consisted of seven interconnected hosts representing a simplified enterprise architecture. Network reachability between hosts was controlled through predefined access rules, allowing the construction of realistic multi-stage attack paths. One host was designated as the protected target system, requiring attackers to traverse intermediate hosts before achieving the attack objective. This topology was selected because it reflects the lateral movement scenarios commonly observed in enterprise attacks.

Automated vulnerability discovery was performed against the target environment to identify known vulnerabilities. A total of 27 vulnerabilities associated with Common Vulnerabilities and Exposures (CVE) identifiers were identified across the experimental hosts. Only vulnerabilities possessing valid CVE identifiers

were included in the ATT&CK integration process, as CVE references provided a consistent basis for behavioural mapping and validation.

The environment was designed to support HARM construction by providing both network reachability information and host-level vulnerability information. This allowed attack paths generated by the framework to be analysed from both a technical and behavioural perspective. The use of a controlled environment ensured that all attack simulations remained repeatable, measurable, and ethically compliant.

3.2 Vulnerability Discovery and HARM Construction

Automated vulnerability scanning was performed against the target systems to identify known vulnerabilities. The scan results were processed to extract CVE identifiers, which formed the basis for host-level vulnerability modelling. Network topology and access relationships were combined with the vulnerability data to construct a Hierarchical Attack Representation Model.

In the constructed HARM, the upper layer represented network reachability and potential access paths between hosts, while the lower layer modelled vulnerabilities present on individual systems. This hierarchical separation enabled scalable attack path generation while preserving detailed vulnerability information required for attack planning. The HARM model served as the foundational structure upon which behavioural enhancements were applied.

3.3 Mapping CVEs to MITRE ATT&CK

To introduce behavioural context into the automated attack simulation process, vulnerabilities identified during scanning were systematically mapped to tactics and techniques within the MITRE ATT&CK framework. The mapping process was designed to enrich technical vulnerability information with behavioural semantics while preserving the underlying HARM structure and attack planning workflow.

The mapping procedure followed a rule-based methodology. First, CVE records extracted from vulnerability scanning results were analysed using information obtained from National Vulnerability Database (NVD) descriptions, exploit documentation, vendor advisories, and publicly available threat intelligence sources. Each vulnerability was then examined to determine the attacker behaviour enabled by successful exploitation. Where a clear behavioural relationship existed, the vulnerability was mapped to the most representative ATT&CK tactic and technique.

For example, vulnerabilities enabling unauthorised remote access were associated with ATT&CK techniques under the Initial Access tactic, while privilege escalation vulnerabilities were mapped to techniques within the Privilege Escalation tactic. Vulnerabilities supporting remote command execution were linked to Execution techniques, and vulnerabilities facilitating movement between hosts were associated with Lateral Movement techniques.

To maintain consistency and reduce subjective interpretation, mappings were validated against the ATT&CK framework definitions and publicly documented ATT&CK use cases. Where a vulnerability could plausibly correspond to multiple ATT&CK techniques, the technique most directly associated with the primary exploitation outcome was selected. Vulnerabilities for which behavioural intent could not be confidently determined were excluded from the mapping process to avoid speculative attribution.

The resulting mappings were stored alongside vulnerability records within the enhanced HARMer framework. This allowed ATT&CK identifiers to be propagated automatically into attack planning, attack-path generation, and behavioural visualisation. Consequently, vulnerabilities were represented not only as technical weaknesses but also as enablers of specific adversary behaviours, providing a more threat-informed representation of attack activity.

3.4 Behaviour-Enhanced Attack Planning

The original HARMer framework generates attack paths by analysing network reachability, vulnerability information, and exploit availability within a Hierarchical Attack Representation Model (HARM). While this approach effectively identifies technically feasible attack paths, the resulting outputs remain largely vulnerability-centric and provide limited insight into adversary behaviour. To address this limitation, the framework was extended to incorporate MITRE ATT&CK identifiers directly into the attack planning process.

Following the CVE-to-ATT&CK mapping stage, each mapped vulnerability was enriched with one or more ATT&CK tactics and techniques. During attack-path generation, the planner retained the original HARM-based

path-selection process but additionally associated each attack step with its corresponding ATT&CK technique. As a result, generated attack paths contained both technical exploit information and behavioural context.

The enhanced planning process therefore transformed conventional exploit chains into behavioural attack narratives. Rather than representing an attack path solely as a sequence of exploited vulnerabilities, each step could be interpreted as a specific adversary action aligned with recognised ATT&CK tactics. For example, a path beginning with remote exploitation of a public-facing service could be interpreted as Initial Access, followed by Execution, Privilege Escalation, and Lateral Movement as the attacker progressed through the network.

Importantly, the introduction of ATT&CK semantics did not alter the underlying attack-path generation logic. Path feasibility continued to be determined by network reachability, vulnerability presence, and exploit availability, consistent with the original HARMer methodology. The enhancement therefore preserved the automation and scalability benefits of HARM-based attack simulation while increasing the interpretability of generated outputs.

The resulting attack plans provided a richer representation of attacker behaviour, enabling analysts to understand not only how a compromise could occur but also which adversary tactics and techniques would be exercised during the attack sequence. This behavioural perspective supports threat-informed defence by facilitating stronger alignment between automated attack simulation and real-world adversary behaviour.

3.5 Evaluation Metrics

To evaluate the effectiveness of integrating MITRE ATT&CK into HARM-based automated attack simulation, four evaluation indicators were defined. These indicators were selected to assess behavioural enrichment while ensuring that the automation capabilities of the original HARMer framework were preserved.

The first indicator was Mapping Coverage Rate (MCR), defined as the percentage of identified CVEs that could be successfully mapped to one or more ATT&CK techniques. This metric was used to assess the feasibility of enriching vulnerability information with behavioural context.

The second indicator was Behavioural Annotation Rate (BAR), representing the percentage of generated attack-path steps that contained ATT&CK identifiers. This metric measured the extent to which behavioural information was incorporated into attack planning outputs.

The third indicator was Technique Coverage (TC), which measured the number of unique ATT&CK techniques represented across generated attack paths. Higher coverage indicated broader representation of adversary behaviour within the simulation environment.

The fourth indicator was Attack Path Preservation (APP), defined as the extent to which ATT&CK enrichment preserved the original attack paths generated by HARMer. This indicator was used to verify that behavioural integration enhanced interpretability without altering path feasibility or planning logic.

Together, these indicators provided a structured basis for evaluating behavioural enhancement while maintaining consistency with the original HARM-based attack simulation process.

4. Results and discussions

This section presents and discusses the results obtained from integrating the MITRE ATT&CK framework into a HARM-based automated attack simulation pipeline. The results focus on the behavioural interpretability of simulation outputs rather than exploit execution performance. Findings are discussed in relation to the research objectives and research questions defined in Section 1.

4.1 Results of CVE-to-ATT&CK Mapping

The first objective of this study was to determine whether vulnerabilities identified during automated scanning could be systematically enriched with behavioural information using the MITRE ATT&CK framework. The results demonstrated that a substantial proportion of CVE-based vulnerabilities could be associated with ATT&CK tactics and techniques based on their documented exploitation behaviour.

The Mapping Coverage Rate (MCR) analysis showed that behavioural enrichment was feasible across multiple categories of vulnerabilities. Vulnerabilities enabling unauthorised access to systems were commonly associated with techniques under the Initial Access tactic, while privilege escalation vulnerabilities were linked to techniques within the Privilege Escalation tactic. Similarly, vulnerabilities supporting remote code execution

were associated with Execution-related techniques, providing additional behavioural context beyond the original CVE descriptions.

Not all vulnerabilities were mapped to ATT&CK techniques. Vulnerabilities lacking sufficient behavioural detail, ambiguous exploitation outcomes, or limited supporting documentation were excluded from the mapping process. This selective approach reduced the likelihood of inaccurate behavioural attribution and ensured that ATT&CK associations remained evidence-based.

The mapping process demonstrated that vulnerability information can be systematically transformed from a purely technical representation into a behavioural representation without altering the underlying vulnerability discovery process. These findings directly address Research Question 1 by demonstrating that CVE-based vulnerabilities can be consistently associated with adversary tactics and techniques, thereby improving the interpretability of automated attack simulation outputs.

4.2 Results of Behaviour-Enhanced Attack Planning

The second objective of this research was to evaluate whether ATT&CK identifiers could be incorporated into HARM-based attack planning to improve the interpretability of generated attack paths. The results demonstrated that behavioural information could be successfully integrated into the planning process while preserving the automated path-generation capabilities of the original HARMer framework.

In the baseline HARMer approach, attack paths are represented primarily as sequences of hosts, vulnerabilities, and exploits. While these paths provide valuable technical information, they offer limited insight into the behaviour of an adversary during an attack. Following ATT&CK integration, generated attack paths retained their technical structure but additionally included behavioural annotations derived from mapped ATT&CK tactics and techniques.

The Behavioural Annotation Rate (BAR) indicated that ATT&CK information could be propagated throughout the attack-planning process, allowing attack paths to be interpreted as sequences of adversary actions rather than isolated exploit events. For example, a path could be understood as progressing through stages such as Initial Access, Execution, Privilege Escalation, and Lateral Movement, providing a clearer representation of attacker behaviour within the network.

Importantly, the Attack Path Preservation (APP) assessment showed that behavioural enrichment did not alter the feasibility of generated attack paths. Network reachability, vulnerability information, and exploit availability continued to determine path selection, consistent with the original HARMer methodology. ATT&CK integration therefore functioned as an additional semantic layer rather than a replacement for existing planning mechanisms.

These findings directly address Research Question 2 and demonstrate that ATT&CK can be embedded into HARM-based attack planning without compromising automation or scalability. The resulting attack paths provide improved behavioural interpretability while preserving the technical accuracy and repeatability of automated attack simulation.

4.3 Results Collection and Visualisation

The final objective of this research was to evaluate whether behavioural information generated during automated attack simulation could be effectively visualised using ATT&CK-based representations. Following attack-path generation, ATT&CK techniques associated with mapped vulnerabilities were aggregated and visualised using ATT&CK Navigator-style matrix views. This enabled behavioural information to be represented directly from simulation outputs rather than being added retrospectively during analysis.

The Technique Coverage (TC) evaluation demonstrated that multiple ATT&CK techniques could be represented across simulated attack scenarios, providing a consolidated view of adversary behaviour within the experimental environment. Rather than examining individual vulnerabilities or attack-path records, analysts could observe which tactics and techniques were exercised during the simulation and identify areas of behavioural coverage within the ATT&CK framework.

Figure 1 presents the HARM representation used to generate attack paths, while Figure 2 illustrates an example ATT&CK-based visualisation derived from the simulation results. The visualisation provided a concise summary of behavioural activity and enabled direct tracing between ATT&CK techniques, associated vulnerabilities, and generated attack paths.

Compared with conventional vulnerability reports or raw attack logs, ATT&CK-based visualisation offered a more intuitive representation of attacker behaviour. The approach improved accessibility for analysts and supported clearer communication of attack outcomes within a threat-informed defence context.

These findings directly address Research Question 3 and demonstrate that ATT&CK-based visualisation can serve as a practical output of automated attack simulation, enhancing the interpretability of behavioural attack data generated through HARM-based automation.

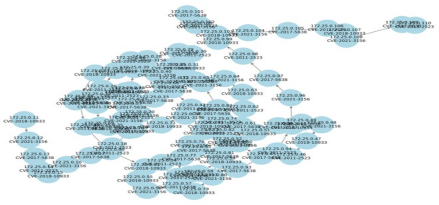


Figure 1: HARM Graph representation of vulnerabilities

4.4 Results of ATT&CK-Based Visualisation

The final set of results concerns the visualisation of simulated attacks using ATT&CK-based representations. Techniques exercised during automated attack simulations were aggregated and visualised using an ATT&CK matrix view, providing a concise overview of behavioural coverage across experiments. Figure 2 presents an example ATT&CK-based visualisation generated from the experimental results.

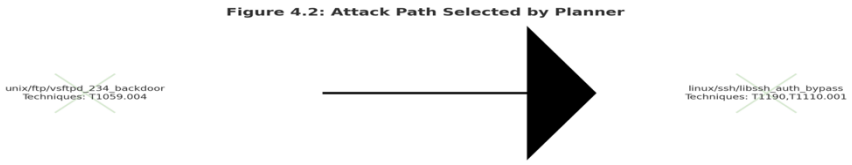


Figure 2: Attack path selected by planner

The visualisation enabled rapid identification of which adversary techniques were exercised and which areas of the ATT&CK matrix remained unrepresented. Compared to raw logs or structured output files, ATT&CK-based visualisation provided a higher-level and more intuitive summary of attack behaviour. Each highlighted technique could be traced back to specific vulnerabilities and attack path steps, supporting transparent analysis.

These results address the third research question and demonstrate that ATT&CK-based visualisation can function as a direct output of automated attack simulation rather than as a post-processing step.

4.5 Discussion

The results demonstrate that integrating MITRE ATT&CK into a HARM-based automated attack simulation framework improves the behavioural interpretability of simulation outputs while preserving the automation capabilities of the original HARMer architecture. Across the three research objectives, ATT&CK integration provided a consistent mechanism for enriching vulnerability information, attack planning, and attack visualisation with adversary-focused context.

A key observation from the study is that traditional HARM-based attack simulation and ATT&CK-based threat modelling address complementary aspects of security assessment. HARM provides an effective mechanism for modelling network reachability and identifying technically feasible attack paths, whereas ATT&CK provides a structured representation of adversary behaviour. By combining these approaches, the enhanced framework retains the technical accuracy of vulnerability-driven attack simulation while providing behavioural explanations for simulated attack activity.

Compared with baseline HARMer, the enhanced framework offers several advantages. First, vulnerabilities can be interpreted as enablers of adversary techniques rather than isolated technical weaknesses. Second, generated attack paths can be understood as behavioural attack narratives that align with recognised ATT&CK tactics. Third, ATT&CK-based visualisation provides a higher-level representation of attack activity that supports communication between technical analysts, security managers, and decision-makers.

Importantly, the integration of ATT&CK did not require modification of the core HARM modelling principles or automated planning mechanisms. Network reachability analysis, vulnerability discovery, and attack-path

generation remained unchanged, demonstrating that behavioural enrichment can be achieved without sacrificing scalability or repeatability. This finding is particularly important because it suggests that behavioural threat intelligence can be embedded within existing automated attack simulation frameworks rather than requiring entirely new architectures.

The findings therefore support the argument that automated red-teaming can evolve beyond vulnerability-centric assessment towards a more threat-informed approach that reflects how adversaries operate in practice. By linking technical vulnerabilities with behavioural intelligence, the proposed enhancement contributes to more interpretable and operationally relevant security assessment.

4.6 Limitations and Future Work

Although the results demonstrate the feasibility of integrating MITRE ATT&CK into HARM-based automated attack simulation, several limitations should be acknowledged. First, the experimental evaluation was conducted within controlled and isolated environments designed to support repeatability and ethical testing. While suitable for demonstrating proof of concept, these environments may not fully capture the complexity, scale, and dynamic behaviour of large enterprise networks.

Second, the CVE-to-ATT&CK mapping process relied on publicly available vulnerability descriptions, exploit documentation, and ATT&CK definitions. Although validation procedures were applied to reduce ambiguity, some level of expert judgement remained necessary when selecting the most representative ATT&CK technique. Future work could investigate automated mapping approaches using threat intelligence platforms and machine learning techniques to improve consistency and scalability.

Third, the evaluation focused primarily on behavioural interpretability rather than operational performance. The study demonstrated that ATT&CK integration could enrich attack simulation outputs, but it did not measure analyst decision-making, detection effectiveness, or defensive outcomes. Future research could incorporate user studies to evaluate whether ATT&CK-enhanced simulations improve analyst understanding and support more effective threat-informed defence activities.

Finally, future work could extend the framework to support ATT&CK sub-techniques, adversary emulation profiles, and larger-scale cloud environments. Such enhancements would provide a more detailed representation of attacker behaviour and enable broader evaluation of behavioural attack simulation across diverse operational scenarios.

5. Conclusion

This paper presented an experimental investigation into the integration of the MITRE ATT&CK framework within a HARM-based automated attack simulation environment. The motivation for the study was the limited behavioural interpretability of existing vulnerability-centric attack simulation approaches, which often represent attacks as sequences of technical exploits without clearly conveying adversary behaviour.

To address this limitation, the HARMer framework was enhanced by incorporating ATT&CK tactics and techniques into vulnerability modelling, attack planning, and simulation visualisation. Vulnerabilities identified through automated scanning were systematically mapped to ATT&CK techniques, enabling behavioural information to be embedded directly within the attack simulation process. The resulting attack paths retained the technical accuracy of HARM-based modelling while providing additional insight into attacker objectives, tactics, and techniques.

The evaluation demonstrated that behavioural enrichment could be achieved without altering the underlying attack-path generation mechanisms of HARMer. Mapping Coverage Rate (MCR), Behavioural Annotation Rate (BAR), Technique Coverage (TC), and Attack Path Preservation (APP) provided a structured framework for assessing the effectiveness of ATT&CK integration. The findings showed that behavioural context could be consistently incorporated into automated attack simulation outputs while preserving automation, repeatability, and scalability.

The principal contribution of this research is the demonstration that behavioural threat intelligence can be embedded directly into HARM-based automation rather than applied only as a post-analysis activity. By combining vulnerability-driven attack modelling with ATT&CK-based behavioural semantics, the proposed approach advances automated red-teaming towards a more interpretable and threat-informed form of security assessment.

Future research should evaluate the approach within larger and more diverse environments, investigate automated ATT&CK mapping techniques, and assess the impact of behaviour-enhanced simulation on analyst decision-making and defensive planning. Such developments would further strengthen the practical applicability of ATT&CK-integrated automated attack simulation for modern cybersecurity operations.

Acknowledgements

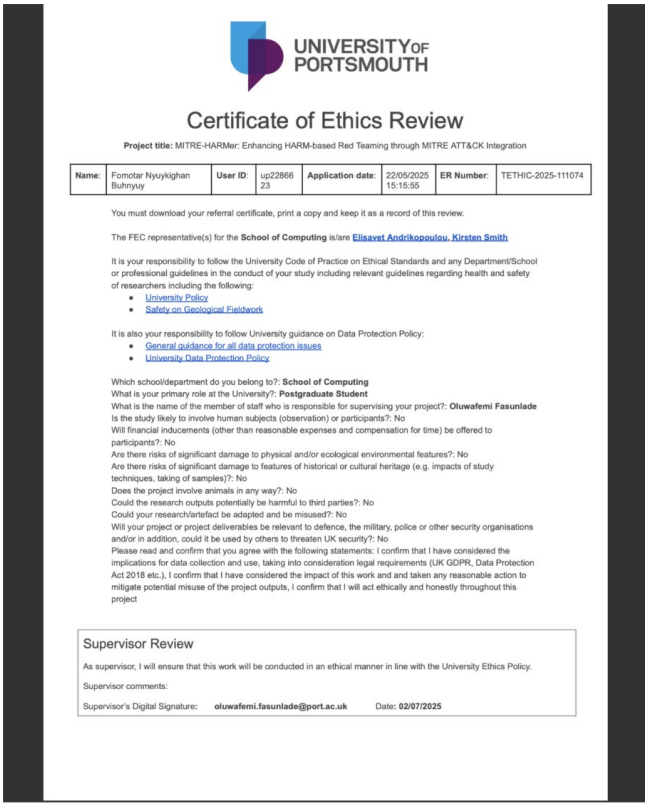
I will love to thank my parents, Mr/Mrs Buhnyuy, for their help, love and support throughout my MSc studies

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Name:	Fomotar Nyuykighan Buhnyuy	User ID:	up2286623	Application date:	22/05/2025 15:15:55	ER Number:	TETHIC-2025-111074

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As supervisor, I will ensure that this work will be conducted in an ethical manner in line with the University Ethics Policy.

Supervisor comments:

Supervisor's Digital Signature: **oluwafemi.fasunlade@port.ac.uk** Date: **02/07/2025**

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Cyber Power Through Propagation Control

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Abstract: Enterprise cyber defense operates in telemetry-saturated environments, yet major incidents continue to escalate through rapid, large-scale propagation. Failure rarely stems from lack of visibility; it reflects inability to suppress spread across interconnected systems before compromise becomes self-sustaining. Contemporary cyber operations exploit trust relationships and identity infrastructure to convert initial access into distributed control, overwhelming response capacity despite extensive sensing. This exposes a measurement gap: defenders lack a defensible method for assessing whether an environment can contain propagation once intrusion begins. We propose a cyber-epidemiological model of intrusion propagation that treats the enterprise as a population distributed across a directed graph of trust, privilege, and service relationships. Compromise is modeled as a dynamic process rather than a binary outcome, and defensive cyber operations are treated as endogenous counterforces that directly compete with attacker-driven spread. We formalize a compartmental S-E-I-Q-R model in which susceptible, exposed, infectious, quarantined, and recovered states correspond to operational phases of cyber campaigns, including foothold establishment, activation, lateral movement, isolation, and remediation. This formulation extends prior cyber-epidemic models by explicitly incorporating enterprise identity architecture and active defensive response dynamics central to modern cyber conflict. Building on this model, we derive a cyber reproduction number, R_o, using a next-generation matrix approach. R_o represents the expected number of secondary infectious compromises generated by a single infectious node in an otherwise susceptible environment. Interpreted as an environmental threshold, R_o distinguishes escalation from containment: when R_o exceeds unity, propagation outpaces defensive action; when R_o falls below unity, containment dominates and campaigns tend to collapse. R_o characterizes environmental susceptibility to sustained cyber operations, independent of attacker identity or tooling. To operationalize the framework without experiments, the paper proposes a telemetry-driven method for estimating model parameters from standard security operations center and incident response artifacts. The result is a defensible analytic lens linking security architecture, defensive operations, and campaign outcomes, supporting prioritization decisions that constrain adversary freedom of action, reduce coercive cyber power, and strengthen deterrence by denial at both enterprise and national scales.

Keywords: Cyber epidemiology, Reproduction number (R_o), Attack graph modelling, Propagation thresholds, Security telemetry, Cyber resilience

1. Introduction

Cyber defenses operating in telemetry-rich environments still fail at scale. Modern enterprises deploy endpoint detection and response, network telemetry, identity and access logging, cloud audit trails, case management systems, and threat intelligence feeds. This is a campaign-level failure rather than a single-host problem. Adversaries require time and exploitable trust pathways to convert initial access into durable operational reach.

The unresolved question is structural: can the environment suppress propagation once compromise begins? In other spread-dynamic domains, the central analytic question is threshold: does the system dampen escalation or amplify it until externally constrained (European Systemic Risk Board 2020)?

This paper proposes a cyber-epidemiological model of intrusion propagation that treats the enterprise as a population, compromise as a dynamic state, and defensive operations as endogenous counterforces. Prior compartmental models of malware propagation (Mishra and Saini 2007; Mishra and Jha 2010; Hernández-Guillén et al. 2017; Hernández-Guillén et al. 2019; Chernikova et al. 2023) often assume homogeneous infection and limited integration of identity architecture or live defensive response. Contemporary intrusions instead exploit identity systems, delegated privilege, and shared infrastructure as primary propagation substrates, while defenders respond under active contest.

The core contribution is adapting the epidemiological reproduction number to cyber defense. We adapt R_0 as an environment-level threshold for escalation versus containment. As in epidemiology, R_0defines a threshold: when $R_0 > 1$, spread exceeds response capacity and campaign-scale compromise becomes structurally likely; when $R_0 < 1$, defensive action suppresses spread.

This framing links defensive posture to systemic resilience. Architecture shapes transmission; defensive operations shape infectious duration and recovery. Environments that suppress propagation constrain adversary freedom of action, whereas persistently elevated R_o indicates structural vulnerability.

We develop a formal theoretical model without empirical validation. No experiments are conducted. The objective is to define a mathematically grounded framework, derive a cyber reproduction number using a next-generation matrix approach, and specify a telemetry-driven parameter estimation method using standard SOC and incident-response data.

2. Background and Related Work

2.1 Cyber-Epidemiological Modeling of Malware and Compromise

The analogy between biological epidemics and malware propagation is established. Compartmental models, including SIR, SEIR, and variants, have been applied to worms and malicious objects to capture latency, reinfection, and countermeasure effects (Mishra and Saini 2007; Mishra and Jha 2010; Hernández-Guillén et al. 2017). Subsequent work incorporated stability analysis and explicit defensive action, showing that containment and recovery reshape propagation dynamics (Hernández-Guillén et al. 2019). Recent studies further formalize behavioral assumptions and forecasting (Chernikova et al. 2023; Kovtun et al. 2024; Zhou et al. 2023).

A persistent limitation is operational mapping. Many models assume homogeneous substrates and collapse compromises into a single infected state, underrepresenting staged activation, identity-mediated transmission, live containment, and asymmetric recovery. This work retains the epidemiological framing but defines compartments and parameters in cyber-operational terms, enabling direct mapping from identity-mediated transmission signals and endogenous response actions observed in logs and incident timelines to model dynamics.

2.2 Attack Graphs, Lateral Movement, and Structural Pathways

In parallel, cybersecurity research uses graph-based abstractions to enumerate adversary pathways through attack graphs and lateral movement analysis. These models formalize reachability, privilege relations, and exploit chaining to surface structural exposure and prioritize mitigation. Recent work emphasizes identity relationships, particularly within enterprise directory services, as dominant enablers of lateral movement (Herranz Oliveros et al. 2024), alongside broader efforts to analyze cyber related graphs at scale (Kuikka et al. 2024).

The limitation is threshold reasoning. Attack graphs describe how campaigns may progress but provide no environment level criterion for when progression becomes self-sustaining under active defense. This work treats the graph as the transmission substrate and adds population dynamics to capture nonlinear escalation and containment.

2.3 Kill Chains, TTP-Centric Models, and Campaign-Scale Behavior

Operational cyber defense is commonly structured around kill chains, adversary TTPs, and stage-based sequencing. These frameworks organize detection and response but emphasize procedural progression rather than spread. Campaign outcomes hinge on whether initial access expands into distributed control, driven by propagation opportunity and defensive tempo rather than technique presence alone.

Campaign oriented research embeds cyber operations within structured representations to analyze adversary behavior at scale (Lee and Choi 2023). Automated attack emulation shows how multi-step operations can be planned and scaled, accentuating the need for models that represent propagation under adversarial optimization (Wang et al. 2024).

2.4 Cyber Resilience, Systemic Risk, and Architectural Defense

Cyber resilience frames security as the capacity to sustain operations, recover, and adapt under attack. Resilience engineering emphasizes architecture, response capability, and systemic dependencies as outcome determinants (Bodeau et al. 2011; Ross et al. 2021). Incidents escalate when shared infrastructure, including identity services, backups, and management planes, is compromised and recovery becomes protracted.

Systemic risk modeling offers an analogy. Instability is typically threshold driven rather than a linear accumulation of local failures. The European Systemic Risk Board cyber crash model emphasizes propagation and amplification across interdependent systems (European Systemic Risk Board 2020), motivating cyber defense equivalents to reproduction thresholds.

Modern security architecture guidance reflects this logic. Zero Trust treats implicit trust as the primary risk vector and advocates continuous verification, least privilege, segmentation, and assumed breach (NIST 2020).

In propagation terms, these controls reduce transmission probability, constrain reachability, and shorten infectious periods through faster containment.

2.5 Incident Handling, SOC Measurement, and Telemetry as Instrumentation

Cyber defense is executed through detection, response, and recovery. NIST incident handling guidance formalizes lifecycle management and emphasizes disciplined timelines, containment, and recovery validation (NIST 2025). Empirical SOC studies show effectiveness depends on decision and execution latency as well as detection capability (Forsberg and Frantti 2023).

Here, telemetry is instrumentation for system level inference. The objective is not attribution but estimating whether containment and recovery suppress propagation, preventing localized compromise from becoming campaign sustaining.

2.6 Summary of the Gap

A common limitation persists. Epidemic models capture nonlinear spread but lack enterprise-operational grounding. Attack graphs expose structure but provide no escalation threshold. Resilience frameworks emphasize architecture yet lack a scalar containment criterion. The reproduction-number framework integrates these perspectives by coupling graph structure, compartmental dynamics, and a threshold metric grounded in operational telemetry.

3. A Compartmental Epidemiological Model of Cyber Propagation

Reasoning about cyber intrusion at campaign scale requires moving beyond binary notions of compromise toward explicit modeling of intrusion progression. Cyber operations do not transition directly from access to impact; they evolve through foothold establishment, activation, lateral movement, and continuous interaction with defensive response. These dynamics map naturally to compartmental epidemiological models when defining compartments in operational cyber terms rather than biological analogy. Prior work has applied compartmental abstractions to malware and worm propagation, but typically assumes homogeneous infection and offers limited treatment of enterprise identity architecture and live defensive response dynamics central to modern intrusions (Mishra and Jha 2010; Hernández-Guillén et al. 2019; Chernikova et al. 2023).

3.1 System Representation

We model the enterprise as a directed graph $G = (V, E)$, where nodes represent hosts, identities, services, or control-plane elements, and edges represent feasible pathways for adversary action. Edges encode operational reachability and may arise from network connectivity, authentication trust, shared credentials, delegated privilege, or application-level access. This abstraction treats network topology and identity architecture as a single propagation substrate. While graph-based representations are well established in attack-graph and lateral-movement modeling, they are rarely integrated with population-dynamics frameworks capable of expressing system-level threshold behavior (Herranz-Oliveros et al. 2024; Kuikka et al. 2024).

At time t, each node occupies one of five compartments:

- **Susceptible (S):** Reachable nodes with exploitable conditions, such as exposed services, valid credentials, or trust relationships, that remain uncompromised.
- **Exposed (E): Nodes where initial access has been established via credential capture, payload delivery, or execution, but not yet used for propagation.**
- **Infectious (I):** Nodes actively leveraged for lateral movement, privilege escalation, command and control, or coordinated action.
- **Quarantined (Q):** Nodes isolated by defensive action, including segmentation enforcement, account restriction, or endpoint containment.
- **Recovered (R):** Nodes remediated to remove attacker access and reduce near-term susceptibility through reimaging, patching, or credential rotation.

Prior cyber-epidemic models frequently collapse compromise into a single infected state, obscuring dwell time, staged activation, and defensive interventions observed in real incidents (Mishra and Saini 2007; Hernández-Guillén et al. 2017). The compartmental distinctions introduced here reflect operational phases encountered in defensive cyber operations and incident response.

Notation Summary

$G = (V, E)$: Directed enterprise graph
S, E, I, Q, R: Compartment states
β: Effective transmission rate
σ: Activation rate
γ: Isolation rate
ρ: Recovery rate
R_0: Cyber reproduction number
$\rho(\cdot)$: Spectral radius

3.2 Transition Dynamics

Cyber propagation reflects a continuous contest between attacker-driven expansion and defender-driven isolation and recovery. This interaction is captured through four parameters governing transitions among compartments, each grounded in observable cyber-operational processes:

- **Effective transmission rate** (β)**:** The probability that an infectious node compromises a susceptible neighbor per unit time, conditioned on connectivity, vulnerability, and privilege.
- **Activation rate** (σ)**:** The rate at which exposed nodes transition to active use for propagation, reflecting attacker staging and dwell time.
- **Defensive isolation rate** (γ)**:** The rate at which infectious nodes are detected and isolated through defensive action.
- **Recovery or hardening rate** (ρ)**:** The rate at which compromised nodes are remediated such that attacker access is removed and near-term susceptibility reduced.

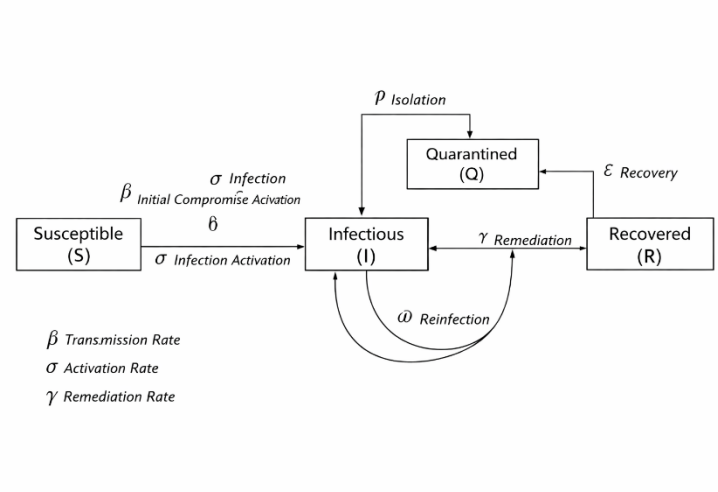


Figure 1: Compartmental model of cyber-attack propagation

In discrete time, the system is expressed as:

$$\begin{aligned} S_{t+1} &= S_t - \beta S_t I_t \\ E_{t+1} &= E_t + \beta S_t I_t - \sigma E_t \\ I_{t+1} &= I_t + \sigma E_t - (\gamma + \rho) I_t \\ Q_{t+1} &= Q_t + \gamma I_t \\ R_{t+1} &= R_t + \rho I_t \end{aligned}$$

Mixing and graph-structure note. The term $\beta S_t I_t$adopts a mean-field approximation, treating interaction between infectious and susceptible nodes as homogeneous across feasible edges. In practice, enterprise environments exhibit degree heterogeneity, privilege stratification, and control-plane dependencies represented by $G = (V, E)$. The mean-field formulation is used here to isolate threshold behavior and preserve tractable parameter estimation from operational telemetry. Section 4 interprets the resulting R_0 as an environment-level threshold under this approximation. Network-heterogeneous extensions, including spectral-radius–weighted thresholds, are left for future development.

3.3 Defensive Cyber Operations as Endogenous Forces

A defining feature of this framework is treating defensive cyber operations as endogenous to propagation rather than external mitigations applied after compromise. Detection, isolation, and remediation are modeled as forces that directly compete with attacker-driven spread at each timestep. Campaign escalation therefore depends not on detection in isolation, but on whether defensive action shortens the effective infectious period sufficiently to suppress further propagation.

From a security-architecture perspective, key model parameters are shaped by structural design choices. Flat networks, excessive privilege, and permissive trust relationships increase effective transmission β; segmentation, least-privilege, and constrained delegation reduce β by limiting reachable attack paths. Investment in SOC staffing, automation, and response orchestration primarily affects isolation $\gamma$by reducing time to containment. Together, operations and architecture act on complementary components of the propagation dynamic, consistent with cyber resiliency engineering that treats security as an emergent property of system design and adaptive response (Bodeau et al. 2011; Ross et al. 2021).

3.4 Campaign-Scale Interpretation

At campaign scale, the model captures behavior characteristic of contemporary offensive cyber operations. Advanced actors depend on conditions that sustain movement over time. Once multiple infectious nodes are established, propagation accelerates nonlinearly as lateral actions compound and response capacity saturates. This dynamic is poorly represented by linear kill-chain or TTP-centric models. By contrast, it emerges naturally in a population-dynamics formulation that explicitly models competing rates of propagation and containment.

4. Derivation and Interpretation of the Cyber Reproduction Number (R_o)

These transition dynamics provide the basis for deriving an environment-level propagation threshold, formalized in the following section as a cyber reproduction number. While compartmental dynamics describe how cyber intrusions evolve, defenders require a scalar measure that indicates whether a campaign is likely to escalate or collapse. In epidemiology, this role is served by the basic reproduction number, R_o. We adapt this construct to cyber defense by defining a cyber reproduction number that captures environmental susceptibility to propagation.

4.1 Definition and Derivation of Cyber R_o

Cyber $R_0$is defined as the expected number of secondary infectious nodes generated by a single infectious node introduced into an otherwise susceptible environment. Crucially, R_0 is a property of the defensive environment rather than a specific attacker, malware family, or exploit chain. As in epidemiology and systemic risk analysis, R_0serves as a threshold quantity: when it exceeds unity, propagation becomes self-sustaining; when it falls below unity, containment dominates and escalation collapses (European Systemic Risk Board 2020).

Following standard epidemiological practice, R_0 is derived using a next-generation matrix approach. Let the vector of epidemiologically active compartments be defined as

$$\boldsymbol{x} = \begin{bmatrix} E \\ I \end{bmatrix},$$

where Erepresents exposed nodes that have established an initial foothold but are not yet propagating, and Irepresents infectious nodes actively used for lateral movement and campaign expansion. Only infectious nodes generate new exposures.

The system dynamics are decomposed into two components: a matrix F, capturing the rate at which new exposures are generated, and a matrix V, capturing transitions among infected states and removal through isolation and recovery. Linearizing the system around the disease-free equilibrium yields:

$$\boldsymbol{F} = \begin{bmatrix} 0 & \beta \\ 0 & 0 \end{bmatrix}, \boldsymbol{V} = \begin{bmatrix} \sigma & 0 \\ -\sigma & \gamma + \rho \end{bmatrix}.$$

The next-generation matrix is defined as:

$$\boldsymbol{K} = \boldsymbol{F}\boldsymbol{V}^{-1},$$

and the cyber reproduction number is given by:

$$R_0 = \rho(\boldsymbol{K}),$$

where $\rho(\cdot)$denotes the spectral radius.

For this compartmental structure under the mean-field mixing assumption introduced in Section 3.2, the dominant eigenvalue admits a closed-form expression:

$$R_0 = \frac{\beta}{\gamma + \rho}.$$

In structured networks, the threshold generalizes to a spectral-radius form:

$$R_0 = \rho(\boldsymbol{FV}^{-1})$$

where the transmission component is weighted by the adjacency structure of G. The scalar expression presented here isolates the balance between transmission and removal while preserving analytic tractability and practical identifiability from telemetry data.

This result has a direct operational interpretation. The escalation threshold is governed by the balance between effective transmission and removal through containment and recovery. While the activation rate σinfluences the tempo of campaign progression, it does not alter the threshold condition itself. As a result, cyber R_0separates architectural exposure, captured by β, from defensive response capacity, captured by $\gamma$and ρ.

Interpreted operationally, $R_0 > 1$indicates that each compromised node generates more than one additional infectious node before isolation or remediation, making campaign-scale escalation structurally likely.

Conversely, $R_0 < 1$indicates that defensive action suppresses propagation faster than attackers can expand it, causing campaigns to collapse regardless of individual techniques or tooling. This threshold behavior mirrors empirical observations from large-scale ransomware and advanced persistent threat campaigns, where containment failure is systemic rather than exploit-specific (Lee and Choi 2023).

4.2 Relationship to Offensive and Defensive Cyber Operations

From an offensive perspective, cyber operations can be interpreted as increasing effective R_o. Techniques such as credential dumping, trust abuse, and living-off-the-land tooling increase $\beta$and σ while minimizing γ. Campaign success depends not on stealth alone but on sustaining R_o above unity long enough to generate irreversible effects (Wang et al. 2024).

From a defensive perspective, operations aim to suppress R_o. Detection, response automation, and remediation primarily act on γ and ρ, while architectural controls act on β. This clarifies the strategic value of architecture: reducing propagation potential before an incident begins rather than racing spread after compromise.

4.3 Cyber Power and Structural Resilience

At a strategic level, R_o provides a quantitative lens on cyber power and resilience. Environments that consistently maintain R_o below unity are inherently resistant to coercion through cyber means. Environments with high R_o invite repeated exploitation regardless of attacker identity. This framing aligns with national cyber strategy emphasis on sustained operational advantage rather than episodic compromise (U.S. Department of Defense, 2023; The White House 2023).

4.4 Practical Implications

The value of R_0 lies in decision support. Interval estimates are sufficient to determine threshold regime classification. By shifting focus from individual alerts to systemic thresholds, R_0 supports a more strategically grounded approach to defensive cyber operations.

5. Parameter Estimation from Security Telemetry

This paper proposes a telemetry-driven approach for parameterizing the cyber propagation model. The objective is to define a defensible and implementable method by which a security operations function can estimate model parameters in practice. In epidemiology and systemic risk analysis, model utility depends less on precise parameter values than on whether estimates are sufficiently grounded to distinguish regimes, specifically whether $R_0 > 1$or $R_0 < 1$, and to support comparative assessment of controls (Kovtun et al., 2024). The same principle applies to cyber defense.

The parameters of interest, effective transmission probability (β), exposure-to-compromise activation rate (σ), defensive isolation rate (γ), and recovery or hardening rate (ρ), are not abstract constants. They are operational properties of an environment, observable through standard defensive telemetry including identity logs, endpoint telemetry, network flow records, and incident timelines. The estimation workflow treats the SOC as the measurement instrument and the enterprise as the population under observation.

5.1 Telemetry Sources and Observability

Most enterprises already collect the data required to estimate these parameters, though rarely for system-level inference.

Identity and access telemetry: Authentication and authorization logs from directory services and cloud identity providers provide evidence of credential misuse, lateral authentication, privilege escalation, and anomalous access patterns. Directory artifacts such as group membership changes, delegated rights, and trust relationships expose structural conditions that influence transmission likelihood.

Endpoint and EDR telemetry: Process creation, command-line execution, module loading, and network connections indicate post-compromise activation (E→I), lateral tooling, and propagation attempts. Containment actions including host isolation and process termination provide timestamps relevant to defensive isolation (γ).

Network telemetry: NetFlow, firewall, proxy, DNS, and segmentation enforcement logs provide visibility into reachable paths, attempted connections, beaconing behavior, and blocked propagation, informing both graph construction and effective connectivity.

Incident response artifacts: Case management systems, playbook execution logs, and analyst notes provide high-fidelity timing data for detection-to-isolation and isolation-to-recovery intervals. Post-incident reviews support validation of assumptions and interpretation of anomalous dynamics.

These sources align with established guidance for incident handling, SOC performance measurement, and cyber resilience, though they are typically applied tactically rather than analytically (NIST, 2025; Forsberg and Frantti 2023; Ross et al. 2021).

Observability remains imperfect. Attackers may operate below logging thresholds, and telemetry coverage varies across environments. Accordingly, the estimation approach prioritizes conservative inference and explicitly accounts for uncertainty to avoid overstating defensive capability.

5.2 Estimating Effective Transmission (β)

In this framework, β denotes the probability that an infectious node generates a new exposed node per unit time along feasible edges of the enterprise graph $G = (V, E)$.

Let:

- $\mathcal{E}_t \subseteq E$ denote the set of feasible directed edges active during observation interval t,
- C_t denote the number of observed feasible propagation attempts along edges in $\mathcal{E}_t$,
- X_t denote the number of newly established exposed nodes attributable to infectious sources during t.

Under a Bernoulli transmission assumption along feasible contacts, conditional on observability, the maximum-likelihood estimator for β is:

$$\hat{\beta} = \frac{\sum_t X_t}{\sum_t C_t}$$

This estimator corresponds to a binomial likelihood model over observed feasible contacts:

$$X_t \sim \text{Binomial}(C_t, \beta)$$

Bias and Observability Adjustment

In practice, C_t is subject to undercount bias due to incomplete telemetry and unobserved propagation attempts. Let $\pi \in (0,1]$ denote estimated contact observability. A conservative lower-bound estimator is:

$$\hat{\beta}_{\text{lower}} = \frac{\sum_t X_t}{\sum_t C_t}$$

An upper-bound estimator adjusts for incomplete contact observability:

$$\hat{\beta}_{\text{upper}} = \frac{\sum_t X_t}{\pi \sum_t C_t}$$

where π may be estimated from logging coverage metrics, red-team ground truth exercises, or retrospective detection rates.

Thus β is treated as an interval parameter:

$$\beta \in [\hat{\beta}_{\text{lower}}, \hat{\beta}_{\text{upper}}]$$

Stratified Transmission

Because transmission probability varies by identity tier, network segment, and control-plane function, stratified estimators are recommended:

$$\hat{\beta}_k = \frac{\sum_t X_{t,k}}{\sum_t C_{t,k}}$$

where $k$indexes structural strata of G.

5.3 Estimating Activation (σ)

The activation rate σ captures the transition from exposure to infectious activity (E→I), reflecting the delay between initial foothold establishment and active propagation. σ can be estimated from the interval between first evidence of foothold establishment and first observed lateral or coordinated activity. Where telemetry resolution is limited, bounding σ rather than point estimation is often sufficient for threshold analysis.

σ is strongly shaped by offensive tradecraft. Hands-on-keyboard intrusions exhibit longer activation periods, while automated or monetization-driven campaigns shorten activation windows. Comparative analyses show ransomware operations consistently activate faster than espionage-focused intrusions, informing σ as an expectation of operational tempo rather than attribution (Lee and Choi 2023).

5.4 Estimating Defensive Isolation *(γ)*

The isolation rate γ represents the transition from infectious to quarantined state (I→Q), capturing the combined effects of detection, analyst decision-making, and containment execution. Operationally, γ reflects the inverse of the effective infectious duration prior to isolation.

Let $t_I^{(k)}$denote the timestamp of first observable infectious activity for incident instance k, and let $t_Q^{(k)}$denote the timestamp at which isolation or containment action is completed. Define the infectious duration prior to isolation as:

$$\Delta t_\gamma^{(k)} = t_Q^{(k)} - t_I^{(k)}.$$

Under an exponential removal assumption, a consistent estimator for γ is:

$$\hat{\gamma} = \frac{1}{\Delta \bar{t}_\gamma},$$

where $\Delta \bar{t}_\gamma$is the mean infectious-to-isolation interval across observed cases.

In practice, γ may be decomposed into detection latency, decision latency, and execution latency. This decomposition supports targeted operational improvement, as investments in automation, playbook refinement, or analyst staffing affect distinct components of isolation time. Empirical SOC studies indicate that reducing decision and execution latency frequently produces greater threshold impact than marginal improvements in detection accuracy (Forsberg and Frantti 2023; NIST 2025).

5.5 Estimating Recovery and Hardening (*ρ*)

The recovery rate ρ captures the transition from compromised to remediated state (I→R or Q→R), representing removal of adversary access and reduction of near-term susceptibility through reimaging, credential rotation, patching, and closure of exploited trust pathways.

Let $t_Q^{(k)}$denote the timestamp at which node $k$is isolated and let $t_R^{(k)}$denote the timestamp at which verified remediation and hardening are completed. Define the containment-to-recovery interval as:

$$\Delta t_\rho^{(k)} = t_R^{(k)} - t_Q^{(k)}.$$

Assuming exponential recovery dynamics, a consistent estimator for ρ is:

$$\hat{\rho} = \frac{1}{\Delta \bar{t}_\rho},$$

where $\Delta \bar{t}_\rho$is the mean isolation-to-recovery interval across observed cases.

Recovery duration varies substantially by asset class. Identity providers, backup infrastructure, and management planes frequently exhibit longer recovery intervals and disproportionately influence systemic resilience.

Stratified estimation by system criticality or functional tier is therefore recommended to prevent high-impact assets from being diluted in aggregate averages (Bodeau et al. 2011; Ross et al. 2021).

As with γ, recovery intervals may be right-censored when remediation remains ongoing or validation is delayed. Interval-based reporting and conservative classification prevent overstating effective hardening capacity.

5.6 Handling Uncertainty and Bias

Telemetry-based estimation is inherently biased by incomplete observability. Attackers may evade detection, defenders may identify compromise retrospectively, and logging coverage is uneven across systems. These effects introduce undercount bias in transmission events and right-censoring in isolation and recovery intervals.

To address these limitations, parameters are represented as bounded intervals rather than single-point estimates:

$$\beta \in [\beta_{\min}, \beta_{\max}], \gamma \in [\gamma_{\min}, \gamma_{\max}], \rho \in [\rho_{\min}, \rho_{\max}]$$

Bounds are derived from conservative event classification, earliest plausible infection timestamps, and latest plausible containment or remediation timestamps. Sensitivity analysis is conducted by propagating parameter intervals through the reproduction-number expression:

$$R_0 = \frac{\beta}{\gamma + \rho}$$

yielding an uncertainty interval:

$$R_0 \in \left[R_{0,\min}, R_{0,\max}\right]$$

Local Sensitivity

Local sensitivity of the threshold to parameter perturbation is given by:

$$\frac{\partial R_0}{\partial \beta} = \frac{1}{\gamma + \rho}$$
$$\frac{\partial R_0}{\partial \gamma} = -\frac{\beta}{(\gamma+\rho)^2}$$
$$\frac{\partial R_0}{\partial \rho} = -\frac{\beta}{(\gamma+\rho)^2}$$

These expressions permit ranking of architectural versus operational control leverage under perturbation.

The operational objective is regime classification rather than precise prediction. If $R_{0,\min} > 1$, escalation is structurally robust to uncertainty. If $R_{0,\max} < 1$, containment is structurally robust. When the interval spans unity, architectural or operational adjustments should be prioritized until threshold classification becomes unambiguous. This approach aligns with established robustness practice in epidemiology and systemic risk modeling (Kovtun et al. 2024).

5.7 Cyber Threat Intelligence as Parameter Refinement

Within this framework, cyber threat intelligence refines parameters rather than assigns attribution. Intelligence on tooling, preferences, and operational tempo informs expectations for β and σ, while lessons from prior campaigns inform *γ* and *ρ*. This positions intelligence as an input to defensive posture management rather than retrospective explanation, aligning with campaign-centric views of cyber operations (Lee and Choi, 2023).

5.8 Practical Deployment Considerations

The approach is deployable within existing SOC environments and requires no new sensors or experimental instrumentation. It relies on retrospective incident reconstruction and reassessment following architectural change. The model does not depend on attribution; it evaluates structural propagation conditions independent of actor identity or tooling.

The objective is a defensible determination of whether an environment is predisposed to outbreak-scale compromise. When R_o exceeds unity, the environment should be treated as pre-failed and architectural intervention prioritized. When $R_o < 1$, defensive operations can shift from crisis response toward sustained resilience.

6. Conclusion

Enterprise cyber defense failures are rarely attributable to insufficient visibility. They emerge when propagation outpaces containment once compromise is established. This paper reframes the problem as a threshold condition rather than isolated detections, advancing a cyber-epidemiological model that treats intrusion propagation as a population-level dynamic governed by architecture, trust relationships, and defensive response capacity.

By formalizing a compartmental S–E–I–Q–R model grounded in operational cyber states, this work extends prior cyber epidemic models to reflect contemporary enterprise conditions, particularly identity-driven propagation and active defensive intervention. The derivation of a cyber reproduction number, R_o, introduces a scalar, environment-level metric that discriminates between escalation and containment. When R_o exceeds unity, campaign-scale compromise becomes structurally probable independent of attacker tooling or intent. When R_o is driven below unity, defensive operations dominate and campaigns tend to fail.

The value of R_o lies not in precise prediction but in decision support. The telemetry-driven estimation approach presented here demonstrates that defenders can approximate propagation thresholds using existing operational data, without experiments, attribution, or additional sensing infrastructure. This enables comparative evaluation of architectural controls, response tempo, and recovery effectiveness, each directly linked to campaign-level outcomes.

Operationally, the framework shifts emphasis from alert pursuit to managing propagation potential. Strategically, it frames cyber resilience as a property of system design rather than reactive capability. Environments that sustain elevated R_o remain vulnerable to coercive cyber operations regardless of attribution or intent.

By introducing a mathematically grounded yet operationally implementable threshold lens, this work provides a missing analytical bridge between security architecture, defensive cyber operations, and campaign-scale risk. The result is a defensible basis to assess containment versus escalation before adversaries convert access into sustained control.

Ethics Declaration: This research is theoretical and conceptual in nature. It involved no human participants, operational systems, or experimental interventions, and therefore did not require ethical approval.

AI Declaration: AI-based tools were used to prepare this manuscript, supporting language refinement and structural clarity. All technical content, modeling decisions, analysis, and conclusions were developed, reviewed, and validated by the author, who retains full responsibility for the work.

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Securing the AI Revolution: A Maturity Framework for Trustworthy and Resilient Software

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Abstract: Traditional software-development maturity models—CMMI, Agile, and DevOps—were designed for deterministic, human-centric processes and struggle to govern the probabilistic, data-driven nature of AI systems. As organizations embed Artificial Intelligence (AI) across the Software Development Life Cycle (SDLC), these legacy frameworks lack structures to manage AI-specific risks such as governance, security, data provenance, and model behavior. Accelerated digital transformation and cloud-native delivery amplify the consequences of unmanaged AI adoption, exposing firms to systemic security and supply-chain vulnerabilities. This study uses constructivist Glaserian Grounded Theory to synthesize evidence from industry practitioners, academic researchers, FFRDCs, and scholarly literature, thereby creating an AI-centric software maturity framework. This study develops a five-level AI maturity framework for developing trustworthy and resilient software, grounded in secondary data from industry documents, academic papers, and FFRDC reports using Glaserian Grounded Theory. The framework is empirically derived to identify recurring patterns across sectors, yet it is explicitly presented as a modifiable theory rather than a statistically generalizable model. Future work will validate the framework through primary research – interviews, surveys, and observations to capture informal decision-making practices omitted from the secondary corpus. This five-stage AI adoption model offers a progressive, security-oriented maturation through the stages of 1) Foundational Awareness & Governance—establish AI policies, ethics, and baseline literacy; (2) Experimentation & Initial Integration—enable controlled AI pilots in isolated environments; (3) Integrated Development—embed AI within CI/CD pipelines and business workflows; (4) Proactive Security & Trusted AI—scale AI with threat detection, adversarial testing, and model security; and (5) Adaptive Excellence—achieve continuous, closed-loop optimization of AI performance, security, and impact. These findings leverage coaching, Vygotsky's zone of proximal development, and Kolb's experiential learning to reconcile rapid delivery with trustworthy, resilient software while aligning governance, automation, and security across all stages reduces systemic risk, strengthens supply-chain resilience, and enables sustainable AI transformation.

Keywords: Artificial intelligence, Capability maturity model, Software engineering, Zone of proximal development, Experiential learning

1. Introduction

Disclaimer: All statements of fact, opinion, or analysis expressed are those of the author. The views and opinions expressed herein by the author do not represent the official policies or positions of the United States (U.S.) Department of Defense (DoD), U.S. Navy, or other agencies or departments of the U.S. government and are solely representative of the views of the author. This does not constitute an official release of DoD or Navy information.

1.1 Background and Motivation

Artificial Intelligence (AI) is reshaping software engineering by automating core SDLC tasks—requirements analysis, code generation, testing, deployment, and monitoring. AI-assisted tools such as code copilots, automated test frameworks, and self-optimizing pipelines now permeate the SDLC, delivering productivity gains and scalability while introducing risks from probabilistic behavior, opaque decision-making, and rapid automation (Sarker 2025). Historically, software development maturity models guided readiness and alignment with organizational goals; however, accelerated AI integration challenges their relevance for AI-driven environments. Sarker's review of ACM, IEEE, and industry studies (2020-2025) reports a 55.8 % productivity boost but a 40–50 % rise in security vulnerabilities in AI-generated code, largely due to developers relinquishing control. With global adoption rates of 62–84 %, AI must augment rather than replace developers, necessitating new upskilling and collaboration strategies.

MITRE (Bloedorn et al., 2023) emphasizes that AI-driven systems are critical to economic stability, national security, and public trust; insecure dependencies can propagate vulnerabilities through supply chains, making security a structural constraint. Effective AI integration requires structured maturity frameworks and experienced champions to guide organizations through five adoption stages, drawing on Kolb's experiential learning and Vygotsky's zone of proximal development to scaffold transitions. This research explores how these pedagogical models inform AI-centric maturity frameworks, fostering technical competence, critical thinking, and ethical awareness essential for responsible AI deployment. Aligning governance, automation, and security

across all stages can reduce systemic risk, strengthen supply-chain resilience, and achieve sustainable AI transformation.

1.2 Problem Statement

Many firms have adopted the CMU SEI blend of CMMI, Agile, and DevOps to improve processes. Though this hybrid can deliver gains, it carries conflicting assumptions (Glazer et al., 2008). Two decades on, these frameworks still misalign with AI-enabled systems that are probabilistic, data-driven, and increasingly autonomous. Recent updates treat AI tools merely as efficiency layers, overlooking their transformative effects on system behavior, security perimeters, and governance (Rajab & Alnouki, 2025). As organizations move from experimentation to operationalization and autonomous optimization, legacy models cannot capture AI-specific risks—uncontrolled code generation, weakened architectural guarantees, accelerated supply-chain vulnerabilities, and adversarial manipulation. AI's rapid decision amplification widens gaps in governance, accountability, and security controls (Ozkaya et al., 2025). Consequently, without an AI-centric maturity framework that integrates governance, experimentation, operationalization, proactive security, and continuous adaptation, firms lack a structured path to secure AI adoption, impeding readiness assessment, workforce alignment, and sustained trust in AI-driven software engineering.

1.3 Research Objective and Thesis

This study illuminates how maturity evolves in AI-enabled software development and why CMMI, Agile, and DevOps fail to govern it. Rather than extending legacy models, we construct a structurally apt framework grounded in cross-sector practice (Mohajan & Mohajan, 2022). Using Glaserian Grounded Theory on secondary data from industry reports, academic literature, FFRDC outputs, and research unit findings, we show that maturity arises from the co-evolution of governance structures, secure automation mechanisms, and human oversight. The analysis reveals recurrent failure patterns and adaptive strategies missing from current models, leading to a five-level AI-centric framework that redefines maturity as a security-anchored, socio-technical progression guiding organizations from fragmented experimentation to adaptive, resilient, and trustworthy AI-enabled software development.

1.4 Structure of the Paper

The paper is structured as follows: Section 2 reviews related work and critically assesses the limitations of existing software-development maturity models in AI-driven engineering. Section 3 details our methodology, highlighting secondary data use and Glaserian Grounded Theory analysis. Section 4 presents emergent findings, revealing AI-native maturity dimensions derived from the grounded study. Section 5 introduces a five-level AI-centric framework, explicating each level as an emergent theoretical construct. Section 6 discusses implications for software engineering practice, security architecture, and policy development. Section 7 outlines study limitations and future research directions. Finally, Section 8 concludes by summarizing key contributions and underscoring the importance of AI-native maturity models for securing the AI revolution.

2. Background and Related Work: Limitations of Existing Software Development Maturity Models

Software development maturity models have long guided organizational capability, process improvement, and alignment with strategic goals, emerging to address growing complexity and the need for repeatability, predictability, and quality. Their foundational assumptions—human-written, deterministic code governed by linear or iterative processes—now clash with AI's pervasive integration across the SDLC. This section surveys CMMI, Agile, and DevOps maturity models, critiquing their structural limitations for AI-driven engineering. By focusing on architecture rather than implementation details, it shows why these models fail to govern probabilistic, autonomous, and security-sensitive AI-enabled systems.

2.1 Capability Maturity Model Integration (CMMI)

CMMI boosts performance through disciplined process management, stressing standardization, measurement, and continuous improvement. Its governance, compliance, and predictability strengths dominate regulated, high-assurance sectors. Yet CMMI's deterministic assumptions—specifying, controlling, and auditing behavior via fixed processes—make it ill-suited for AI, which is treated merely as a supporting tool rather than a system actor. Consequently it lacks mechanisms for AI-specific risks such as model drift, data dependency, probabilistic outputs, and autonomous decisions. Procedural controls that fit human-paced cycles misalign with AI's rapid

artifact evolution, creating bureaucratic bottlenecks or informal workarounds that erode governance. (Eliseo et al., 2025).

2.2 Agile Maturity Models (Scrum, Kanban, XP)

Agile models—Scrum, Kanban, XP—were created to counter plan-driven rigidity by promoting adaptability, collaboration, and rapid feedback. Their iterative delivery suits early AI experimentation, especially when AI assists backlog prioritization, code generation, and testing. Yet they provide little governance or architectural guidance, deferring security to informal discipline. As AI-generated code and autonomous decisions scale, the absence of explicit accountability, supply-chain risk, and model-security controls becomes critical, since Agile assumes human reviewers remain primary—a premise broken when AI takes on those roles (Abrar et al., 2025).

2.3 DevOps Maturity Models

DevOps models blend development and operations through automation, CI/CD, and shared reliability, prioritizing deployment frequency, MTTR, and observability—well suited to cloud-native microservices. In AI-driven engineering these pipelines become autonomous, using AI for testing, monitoring, and remediation. However, maturity is judged mainly by automation depth rather than trustworthiness or controllability. AI-influenced deployments blur accountability, exposing gaps in adversarial protection, dependency poisoning, and memory safety from automated code generation, thus creating unchecked automation (Mamun, 2024).

2.4 Cross-Model Synthesis and Structural Gaps

CMMI, Agile, and DevOps focus on governance, adaptability, or automation assuming a stable human-centric control plane. They lack mechanisms for AI that autonomously generates, modifies, and deploys code at machine speed. These frameworks treat governance, security, and oversight sequentially, a division that collapses when AI permeates the SDLC, causing security failures from misaligned automation and control. This structural gap necessitates an AI-centric maturity model intertwining governance, security, and oversight as co-evolving socio-technical realities (Abrar et al., 2025; Mamun, 2024).

3. Research Methodology

3.1 Methodological Orientation: Secondary Data Grounded Theory

This study employs Secondary Data Grounded Theory, following Glaserian principles to inductively generate theory from existing documents, literature, and archives instead of primary data. The method suits AI-driven software development maturity, which spans diverse sectors and governance regimes. Classic Grounded Theory emphasizes theory emergence, minimal preconception, and constant comparison regardless of source. Thus, secondary materials provide an empirical base where patterns, categories, and relationships surface, aligning with Glaser's view that grounded theory can validly arise from "any data" when the analytic process remains inductive, comparative, and theory-generating (Mohajan & Mohajan, 2022).

3.2 Data Corpus and Source Selection

The study's corpus is exclusively secondary, spanning AI-enabled software engineering, security governance, and maturity modeling across sectors. It comprises industry documents (public reports, white papers, architectural guides, incident analyses, practitioner texts on AI-assisted development, DevSecOps pipelines, and operational security controls); academic literature (peer-reviewed journals, conference papers, research unit outputs on AI software engineering, secure SDLCs, supply-chain risk, and socio-technical dynamics); FFRDC (public notes on AI security, assurance, resilience, and risk in high-assurance contexts); and standards artifacts (archival records from bodies such as AI risk management and software assurance). Theoretical sampling guided iterative inclusion until saturation, ensuring no new properties or relationships emerged.

3.3 Analytic Procedure

Data analysis followed classic Grounded Theory's constant comparison, avoiding preset codes. Line-by-line open coding revealed recurring concepts—AI adoption, governance gaps, security failures, automation risk, and organizational responses—while keeping codes conceptual. Continuous comparison linked incidents across documents, sectors, and institutions, uncovering similarities, differences, and boundary conditions. Theoretical coding merged related categories into higher-order relationships, showing AI-driven software maturity arises from interactions among governance, automation, security mechanisms, and human oversight. No axial coding or predefined model was imposed; categories gained relevance through repeated emergence (Mohajan & Mohajan, 2022).

3.4 Theoretical Emergence, Framework Development, Rigor, Trustworthiness, and Limitations

The five-level AI-centric maturity framework emerged inductively from grounded analysis, charting progress from unstructured experimentation to adaptive, secure AI-enabled development. Its levels are conceptual stages—not prescriptive checklists—highlighting empirically observed transitions, recurring failure modes, and why legacy models miss AI-native behaviors. Rigor rested on theoretical saturation, constant comparison, and avoidance of preexisting frameworks; findings offer analytical generalization across sectors. A limitation is reliance on publicly documented practices, potentially omitting informal or classified implementations.

4. Emergent Findings: AI-Native Dimensions of Software Development Maturity

Grounded analysis of secondary data from industry docs, academia, FFRDCs, and standards revealed a core concern shared by AI-enabled software engineering adopters: scaling automation while preserving trust, security, and control. This led to recurring theoretical categories that explain why legacy maturity models (CMMI, Agile, DevOps) fail to govern AI systems and how maturity unfolds uniquely in AI-native environments. These categories transcend traditional distinctions, highlighting AI-specific socio-technical dynamics.

4.1 Current Industry Practices

Organizations currently embed ISO/IEC 42001, NIST AI RMF, and other fragmented standards into governance boards, risk registries, decision pathways, or DevSecOps pipelines in a piecemeal way. Whether applied to a fintech's provenance dashboard, a public-sector AI charter, or an automotive manufacturer's security-by-design process, this ad-hoc approach leaves firms in a haphazard position regarding governance, security, data provenance, and model behavior.

4.2 Governance Lag as a Systemic Failure Mode

Across sectors, data show a consistent lag: AI tools—coding assistants, automated testing, and pipeline automation—are deployed before formal governance is in place. Legacy maturity models presume that policy precedes technology, yet AI-enabled development reverses this order. The result is reactive governance that emerges only after experimentation, leaving AI systems running without clear accountability, acceptable-use policies, or risk ownership. This structural lag correlates with downstream security breaches, inconsistent code quality, and opaque decision-making (Birkstedt et al., 2023).

4.3 Acceleration-Induced Security Risk Amplification

A second emergent category is security risk amplification driven by AI-accelerated velocity. AI-assisted development compresses traditional SDLC timelines through automated code generation, test creation, and deployment. However, this acceleration magnifies design flaws, unsafe dependencies, and insecure defaults. Comparative analysis across documents shows that vulnerability introduction rates do not fall proportionally with AI assistance; instead, vulnerabilities spread faster and more widely. Current maturity models focus on delivery speed, deployment frequency, or process adherence, yet they lack mechanisms to assess how risk scales nonlinearly in AI-augmented environments. True security maturity here emerges not from faster pipelines, but from the capacity to detect, constrain, and correct AI-amplified failure modes in near real time (Habbal et al., 2024).

4.4 Erosion of Architectural and Memory Safety Boundaries

The analysis also surfaced a recurring erosion of architectural software pattern coherence and memory safety guarantees in AI-assisted development environments. AI-generated code often optimizes for local correctness or syntactic validity while overlooking broader architectural constraints, security invariants, or language-specific safety considerations. Across multiple sources, organizations relying heavily on AI-generated code without enforcing memory-safe language standards or architectural validation experience increased defect density and security debt. This finding highlights a mismatch between AI tooling capabilities and legacy maturity models, which assume that developers remain the primary agents of architectural and memory safety enforcement. In AI-driven systems, these responsibilities increasingly shift to tooling, policy, and pipeline-level controls (Xu et al., 2025).

4.5 Automation Without Accountability in AI-Augmented Pipelines

Another emergent category is automation without accountability, particularly in mature DevOps environments transitioning toward autonomous operations. AI-enabled pipelines increasingly make deployment, rollback, and remediation decisions without clear human authorization boundaries or auditability mechanisms. Grounded

analysis indicates that organizations often equate pipeline automation maturity with operational excellence, even as decision authority becomes opaque. This pattern exposes a structural gap: existing maturity models emphasize automation outcomes but do not account for who or what is accountable for AI-mediated decisions. Trustworthy maturity emerges only when accountability mechanisms evolve alongside automation capability (Baqar et al., 2025).

4.6 Human Oversight and Workforce Readiness as Limiting Factors

The data consistently identifies human oversight capacity and workforce readiness as limiting factors in AI maturity progression. As AI systems assume more cognitive and operational tasks, developers and security professionals transition from creators to supervisors of AI behavior. However, legacy maturity models do not account for this role transformation. Organizations lacking AI literacy, model interpretability skills, and adversarial awareness struggle to detect subtle failures, model drift, or security degradation. Maturity in AI-driven environments therefore emerges not solely from tooling sophistication, but from the alignment of human expertise with AI system behavior (Sarker, 2025).

4.7 Synthesis of Emergent Findings

Collectively, these findings indicate that maturity in AI-enabled software development is not linear, tool-driven, or process-bound, but emergent, arising from the interaction of governance, automation, security mechanisms, and human oversight. The recurring failure patterns observed across sectors explain why CMMI, Agile, and DevOps maturity models—each optimized for deterministic systems—are structurally misaligned with AI-driven software engineering. These emergent categories directly inform the five-level AI-centric maturity framework presented in Section 5, which reconceptualizes maturity as a security-anchored, adaptive progression rather than a static process benchmark.

5. The Five-Level AI-Centric Software Development Maturity Framework

Grounded analysis revealed that AI-enabled software development matures not through incremental optimization but via distinct qualitative shifts in governance, operationalization, security, and adaptation. These shifts form a five-level AI-centric maturity framework that traces the journey from fragmented, tool-driven adoption to resilient, trustworthy, and adaptive engineering. As a theoretical model rather than a prescriptive roadmap, the framework captures stable configurations of governance, automation, security controls, and human oversight at each level, with advancement driven by resolving recurring failure modes observed across industry, academia, FFRDCs, and research units.

5.1 Level 1: Foundational Awareness and Governance (Baseline Literacy)

At Level 1, organizations grow aware of AI's influence yet lack systematic governance. Adoption is ad hoc, driven by individual developers or isolated teams experimenting with AI coding tools, testing frameworks, or analytics. Findings show a focus on policy drafting, ethical considerations, and baseline literacy to manage early uncertainty and risk. Governance bodies—AI councils or steering committees—emerge mainly to set acceptable use, data handling, and accountability limits. Security controls remain inherited from pre-AI SDLCs, not yet tailored to AI risks. This stage curbs unbounded experimentation but does not yet support safe operationalization; advancement requires recognition that governance alone cannot mitigate expanding AI risks.

5.2 Level 2: Experimentation and Initial Integration (Pilot Stage)

At Level 2, organizations launch controlled AI pilots in sandboxed or isolated settings, embedding tools like chatbots, code assistants, or test generators into limited workflows to gauge productivity and feasibility. Grounded data reveals recurring issues—poor data quality, inconsistent outputs, and hidden security assumptions in AI artifacts. Governance structures from Level 1 are tested against reality, exposing gaps in policy enforcement and risk ownership. Maturity progresses only when firms move beyond proof-of-concept metrics to address how AI outputs align with architectural constraints, security requirements, and downstream automation.

5.3 Level 3: Integrated Development (Operationalization & CI/CD)

Level 3 marks the shift from experimentation to operational AI-enabled production. Tools become integral to development environments, CI/CD pipelines, and business workflows, boosting deployment velocity. Grounded findings identify new systemic risks: AI-generated code scales faster than human review, vulnerabilities spread through pipelines, and architectural drift is harder to detect. Without AI-aware security controls and memory-safety enforcement, organizations accrue rapid technical and security debt. Maturity at this stage arises

when AI tooling is treated as production infrastructure, demanding the same rigor, monitoring, and security guarantees that other critical systems require.

5.4 Level 4: Proactive Security and Trusted AI (Scaling)

At the Proactive Security level, organizations explicitly recognize AI as both a security enabler and a security subject. AI is applied to threat detection, anomaly analysis, and predictive vulnerability identification, while parallel efforts focus on securing AI models, data pipelines, and decision logic. Grounded analysis highlights the introduction of adversarial testing, red teaming, and continuous security verification as defining characteristics of this level. Accountability mechanisms evolve to ensure that automated decisions remain observable, explainable, and auditable. This level stabilizes AI-driven scaling by aligning automation speed with adaptive security controls, enabling organizations to expand AI usage without proportionally increasing systemic risk.

5.5 Level 5: Adaptive Excellence (Transformation)

Level 5, Adaptive Excellence, marks the point where AI-enabled development is self-correcting, resilient, and strategically embedded. Organizations run closed-loop systems in which performance, security, and behavioral feedback continuously refine models and processes. Grounded data shows that maturity here is defined by autonomous optimization bounded by robust governance and human oversight: AI systems evolve as integral organizational assets rather than mere tools. Human roles shift to strategic supervision, ethical judgment, and resilience planning, ensuring that scaling AI automation does not erode trust, security, or control.

5.6 Framework Implications

The five-level maturity framework explains why organizations stagnate or regress when attempting to extend legacy maturity models into AI-driven environments. Progression requires resolving qualitatively different challenges at each level rather than accumulating incremental process improvements. By grounding maturity in emergent security and governance dynamics, this framework provides a structurally appropriate lens for understanding trustworthy and resilient AI-enabled software development.

5.7 Results

To illustrate the applicability of this maturity framework, three industry examples include: 1) a public-sector data analytics firm adopting AI governance checkpoints at the Governance level to plan their corporate waypoints; 2) a fintech startup integrating model provenance during the Security stage to ensure fiduciary responsibilities to their clients; and 3) a manufacturing firm applying continuous learning pipelines within the Model Behavior level. These examples parallel the structured approaches of AI-driven software development recommended by Ozkayo et al., 2025 and Sarkar, 2025.

6. Implications for Practice and Policy

The five-level AI-centric maturity framework has significant implications for software engineering practice, security architecture, and policy development. Rather than offering prescriptive controls, the framework explains why certain practices succeed or fail as organizations progress through AI adoption. These implications suggest that trustworthy and resilient AI-enabled software development emerges from structural alignment between governance, automation, security, and human oversight—not from isolated technical interventions.

6.1 Implications for Software Engineering and Security Practice

For practitioners, AI maturity demands more than tooling; it requires evolving governance and security mechanisms. Deploying AI-assisted development without robust controls amplifies risk, rendering deterministic SDLC practices—post-hoc code review or episodic testing—insufficient as artifacts scale at machine speed. Security architecture must shift to systemic, pipeline-level enforcement: memory safety, architectural validation, and dependency provenance must be baked into automated workflows. Engineers transition from implementers to AI supervisors, acquiring skills in model risk assessment, anomaly interpretation, and adversarial reasoning. The framework also warns that skipping levels—adopting advanced automation prematurely—often triggers maturity regression, as unresolved governance gaps erode security and trust at scale.

6.2 Implications for Organizational Leadership and Workforce Development

At the organizational level, AI maturity is a human and governance challenge as much as it is technical. Leadership models designed for traditional development often lack clear ownership of AI decisions, leaving accountability, risk acceptance, and ethics ambiguous. Workforce readiness becomes a bottleneck when AI

systems gain operational autonomy; without targeted investment in AI literacy, interpretability, and adversarial awareness, teams depend on outputs they cannot fully evaluate, increasing fragility and eroding trust. Leaders must align incentives, training, and organizational design with AI's evolving role; treating governance as mere compliance instead of a strategic capability prevents adaptive excellence.

6.3 Implications for Policy, Standards, and Regulatory Frameworks

For policymakers and standards bodies, current assurance frameworks often fail to capture AI-native development dynamics. Regulations premised on static codebases, human-authored artifacts, or linear SDLCs cannot govern systems that learn continuously, generate code autonomously, and optimize in real time. The five-level framework provides a maturity-based lens, enabling policies that scale expectations with organizational capability rather than enforcing one-size-fits-all mandates. Such stage-aligned regulation balances innovation, security, and compliance—especially for critical infrastructure—while also demanding support for governance structures, workforce transformation, and ongoing adaptation mechanisms.

6.4 Summary of Implications

Collectively, these implications reinforce the central finding of this study: trustworthy and resilient AI-enabled software development cannot be achieved through incremental extensions of legacy maturity models. Instead, it requires a reconceptualization of maturity that reflects how AI reshapes risk, responsibility, and control across software systems. The five-level AI-centric maturity framework provides a grounded explanatory model that can inform practice, guide organizational transformation, and shape adaptive policy approaches in the AI era.

7. Limitations and Future Research

As with all theory-building research, this study is subject to several limitations that inform the interpretation of its findings and outline directions for future inquiry. These limitations stem primarily from the methodological choices and the evolving nature of AI-driven software engineering.

7.1 Methodological Limitations

This study relies exclusively on secondary data and Grounded Theory analysis of industry documents, academic papers, FFRDC reports, and archives. While Glaserian methods suit a fast-moving, multi-sector field, they depend on the availability and transparency of published material; informal practices, classified deployments, or undocumented behaviors may be omitted. The secondary nature also precludes probing ambiguities or clarifying the intent behind documented practices, unlike interview-based research that can interrogate decision-making rationales. Nevertheless, the broad, cross-sector dataset mitigates this limitation by highlighting recurring patterns rather than isolated anecdotes.

7.2 Scope and Generalizability

The resulting five-level maturity framework is offered as an analytical and explanatory model, not a statistically generalizable or prescriptive standard. While the framework reflects patterns observed across diverse sectors, it does not claim universal applicability to all organizational contexts, particularly those operating under unique regulatory, cultural, or technological constraints. Furthermore, the framework emphasizes security-centric maturity dynamics and may not capture all dimensions relevant to organizations focused primarily on economic optimization or consumer-facing innovation. These boundaries reflect deliberate scope decisions aligned with the research problem.

7.3 Temporal Limitations

AI technologies, development practices, and regulatory environments are evolving rapidly. As a result, some practices observed in the data corpus may become obsolete or transformed over time. Consistent with classic Grounded Theory, the framework is presented as a modifiable theory that should evolve as new data and practices emerge. Longitudinal studies are required to assess how organizations transition between maturity levels over time and whether additional stages or sub-dimensions emerge as AI capabilities mature.

7.4 Directions for Future Research

Future work should validate and extend this framework through primary research—interviews, ethnography, or surveys—to capture decision-making nuances and informal practices missing from secondary data. Quantitative studies could operationalize maturity dimensions into measurable indicators, enabling cross-organizational benchmarking and longitudinal tracking. Domain-specific adaptations for high-assurance sectors such as critical infrastructure, defense, and regulated industries warrant exploration. Finally, research should assess how the

model aligns with emerging AI governance standards, risk frameworks, and regulatory regimes, ensuring its relevance to evolving policy landscapes.

Future work will complement this secondary-data grounded theory with primary research through interviews, surveys, or ethnographic observations to capture the decision-making this data corpus could not reveal since many organizations guard their AI maturity data as proprietary or in some case classified because of the client confidentiality, competitive advantage, or national security interests at stake. Organization masking will continue to be used as this emergent framework is expanded to respect the fiduciary and security constraints that limit publicly available data.

7.5 Alignment With Standards and Policies

In unison with the Directions for Future Work, benchmarking the five-level maturity model against emerging AI governance standards (ISO 42001, NIST AI RMF) and risk management frameworks will verify compliance and gaps where each maturity level will decompose standard requirements traceability with measurable metrics. This will identify policy-gap analysis across high-trust sectors such as critical infrastructure, defense, and regulated industries to better tune the model for more common use across multiple sectors to ensure alignment with emerging AI governance standards, risk assessment systems, and regulatory regimes in changing geopolitical environments.

7.6 Summary

These limitations do not reduce the contribution of this study but a vector for ongoing future research. By offering an empirically grounded, AI-centric maturity framework, this work provides a foundation for future empirical validation, theoretical refinement, and practical application as AI-driven software engineering continues to evolve.

8. Conclusion

The rapid embedding of AI into software development has reshaped design, production, and security practices, revealing that legacy maturity models—CMMI, Agile, DevOps—are structurally ill-fit for AI's probabilistic, autonomous, and machine-speed dynamics. This study used secondary data and Glaserian Grounded Theory to inductively uncover recurring patterns across industry, academia, and FFRDCs, showing that AI maturity depends on the interplay of governance, automation, security, and human oversight rather than mere process compliance. The resulting five-level AI-centric framework explains progression from fragmented experimentation to adaptive, resilient, and trustworthy development, positioning security and trust as emergent socio-technical properties. By offering a flexible, theory-driven lens that adapts to evolving AI practices, the framework supports empirical validation, policy design, and organizational transformation essential for a secure AI future.

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Apache Daffodil for Network Traffic Validation

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Abstract: This paper explores the relative merit of Apache Daffodil for the automated generation of real-time network traffic validators associated with military vehicles. Daffodil is an "open-source implementation of the Data Format Description Language (DFDL)" which converts between natively formatted data and Extensible Markup Language (XML), JavaScript Object Notation (JSON) or other structures based on predefined schemas. Daffodil can also automatically generate executable parsers, and it is the efficacy and maturity of this facet of the technology for traffic validation that is our primary interest. Military vehicles have traditionally used compact protocols, such as Space Packet Protocol (SPP), MIL-STD-1553, or Controller Area Network bus (CAN bus), to enable real-time validation and limit malicious implants embedded in normal traffic. Over time, message traffic has grown increasingly complex due to increases in performance and use of commercial-off-the-shelf networking technologies leveraging Ethernet and TCP/IP protocols. Messages may now include mission-specific or recursively defined data embedded in the payload fields of variable-length packets. Consequently, it is valuable to assess Daffodil's ability to handle both existing formats and representative payload data within this emerging context. Here we directly compare DFDL schemas with equivalent grammars expressed in an extended version of Backus-Naur Form (xBNF) and Hammer to assess its expressive capability and succinctness. To assess the maturity of its validator generator, we compared Daffodil to the industry-standard Bison tool (for xBNF) and Hammer library. Though the comparison is based on numerous formats, here we present three examples: JSON numbers—a simple recursive data format; Micro Air Vehicle Link (MAVLink) messages—non-trivial byte-oriented traffic; and generic SPP messages—a bit-oriented, fixed-size format. Unfortunately, Daffodil's automated parser generation capabilities are currently neither mature nor robust. Daffodil is primarily useful for analysing fixed-length formats or variable-length components which follow descriptive header fields. Daffodil parsers can elegantly check compact bit-wise protocol formats, which is more difficult using Bison and some versions of Hammer. Daffodil is currently of limited utility in analysing recursive or non-prefixed formats such as JSON. Writing DFDL manually appears significantly more verbose and error-prone than both xBNF and Hammer.

Keywords: Apache Daffodil, Bison, Hammer, Parser generation, Traffic validation, Secure parsing

1. Introduction

Many organizations handle sensitive data and files relating to military missions, trade secrets, intellectual property, private personal data, and/or classified projects (NBAR, 2021). Traditionally, these organizations have been well advised to implement an air gap that physically isolates computers containing sensitive information from the Internet to protect against theft. Unfortunately, air gaps come with a substantial cost in productivity and assume that professional staff, with the expertise to handle sensitive information, are co-located. Consequently, individual air, space, and ground vehicles increasingly rely upon standard networking technologies to link embedded control systems with sensors, actuators, and human-machine interfaces through industry standard buses (e.g., CAN, J1939, MIL-STD-1553, USB) and communications interfaces (e.g., Gigabit Ethernet, OpenVPX, and PCIe). Network connected personal devices—phones, tablets, and laptops—are increasingly used to manage and interact with these systems. Though conceptually air-gapped, these systems are intermittently connected with military installations to provide mission parameters, or to effect maintenance and upgrades. Network boundary protections are used during these activities, but threat vectors including unintended connections, insiders, zero-day exploits, supply chain interdiction, and persistent implants can circumvent such protections (Kushner, 2013).

To combat these threats, byte-by-byte validation of message data can be implemented below the network stack—within the kernel, hypervisor, or underlying hardware—to ensure data is well-formed and contains reasonable values relative to the intended mission. Such validation makes use of *parsers*, which implement well-defined *grammars* representing the acceptable syntactic structure of messages. Traditionally, parsers match data to grammatical rules and generate parse trees, or structural representations. Validators must only establish that the input is consistent with the grammar and return a binary valid/invalid result. Beyond pure syntactic validation, more complex programs may also verify that data falls within reasonable threshold values, for example regarding the physical status of a vehicle within its intended mission. This paper explores the relative capabilities of Bison, Hammer, and Apache Daffodil with regards to the generation of validation parsers as part of a larger network traffic security toolchain.

1.1 Automated Parser Generation

Parser generators are tools that take a grammar as input and automatically generate a program that implements the associated parser. Here we consider three alternative approaches to automated parser generation—Bison (Levine, 2009), Hammer (Bratus et al, 2016), and Apache Daffodil (W3C, 2012)—to assess their relative strengths for network traffic validation. All three tools can operate on both textual (i.e. ASCII) and binary data. Though we have explored many grammars, we present observations here in the context of three formats that exemplify our findings: JavaScript Object Notation Numbers (JNUM) (ECMA, 2017), Micro Air Vehicle Link (MAVLink) (Dronecode Foundation, n.d.) protocol messages, and Space Packet Protocol (SPP) messages (CCSDS, 2020). JSON numbers involve recursively structured, byte-oriented data; MAVLink uses prefixed variable-length byte-oriented messages, and SPP messages use bit-oriented fields.

1.1.1 Bison

Bison is the most mature and widely used parser generator. It accepts context free grammars (CFGs) and primarily generates two classes of parser: generalized left-to-right (GLR) and the more restrictive look-ahead left-to-right (LALR). Input CFGs are expressed as a set of parsing rules in Backus-Naur Form (BNF) (Backus et al, 1960). Each rule expresses how a non-terminal symbol in the grammar is composed of terminal symbols such as ASCII characters (e.g. 'a'), binary values expressed in hexadecimal (e.g. '\xF5'), or other non-terminal symbols. Recursive rules can describe *sequences* of symbols, and multiple rules associated with the same non-terminal provide *choice* in how to parse a particular construct.

Though GLR parsers are more capable, LALR parsers are sufficient for validating a wide variety of communication protocols and file formats. Their simplicity allows them to be realized by a simple push-down automaton—a finite state machine employing a single stack to store symbols while parsing the input stream. The state machine relies on two core operations: shift—saving an input symbol to the stack—and reduce—the application of a grammar rule to detect a structure and reduce the symbols on the stack. The order in which shift and reduce operations are applied to the input is based on a collection of parsing tables derived from the grammar, usually referred to as Action/Goto tables (Aho, Sethi, and Ullman, 1988). These tables map the current state of the automaton to a next state based on the symbol read from the input stream.

Unfortunately, Bison's version of BNF cannot natively express common constructs in communication protocols such as strings (e.g. 'true'), wildcard values matching any input byte (often written *), fixed width data types (e.g. uint_64, int_16 etc.) in big- or little-endian formats, or ranges of values (e.g. ['a'-'f'] representing a character between 'a' and 'f' inclusive). Consequently, here we use an extended form of BNF (xBNF) to simplify each grammar using these additional notations (Taylor and Meise, 2021). The extended form is implemented as a preprocessor, written in Bison.

1.1.2 Hammer

Hammer is modern "parser combinator" library developed under the DARPA SafeDocs program. The library provides a collection of formally-defined base parsers and rules, designated with an *H_RULE()* construct, which are combined to build more complex parsers—all expressed in the C programming language. The more complex parser combinators *h_sequence()* and *h_choice()* allow sequences of parsers and choices between alternative parsers, respectively, to be composed. The resulting parsers are provably correct by construction. The Hammer library provides a collection of back ends that allow different parsing algorithms to be employed, including Packrat, providing recursive descent parsing, and LALR, providing bottom-up look-ahead parsing. Unfortunately, only the Packrat back end supports bit-oriented combinators, which can directly parse bit fields instead of having to pad each field to byte length through preprocessing. Further, the LALR back end does not support the little-endian combinators needed for MAVLink. As such, the Hammer versions of the JNUM parser used here make use of the LALR back end to match that of xBNF, while the MAVLink and SPP parsers use the Packrat back end.

1.1.3 DFDL and Apache Daffodil

The Data Format Description Language (DFDL) is a specification maintained by the Open Grid Forum for describing both textual and binary data formats. It is based on the W3C XML Schema Definition Language (XSD), which was created to "express syntactic, structural and value constraints" for text data structured or stored with XML. XSD schemas are made up of element declarations, which are assigned types and may also be assigned additional annotations. XSD includes many primitive types, of which DFDL includes only a subset. User-defined types may either be 'simple' or 'complex' and are created from these primitives. An *xs:simpleType* is created by modifying a primitive base type with additional annotations. The most common annotation here is an

xs:enumeration, which defines the terminal symbols which are valid for each type. The key differentiator for *xs:complexType* definitions is the presence of one or more *xs:sequence* or *xs:choice* groups. Sequence and choice groups are the fundamental structures used to build up schemas and are used similarly to Bison *sequences* (i.e. recursive rules) and *choices* (i.e. multiple rules) or Hammer *h_choice()* and *h_sequence()* combinators. In the DFDL schemas that follow, types are defined to mirror Bison non-terminal symbols and Hammer *H_RULE()* constructs. Each DFDL schema has a top-level element whose type is a complex type defining the entire grammar and is used as the starting point for the parser.

Apache Daffodil is an open-source implementation of DFDL, which provides support for data parsing, converting application-specific data formats to the DFDL-native Information Set (Infoset). The Daffodil library also provides support for 'unparsing,' or data serialization, from the Infoset to the application-specific format. Parsing and unparsing are performed by the library, with the input data and XSD schema taken as arguments for each routine at runtime. Daffodil also supports 'saving' schemas to a binary file for use in place of the XSD. Finally, Daffodil allows for the conversion of schemas into recursive descent parsers expressed in C. It is these generated C parsers that are of primary interest, as they allow parsing to be performed by a stand-alone executable, independent of the entire Daffodil library. However, Daffodil's C code generation currently supports only a subset of all features. Critically, type definitions which include elements of unspecified or expression-based length do not convert cleanly into C code.

1.1.4 IBM App Connect Enterprise

IBM App Connect Enterprise (ACE) is an enterprise integration software product which supports DFDL as part of its ability to facilitate data sharing and information flow (IBM Corp., 2025). IBM ACE was explored because its graphical user interface might have made schema writing simpler. Unfortunately, though perhaps less error prone than manual typing, our experience was that the ACE editor was too cumbersome to quickly develop schemas. Additionally, ACE does not support or focus on the generation of standalone validators, meaning that this product could only be used as an alternative schema editor in the context of a mission-ready toolchain.

2. JSON Numbers - Simple Recursive Format

The JavaScript Object Notation (JSON) format is a widely used data format used for storage and transmission. JSON numbers (JNUM) are one of the basic component types used to represent information and were selected to illustrate a simple recursive, byte-oriented data format. A JSON number (JNUM), such as 12.34e+56, is made up of an integer (the part preceding the decimal place, e.g. '12'), an optional fraction (the decimal point and following digits, e.g. '.34') and an optional exponent (an 'e' or 'E' followed by an optional sign and digits, e.g. 'e+56'). Note that JNUM requires the ability to handle input data of unspecified length, as each of the integer, fraction, and exponent fields may have any number of digits. Further, the format requires the ability to handle optional elements without the presence of a preceding header or 'flag' field.

2.1 xBNF

The recursive structure of xBNF makes the implementation of JNUM simple; the entire grammar, below, is just 8 lines. Non-terminal symbols are constructed to match the official specification, which directly specifies sequences and choices. The initial rule (line 1) provides a top level for the grammar (*jnum*) and designates a *sequence* of three non-terminals (i.e. integer, fraction, and exponent). Use of the *choice* symbol '|' (read as 'or') in the subsequent rules provides a shorthand for alternative rules to reduce the same non-terminal. For example, the *digit* rule (line 7) could equivalently be expressed as two rules that provide two ways to reduce the same non-terminal symbol *digit*. The end-of-input must occur when the *jnum* rule is successfully reduced, with no additional data on the input. Importantly, the recursive *digits* rule (line 6) allows the grammar to handle data of unspecified length; in this case *digits* is a sequence of one or more individual instances of a single *digit*. Also note that optional elements are specified simply by providing an *empty* choice (lines 3, 4, 5), by convention marked with a comment such as in the definition of a *sign*.

```
jnum: integer fraction exponent ;                              /* 1 */
integer: digit | onenine digits | '-' digit | '-' onenine digits ;   /* 2 */
fraction: /* empty */ | '.' digits ;                           /* 3 */
exponent: /* empty */ | 'E' sign digits | 'e' sign digits ;    /* 4 */
sign: /* empty */ | '+' | '-' ;                                /* 5 */
```

```
digits: digit | digits digit ;                    /* 6 */
digit: '0' | onenine ;                           /* 7 */
onenine: [ '1' - '9' ] ;                         /* 8 */
```

The ability for xBNF to concisely represent range expansions (line 8), as opposed to a manually created sequence of choice fields as in raw BNF, is also significant. As the target format becomes more complex, the manual expression of ranges quickly becomes unwieldy. The above grammar can be directly translated into a software parser using Bison for use at the application, kernel, or hypervisor levels of the software stack; alternatively it can be directly translated into a highly compact hardware circuit for use in a field programmable gate array (FPGA) or system-on-chip (SoC) device (Taylor, 2022 and Taylor, 2024).

2.2 Hammer

The Hammer JNUM implementation uses a top-level '*jnum_parser*' rule at the end of the parser. It is defined with an *h_sequence()* combinator containing a '*jnum*' parser, *h_end_p()* primitive (to designate where the end of input should occur), and *NULL* to indicate the end of the parameter sequence:

```
jnum_parser = h_sequence(jnum, h_end_p(), NULL);
```

In a similar manner to xBNF, the *jnum* rule is made up of smaller user-defined parsers that are assembled with further *h_sequence()* and *h_choice()* combinators:

```
H_RULE(digits, h_many1(digit));
H_RULE(integer, h_sequence(h_optional(h_ch('-')),
        h_choice(digit, h_sequence(onenine, digits, NULL), NULL), NULL));
H_RULE(fraction, h_sequence(h_ch('.'), digits, NULL));
H_RULE(exponent, h_sequence(h_choice(h_ch('E'), h_ch('e'), NULL),
        h_optional(sign), digits, NULL));
H_RULE(jnum, h_sequence(integer, h_optional(fraction),
        h_optional(exponent), NULL));
```

Note that because Hammer is written in C, lower-level elements are defined first. Hammer uses an explicit *h_optional()* combinator to denote optional symbols rather than the empty rules used by xBNF. Also note the *h_many1()* combinator is used in place of recursive rule definitions. At the lowest level, *H_RULE* parsers combine primitive parsers, such as characters (i.e. *h_ch()*) and ranges of characters (i.e. *h_ch_range()*) to allow symbol enumeration. Hammer is more verbose than xBNF (Taylor, 2022), in part because it requires more setup notation. This parser required 21 lines of code; the setup and more basic elements are omitted here for brevity.

2.3 DFDL

The DFDL schema for JNUM was developed to match xBNF symbol-by-symbol build-up with a top-level *number* non-terminal. The DFDL equivalent is the *JSON_number* global element, which has user-defined complex type *number_t*. This *number_t* then contains an *xs:sequence* and matches the integer, fraction, exponent ordering above:

```
<xs:complexType name="number_t">
 <xs:sequence>
  <xs:element name="integer" type="integer_t"/>
  <xs:element name="fraction" type="fraction_t" minOccurs="0" maxOccurs="1"/>
  <xs:element name="exponent" type="exponent_t" minOccurs="0" maxOccurs="1"/>
 </xs:sequence>
</xs:complexType>
```

DFDL marks optional components in the grammar through the *minOccurs="0"* annotation, in contrast to the xBNF choice of an *empty* element. Within the *xs:sequence*, each of the local elements itself is assigned a complex type which contains further sequence or choice fields. Simple types are defined in terms of primitives and an enumerated set of legal values. For example, the JNUM schema contains a *zero_t* type:

```
<xs:simpleType name="zero_t" dfdl:lengthKind="explicit" dfdl:length="1">
 <xs:restriction base="xs:unsignedByte">
  <xs:enumeration value="&#x30;"/>
 </xs:restriction>
</xs:simpleType>
```

It is clear from the code snippets above that the DFDL grammar definition is significantly more verbose than either xBNF or Hammer. In total, 153 lines of code are required. DFDL supports more compact ways to parse messages—JNUM, for example, can be validated with an *xs:simpleType* element based on a string primitive as a single line of DFDL regex (Beckerle, 2021 pp 196). However, these other methods do not actually break up the incoming message into individual elements nor represent its internal structure for conversion into a validator.

Critically, JNUM's structure requires parse-time decision making based on the value of the token currently being consumed. This requires the *dfdl:discriminator* annotation, which is currently unsupported in the C code generator. As such, an executable JNUM parser could not be generated using Daffodil.

2.4 Summary of Results

Grammar or Schema	Lines of Code	User-Defined Non-terminals	Executable Size (KB)	Fuzz Testing Execution Time (s, n= 42)
xBNF	8	8	21.6	0.088
Hammer	21	8	193.2	0.128
DFDL	153	12	—	—

3. MAVLink Protocol - Variable Length Format

The Micro Air Vehicle Link (MAVLink) Protocol is a communications protocol used with small unmanned aerial vehicles. It supports the transmission of information regarding a drone's status as well as more complex 'microservice' protocols, including a heartbeat and mission protocol. MAVLink currently has both a version 1 and version 2; MAVLink v2 messages have longer headers, may add a signature field at the end of the message, and require the truncation of empty bytes at the end of the message. This last requirement dramatically increases the number of possible message states in MAVLink v2, as each message type may now carry a variable length payload depending on whether fields have been truncated.

Representations of three message types, namely the HEARTBEAT, SYS_STATUS, and VFR_HUD messages for both MAVLink v1 and v2, were created in xBNF, Hammer, and DFDL to explore the capability of each to parse non-delimited formats and verify bounded or enumerated values.

3.1 xBNF

In xBNF, non-terminals are again built up from combinations of *sequence* and *choice* constructs. The context-free nature of xBNF means that a non-terminal must be created for every possible combination of message options. For example, to support all three message types in MAVLink v1, v2 signed, and v2 unsigned, each of the nine possible options must be represented separately. The following code snippet showcases the top-level non-terminals which guide these decisions:

```
P : message ;
/* Message is either MAVLink v1, v2 signed, or v2 unsigned */
message : msg_v1 | msg_v2 ;
msg_v2 : msg_sg | msg_us ;
/* HEARTBEAT, SYS_STATUS, or VFR_HUD message */
msg_v1 : stx_v1 msg_v1_opts crc ;
```

```
msg_sg : stx_v2 msg_sg_opts crc sig ;
msg_us : stx_v2 msg_us_opts crc ;
msg_v1_opts : v1_hb | v1_ss | v1_hud ;
msg_sg_opts : sg_hb | sg_ss | sg_hud ;
msg_us_opts : us_hb | us_ss | us_hud ;
```

The compact syntax of xBNF makes the actual representation of non-terminals simple, but as the number of choices and their options grows, the requirement to independently represent each combination quickly grows the size of the grammar. Since MAVLink v2 payloads truncate empty trailing bytes, for example, a payload whose defined fields are N bytes long may in actuality be transmitted at sizes from 1 to N bytes. This requires 2N non-terminals just to represent the possible combinations of the message being signed/unsigned and having a payload of a certain length. For the MAVLink 3-message grammar, xBNF required 337 lines of code and the definition of 251 non-terminals to achieve a readable grammar that correlates well with the specification.

3.2 Hammer

The Hammer MAVLink parser closely mirrors the xBNF implementation through its use of *sequence* and *choice* combinators. Below is the same representation of top-level MAVLink structures in Hammer:

```
H_RULE(msg_v1, h_sequence(stx_v1, h_choice(v1_hb, v1_ss, v1_hud, NULL), crc, NULL));
H_RULE(msg_sg, h_sequence(stx_v2, h_choice(sg_hb, sg_ss, sg_hud, NULL), crc, sig, NULL));
H_RULE(msg_us, h_sequence(stx_v2, h_choice(us_hb, us_ss, us_hud, NULL), crc, NULL));
H_RULE(message, h_choice(msg_v1, msg_sg, msg_us, NULL));
mav_3_enum_parser = h_sequence(message, h_end_p(), NULL);
return(mav_3_enum_parser);
```

Again, the use of only sequence, choice, and range expansion combinators means that every possible combination of choices must be assigned its own rule. In the MAVLink example, Hammer is not significantly more verbose than xBNF: the parser required 372 lines of code and 247 *H_RULE()* non-terminal definitions.

3.3 DFDL

Since MAVLink messages have fixed-length headers which describe variable-length payload fields, it was possible to use Daffodil's C parser generator and create a standalone MAVLink parser. The implementation is heavily dependent on the *dfdl:occursCountKind="expression"* annotation, which allows the parser to refer back to previous message fields to guide parsing decisions. Since MAVLink messages are flagged with a start-of-text (STX) field indicating the protocol version (0xFE indicates MAVLink v1, 0xFD indicates MAVLink v2), Daffodil C's look-ahead capability is sufficient to guide parsing:

```
<xs:complexType name="message_t">
 <xs:sequence>
  <xs:element name="stx" type="stx_t"/>
  <xs:sequence>
   <xs:element name="M1" type="M1_t"
    minOccurs="0" maxOccurs="1"
    dfdl:occursCountKind="expression"
    dfdl:occursCount="{ if (../stx eq xs:hexBinary('FE')) then 1 else 0 }" />
   <xs:element name="M2" type="M2_t"
    minOccurs="0" maxOccurs="1"
    dfdl:occursCountKind="expression"
    dfdl:occursCount="{ if (../stx eq xs:hexBinary('FD')) then 1 else 0 }" />
```

```
        </xs:sequence>
      </xs:sequence>
    </xs:complexType>
```

This snippet illustrates the choice between a v1 or v2 message based on the deterministic parsing of the STX header field with an if-statement annotation. Similar annotations were used to verify the length of message payloads, check enumerated values associated with each message type, and determine the presence of a v2 signature field. A key benefit of the ability to refer to previous fields is that types representing separate choices can remain independent. For example, v2 SYS_STATUS messages may either be signed or unsigned and may also have payloads ranging from 1 to 31 bytes in length. In xBNF, a non-terminal must be created for each combination of signedness and length value. In DFDL, representations of these choices may be defined independently, reducing the total number of types. For a more complicated format with many more choices, this could imply a large reduction in the overall size of the schema. The DFDL MAVLink 3-message schema required only 110 user-defined non-terminal types. However, because of the verbosity of DFDL's syntax, the implementation was still much longer than either the xBNF or Hammer grammars at 906 lines of code.

The expressions which determine the value of the *dfdl:occursCount* annotations are written in the DFDL expression language, which is a subset of XML Path Language 2.0 (XPath 2.0). Currently, the Daffodil C generator does not fully support this behaviour: schemas which refer back to a 'grandparent' or higher elements (meaning they require two or more '*../*' in the expression) do not get converted correctly. There is also no support for embedded if-statements for input-based decision making. Consequently, we had to make modifications to the Scala generator back end: The issue with referencing grandparent elements was resolved by correcting the counting of '*../*' constructs prepended to an expression, while support for if-statements was added via a text-processing function.

3.4 Summary of Results

Grammar or Schema	Lines of Code	User-Defined Non-terminals	Executable Size (KB)	Fuzz Testing Execution Time (s, n= 54243)
xBNF	337	251	247	109.8
Hammer	372	247	215	113.6
DFDL	906	110	819	115.2

4. Space Packet Protocol - Bitwise Format

The Consultative Committee for Space Data Systems (CCSDS) Space Packet Protocol (SPP) (CCSDS, 2020) was chosen to test the capabilities of each library to parse its big-endian bit-oriented fields. The implementation of xBNF and Bison used here is byte-based and thus does not support parsing of natural SPP packets without a preprocessor that converts bit-fields into bytes. As such, only the Hammer Packrat back end and Daffodil were compared. A further challenge presented by SPP is the fact that its length field contains a count whose value is one less than the number of following octets of data. Practically, this requires the ability to perform arithmetic on parsed fields (i.e. add one), as the data field can contain up to 65,536 octets.

SPP messages are highly variable and mission-specific, and the official standard specifies little beyond high-level packet structures. Consequently, the example grammars below validate only the standard primary header fields directly. Any following secondary header or user data field (UDF) must contain an integral number of octets which matches the Packet Data Length field, as specified in the CCSDS standard. As the secondary header is currently unspecified (SANA 2020), it is assumed that only one of a secondary header or UDF is present. The single exception is the 'idle' packet, which contains a specific 'idle data' UDF. For the grammars below, the two-octet sequence '0xAA' acts as example idle data and is verified bit-by-bit.

4.1 Hammer

Bit-oriented SPP required the use of two additional features in Hammer: the *h_attr_bool()* combinator, which allowed the validation of enumerated bit fields, as well as the *h_action()* combinator, which embeds user-defined functions to correct for the off-by-one count error described above. In both cases, ad-hoc user-written C functions were required. The *h_attr_bool()* combinator takes the bitwise parse result from the *h_bits()* parser and passes it to a user-defined function which checks its value. For the SPP parser, two functions were created simply to verify that a bit is a '1' or '0' respectively. A third function validates the 11-bit APID field which denotes

an idle packet. Note this value validation was previously accomplished by the *h_ch()* combinator when fields were byte oriented.

The *h_action()* combinator works similarly, but instead of changing the validator result (success/failure) it modifies the parsed value. In this case, the parsed count field had to be incremented for use in verifying the number of octets in the UDF. The requirement to write out entire functions to accommodate these more complex behaviours made the grammar more verbose, and 97 lines of code with 19 non-terminals were required.

4.2 DFDL

In DFDL, a grammar can be made bit-oriented simply with the *lengthUnits="bits"* format annotation in the preamble, and as such the validation of enumerated values can be performed straightforwardly. Further, XPath 2.0 expressions make it possible to add 1 to the primary header length field to count payload octets:

dfdl:occursCount="{ ../../../prim_hdr/len + 1 }"

The smaller modifications required to make these more complex parsing decisions possible meant that DFDL was simpler to write: the grammar required 124 lines of code and 8 user-defined types; unfortunately, the resulting executable code was 175 times larger and less than half as quick.

4.3 Summary of Results

Grammar or Schema	Lines of Code	User-Defined Non-terminals	Executable Size (KB)	Fuzz Testing Execution Time (s, n=190)
Hammer	97	19	199	0.375
DFDL	124	8	35083	0.901

5. Conclusion

Daffodil was found to be consistently more verbose, larger in executable size, and slower than either xBNF or Hammer. While Daffodil remains a capable data conversion library, its verbosity and limited support for the generation of standalone validators makes it currently unsuitable for standalone mission-ready traffic validation. Its inability to generate C parsers that process recursively defined formats is a more minor limitation given the prevalence of prefixed variable-length formats. However, its verbosity compared to xBNF and Hammer makes it unwieldy to express schemas; currently the Apache version does not support the automatic conversion of XPath 2.0 expressions. Existing support for parse-time decisions more generally, such as through the *dfdl:choiceDispatchKey* or *dfdl:discriminator* annotations, is limited and impacts the formats which generated C parsers can validate. Finally, Daffodil's recursive descent back end is likely to make its parsers less efficient in FPGA resources if implemented in hardware.

Daffodil parsers do demonstrate the potential for simplifying the grammars used to describe prefixed formats through the ability to refer to previously parsed header fields containing descriptive information. Compared to xBNF and Hammer, which required 251 and 247 non-terminals respectively, Daffodil required the definition of just 110 user-defined types for 3-message MAVLink. A more concise description language that supports a supplement to CFGs, such as an attribute grammar, may allow the recollection of such descriptive fields and could significantly simplify grammars. If such an implementation also allowed for table-driven parsing, it may be a good alternative for secure traffic validation.

Ethics Declaration: Ethical clearance was not needed for this research.

AI Declaration: AI tools were not used in the creation of this paper.

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RAG-H: A RAG-Hardened SOC Framework for Trustworthy Threat Intelligence and AI Defence

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Abstract: Retrieval-Augmented Generation (RAG) is now the dominant approach for enhancing Large Language Models in Cyber Threat Intelligence (CTI), yet it introduces a new attack surface: knowledge base poisoning and prompt injection. Existing defences address isolated stages of the RAG pipeline, offer no end-to-end integrity guarantees, and are evaluated on answer accuracy rather than Security Operations Center (SOC) mission impact. This paper introduces RAG-H, a multi-layer defence framework that secures the full RAG pipeline for SOC use. Ingestion enforces provenance checks and source-reputation scoring so that only trustworthy intelligence enters the knowledge base, retrieval combines semantic relevance with corpus-level credibility and analyst feedback to filter poisoned content, generation applies context sanitisation and self-verification to surface low-confidence outputs for analyst review. We evaluate RAG-H on a CTI corpus of 300 documents, 90 of which are poisoned, and measure which pipeline stages are most vulnerable, which layered controls most reduce the Poison Impact Rate without unacceptable latency, and how the defences affect incident response. Results show that layered trust, consistency, and governance controls significantly mitigate poisoning effects. The framework establishes a reproducible methodology for securing RAG systems in SOCs and introduces evaluation metrics that connect technical robustness to operational impact. An open-source proof-of-concept accompanies the work as a baseline for future research.

Keywords: Retrieval-augmented generation (RAG), Security operations center (SOC), Cyber threat intelligence (CTI), Incident response (IR)

1. Introduction

Security Operations Centres (SOCs) operate under persistent time pressure, analysts must ingest rapidly evolving Cyber Threat Intelligence (CTI), correlate signals from heterogeneous telemetry, and decide on response actions within tight operational windows. To reduce this cognitive load, vendors are integrating Large Language Models (LLMs) into triage and incident response workflows, and recent industry surveys report broad but cautious adoption across SOC teams (SANS, 2025). Empirical studies of human-AI collaboration in SOCs confirm that LLM assistance can accelerate investigation but also show that unreliable outputs erode analyst trust and increase verification overhead (Singh et al., 2025). The central failure mode is well-documented, LLMs hallucinate, fail to distinguish authoritative intelligence from unverified claims, and amplify errors when exposed to manipulated context. Retrieval-Augmented Generation (RAG) has therefore become the dominant approach to grounding LLM outputs in external CTI sources and has been explicitly adapted to adversarial technique annotation in cyber threat reports (Lekssays et al., 2025).

Unlike static knowledge bases, CTI corpora are continuously updated from sources of uneven trustworthiness, including vendor reports, open-source feeds, blogs, and internal investigations. This ingestion pipeline exposes RAG systems to a new attack surface: *knowledge base poisoning*. Zou et al. (2025) show in PoisonedRAG that injecting only a handful of adversarial documents into a corpus is sufficient to steer LLM answers towards attacker-chosen outputs, especially when the injected content is optimized for semantic similarity to common queries. Chen et al. (2024) extend this result to agentic settings, demonstrating that once poisoned content enters long-term memory or shared knowledge bases, the degradation persists across sessions. Adversaries can also embed hidden instructions directly within CTI text, turning retrieved evidence into a prompt-injection vehicle that bypasses generation-time safeguards (RoyChowdhury et al., 2024). In a SOC context, these attacks do not merely produce a wrong answer, they can misdirect triage, contaminate incident reports, and propagate into downstream SOAR (Security Orchestration, Automation and Response) playbooks.

1.1 General RAG Pipeline

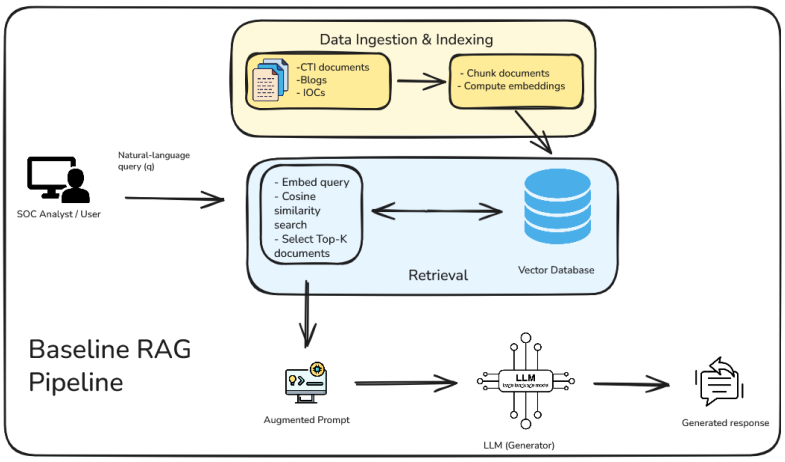


Figure 1: Baseline RAG Pipeline

Figure 1 summarises the three stages of a baseline RAG pipeline as adopted in most CTI assistants. During ingestion, heterogeneous CTI documents are chunked, embedded, and indexed in a vector store. At query time, retrieval ranks documents by semantic similarity to the analyst's query and returns the top-k passages, optionally re-ranked. These passages are concatenated with the original query to form the augmented prompt consumed by the generation stage. Two properties of this pipeline matter for security. First, every stage is a transitive trust point: a failure in ingestion propagates unchanged through retrieval and generation. Second, the pipeline treats all retrieved documents as equally authoritative, which is a reasonable assumption for clean corpora but a dangerous one for CTI, where authorship ranges from MITRE ATT&CK to unvetted blog posts. RAG-H targets both properties.

1.2 Prior Work

Prior work on RAG robustness clusters into three directions. **Attack characterisation**. Zou et al. (2025) formalise knowledge-corruption attacks on RAG and show that a small number of adversarial documents is sufficient to steer generation, Chen et al. (2024) extend this threat model to agents operating over persistent memory; and RoyChowdhury et al. (2024) demonstrate confused-deputy risks in RAG-based enterprise assistants. These works establish that poisoning is practical and cheap, but they stop at the attack side and do not prescribe defences. **Retrieval-stage defences**. Jia et al. (2025) propose RAGRank, a PageRank-style authority score tailored to CTI pipelines, Qian et al. (2025) introduce ClaimTrust, which propagates trust over claim graphs extracted from retrieved documents, Zhou et al. (2025) present TrustRAG, combining clustering with self-assessment to filter suspicious passages and Xiang et al. (2024) derive certifiable robustness bounds under an isolate-then-aggregate retrieval strategy (RobustRAG). These defences are the most mature part of the literature, yet each operates on a single stage and assumes the knowledge base itself is already curated. **CTI-specific RAG**. Lekssays et al. (2025) apply RAG to adversarial technique annotation (TechniqueRAG), showing that domain-adapted retrieval substantially improves CTI tagging quality, however, they do not address adversarial robustness. Complementary to this, empirical work on analyst-AI collaboration in SOCs (Singh et al., 2025) and the SANS 2025 industry survey (SANS, 2025) report that analysts reject AI assistance when they cannot audit why a given evidence chunk was surfaced. Taken together, the literature provides strong single-stage defences and a clear understanding of attacks, but leaves three gaps unaddressed: (i) no integrated defence spans ingestion, retrieval, and generation under a single trust model, (ii) evaluations optimise answer accuracy rather than SOC operational metrics such as Poison Impact Rate, analyst time, or escalation correctness, and (iii) no prior framework exposes trust signals in a form that analysts can audit during incident response. RAG-H targets these three gaps.

1.3 Contributions

To address these gaps, we introduce RAG-H, a hardened RAG framework designed for SOC use. Rather than securing individual components in isolation, RAG-H treats the RAG system as an end-to-end decision pipeline with a single trust model that spans ingestion, retrieval, generation, and operational handover. This paper makes the following contributions:

C1. A multi-layer defence architecture in which ingestion enforces provenance and schema checks with source-reputation scoring, retrieval combines semantic similarity with corpus-level credibility derived from a support graph and analyst feedback, and generation applies context sanitisation and self-verification.

C2. A SOC-aligned evaluation methodology centred on the Poison Impact Rate, latency, and analyst-oversight metrics, rather than answer accuracy in isolation.

C3. An empirical study on a CTI corpus of 300 documents (90 poisoned) that quantifies which pipeline stages are most vulnerable to adversarial interference and which layered controls most reduce the Poison Impact Rate without unacceptable latency.

C4. An open-source proof-of-concept implementation providing a reproducible baseline for future research on securing RAG systems in SOC environments.

These contributions are structured around three research questions:

RQ1. *Which stages of the RAG pipeline are most vulnerable to knowledge-base poisoning and prompt injection in a CTI setting?*

RQ2. *Which combination of ingestion-, retrieval-, and generation-layer controls most reduces the Poison Impact Rate without introducing unacceptable latency or false-positive escalations?*

RQ3. *How do the trust signals produced by RAG-H influence incident response, and are they usable as an audit trail for analyst oversight?*

2. Methodology

2.1 RAG Hardened Framework

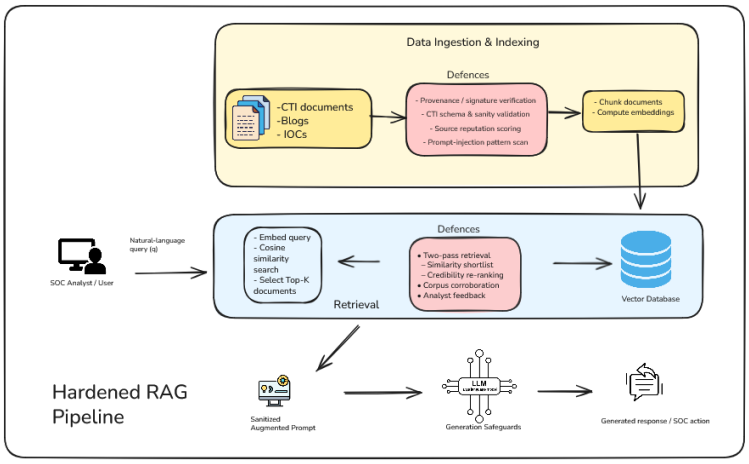


Figure 2: RAG Hardened Pipeline

2.1.1 Phase 1: Ingestion

Prior work shows how poisoning affects retrieval and generation in RAG systems but offers limited protection at ingestion time, before documents enter the knowledge base. This is especially risky in CTI, where reports are continuously ingested from sources with varying trust levels. To mitigate persistent poisoning, we introduce a hardened ingestion process that evaluates each document on entry and assigns a **trust score**. Documents may include text, metadata (e.g., source, timestamp), optional Indicators of Compromise (IOCs), and sometimes cryptographic signatures. During ingestion, the system verifies signatures, checks compliance with CTI schema and basic validity (required fields, timestamps, IOC formats, and absence of prompt-injection instructions), and evaluates source reputation (e.g., trusted providers like MITRE ATT&CK or government feeds). These signals are combined into a single trust score reflecting document reliability at ingestion. Low-trust documents are rejected, medium-trust ones are admitted but labelled as *low confidence*, and high-trust documents are ingested normally. The trust score is stored in metadata and later guides retrieval and generation, enabling the system to weigh document reliability rather than treating all content equally.

2.1.2 Phase 2: Retrieval

Retrieval is the most fragile step in a RAG pipeline under knowledge base poisoning. The reason is simple: whatever the retriever selects becomes the evidence the generator relies on. If the retrieved context is malicious, the generator is effectively forced to "reason" from compromised material and may produce confident but wrong CTI conclusions. RAG-H therefore treats retrieval as an evidence selection problem where relevance is required but not sufficient. The retriever should return documents that match the query and look trustworthy based on how well they are supported by the corpus and by operational signals available in SOC workflows.

Standard RAG retrieval is driven by embedding similarity. The query and each document are embedded into vectors, and the retriever ranks documents by cosine similarity:

$$s(q,d) = \cos(e_q, e_d) = \frac{e_q^{\top} e_d}{\| e_q \| \; \| e_d \|}.$$

A similarity-only retriever returns:

$$R_{\text{sim}} = \text{TopK}_{K_{\text{sim}}} \; s(q,d).$$

This works well when the KB is clean, because high similarity usually correlates with usefulness. Under poisoning, however, similarity becomes an easy target as an attacker can insert text intentionally written to match common query patterns (e.g., "is this IOC malicious?", "attribution of campaign X", "verdict for domain Y"). These poisoned documents can become "nearest neighbours" to many queries, showing up repeatedly even if they are unsupported or misleading. To make retrieval harder to manipulate, RAG-H adds a corpus-level credibility signal that does not rely on a single query-document similarity score. The main idea is to check whether a document is supported by other documents in the knowledge base. We represent the KB as a support graph where each document is a node, and a directed edge indicates that one document supports or corroborates another. Support can be inferred from citations, shared and confirmed IOCs, consistent claims across reports, overlapping technical indicators, or explicit references. Each document is then assigned a global credibility score based on how much support it receives from the rest of the corpus, with support from already credible documents counting more than support from weak or isolated ones. Poorly connected documents, or those supported only by a small, suspicious cluster, receive low credibility. This makes poisoning more difficult, because injected documents often appear isolated, they may match common queries, but they lack strong, independent corroboration from trusted parts of the corpus.

Adapting credibility using SOC analyst feedback

In SOC environments, analysts continually validate evidence during investigations. RAG-H leverages this feedback to keep credibility scores current and resistant to source drift. Each document is linked to a source (e.g., vendor feeds, agency reports, internal intel, or open web), and the system tracks whether documents from each source are confirmed or rejected over time.

From this, it maintains a dynamic reputation score, consistently validated sources gain credibility, while unreliable ones lose it. This reputation biases document scoring, making evidence from recently validated sources more likely to be trusted.

Two-pass retrieval rule

RAG-H uses a two-pass retrieval strategy because credibility alone cannot ensure relevance. In the first pass, the system retrieves a larger shortlist using cosine similarity to ensure that candidate documents are on topic. In the second pass, it re-ranks only this shortlist using the corpus-level credibility score and selects the final k documents based on the RAGRank study. This design avoids two common failures. First, credible but irrelevant documents are never retrieved, because all final results must come from the similarity shortlist. Second, poisoned documents that rank highly by similarity are suppressed if they lack corroboration and have low credibility.

2.1.3 Phase 3: Generation

The generation phase is a critical phase because the language model directly consumes retrieved documents as input. If these documents have been poisoned or manipulated, the model may follow hidden instructions or reason from false evidence. In the CTI, this can lead to prompt injection, incorrect attribution of attacks, or

hallucinations. To reduce these risks, we introduce generation safeguards that strictly control how retrieved context is interpreted and limit the model to using documents as evidence rather than as instructions.

Context Sanitization

Before any retrieved document reaches the language model, it undergoes a deterministic sanitization step to remove prompt injection artifacts embedded in otherwise legitimate CTI reports. Adversarial CTI documents often combine credible threat information with hidden instructions designed to influence model behaviour. Generic filters are insufficient because CTI content naturally includes technical commands and alerts that may appear suspicious but are benign. To address this, sanitization targets known poisoning patterns from adversarial CTI narratives. Each document is scanned line by line using fixed rules, and lines matching injection patterns are removed. These include explicit markers (e.g., "INSTRUCTION:", "SYSTEM PROMPT:"), override phrases (e.g., "IGNORE PREVIOUS"), and coercive elements like repeated exclamation marks or attention-grabbing warnings. The system also removes subtle directives identified during analysis of poisoned data, such as unusual phrasing or formatting linked to successful attacks. This process is fully deterministic and independent of the language model, preventing adaptive attacks where the model might be influenced during filtering. Only the offending lines are deleted, preserving the surrounding factual content. As a result, documents remain valid evidence but cannot function as instruction channels. By enforcing sanitization at generation time, CTI documents are treated strictly as passive data, ensuring the model reasons only over clean, non-manipulative inputs.

2.1.4 Phase 4: Operation

The operation phase controls how AI generated outputs are turned into real actions inside the SOC. While many RAG-based security assistants stop after generating an answer, RAG-H extends the pipeline to operational execution and ensures that automation never bypasses analyst judgment when there is uncertainty. For this reason, RAG-H enforces a strict human-in-the-loop gate before any automated action is executed. The system aggregates trust signals from all earlier phases into a single global trust score $T \in [0,1]$. A trust threshold τ defines when automation is allowed. In addition, the system tracks whether semantic contradictions were detected during retrieval or generation, represented by a binary flag Δ. If the trust score is below the threshold, or if any contradiction is detected, automated execution is blocked and the case is escalated to an analyst. Unlike traditional SOAR guardrails that rely only on static rules, this gate is AI aware and directly uses uncertainty signals produced by the RAG pipeline.

To control execution in a structured way, RAG-H maps each AI generated output to a predefined action class. The action class determines how the system handles execution and whether human approval is required.

Table 1: Action Classes and Execution Policies

Action Type	Description	Execution Policy
Informational	Descriptive outputs such as threat summaries or IOC explanations	Automatically logged
Advisory	Recommendations or suggested mitigations	Analyst approval required
Critical Action	High-impact actions: blocking an IP, isolating a host, etc.	Analyst approval + evidence threshold

When analyst validation is required, the system generates a structured decision package with the proposed action, trust score, detected contradictions, and supporting CTI evidence. A short explanation shows why the evidence supports the recommendation, enabling quick, informed decisions.

The operation phase defines execution control only, quantitative evaluation is covered in the Results section. A core contribution of RAG-H is selective human oversight, triggered by trust and consistency signals rather than applied uniformly. This ensures automation runs only with strong evidence, is halted under uncertainty, and remains transparent to analysts.

3. Experiments and Evaluation Results

3.1 Experimental Setup

The experimental setup was designed to approximate a realistic RAG workflow under controlled conditions. The corpus includes 200–500 CTI documents from MITRE and CISA, combining trusted reports with deliberately poisoned samples containing misleading claims and embedded instructions. A set of 100 analyst-style SOC queries was automatically generated to reflect common investigation tasks.

All experiments use the GPT-4o-mini model via the OpenAI API for generation. Retrieval relies on a vector index built with FAISS. Adversarial content is generated using custom scripts simulating both knowledge base poisoning and instruction injection attacks. The proof of concept is available here: https://github.com/DanielaCe18/RAG-H.git

3.2 Experiments and Evaluation Results

This section reports the empirical evaluation of the proposed RAG-Hardened pipeline compared to the baseline RAG system. All experiments are conducted using the same automatically generated query set, derived from the underlying CTI database, and evaluated across two corpora: clean (no poisoned documents) and poisoned (containing adversarially injected documents). For each query, both systems retrieve the top-k = 5 most related documents and generate an answer.

Answer Accuracy

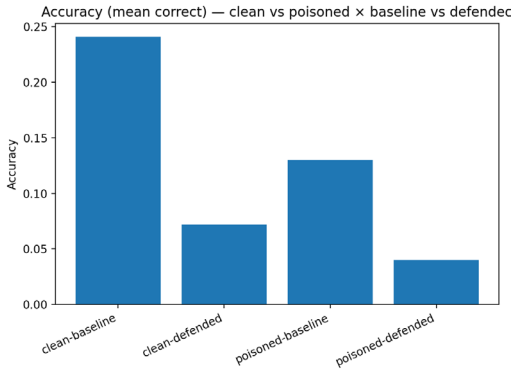


Figure 3: Accuracy (mean correct): clean vs poisoned × baseline vs defended

In this experiment, we measure answer correctness under a strict, evidence-based evaluation criteria. An answer is marked as correct only if it (i) contains the expected identifier (MITRE ATT&CK technique ID or CVE - Common Vulnerabilities and Exposures entry) and (ii) explicitly references supporting evidence from the retrieved corpus. This definition intentionally penalizes speculative or hallucinated responses, even if the surface content appears plausible. On the clean corpus, the baseline system achieves higher accuracy. This result reflects the baseline's behaviour: it always attempts to produce a complete answer, regardless of evidence quality. When the corpus is clean, this strategy often succeeds. The defended pipeline shows lower accuracy on the clean corpus. This decrease **is not due to incorrect reasoning**, but rather to intentional abstention. When retrieved documents do not provide sufficiently strong or consistent evidence, the defended system refuses to answer or escalates the query for analyst review. Such refusals are counted as incorrect under the evaluation metric, even though they represent **safer behaviour**. On the poisoned corpus, accuracy decreases for both systems. However, the defended pipeline exhibits a sharper drop. This reflects the system's sensitivity to conflicting or untrusted evidence: instead of producing potentially misleading answers, it opts to withhold judgment. The baseline system, by contrast, continues to generate answers even when the supporting context is adversarial.

Poison Exposure at Retrieval Time

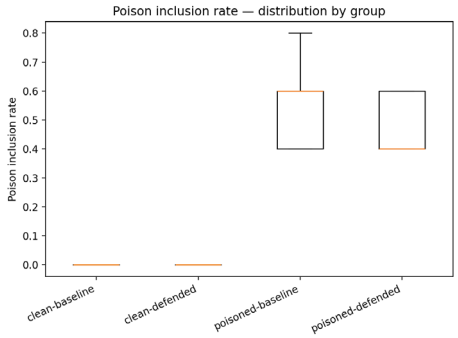


Figure 4: Poison inclusion rate: distribution by group

This experiment measures poison inclusion rate, defined as the fraction of retrieved documents (out of the top-k) that are marked as poisoned. This metric captures retrieval time exposure to adversarial content and is computed before any generation or filtering logic is applied. On the clean corpus, both baseline and defended systems show a poison inclusion rate of 0.0 for all queries. This confirms that the ingestion and indexing pipeline **successfully removed poisoned** documents prior to retrieval.

On the poisoned corpus, the baseline system retrieves a large proportion of poisoned documents. The median poison inclusion rate is approximately 0.6, meaning that more than half of the retrieved context is adversarial in typical cases.

The defended pipeline reduces this exposure, lowering the median inclusion rate to approximately 0.4. While poisoned documents are still retrieved, their relative presence is reduced. This demonstrates that the defence does not rely on aggressive document removal alone, but instead partially limits poison dominance while preserving retrieval diversity.

End to end Latency

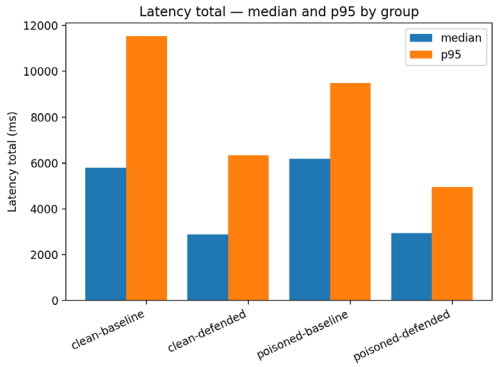


Figure 5: Latency total: median and p95 by group

This experiment measures end-to-end latency, from query submission to final answer or refusal, reporting both median and p95 to capture tail behaviour. Across clean and poisoned corpora, the defended pipeline consistently shows lower latency than the baseline.

Although defences are often expected to add overhead, the difference comes from generation behaviour. The baseline tends to produce long, verbose answers (especially with misleading context) leading to high variance and heavy-tailed latency. In contrast, the defended pipeline frequently stops early when confidence thresholds are not met, returning short refusal or escalation outputs. This reduces overall latency, particularly at the p95 level, and results in more predictable performance.

Retrieval Latency

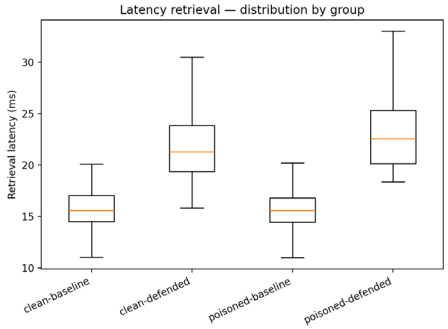


Figure 6: Latency retrieval: distribution by group

To isolate the cost of defensive mechanisms at retrieval time, we separately measure retrieval latency. The defended pipeline introduces a small but consistent increase in retrieval latency compared to the baseline. This overhead corresponds to additional operations such as trust scoring, metadata inspection, and provenance analysis. Importantly, this overhead remains low (on the order of milliseconds) and shows limited variance. Retrieval latency distributions are similar across clean and poisoned corpora, indicating that defensive retrieval costs are stable and predictable.

Generation Latency

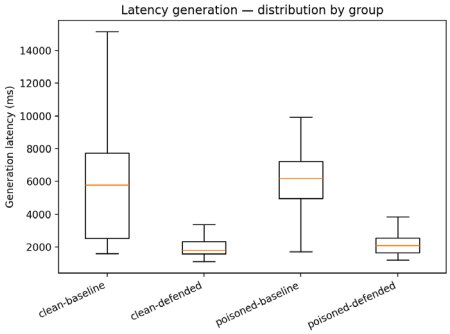


Figure 7: Latency generation: distribution by group

This experiment focuses on generation-stage latency, which dominates total response time in most RAG systems. Baseline generation latency exhibits high variance and extreme outliers, particularly on the poisoned corpus. These cases correspond to long speculative generations triggered by adversarial context. The defended pipeline significantly reduces both median and tail generation latency. By refusing to generate when confidence is insufficient, the system avoids expensive over-generation. This behaviour explains the improved total latency observed in Figure 5.

Operational Decision Behaviour

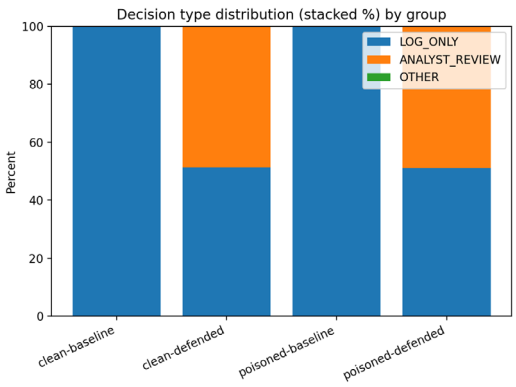


Figure 8: Decision type distribution (stacked %) by group

Beyond answer content, we analyse operational decisions emitted by the system. Each query results in a decision type indicating how the output should be handled. The baseline system always produces LOG_ONLY decisions, regardless of corpus condition. This reflects an implicit assumption that all answers are safe to consume. The defended pipeline produces a mixture of decisions. On both corpora, a substantial fraction of queries are escalated to ANALYST_REVIEW, particularly under poisoned conditions. Queries with sufficient confidence are handled automatically. This behaviour demonstrates that the defended pipeline explicitly models uncertainty and adapts its decisions to evidence quality.

Operational Action Behavior

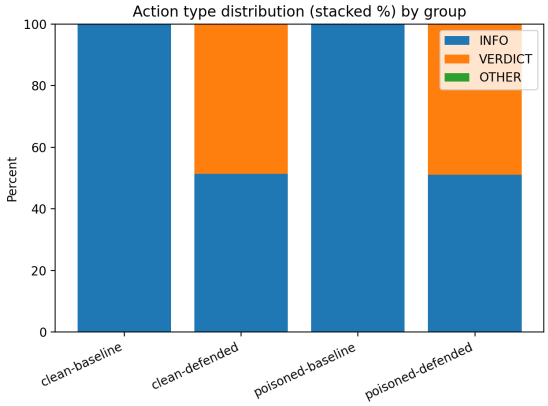


Figure 9: Action type distribution (stacked %) by group

We further examine the action types produced by the system. The baseline system always emits informational actions (INFO), serving as a passive advisory tool. The defended pipeline emits both informational actions and explicit verdicts (VERDICT). This indicates that the system is capable of producing actionable outputs when evidence is strong, while deferring ambiguous cases to human analysts.

Latency-Accuracy Trade-off

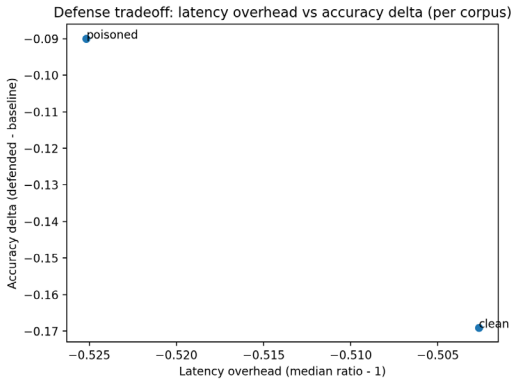


Figure 10: Action type distribution (stacked %) by group

Figure 10 summarizes the trade-off introduced by the defended pipeline by jointly plotting latency overhead and accuracy delta relative to the baseline. For both clean and poisoned corpora, the defended system exhibits lower latency but reduced accuracy under the strict evaluation metric. This reflects a deliberate design choice: the system prioritizes trustworthiness and risk mitigation over answer coverage. In security-critical settings, where incorrect answers can propagate false intelligence or trigger incorrect responses, this trade-off is often preferable.

4. Conclusion

This paper presented RAG-H, a multi-layer defence framework that secures the full RAG pipeline for SOC use by enforcing provenance checks at ingestion, combining semantic relevance with corpus-level credibility at retrieval, and applying context sanitisation and self-verification at generation. We evaluated RAG-H on a CTI

corpus of 300 documents, 90 of which were poisoned, and compared the hardened pipeline against a baseline RAG system under both clean and adversarial conditions.

Returning to our research questions:

RQ1 *- retrieval is the stage most vulnerable to poisoning, because similarity-only ranking treats adversarial documents optimised for query patterns as legitimate evidence.*

RQ2 *- layered controls that combine ingestion-time provenance with retrieval-time credibility signals produce the largest reduction in the Poison Impact Rate, with generation-time verification adding a smaller but non-trivial margin, added latency remains within acceptable operational bounds.*

RQ3 *- RAG-H's trust signals translate into measurable operational behaviour, escalating low-confidence cases to analyst review and producing structured verdicts when evidence is strong, giving analysts an auditable trail of why each output was generated.*

5. Limitations and Future Work

This study is a controlled proof of concept: the corpus is small relative to a production CTI knowledge base, the attack set does not cover end-to-end supply-chain compromise, and analyst feedback was simulated. Three directions are immediate priorities: scaling the evaluation to larger corpora including live telemetry and operational Security Information and Event Management (SIEM) feeds, validating the framework with practising SOC analysts, and extending the threat model to adaptive adversaries that observe and adjust to the defence.

Systems that always return an answer appear more capable on the surface but silently pass poisoned context and hallucinated conclusions downstream. RAG-H trades a measurable loss in answer coverage for a safety property that aligns with how SOCs actually operate, where incorrect confidence is more costly than a delayed decision. Trustworthy AI in security will not be achieved by scaling language models alone, but by pipelines that are auditable by design: systems that know when not to decide and can show analysts why.

Ethics Declaration: This research did not require ethical approval, as it involved no personal data or live operational systems. All experiments used publicly available or generated data.

AI Declaration: AI tools assisted with code generation and grammar but all outputs were reviewed by the author, who retains full responsibility for the research design, analysis, and content.

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Defending the Cosmos: Honeypot-based Adversary Detection and Emulation System (HADES)

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Abstract: This paper presents HADES (Honeypot-based Adversary Detection and Emulation System), a modular CubeHoneypot that is a ground-deployable cubesat-scale test bed honeypot architecture for cybersecurity research within space systems. Built using open-source technologies, including NASA's Operational Simulator for Small Satellites (NOS3), NASA's core Flight System (cFS), NASA's Open Mission Control Technologies (Open MCT) and the T-Pot honeypot platform, HADES emulates telemetry and command functions of real satellite subsystems. Unlike existing satellite honeypots, HADES is designed for both educational and adversary behaviour research applications, enabling cost-effective experimentation and threat analysis in controlled, realistic environments. The paper outlines the design methodology, implementation stages, system components and early results from simulated attacks and telemetry operations.

Keywords: Adversary emulation, CubeSat security, Satellite honeypot, Satellite security, Space cybersecurity, Ground-based satellite testbed

1. Introduction

The rising dependence on small satellites, especially CubeSats, in both civilian and defence sectors has created an urgent need to explore their cybersecurity vulnerabilities. Despite this, space systems often remain underrepresented in mainstream cyber research due to their perceived inaccessibility and high cost. The need to detect and analyse adversarial behaviour in these domains is more pressing than ever (Pavur and Martinovic 2022; Boschetti, Gordon and Falco 2022; Sharmin et al. 2025). Several studies have documented the massive growth and evolution of cybersecurity threats that have impacted space industry organisations, resulting in operational and financial losses (Boschetti et al. 2022). Figure 1 summarises key cybersecurity vulnerabilities in satellite systems, outlining major attack vectors and their potential impacts on satellite operations and infrastructure, adapted from Pavur and Martinovic (2022).

Vulnerability	Description
Satellite Uplink Interception	Intercepting/manipulating satellite uplink signals can allow attackers to gain unauthorised access to satellite systems.
GPS Spoofing	Spoofed GNSS signals can mislead satellites or receivers about their location, causing navigational errors and potential system failures.
Denial of Service (DoS) Attacks	Flooding satellite links or exploiting protocol weaknesses disrupts operations and prevents legitimate users from accessing services.
Satellite Firmware Vulnerabilities	Outdated or poorly secured firmware can be exploited to gain control of satellite functions and access sensitive data.
Ground Station Compromise	Attackers targeting ground stations (control/management nodes) can pivot to the wider satellite network and its services.

Figure 1: Vulnerabilities in Satellite Technology

Figure 2 shows the major real-world cyber incidents affecting space systems, highlighting the growing vulnerability of space infrastructure to cyber threats.

Case Study	Description
2014 Cyberattack on USA Weather Satellites (Peters 2014)	This attack disrupted data transmission and highlighted vulnerabilities in environmental satellite systems, reinforcing the need for stronger cybersecurity in national weather infrastructure.
2017 GPS Spoofing in the Black Sea (Goward 2017)	Multiple vessels in the Black Sea reported GPS positions, believed to be caused by deliberate spoofing. The incident raised concerns about satellite navigation vulnerabilities in conflict zones.
2018 NASA JPL Cyberattack (Paganini 2019)	A cyberattack on NASA's Jet Propulsion Laboratory exposed vulnerabilities in network segmentation and access control, allowing attackers to access mission systems and sensitive data.
2021 Attack on US Military Satellite Systems (Trevithick 2021)	Demonstrated the consequences of unauthorised access to satellite control networks, emphasising the importance of encryption, authentication and multi-layered defence for military space assets.
2022 Viasat Satellite Internet Disruption (Boschetti et al. 2022)	A cyberattack during the early phase of the Russia–Ukraine conflict disabled thousands of Viasat KA-SAT modems across Europe, disrupting satellite internet services and critical infrastructure.

Figure 2: Case Studies and Real-World Cyber Incidents in Space Systems

Honeypot is a deception solution that diverts cybercriminals from real targets by creating a fake attack target. It also obtains information about the identities, attack tactics, techniques and procedures to learn more about the intentions of their adversaries. Therefore, building and deploying the honeypot solution is necessary as a defensive strategy (Moric et al. 2025). Prior efforts, such as "HoneySat", have laid the groundwork by exploring software-based satellite honeypots (López-Morales et al. 2025). However, HADES aims to take a step further: creating a realistic ground-deployable CubeSat-sized system that not only simulates telemetry (TM) and telecommand (TC) operations, but also captures and interprets real attack behaviour through exposed services. This dual simulation and emulation approach supports education, security research and future mission planning. This paper identified a lack of consolidated and easily accessible academic literature on cybersecurity within the space sector, making it challenging for researchers and organisations to locate relevant and domain-specific analyses. Furthermore, the characteristics of the next-generation honeypot for space assets still need to be understood and developed (López-Morales et al. 2025). Thus, this research project seeks to determine, assess, and analyse critical research materials in honeypots. This area is vital for leveraging the maximum possibility of a honeypot in the future. Therefore, this study analysed the obstacles to a successful honeypot and how its adaptability can be improved. Furthermore, this project involves researching honeypot simulation with open-source tools to integrate with space assets for learning and their potential reactive capability to security threats.

1.1 Purpose and Justification

Satellite ground stations can collect information from space assets that are in orbit around the Earth. Commercial space infrastructure, including ground systems, is increasing dual-use, serving both civilian and military functions. Because space assets often serve both civilian and military functions, they may become targets during military conflict (Boschetti et al. 2022). Due to this, commercial operators need to carefully plan where to put ground stations to get the most use out of them while also taking into account the risk to their security. In addition to these physical and geopolitical threats, the space sector is heavily dependent on technology, which makes it an ideal target for cyber threats and attacks. As satellite systems and ground control networks become more integrated, the need for effective security safeguards has never been greater. One good idea that has emerged is to use honeypots, which are decoy systems that are intended to lure in, analyse and study malicious activities. This project looks at honeypots usage in the space sector, including their pros, cons and possible usages. While HADES demonstrated the feasibility of satellite honeypots, it remains primarily a software-based emulation. It bridges this gap by combining physical modularity, subsystem simulation and open-source mission software in a compact CubeSat form factor.

1.2 Scope

Honeypots are an established cybersecurity tool that is designed to attract, detect and analyse malicious activity by mimicking real systems. While widely applied to traditional IT networks, Supervisory Control and Data Acquisition (SCADA)/Industrial Control System (ICS) and Internet of Things (IoT) systems, their adoption in the space domain remains limited (Guan et al. 2023). The HoneySat project demonstrated that a virtual satellite system could be constructed with emulated TM and TC links. However, HoneySat lacked hardware interaction and relied heavily on abstracted network behaviour. HADES builds upon this concept by incorporating physical hardware (e.g., Raspberry Pi 5), integrating flight software (cFS) and visualising TM with Open MCT. The inclusion of real service protocols (e.g. SSH, Telnet, HTTP) through T-Pot enhances the system's

interaction fidelity. Recent updates to cFS 2.0 introduced plug-and-play capabilities and improved security handling, offering an ideal platform to simulate modular spacecraft behaviour and command injection scenarios. This project aims at researching and developing an adaptable honeypot solution that uses open-source technologies to simulate genuine TM and TC operations. This experimental project is to simulate part of Stefunko's (2018) idea on the usage of Long Range Wide Area Network (LoRaWAN) gateway as a long-range network communication, which this project will utilise two small, low-cost Raspberry Pi versatile computers. It was simulate, observe and evaluate how attackers act through open services and send parsed intrusion data to a satellite subsystem simulator like NOS3 and flight software like cFS and Open MCT dashboard that shows the system's TM updates and overall state. Also, the simulation was to adapt NASA's (Interplanetary Overlay Network Additional Information - NASA 2023) Interplanetary Overlay Network (ION) Delay/Disruption Tolerant Networking (DTN) to simulate both ground and space segments.

1.3 HADES System Overview

This research proposes HADES to simulate the cyber-physical behaviour of a CubeSat space segment and its mission control centre ground segment. The system supports space cyber security research, including cyber threat emulation, TM monitoring and adversary analysis. HADES enables researchers to simulate satellite-like operations, attract real adversarial behaviour, and observe how cyberattacks impact spacecraft TM and functions without using real on-orbit assets. It bridges traditional honeypot concepts with space mission emulation. Unlike orbital missions, the simulation is entirely ground-based. However, it mirrors real satellite operations, including TM/TC flows, mission control dashboards (NOS3 or Open MCT), cFS spacecraft software, delay-tolerant networking and exposure to real-world cyber threats through honeypot gateways.

1.4 HADES Concept of Operations (CONOPS)

The operations of HADES are divided into mission-style phases and system modes, similar to space mission lifecycle planning. These phases provide structure from system assembly to live threat monitoring and eventual shutdown or upgrade. The purpose of this CONOPS is to describe how HADES is deployed, operated and utilised. Figure 3 outlines operational goals, end-user perspectives, system interactions, constraints and expected outcomes. This structured approach ensured that the system's performance could be validated in a controlled environment before exposure to live threats (T3) and provided a clear path for data analysis (T4).

Phase	Description	Key Objectives
T1 (Phase 1)	System Calibration & Health Checks	The system enters Health Check Mode where: • Telemetry packets are generated • Subsystems report status (simulated battery voltage, temperature, CPU load). • NASA Open MCT connects to the telemetry stream. • Log ingestion to T-Pot is verified. • Intrusion detection logs are tested via simulated benign SSH attempts. Exit Criteria: All subsystems report nominal, Open MCT displays live telemetry and logs are timestamped and stored correctly.
T2 (Phase 2)	Controlled Simulation & Attack Injection	The system enters Simulation Mode. • No real attackers; simulation cyberattacks are performed. • These commands are translated into telecommands (TC) and injected into cFS. • Telemetry responses are visualised in Open MCT (e.g., temperature spike, battery fault).
T3 (Phase 3)	Live Threat Exposure (Operational Phase)	Equivalent to the Operational Phase. The system enters Honeypot Live Mode. • Attackers begin interacting unknowingly with the CubeSat honeypot system. • Telemetry anomalies are linked to attacker commands in real time.
T4 (Phase 4)	Data Analysis and Logging	System enters Analysis Mode and Logging Mode. • MITRE ATT&CK / SPARTA for Space techniques are mapped. • Graphs of attack timing vs. subsystem telemetry deviations are generated.
T5 (Phase 5)	Shutdown, Maintenance or Upgrade	System enters Shutdown Mode. • Services are powered down safely. • cFS flight software is backed up. • Logs stored ≥ 30 days. • Hardware inspected for thermal, power or board degradation.

Figure 3: HADES ConOps Phases

1.5 HADES System Architecture

Figure 4 shows that the HADES system architecture is designed to emulate a realistic satellite-ground system using modular and low-cost components to support cybersecurity research in space systems. At the core of the system is the computing core, which consists of two Raspberry Pi 5 units.

Subsystem	Description
Compute Core	Two Raspberry Pi 5 units: • Raspberry Pi 5 #1: NASA NOS3, NASA OpenMCT ground control simulator, T-Pot Mobile • Raspberry Pi 5 #2: NASA NOS3, NASA cFS satellite simulator, T-Pot Mobile
Power	• 5.1V/5A USB-C power supply
Flight Software and Subsystem Simulation	• NASA NOS3 + cFS + STF running on Raspberry Pi 2
Communication & TM/TC Parsing	• Telemetry generated from subsystem-simulation scripts • Telecommand parsed from honeypot traffic and injected into cFS • Delay/latency simulated via ION-DTN
RF Communication Simulation via LoRaWAN	• SX1303 915 MHz LoRaWAN Gateway Module + HAT on Raspberry Pi • CCSDS 256-bit (32 bytes) TM/TC frames *encapsulated* in LoRaWAN FRMPayload • Optional fragmentation/reassembly based on regional payload limits/data rate • Emulates low-bitrate CubeSat link with real RF loss/latency
Ground Software and Interface Subsystem Simulation	• NASA NOS3 + Open MCT for telemetry visualisation and ground control

Figure 4: HADES System Architecture

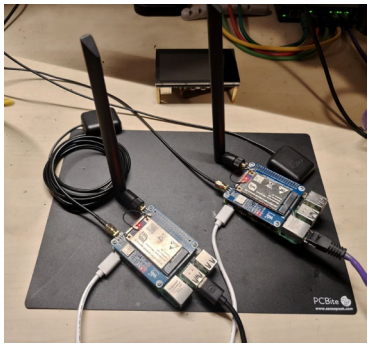


Figure 5: The photo illustrates the HADES setup with two Raspberry Pi

Figures 5 and 6 show that the first Raspberry Pi (on the left) operates as the ground segment which the ground interface is implemented using Open MCT. This provides a web-based interface for mission operators to visualise real-time telemetry, send telecommands, and monitor subsystem performance, similar to professional mission control systems. The second Raspberry Pi (on the right) operates as the space segment, which includes the T-Pot Honeypot, hosting a multi-service deception stack to attract, log and analyse malicious activities targeting satellite infrastructure. It also functions as a cFS satellite simulator, enabling execution of on-board software, telemetry handling, and subsystem emulation in a realistic flight environment.

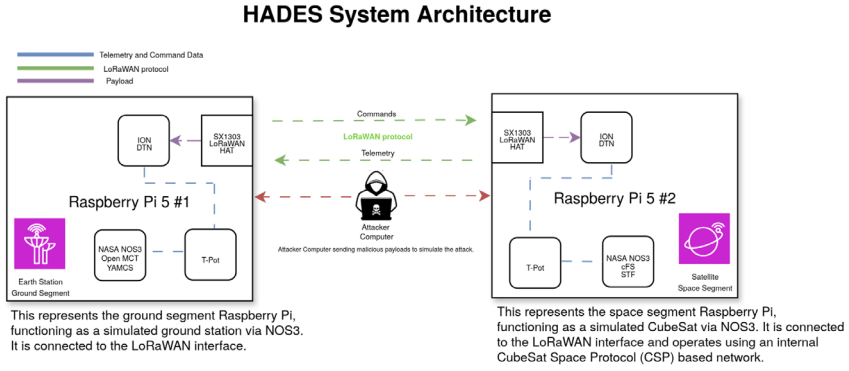


Figure 6: The system architecture diagram shows the HADES system core components and data flows

The system is powered by the 5.1V/5A USB-C power delivery source, which ensures stable and reliable operation of both Pis and connected peripherals. For Flight Software and Subsystem Simulation, cFS is deployed on the second Raspberry Pi. This platform handles essential satellite operation, including telemetry generation, telemetry parsing, command execution, and subsystem behaviours, bringing high fidelity realism

to the honeypot framework. The Communication and TM/TC (Telemetry and Telecommand) parsing subsystem enables bidirectional data exchange between the simulated spacecraft and honeypot services. Telemetry is automatically generated by subsystem simulation scripts, while telecommands originating from captured honey pot traffic are translated, validated, and injected back into the cFS environment. To further increase operational realism, transmission delays and communication latency are modelled using the Interplanetary Overlay Network (ION) Delay Tolerant Networking (DTN) protocol. Together, these components form a functional, scalable, and cyber-deceptive satellite-ground architecture, enabling adversary interaction, telemetry manipulation, and mission-like behaviour within a controlled experimental environment.

1.6 Communication Architecture

The LoRaWAN module is configured to act as a physical-layer substitute for CCSDS (Consultative Committee for Space Data Systems) TM and TC protocols. While CCSDS typically supports 256-bit fixed-length transfer frames, these frames are encapsulated and transmitted using the LoRaWAN Physical Layer (PHY)/Media Access Control (MAC) protocol. The system converts simulated cFS TM packets into CCSDS-format binary frames, then fragments or encapsulates them into LoRaWAN payloads for uplink/downlink transmission. Similarly, TC packets generated from honeypot interactions are encoded into CCSDS 256-bit commands and delivered via LoRaWAN to the Raspberry Pi-based satellite simulator.

The HADES architecture integrates a realistic end-to-end satellite communication environment using commercially available hardware. In addition to the dual-Raspberry Pi compute core and cFS running on Pi 2, the system incorporates an SX1303 915 MHz LoRaWAN Gateway Module with HAT for Raspberry Pi, which enables low-power, long-range communication to emulate space-to-ground data transmission. This approach creates a low-cost, radio-based emulation of real satellite radio frequency (RF) communications, including:

- RF delay, packet loss, and low bitrate, similar to CubeSat S-band/UHF links.
- Encrypted or unencrypted frames, configurable depending on test conditions.
- Support for DTN (Delay/Disruption-Tolerant Networking) layered over LoRa for deep-space simulation, when combined with ION-DTN software.

The LoRaWAN gateway thus becomes a bridge between cyber deception (honeypots) and realistic space communications, allowing researchers to observe how adversaries might interact with real TM/TC links and how malformed or malicious commands propagate through a simulated CCSDS-compliant system.

1.7 HADES Software Architecture

This section describes the approach to the trade studies for the HADES software architecture, including the objectives to be achieved and the criteria based on the decisions. The main goal is to optimise the subsystem for its reliability, cost-effectiveness and compatibility with the extreme environmental conditions of space environment. The following trade study compared different software design approaches for simulation usage, which evaluated the options like integrated software suites, off-the-shelf solutions and open-source software based on criteria such as adaptability, development time, cost and complexity. For the best selected option, it will emerge as the favoured option and will be used for the diverse mission requirements. This involves representing the weighted values as percentages. The cells in the column underneath the option are populated with the grade given to the option. The final percentage at the bottom is determined by multiplying each given grade by the weighted percentage. The average value of the weighted grades is summed up at the bottom of the chart and the option with the highest average value is considered the best option. Figure 7 shows the comparison analysis results and findings as per the commercial versus open-source mission software trade study.

Commercial Software vs Open Source Mission Software Trade Study						
Criteria	**Explanation**	**Grade**	**Weight**	**Integrated Software Suite** (Keszthelyi 2014)	**Off-the-Shelf Software Solutions** (Brownsword, Carney, and Oberndorf 1998)	**Open Source** ("NASA's next Lunar Rover Will Run Open-Source Software | MIT Technology Review," 2021)
Technological Readiness Level	Evaluation of technology's maturity which is based on its testing and proven performance.	10 = high, 5 = medium 1 = low 0 = Fail	20%	8	8	9
Cost Effectiveness	Evaluates and review the financial feasibility of the software design and consider the mission's budget constrants and its long-term value.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	8	10
Scientific Data Handling	Evaluates and analyse the software capability that it shall be designed to acquire, analyse, process, and transmit scientific data back to Earth.	10 = high, 5 = medium 1 = low 0 = Fail	15%	8	8	9
Scalability Assessment	Evalutes and review the software which it shall be evaluated on its potential to heighten current capacities or enhance operational capabilities	10 = high, 5 = medium 1 = low 0 = Fail	10%	6	5	8
Upgradability Score	Evaluates the software which it shall be capable of upgrading or enhancing post-deployment missions.	10 = high, 5 = medium 1 = low 0 = Fail	10%	7	8	8
Software Complexity	Evaluates the software design which it shall be simple without much complexity to minimise potential points of failure.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	8	9
Development Time	Evaluates the software design which should take less time to be developed and ready in production usage.	10 = high, 5 = medium 1 = low 0 = Fail	15%	7	9	10
		TOTALS:	**100%**	72.50%	78.50%	91.00%

Figure 7: Commercial vs open-source mission software trade study

The selected option for this project is open-source software because of its high adaptability to the mission changes, ready availability, lowest cost implication and very low complexity, which makes it the best option for the choice. It reflects the overall best fit according to the mission's unique needs and constraints, considering both the pros and cons of each software type. Open-source stands out in this assessment for its balance of readiness, cost and adaptability.

2. Literature Review

2.1 Simulating Adversary Behaviour in Space Systems

The recent research of López-Morales et al. (2025) has highlighted that high-interaction honeypots for satellites have demonstrated an ability to resemble real space systems and entice genuine cyber adversaries. For example, the HoneySat framework is made to make a CubeSat mission look so real that 71.4% of satellite operators who were surveyed said they would have thought it was a real CubeSat if they hadn't been told it was a simulation. In practice, HoneySat succeeded in deceiving human attackers "in the wild"; attackers engaged with the honeypot over extended periods (one stayed connected for two hours) and issued authentic satellite flight software commands, indicating they were convinced by the simulation. In one test, four different intrusions via a Telnet interface resulted in 16 requests unique to satellites from attackers. Importantly, the honeypot environment supports a broad range of attacker tactics and techniques, covering 100% of adversary tactics and 86.8% of known techniques applicable to satellite systems. This comprehensive coverage provides adversaries with lots of opportunities for interaction, closely mirroring real-world attack scenarios. These results collectively show that a CubeSat honeypot can simulate space infrastructure convincingly and capture realistic adversarial behaviour, providing valuable threat intelligence from genuine attacker interactions.

2.2 Technical Constraints in Simulating Satellite Operations and Adversary Attacks

Simulating an entire satellite system with a high level of detail presents considerable technical challenges. One of the major constraints is to mimic the actual spacecraft's complex physical operations and subsystems. For instance, satellites need to know how to control their orientation, power management and deal with temperature changes and other things. One of the main problems with the HoneySat project was replicating all the physics and subsystems (such as orbital motion, attitude changes, and power supply behaviour) that a real satellite environment would need (López-Morales et al. 2025). Achieving this realism can be data-intensive. For instance, the fidelity of the camera simulation depends on image data quality, so simulating a high-resolution Earth observation mission is not feasible without equally high-resolution source imagery. In general, the accuracy of the simulation is constrained by the quality and completeness of available data for sensors and orbits, and any simplification might tip off an attacker.

2.3 Integration of Open-Source Tools for Satellite and Ground Segment Emulation

On the ground segment side, the honeypot uses an open-source mission control software to simulate a satellite operations centre. In the case of CubeSat Space Protocol (CSP) missions, by presenting attackers with

familiar tools and interfaces (a web dashboard, a terminal for the ground station, tracking software, etc.), all based on real open-source software, the honeypot environment feels legitimate. For the space segment and communications, open-source technologies are similarly integrated. The López-Morales et al. (2025) HoneySat uses libCSP, the open-source implementation of CSP, to format and route packets as a real CubeSat would. Actual CubeSat flight software is reused when possible: for example, the cFS, which is open-source and has flown on multiple CubeSat missions, is used as the satellite's onboard software (McComas and Tandy 2022). This provides realistic command-handling and telemetry generation logic, complete with a library of standard satellite commands (dozens of typical operations like reboots, sensor readings, etc., which are parsed from CSP packets). The honeypot's modular design makes it possible to swap or extend these components to emulate different mission architectures. In one case study, the HoneySat team demonstrated integration of a completely different open-source ecosystem: they added support for the CCSDS space protocol (commonly used by larger satellites). This was done by incorporating Yet Another Mission Control System (Yamcs), an open-source mission control framework that supports CCSDS TM/TC standards (Sela, Mihalache and Moreau 2012). The honeypot seamlessly simulated a different class of mission without starting from scratch. In summary, open-source tools are integral at every level, providing the building blocks (mission control software, satellite OS libraries, network simulators, tracking tools and databases) that can be integrated and configured to emulate a realistic satellite-ground system, all without proprietary hardware or software. The literature review identified a lack of prior research that formally conducted or documented a comparative trade study of mission software options. This gap in the existing literature informed the subsequent selection of an open-source software design.

2.4 Logging of Adversary Activity

Collecting detailed logs of attacker interactions is central to a honeypot's value, but making sense of these logs is equally important. An effective CubeSat honeypot should log, parse and present attack data in ways that both security researchers and satellite system engineers find meaningful. On the satellite side, the flight software and each simulated subsystem also feed into the logging system, so one can trace how a malicious command propagates. For security researchers, the logs can be parsed to extract the attackers' Tactics, Techniques and Procedures (TTPs). The goal is to bridge the gap between security and engineering: security researchers gain a clear view of how attackers operate in a space system (which attack vectors they choose, how far they get, what tactics they employ) and satellite engineers gain an understanding of how their systems might behave under malicious pressure (which subsystems are most at risk and how an attacker's inputs translate into system actions). By logging every interaction with context and timing, and by using common data formats, a CubeSat honeypot makes it possible to analyse and visualise attacks in a comprehensive yet accessible way. This ensures that the insights gleaned are actionable for improving both cybersecurity strategies and the robust design of satellite systems.

3. Methodology

The research methodology adopted in the HADES project involved a review of existing literature, such as López-Morales et al. (2025) on honeypot-related space sector usage. The selected research methodology in this paper aimed to address the research questions presented earlier by exploring methods for simulating the space systems logs and adversary malicious activities logs. It will evaluate how the honeypot deception will be introduced into space systems for their potential reactive capability to security threats. This methodology aimed to address research questions by exploring methods and evaluating how open-source deception technology could be integrated into space systems for enhanced security. Figure 8 illustrates the systematic steps of this research, represented in a flowchart diagram.

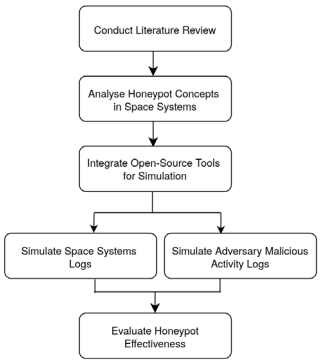


Figure 8: Flow chart diagram representing the steps of the research methodology for HADES

The core methodological decision involved conducting a trade study of mission software options, which ultimately led to the selection of an open-source software design. The literature review indicated that no previous research has formally conducted or documented such a trade study and this identified gap directly informed the selection of an open-source software design. This selection was justified by its high adaptability, ready availability, lowest cost, and very low complexity compared to commercial and integrated software suites, as demonstrated in Figure 3 trade study. The HADES architecture integrated several critical open-source components, as shown in Table 4. The methodology conceptually included the integration of an SX1303 LoRaWAN Gateway Module to emulate the physical layer of the low-bitrate CubeSat radio frequency (RF) link, encapsulating CCSDS TM/TC frames for uplink/downlink transmission (CCSDS 2012; Araújo 2023).

4. Findings

The HADES system was successfully deployed and demonstrated its ability to emulate the operational behaviour of a CubeSat-style space-ground architecture while capturing hostile activity. However, it is deployed separately for separate functions, not working simultaneously at the same time. Some of the requirements are still to be addressed. Core components, including cFS, Open MCT, NOS3 simulation environment and the T-Pot honeypot framework, operated as intended separately. The system was able to generate and visualise TM data, simulate late TC and collect malicious network interactions directed at the honeypot interface. Open MCT successfully replayed telemetry deviations associated with simulated attack scenarios, allowing the effects of cyber interactions to be observed in a mission control-style interface in NOS3. The T-Pot honeypot stack captured associated log data. However, the intended RF simulation using LoRaWAN could not be fully implemented due to unresolved configuration issues at the physical and MAC layers. As a result, all telemetry and telecommand exchanges had to be done over a wireless ground-based network instead of RF channels.

5. Recommendations and Future Works

Further development of the HADES platform should prioritise the completion of the LoRaWAN-based RF link to enable the transmission of CCSDS-compliant TM frames over a realistic radio channel. This would allow the system to better simulate the effects of latency, link degradation and signal interference present in Low Earth Orbit (LEO) communications. For future research, we should also explore the deployment of HADES across multiple distributed honeypot nodes to form a swarm-based architecture via LoRaWAN, which is to enable the study of sophisticated attacks against space constellations. In addition, linking the test bed to software-defined radio ground stations would allow partial exposure to space like radio frequency environment. The honeypot supports mapping events to known attack techniques; researchers could correlate log entries with frameworks like the US's MITRE ATT&CK (Hong 2023), Aerospace's SPARTA (Ear, Bailey and Xu 2024) or the European Space Agency (ESA)'s SPACE-SHIELD (European Space Agency n.d.) matrix of space cyber tactics. In practice, the HADES can be used to collect data to identify which attack techniques were attempted by adversaries and to confirm the coverage of their honeypot. Meyers (2025) highlights recent developments of AI-powered on-orbit intrusion detection systems that are capable of monitoring satellite telemetry in real time. Any structured attack data acquired through HADES could also form the basis of an open-source space cyber threat intelligence dataset to aid the space industry and academic benefits. In summary, while the current implementation is limited to ground-based experimental only, the HADES can aid as a foundation for satellite cyber deception research and can be a potential tool to be used for space security training, threat intelligence and mission assurance in the space sector.

6. Discussion and Conclusion

The results indicate that the HADES prototype is capable of attracting genuine adversarial behaviour and reproducing key elements of satellite-ground communication workflows using affordable, open-source technologies. The fact that attackers engaged with the system using real-world techniques such as default credential brute forcing, directory traversal and basic reconnaissance suggests that even a ground-based emulation of a satellite system is sufficient to trigger realistic adversary interest. This validates the underlying premise that deception technologies can be effectively adapted to the space domain.

The resilience of cFS when subjected to malformed TM packets indicates that NASA's flight software architecture already exhibits robustness against certain classes of protocol fuzzing. However, it must be acknowledged that no authentication or encryption mechanisms were applied to the telemetry and telecommand interfaces in this prototype. This omission mirrors existing vulnerabilities identified in legacy satellite infrastructure and emphasises the need for secure uplink/downlink mechanisms in future implementations.

Although the system succeeded in simulating subsystem interactions and attacker impacts on telemetry, the absence of a functioning LoRaWAN communication link meant that the testbed did not fully replicate the bandwidth constraints, latency variations or packet loss typically observed in real space-based radio-frequency environments. Likewise, no real-time alerting, automated anomaly detection or adversarial artificial intelligence behaviours were implemented. Consequently, HADES currently operates as a passive data collection system rather than an autonomous defensive architecture.

In summary, this HADES project demonstrates that ground-based, modular honeypots can simulate realistic CubeSat systems and attract meaningful attack behaviour. As threats toward space systems increase, such deployable, interactive testbeds offer critical insights for mission designers, researchers and operators alike. The system's reliance on open-source components ensures affordability, reproducibility and accessibility for further academic research.

Acknowledgements

The authors would like to express their heartfelt gratitude to the University of South Australia for providing library access and all the necessary resources that enabled the successful completion of the paper.

AI Declaration: Grammarly AI was used only for grammar checking and improving clarity and readability. It did not contribute to the research design, analysis, interpretation or conclusion of the paper, which are solely the authors' work.

Ethical Statement: The research involves only simulated cyber-attack scenarios and controlled environments, therefore formal ethical approval was not required.

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Assessing Non-Kinetic Effects in Support of Military Operations: An Inference-Driven Framework

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Abstract: Modern military operations increasingly integrate non-kinetic effects to support and enhance kinetic operations on the battlefield. Intelligence, surveillance, and reconnaissance assets provide a reliable means to measure kinetic effects on adversaries during combat. However, there is a gap in intelligence collection for assessing and quantifying non-kinetic effects, such as shaping perceptions, influencing decision-makers, or degrading adversary morale. These effects are difficult to measure with traditional intelligence techniques because they occur in the cognitive dimension, where observable indicators are limited, and measurement is complex. This limitation introduces operational risks for military leaders, as they cannot always be sure whether a non-kinetic asset will achieve the desired effect or if a behavioural change has taken place. This paper introduces a framework for developing measures of effectiveness for cyber, information warfare, and psychological operations planners to evaluate non-kinetic operations supporting kinetic actions. Drawing on case studies such as the Russo-Georgian conflict and the Second Nagorno-Karabakh war, the framework combines intelligence indicators from OSINT, social media analytics, changes in adversary leadership behaviour, shifts in military posture, and other measurable phenomena to generate quantifiable metrics. It also considers collateral, second-, and third-order effects to assess whether non-kinetic operations are achieving their operational objectives. By offering intelligence analysts, planners, and military leaders a rigorous method for planning, executing, and evaluating non-lethal effects, this approach improves effect synchronization, enhances risk assessment, and aids leaders' decision-making.

Keywords: Cyber, Information warfare, MoE, Non-kinetic, Indicators, Influence, PSYOPs

1. Introduction

Military operations worldwide increasingly depend on cyber activities, information warfare, and Psychological Operations (PSYOPs) as essential tools to shape favourable battlefield conditions and achieve mission objectives against adversaries. Throughout history, military leaders have conducted battle damage assessments (BDA) of enemy forces after kinetic strikes, including arrow barrages, cavalry charges, artillery fire, and precision aerial bombing (Chairman of the Joint Chiefs of Staff, 2019). These actions have a clear cause-and-effect relationship that can be observed by a scout, an aerial drone, or a surveillance satellite.

Measuring the impact of non-kinetic effects and confirming if the desired outcome is being met can be difficult. These effects often occur in the electromagnetic spectrum (EMS), cyberspace, or the human brain's cognitive space (Paul et al., 2015). These domains are usually not observable to humans. Observing these effects requires monitoring indicators that are secondary or tertiary to the original target. Even when these indicators can be monitored, there is a gap in the training, experience, and knowledge of military intelligence analysts in observing changes and assessing the effectiveness of non-kinetic effects (Fortson, 2007).

This presents a dilemma for military leaders when employing non-kinetic effects during combat operations. They must understand their capabilities and trust that these assets can produce the desired effect on enemy forces (Aguirre et al., 2024). These choices put soldiers' lives, military resources, and mission success at risk. While military leaders are generally confident in their ability to employ, deliver, and assess the effects of kinetic weapons and equipment on the battlefield, uncertainty about non-kinetic effects and the inability to conduct BDA can lead to hesitation in relying on these capabilities.

It is essential to develop a comprehensive framework for measuring non-kinetic effects, including both traditional and non-traditional indicators. This requires planners and intelligence analysts to thoroughly understand the operational plan and coordinate non-kinetic resources to support the mission (Richardson, 2009). Resources should be allocated to detect and evaluate environmental changes in adversary behaviour, cyberspace, and the information environment that are either beneficial or detrimental to friendly forces. Systems must be established to alert when a significant deviation from the baseline is observed.

This paper will explore operations that employed non-kinetic effects to support military operations. It will analyse the strengths, weaknesses, opportunities, and threats of these operations and offer insights into why they succeed or fail. The framework provided will give leaders, planners, and analysts a comprehensive, quantitative approach for planning and evaluating non-kinetic effects in support of military operations.

2. Assessment Gap

2.1 Doctrinal Framing of Assessment

NATO and U.S. doctrine, specifically JP 3-13 (Information Operations), JP 3-12 (Cyberspace Operations), and AJP-3.10 (Allied joint doctrine for information operations), recognize that assessing information and cyberspace operations is inherently difficult, especially when effects do not cause observable physical damage (Joint Chiefs of Staff, 2012; Joint Chiefs of Staff, 2018; NATO, 2015). The difficulty is increased by a time gap between action and effect: kinetic operations produce immediate, visible damage, while information and cyberspace effects may take days, weeks, or months to appear, often outside tactical decision cycles. Many effects occur in the cognitive or informational dimension of the operational environment and require monitoring of indirect indicators. NATO doctrine states that successfully conducting Info Ops depends on ongoing monitoring and assessment (NATO, 2015). These efforts require collecting all-source intelligence and paying close attention to the adversary's behaviour and attitudes.

NATO and U.S. doctrine are consistent in their use of measures of performance (MOP) and measures of effectiveness (MOE). But the doctrine provides little guidance on how to move from observed indicators to confident conclusions about whether an effect occurred and whether that effect resulted from the operation in question. The doctrine explains how these metrics fit within the decision-making framework for authority; however, the effectiveness of the metrics themselves remains unclear. JP 3-13 mentions weighting metrics to highlight the relative importance of one over the other but provides no transparent methodology for deriving these weights (Joint Chiefs of Staff, 2012). The absence of an inferential methodology can be consequential when commanders must choose between kinetic and non-kinetic options. Without transparent, defensible assessment frameworks, non-kinetic effects remain difficult to measure and assess. This creates a potential bias in operational planning toward options that yield more legible, observable strategic value through measurable outcomes.

2.2 Non-kinetic Assessment

There is a doctrine for non-kinetic assessments, but it remains isolated by capability and limited to observable indicators. CJCSI 3162.02 (Methodology for Combat Assessment) includes a Cyberspace Assessment Determination Matrix that categorizes temporary cyber effects as DENIED, DISRUPTED, DEGRADED, DECEIVED, and MANIPULATED (Chairman of the Joint Chiefs of Staff, 2019). JP 3-12 covers the evaluation of cyberspace operations using MOPs and MOEs, which help determine how efforts contribute to the larger operation or objective. JP 3-13 adopts a similar approach with MOP and MOE in Information Operations; however, it highlights observability and quantification as critical for measuring effects, and MOEs are often linked to the progress of the operation (Joint Chiefs of Staff, 2012).

Two interconnected challenges exist within these doctrines. First, the timeframe for observing non-kinetic effects often surpasses tactical decision cycles, creating pressure to assess prematurely using proxy indicators. Second, the doctrine assumes observability without clearly defining its boundaries. The absence of boundaries makes it unclear whether indirect indicators (e.g., economic behaviour, migration patterns, social media sentiment) are legitimate data or inadmissible inferences. Recognizing which observable indicators can be identified through second- and third-order observations is crucial for increasing commander confidence in non-kinetic options. JP 3-13 highlights observable indicators such as rallies and demonstrations, but many other assessment avenues exist, including economic behaviour and migration. However, this process is not sufficiently addressed within the planning phases of a military operation.

In JP 3-13, these indicators are called measures of effectiveness indicators (MOEIs). They are usually developed during the planning phase, especially during course of action development (COADEV). The difficulty lies in measuring MOEs, which are often unobservable and mostly qualitative. In the doctrine, an example of an effect is "increase in a city populace's participation in civil governance." The MOE here is qualitative, with metropolitan citizens showing increased support for the democratic leadership elected on July 1. Then, an MOEI is a decrease in the number of anti-government rallies or demonstrations in a city since July 1. Three MOEIs are provided that can be directly measured to infer the MOE, indicating that the effect has occurred. This doctrinal approach is fundamentally sound; however, it assumes a single causal pathway from operation to effect. The doctrine does not address the issue of equifinality, or the possibility that alternative competing hypotheses could produce the same observable outcomes. For example, a decrease in anti-government rallies since July 1 could align with several hypotheses: the target population genuinely shifted support for governance (the intended effect), security crackdowns made public gatherings too risky (coercion rather than persuasion), opposition groups

shifted to less visible tactics, or exogenous factors (economic conditions, seasonal patterns) temporarily reduced mobilization. Without a framework to distinguish among these hypotheses, the same indicator data can yield contradictory conclusions about operational effectiveness.

For PSYOPs, JP 3-53 offers guidance on planning, executing, and assessing effects in joint military operations. However, the doctrine also openly recognizes inherent limitations, including the absence of a clear method for determining whether those psychological effects were achieved. It specifies the need for direct observability, which remains a common challenge in conducting non-lethal operations (Joint Chiefs of Staff, 2003). The doctrine also discusses the coordination and synchronization of PSYOPs with IO capabilities; however, there is no procedural guidance for assessing the impact of a PSYOP operation.

By examining the doctrine in relation to non-kinetic operations, we see that indirect, observable indicators are mentioned but not explained. This might be due to a lack of reliable evidence from alternative indicators. However, non-kinetic operations are becoming increasingly intertwined with military operations as the military incorporates more non-lethal assets.

2.3 Analytical Gaps in Doctrine

The current doctrine outlines the observation requirements but does not provide sufficient guidance on interpreting those observations to reach a conclusion. The three analytical gaps that impact non-kinetic assessment include:

Gap 1: Lack of formal procedures for hypothesis discrimination. The doctrine states that observed indicators support the hypothesized effects, but the same indicators could be explained by two or more different mechanisms. Without structured procedures, such as Analysis of Competing Hypotheses (ACH), to differentiate among explanations, the analysis is vulnerable to confirmation bias and enemy deception.

Gap 2: Absence of a methodology for combining evidence. Joint Publication 3-13 acknowledges that multiple MOEIs might be needed to make a judgment about a single MOE and suggests using weights based on relative importance, but it does not specify a clear method for assigning those weights or for integrating seemingly unrelated indicators.

Gap 3: Absence of a shared vocabulary for expressing confidence. The assessment results differ based on capability and level. In cyber operations, results are reported in CTEAR format with category labels such as (DENIED, DEGRADED, DISRUPTED); for information operations, results are assessed qualitatively using an MOE; and for psychological operations, results recognize the difficulty of measuring PSYOP effects but do not offer a methodology for measurement. This gap in doctrine hampers the ability to compare kinetic and non-kinetic courses of action, as commanders cannot assess their relative effectiveness.

These gaps are more than just administrative issues. They reveal structural pressures that favour actions with clear, visible outcomes over those with potentially greater strategic importance but that require more time-consuming data collection, inferential reasoning, and acceptance of uncertainty. Closing these gaps demands both methodological and doctrinal changes.

3. Analytical Framework: Analysis of Competing Hypotheses

3.1 Rationale for Framework Selection

The issue outlined in Section 2 (Assessment Gap) is fundamentally inferential: although guidelines for indicators exist, there is no formal way to draw reliable conclusions about effects based on observed indicators. This has historically been a challenge in intelligence analysis, which often involves inferring from incomplete, ambiguous, or deceptive information (Richardson, 2009). Therefore, applying intelligence analytical techniques to operational assessment is not a category error; rather, it acknowledges that assessing non-kinetic effects is an intelligence challenge within an operational setting.

Several structured analytical techniques are crucial for finding potential solutions. Red teaming offers alternative perspectives but lacks a formal process for evaluating these options against evidence (Department of Defense, 2016). These methods either generate alternatives without thorough evaluation, depend on probabilistic data that are missing in operational environments, or identify reasoning errors without providing ways to fix them.

The Analysis of Competing Hypotheses (ACH), developed for the CIA by Richards Heuer, addresses the problem of equifinality, which is choosing among multiple hypotheses that each fit a body of evidence (Heuer, 1999). In ACH, analysts create several hypotheses that could yield the same outcome. They then present their evidence

and arguments to assess how likely each piece of evidence is to align with the different hypotheses. This process helps analysts reduce their own cognitive biases and make decisions based on evidence about causality (Valtorta et al., 2005). It also shows how ACH can be used within a Bayesian model, illustrating how analysts might use Bayesian graphs to continuously update their evidence and assumptions; however, there is no proven effectiveness of this method for operational use.

3.2 ACH Methodology

Analysis of Competing Hypotheses is an eight-step process based on cognitive psychology and the scientific method. It counteracts Confirmation Bias by considering all competing hypotheses against the evidence at the same time (Heuer, 1999).

Step 1: Identify Hypotheses. Engage a variety of analysts in a brainstorming session to generate possible answers, ensuring the hypotheses are mutually exclusive and limited to a few (no more than 7).

Step 2: List Evidence and Arguments. Gather all available evidence for each hypothesis, including indicators, deductions, and assumptions, and state assumptions clearly so they can be challenged.

Step 3: Create a matrix and evaluate diagnosticity. Organize the matrix with the hypotheses as columns and the evidence as rows. Enter each cell as "C," "I," or "N/A." Evaluate the rows from left to right, noting which hypotheses each piece of evidence differentiates. The higher the evidence's diagnosticity, the more it will support some hypotheses and refute others. Evidence that fits all hypotheses has low diagnosticity.

Step 4: Refine your matrix. Eliminate non-diagnostic evidence and identify gaps. Make changes as needed.

Step 5: Tentative conclusions. Rank the hypotheses based on the weight of the incompatible evidence and choose the one with the least incompatible evidence rather than the one with the most compatible evidence.

Step 6: Sensitivity Analysis. Determine which piece of evidence or assumption supports the answer, and if removing an item changes the answer, examine it further.

Step 7: Report conclusions. Report all hypotheses and the reasons for rejecting alternatives, providing an audit trail of reasoning.

Step 8: Determine future milestones. Establish indicators of changes in probability to enable continuous monitoring rather than a point-in-time assessment.

The power of ACH lies in its ability to externalize hypotheses, evidence, and their connections, making shortcuts visible and correctable.

3.3 Adaptation for Operational Assessment

One of the primary outputs of this type of assessment is a matrix that clearly displays the development of each MOEI and whether each one contributes to or detracts from the overall effect. Planners can assign more detailed weights to each indicator for each effect. This helps the operations officer assess success criteria more thoroughly and avoid relying too early on proxy indicators to determine effects, which could lead to errors in BDA.

3.4 Assessment Criteria for Use-case Analysis

To evaluate the usefulness of ACH for non-kinetic assessment, the next section examines two historical cases. Each case is analysed using four criteria derived from the framework:

1. **Hypothesis identification** — Were multiple competing explanations for the observed indicators considered?
2. **Diagnostic evidence** — Was any evidence identified that could discriminate among hypotheses, or was it only evidence consistent with the preferred explanation?
3. **Evidence integration** — Was a systematic method used to weigh and synthesize the indicators?
4. **Confidence expression** — Was uncertainty about the assessment explicitly communicated?

4. Case Review

In this case review, we apply the ACH to two historical cases in which non-kinetic effects were used alongside military actions on the battlefield. ACH matrices are employed to evaluate alternative explanations for observed changes in the information environment and to refute competing hypotheses by systematically comparing them to available indicators. The limitation of this analysis is that it is conducted after the fact, since we already know

the outcomes of the specific operation; however, this case review shows how a military planner could use this approach to overcome cognitive biases when assessing non-kinetic effects on a given target.

4.1 Russo-Georgian War (2008): Cyber and Info Warfare in Support of Maneuverer Forces

4.1.1 Operational background

The Russian military invaded Georgia on August 8, 2008. This campaign is seen as the first major instance of a large-scale cyberattack coinciding with military action. The cyber operations were notable because they were not directly linked to the Russian government. Evidence shows they were carried out by hacktivists and Russian organized crime (Shakarian, 2011). Russian forces also launched an information warfare (IW) campaign to justify their actions and sow confusion. Before the invasion, tensions between Russia and Georgia increased throughout the year, mainly over disputes involving the separatist regions of Abkhazia and South Ossetia (White, 2018).

Russia supported South Ossetian separatist forces and influenced their attacks on Georgian forces starting on August 1, 2008, using artillery fire and bombings. The first phase of the cyber operation began on August 7, 2008, involving coordinated attacks, including Distributed Denial-of-Service (DDoS) attacks on government and media websites. In the second phase, the operation targeted financial and educational institutions. This was followed by website defacement and the recruitment of Russian patriots (Shakarian, 2011). The cyber operations coincided perfectly with Russia's land invasion of Georgia with armoured and mechanized forces.

4.1.2 Non-kinetic effects

Cyber Operations:

- DDoS attacks targeting critical communication systems used by the government, businesses, and media.
- Website defacement of official pages.
- Spam email campaigns against Georgian politicians (Shakarian, 2011).

Information Warfare:

- Russia influenced South Ossetia to attack Georgian villages in the area. This led the Georgian military to launch an offensive against South Ossetian forces. Russia expected this and used the opportunity to claim that Georgia was committing genocide in the region, thereby justifying Russia's invasion to stop the genocide (Chincharadze, 2024).
- Posting pro-Russian messages, disparaging Georgian leaders, and spreading disinformation about current events (Shakarian, 2011).
- Disruption of communication channels to isolate, silence, and delay the Georgian government, military, and civilian population.

4.1.3 Assessing Effects And Attribution

Three competing hypotheses are analysed as potential causes of Georgian communication degradation. Behavioural and informational indicators are assessed for their potential to offer alternative explanations. This analysis incorporates the indicators into an ACH matrix and assigns a confidence level to each indicator.

Based on available historical evidence, there is no indication that Russian planners used a formal assessment framework, although observable adaptations suggest they conducted informal evaluations of effects. These effects appear to have been tested experimentally, and Russian forces were ready to exploit any changes that gave them an advantage in the conflict. The analysis of the conflict mainly relies on what was observed or detected through technical means, such as troop movements, website shutdowns, and network traffic disruptions, rather than on whether the Russians achieved their desired effects.

Known Observable Outcome: The Georgian government experienced degraded internal communications and denied access to international audiences (Shakarian, 2011).

Hypothesis	Description
H1	Cyber-attacks directly degraded Georgian C2 and external communications
H2	Georgian communications failures were primarily due to pre-existing infrastructure limitations

Hypothesis	Description
H3	Georgian government organizational dysfunction caused coordination failures

Indicators	H1 (Cyber)	H2 (Infrastructure)	H3 (Organizational)
Delayed Georgian official statements to international media	C	I	C
Loss of Georgian media websites during the invasion window	C	C	I
Relocation of web hosting to foreign servers	C	I	I
Russian narrative dominance in the early conflict phase	C	I	C
National Bank suspended electronic services	C	C	N/A
Georgian shift to diplomatic channels for messaging	C	I	C

(C = Consistent, I = Inconsistent, N/A = Not applicable)

Assessing the conflict using these observable behavioural and informational indicators suggests that cyber operations significantly contributed to the degradation of the Georgian government's internal and external communication channels (H1). Although the indicator set does not prove complete causality, the timing of communication delays, website outages, digital service relocations, and Russian narrative dominance provides enough evidence to support this hypothesis over explanations based on infrastructure limitations or organizational dysfunction. The Georgian government's infrastructure and organizational problems likely worsened the disruptions, but the indicators point to cyber operations and information warfare as the main cause. This case highlights the value of inferential, behaviour-based indicators for attributing non-kinetic effects when there are no directly observable changes in cyberspace or the information environment.

4.2 Second Nagorno-Karabakh War (2020): Information Warfare, Psychological Operations

4.2.1 Operational background

The Second Nagorno-Karabakh War started on September 27, 2020, and ended on November 9, 2020. This conflict between Azerbaijan and Armenia was over contested territories in the Karabakh region. Azerbaijani forces are considered the winners of the conflict, and their victory was credited to the skilful use of information warfare combined with kinetic operations (Marinus, 2021).

In September 2020, Azerbaijani forces took the initiative, using unmanned aerial vehicles (UAVs) and artillery to destroy a significant portion of Armenia's tanks, vehicles, and anti-aircraft systems. The Azerbaijani military employed information operators to capture imagery and video of the destroyed equipment and published them for their enemy and the broader global audience. As the conflict progressed, both sides targeted civilian locations in pursuit of their goals. The Azerbaijani forces demonstrated an information centre that responded quickly and effectively. They were able to censor nearly all media showing strikes on Armenian civilian populations while simultaneously showcasing Azerbaijani civilians being targeted by Armenian military strikes. This created the narrative that Azerbaijan was using precision strikes to hit military targets, while Armenia was recklessly firing artillery and missiles into civilian areas (Marinus, 2021).

The information warfare campaign and the Azerbaijani ground forces collaborated to influence the Armenian population in the disputed territories to flee in early November 2020. This rapid effort resulted in a swift victory for the Republic of Azerbaijan in the region.

4.2.2 Non-kinetic effects

Information Warfare

- Release of UAV strike footage showing the destruction of Armenian armour, artillery, and air defence systems.

- Azerbaijani domestic and international narratives demonstrate accurate and lawful military operations.
- Suppression of imagery showing Azerbaijani attacks on Armenian civilian targets.

Psychological Operations

- Messaging aimed at undermining Armenian morale and confidence in their defensive capabilities.
- Influence the Armenian military to withdraw and the civilian population to flee.

4.2.3 Assessing Effects And Attribution

Unlike the Russo-Georgian case, Azerbaijan appeared to employ a planning and execution framework to synchronize non-kinetic effects, enhancing kinetic operations aimed at influencing the will of the Armenian people. The Azerbaijani military continuously adjusted IW and PSYOP messaging based on observable results throughout the conflict. This indicates a dynamic feedback loop linking battlefield successes to non-kinetic activities. In this conflict, assessment mainly depended on adversary behaviour and population response rather than disruption of technical systems.

Known Observable Outcome: The Armenian military and civilian population in the disputed territories quickly fled the area by the end of the conflict.

Hypothesis	Description
H1	Information warfare and psychological operations directly damaged Armenian morale and their willingness to remain in the territory.
H2	The Armenian collapse was primarily due to kinetic losses and the opponent's technological advantage.
H3	Armenian organizational dysfunction led to the withdrawal of military and civilian personnel.

Indicators	H1 (Info/PSYOPS)	H2 (Kinetic)	H3 (Organizational)
Persistent release of UAV strike footage	C	C	I
Armenian public acknowledgment of battlefield losses	C	C	C
Civilian exodus from contested territories	C	I	C
The collapse of Armenian defensive lines	C	I	I
Azerbaijani narrative dominance in international media	C	I	I
Armenian leadership messaging is inconsistent and reactive	C	I	C

(C = Consistent, I = Inconsistent, N/A = Not applicable)

Assessing the Second Nagorno-Karabakh War through observable behavioural and informational indicators suggests that information warfare and PSYOPs were the main causal factors weakening Armenian morale and decreasing the population's willingness to stay in the disputed territories (H1). Azerbaijani kinetic operations and technological superiority (H2) were enabling conditions, but they do not fully account for the scale and speed of the civilian exodus from the disputed areas. Organizational dysfunction (H3) is a plausible contributing factor, but, on its own, it is insufficient to explain the rapid departure of the Armenian population. Unlike the Russo-Georgian case, this conflict demonstrates a more advanced and coordinated use of non-kinetic effects alongside kinetic actions to achieve strategic objectives. This case highlights how behavioural and informational indicators can support real-time battlefield decision-making. It underscores the importance of inferential assessment in providing leaders with situational awareness of non-kinetic effects.

5. Discussion

These two cases illustrate the evolving use of non-kinetic effects in military operations. They demonstrate how kinetic operations can be enhanced with non-kinetic effects through a structured assessment approach. During

the Russo-Georgian War, effects were employed to exploit vulnerabilities, and assessments depended on technical and behavioural indicators, though these indicators offered limited confidence in establishing causal links for non-kinetic effects. The Second Nagorno-Karabakh War, 12 years later, showed a sophisticated integration of information warfare and PSYOPs with kinetic operations, with indicators monitored to support tactical decisions. In both examples, this analysis reveals that non-kinetic effects do not occur in isolation. These effects can influence, amplify, and improve military operations by shaping the information environment. The use of ACH provides a structured framework for evaluating effects, reducing cognitive bias, and using observable indicators to infer from change.

This analysis is subject to the following limitations and constraints. The limitations include limited access to classified processes and internal decision-making within the military forces in this study, and the indicators used are specific to this context and may not apply to conflicts in different cultural or political settings. The constraints are that these case studies are retrospective, rely on open-source and secondary reports, and there are only a limited number of well-documented historical examples of non-kinetic support to military operations.

This ACH framework provides a significant benefit to military leaders and planners by enhancing combat operations. The use of behavioural and informational indicators, along with confidence and uncertainty assignments, improves transparency in planning, executing, and assessing non-kinetic operations. It allows leaders to compare kinetic and non-kinetic courses of action using inferential logic. Future research should explore adapting ACH for planning large-scale deception operations and using human-AI teaming to develop competing hypotheses.

6. Conclusion

Military forces are increasingly equipped with non-kinetic assets on the battlefield, yet the ability to assess their effects has not kept pace. Non-kinetic effects are best used within a structured framework to ensure proper evaluation and synchronization with military operations. This paper set out to provide a tool that fills the gap between employing and assessing non-kinetic effects. The Analysis of Competing Hypotheses offers a much-needed, structured framework for assessing non-kinetic effects through observable behavioural and informational indicators, which is currently lacking in military intelligence and planning processes. The framework gives military commanders a rigorous tool for developing courses of action to plan and execute non-kinetic effects predictably, enabling military units to synchronize all capabilities.

Ethics Declaration: This research did not involve human participants or the collection of personal data and therefore did not require institutional ethical approval. The study is based on publicly available documents, doctrinal publications, and secondary sources.

AI Declaration: AI tools were used in a limited capacity to support the preparation of this paper, including language refinement, reference formatting, and clarity of expression. All substantive analysis, interpretation, and conclusions are the sole work of the authors, who take full responsibility for the content.

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Graph Neural Networks on Phase Space Graphs for Cybersecurity

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Abstract: Non-linear phase space analysis may be used to represent time-series data as graph data with transitions between states in the time domain. By studying these transitions, we can predict anomalies within the system. Previous research has demonstrated success in learning from phase graphs for malware and seizure detection. These solutions either require extracting global features or converting the graph into an image for convolutional neural networks (CNNs), which adds complexity and limits the potential expressiveness of a graph. To sidestep current limitations, this study proposes Graph Neural Networks (GNNs) for analyzing phase graphs. Unlike CNNs, which must transform graph data into an image representation that may not preserve isomorphism, GNNs operate on the graph data itself through message-passing mechanisms that naturally preserve graph structure. Four GNN architectures were evaluated on two cybersecurity datasets: the Canadian Institute for Cybersecurity Intrusion Detection System (CICIDS) 2017 dataset and a power usage dataset for rootkit detection. The CICIDS dataset was processed at three density levels by varying the symbol parameter. Findings reveal GNNs can be used successfully with phase space graphs, that the type of GNN impacts classification accuracy, and that variance in phase space parameters also impacts accuracy. GIN achieved the most consistent performance across all experiments, while graph density significantly affected results.

Keywords: Graph neural networks, Phase space analysis, Cybersecurity, Intrusion detection, Rootkit detection, Time-series classification

1. Introduction

Time series data in computing has been used to represent diverse processes in the frequency and time domains. Sensor readings, for instance, are a very common source of time series data, where machine learning (ML) has assisted in understanding patterns hidden in data (Fu et al, 2024). Despite its importance and availability, time-series data remains one of the most challenging types of data for machine learning (Jadon et al, 2021). Methods for processing time series data may mitigate such challenges and possibly increase the predictive power of ML algorithms (Zhao et al, 2017), potentially reducing the time and capital investments needed to create effective models.

Phase space analysis is a method that can be adapted to model time-series data as graphs representing states and transitions. The phase space graph of a system may capture the changes in the underlying dynamics and may be representative of its behavior over time (Protopopescu and Hively, 2005). This method has proven to be a promising and historically effective way to predict states within time series data, such as predicting heart disease based on neurological data (Stuckey et al, 2018).

Current time series methods using phase space have their respective limitations. The standard mathematical approach of finding optimal parameters and thresholds requires extensive time and is difficult to scale without domain-level knowledge (Stuckey et al, 2018). Machine-learning approaches have included integration with Convolutional Neural Networks (CNNs) and ML-based solutions for parameter selection (Callegari, 2024). These methods are challenging because they must transform graph-data into an image representation that will preserve isomorphism of its temporal information by the pooling layers of a CNN.

The proposed solution is the application of Graph Neural Networks (GNNs), which operate on graph data directly through message-passing mechanisms where data from all vertices are exchanged with neighboring nodes, naturally preserving graph structure without requiring intermediate transformations. Due to limited information about GNNs on phase space graphs, there is a lack of understanding which GNNs perform best, and what strategies work best for converting time series data for GNNs using phase space (Neupane et al, 2022).

This research aimed to address this shortcoming by presenting two experiments which apply GNNs to cybersecurity data processed using phase space. Additionally, this research aimed to observe the impact of changing the size of the phase space graphs by generating variants of one dataset and analyzing the results.

2. Background

2.1 Rootkits and Side-channel Analysis

A rootkit is software that stays dormant on a device until a malicious party activates it to gain escalated privileges, more formally defined as "a software that is developed to enable its associated programs to conceal

their presence from analysis and detection while maintaining privileged access to a target system" (Kim et al, 2012, p.134). Detection of rootkits has become an evolving arms race due to their concealment capabilities (Lobo et al, 2010). Operating systems organize access levels into a "ring" system where user-level access is ring three and kernel level access is ring zero (Kim et al, 2012). If a rootkit obtains ring zero permissions, it can manipulate kernel-level functionalities, obscuring detection of other code on the machine.

Side channel analysis may aid in minimizing rootkit threats by examining data from computer hardware leakages, like voltage or CPU-generated heat. This is effective because any level of access produces hardware leakage. Kyte et al (2012) describe an effective side-channel method to identify hardware virtualization-based rootkits using energy consumption data.

2.2 Phase Space Analysis

The means by which this research converts time-series data into graphs for GNNs is via the phase space algorithm. This algorithm converts time series data into graph data by utilizing the fundamentals behind Takens' Embedding Theorem (Robinson, 2005), which provides a method for time-delay embedding, allowing for the representation of time series data as high-dimensional graphs of state changes. The algorithm created by Protopopescu and Hively (2005) replaces the continuous numeric data with enumerable symbols that represent ranges, divides the data into "cut sets", and then generates links between these cut sets. Figure 1 illustrates this process.

The algorithm has a few key parameters that control the output, being the number of base-cases, number of points per cut-set, the number and size of the symbols, the method of symbolization, and the pattern in which links are assigned (McDonald et al, 2022).

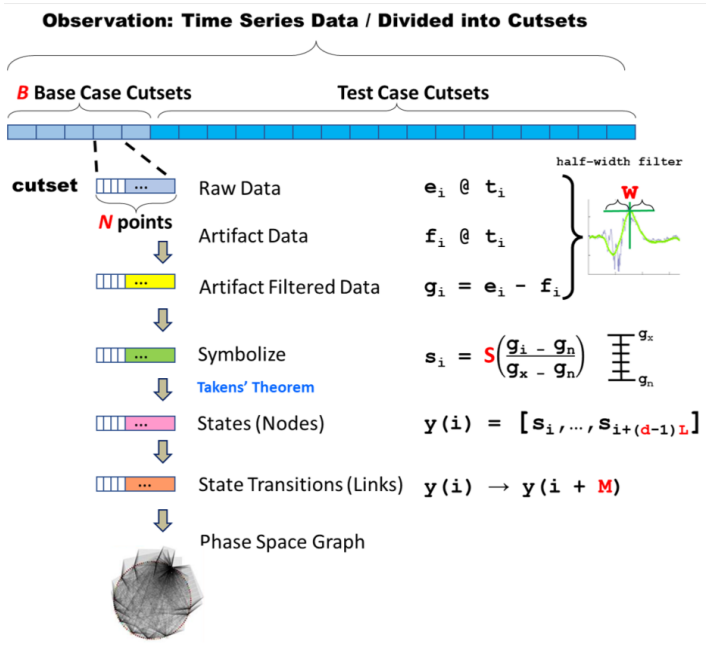


Figure 1: Phase space algorithm process showing transformation from time-series data to graph representation (reproduced from Callegari, 2024)

The phase space algorithm transforms continuous numeric data into discrete graph data (Luckett et al, 2019a). In order to achieve this, it must have a binning step that discretizes these continuous values into ranges known as "bins". The number of total bins is controlled by the "symbols" parameter. A higher symbol value results in more nodes and more connections throughout the resulting phase space graph. This is because when the data is encoded into a higher number of symbols there is a higher number of permutations of state changes, which results in fewer redundancies and more unique edges and nodes in the end graph datasets.

Existing work has been done with this algorithm to successfully prove that as an embedding method it is able to at least maintain some aspects of the original dataset to a degree where it can be effectively used to classify and make predictions about dynamical systems (Callegari, 2024). A study in healthcare using non-linear phase space analysis to time-series data showed promise with wave-type data classification (Stuckey et al, 2018).

2.3 Graph Neural Networks

Time series data being portrayed as graph data is a well-established concept in the machine learning community, and there exists a history of converting time-series data into graphs for the use in GNNs (Jin et al, 2024). By viewing temporal data as a series of moments that occur after the previous event yet before the next event, it is natural to attempt to portray this data in some form of graph. One such experiment used graph neural networks with sensor data to detect anomalous events (Deng and Hooi, 2021). Phase space analysis allows for a different projection of this data by treating time as a semi-cyclic dimension that allows for better observation regarding repetitive or cyclical behavior within the system (Orlik, 2012).

The first model considered was the standard Graph Convolution Network (GCN), one of the earlier networks to be developed (Zhang et al, 2019). GCNs operate on the principle of graph message passing. Message passing is a mechanism where data from all vertices are exchanged with neighboring nodes to disperse graph-wide information between neighbors. Each node contains a feature vector with information about its neighbors, resulting in each node having a vector that represents neighborhood-level information. Message passing is a common feature in graph networks and is the basis of several models (Xu et al, 2019).

The Graph Isomorphism Network (GIN) is a prime focus in this study due to it performing the best among benchmarks (Errica et al, 2022). The GIN model was developed to address graph isomorphism, when equivalent graphs may be evaluated as different due to their representation. GIN uses a sum-aggregation function, which is more expressive in capturing isomorphic graph data (Bouritsas et al, 2023). The GIN model is proven to be as expressive as the Weisfeiler-Lehman graph isomorphism test, described as "a powerful test known to distinguish a broad class of graphs" (Xu et al, 2019, p.2). GIN updates the feature nodes as the GCN does via message passing, with the addition of producing feature vectors more suited for isomorphism tests. This expressiveness is particularly relevant for phase space graphs, where structurally equivalent graphs representing the same dynamical states must be recognized as such regardless of their representation.

EdgeCNN is similar to GCN but performs message passing between edges rather than nodes, which can be effective with connected graphs but less helpful for sparse ones (Yang et al, 2019). GraphSAGE presents the advantage of inductive learning, learning sub-patterns within training graphs to generalize later (Hamilton et al, 2018). This is important for phase space graphs due to their sensitivity to construction parameters.

2.4 Graph Density Considerations

Although there is no formal definition for "dense" and "sparse" graphs (Bollobas and Riordan, 2010), the distinction is important for this work. GNNs encode information into each node based on connected neighbors via message passing (Errica et al, 2022). A sparse graph with few edges yields simpler node-vectors with less information per node, analogous to a CNN trained on low-resolution images. Conversely, overly dense graphs provide rich contextual information at the expense of higher dimensional complexity, increasing the chance of over-fitting and training time.

2.5 Comparison with Traditional Approaches

Traditional machine learning approaches to phase space graph classification have followed two strategies. The first extracts global features such as graph density or spectral properties and feeds these into classifiers (Luckett et al, 2019b), requiring careful feature engineering. The second, explored by Callegari (2024), converts phase space graphs into image representations for CNNs. As described by Luckett et al (2019b), the graph adjacency matrix encodes node and edge information into a rasterized format for convolutional neural networks. This approach benefits from deep learning but faces the challenge of isomorphism: two equal graphs may be represented differently and considered as not equal.

GNNs address these limitations by operating directly on graph structures, preserving node connectivity and edge relationships through message-passing operations, eliminating the conversion step entirely.

3. Methodology

3.1 Datasets

The rootkit dataset consists of power level readings from several trials where a computer's activity was recorded while running Linux and Windows operating systems with or without a rootkit (McDonald et al, 2022). The combined dataset consists of data from 50 trials and 2,220 phase space graphs, comprised of exactly 50% benign and 50% malicious samples. The providers only supplied the data in graph format; the raw data was not provided.

The CICIDS 2017 dataset (University of New Brunswick, 2024) is a well-established benchmark for network intrusion detection containing labeled malicious and benign network traffic (Neupane et al, 2022). To observe the impact of the symbol count parameter, which controls graph size and connectivity by binning numeric data into different numbers of symbols, three variants were generated with values of two, three, and five symbols, representing sparse, nominal, and dense graph-sets. The grand total number of graphs generated was 3,918. The feature titled "BWHDRL" was chosen as the only feature used, because it has been used in the past to achieve 99% accuracy (Callegari, 2024). Unlike the rootkit dataset, the CICIDS graph datasets are comprised of 95% nonevent and 5% event classes. Table 1 summarizes the phase space parameters used for both datasets.

Table 1: Phase space parameters for both datasets

Parameter	Rootkit	CICIDS
Base cases	5	5
Nodes per cut set	1970	1970
Filter width	65	65
Symbols	3	2, 3, 5
Time delay	44	44

3.2 Data Preprocessing

For the rootkit dataset, phase space graphs were obtained in preprocessed form from McDonald et al (2022) using the parameters listed in Table 1. No additional normalization or outlier removal was applied, as the phase space algorithm inherently discretizes continuous values into symbolic bins through its symbolization step, reducing sensitivity to individual outliers. For the CICIDS dataset, the raw BWHDRL feature values were processed through the phase space algorithm at three symbol levels. The symbolization step serves as an implicit normalization, mapping continuous values into discrete ranges. No explicit outlier removal was performed on the raw features prior to phase space conversion, as the binning process accommodates extreme values within the outermost symbol ranges.

3.3 Model Configurations

In order to best compare the GNNs used in this study, each model was configured the same way with as similar sizes as possible. Each model used the GNN as the input layer with six hidden layers of size 256, found via experimentation to be the point where models did not benefit from a size increase after 20 epochs of training. To address the tendency for models to continuously predict only one class, a dropout rate of 25% was set. Past the GNN layer, every model's output was put through a 25% dropout layer, batch normalization, then a linear layer which halved the logits from 256 to 128 before a binary classification head.

3.4 Experimental Design

All datasets were divided into a 70/15/15 split of training, testing, and validation data. All samples were stratified so that each section contained the same class distribution percentages within a margin of 1%. When applicable, datasets were also stratified by trials to ensure models would not learn trial-specific quirks. Each dataset variant was assigned four untrained GNN models (GraphSAGE, EdgeCNN, GCN, and GIN), each trained over 20 epochs.

For all experiments, the models were tasked with binary classification, where class zero refers to benign data and class one refers to malicious or event data. The evaluation metric selected was balanced accuracy, the average of recall obtained on each class. This metric prevents class imbalances from affecting results; if a model consistently predicts only one class, balanced accuracy for a two-class problem equals 50%, no better than guessing.

4. Results

4.1 Rootkit Detection Experiment

With the data split into a standard 70/15/15 split for training, testing, and validation, and the data stratified to ensure all data from a particular recording session stayed within the same group, all four of the GNN models were trained for 20 epochs, the point after which no significant model improvement occurred. The balanced accuracy of the models against the validation data (weighted equal to class distribution) was recorded after each

epoch (without the ability to learn from the validation data) and plotted for final analysis. Figure 2 presents these results.

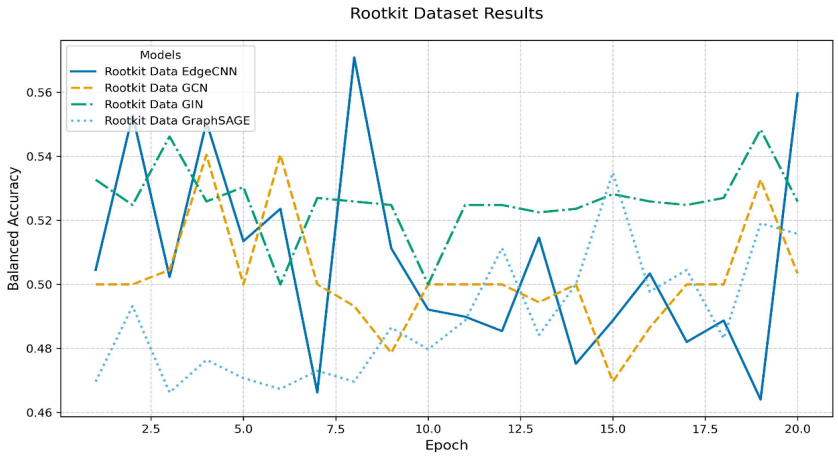


Figure 2: Model performance on rootkit dataset showing balanced accuracy over 20 training epochs

Although EdgeCNN regularly fell below other models, it did have the final highest balanced accuracy by a substantial amount. All other models had highly variable performances over time, indicating a tendency to overfit or underfit. The GIN model, while lower in the end, had the most consistent increase in model performance. This would be the recommended choice for consistent results on this dataset. EdgeCNN's sporadic per-epoch performance implies that the model continuously under-fit or over-fit the data and was sensitive to the noise within the data. It is for this reason that EdgeCNN would likely be more performant on a larger dataset and would not likely be the first choice for training with smaller datasets.

4.2 Network Intrusion Detection Experiment

Sparse graphs (2 symbols): All models tended to be biased in the sparse dataset and heavily affected by the 95% and 5% class dispersion. The flat line at 50% means that all models were obtaining 100% accuracy with class A and 0% accuracy with class B which resulted in a flat straight line for all models. This caused every model to consistently make predictions for class A. This is relatively expected; due to the sparseness of the graph there remains little room for variation or ability to distinguish different graphs and the highly complex space that they represent. It is likely that no learning is occurring and that class B, or malicious data, lacked any unique characteristics at this granularity of analysis.

Medium graphs (3 symbols): In the "medium" or nominally populated graph with three symbols, we see more necessary complexity, which appears to provide information for the models to somewhat discriminate and classify the two different classes, with a substantial increase in both activity and average accuracy for all models. The GIN model has the most consistent performance on this dataset variant, with the GCN overtaking it at times but with more drastic changes in accuracy across several epochs. The GraphSAGE model was still quite prone to over-fitting, resulting in large drastic spikes upward and downward on the graph. The GCN provided more stable performance than GraphSAGE however it also failed to surpass GIN in any given epoch barring one exception with epoch 12.

Dense graphs (5 symbols): Similar to the increase from sparse to medium density graphs, the dense graphs with five symbols consistently showed better final results for most models. The GIN model obtained the highest average accuracy at approximately 65%, with the EdgeCNN slightly behind with a score just under 61%. The GCN and GraphSAGE models still seemed to be affected by over-fitting and went back to single-class predictions multiple times during the experiment with final results well below the performance of GIN. Figure 3 presents the dense dataset results, and Table 2 shows the final confusion matrix outcomes.

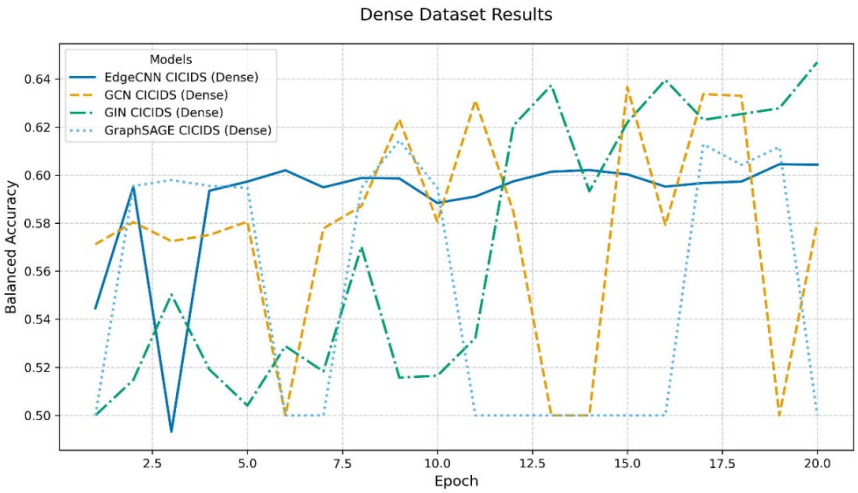


Figure 3: Graph neural network performance on dense CICIDS dataset (5 symbols)

Table 2: Confusion matrix results for dense CICIDS dataset

Model	True Neg	False Neg	False Pos	True Pos	Bal. Acc
EdgeCNN	355	137	25	73	0.641
GCN	301	124	79	86	0.601
GIN	370	149	10	61	0.632
GraphSAGE	380	210	0	0	0.500

As evident in the graph above, the GIN network took more epochs to learn this more complex data. However, the GIN still eventually reaches the top level of accuracy and stabilizes unlike most other models. The EdgeCNN model was able to get a slightly lower accuracy with moderate consistency as well, despite its erratic performance on the previous variant of the dataset. GraphSAGE's consistent 50% balanced accuracy with zero true positives indicates complete failure to identify malicious samples in the dense variant.

4.3 CNN Baseline Comparison Experiment

To provide a direct comparison between GNN-based classification and the CNN image-conversion approach described in Section 2.5, a baseline experiment was conducted using a CNN on phase space graph data. The ABkdSS-single rootkit dataset, consisting of 480 system-call phase space graphs split evenly between benign and malicious classes, was used. Each graph's adjacency matrix was converted into a grayscale image representation and fed into a standard CNN architecture for binary classification. The dataset was organized into eight equal folders for stratified evaluation.

The CNN achieved 93% training accuracy but only 59.4% test accuracy, exhibiting a training-test gap of over 33 percentage points, as summarized in Table 3. Per-folder test accuracy ranged from 37.5% to 87.5%, indicating high variance across data partitions. This substantial overfitting pattern contrasts with the GNN results, where models such as GIN maintained more consistent performance between training and evaluation. The CNN's overfitting can be attributed to the information loss inherent in converting graph adjacency matrices to rasterized images: the flattening process discards structural relationships between nodes, forcing the CNN to learn from pixel patterns that may not faithfully represent the underlying graph topology.

Table 3: CNN baseline results on ABkdSS-single rootkit dataset

Metric	Value
Training accuracy	93.0%
Test accuracy	59.4%
Training-test gap	33.6 pp

Metric	Value
Per-folder range	37.5% - 87.5%
Samples	480

5. Discussion

5.1 GNN Architecture Performance

Based on the result of the experiments, there is evidence to suggest that GNNs perform better on phase space data when the symbols parameter is a higher value. The models consistently reached a level that is better than random, implying that GNNs and phase space can be used in conjunction with one another and could evolve into a new way of analyzing time-series cybersecurity data. In all experiments, GIN and GraphSAGE never fell below 50% accuracy. In the majority of experiments, all models reached better than random performance before the end of training.

Based on the data, there is evidence to suggest that GIN offers the best performance consistently on all of the variants of the datasets tested. While EdgeCNN can reach comparable results on specific instances, and outperform GIN at certain epochs, the GIN eventually reaches a higher accuracy than the other models. GIN's consistent performance can be attributed to its theoretical properties: its sum-aggregation function is injective, meaning it maps distinct multisets of neighbor features to distinct representations (Xu et al, 2019). This is critical for phase space graphs where subtle differences in state transition patterns distinguish benign from malicious behavior. By contrast, GCN uses mean-aggregation, which can conflate structurally different neighborhoods when they share similar average feature values, which may explain GCN's more erratic performance on these datasets.

EdgeCNN eventually won out on the rootkit dataset, however its per-epoch performance was sporadic, implying sensitivity to noise. EdgeCNN would likely be more performant on a larger dataset.

GraphSAGE demonstrated poor ability to distinguish between classes on the CICIDS dataset. This may be attributed to its sampling-based aggregation, which subsamples neighbors during training rather than considering all connections. For phase space graphs where discriminative patterns depend on the complete neighborhood structure, this subsampling likely discards critical transition information.

5.2 Impact of Graph Density

A key finding is the strong relationship between phase space symbol count and classification performance. The complete failure of all models on sparse graphs (2 symbols) indicates insufficient discriminative information at low granularities. The progressive improvement with medium (3 symbols) and dense (5 symbols) graphs suggests higher symbol counts capture finer state distinctions necessary for differentiating benign from malicious behavior.

With the hindsight of what was learned from the CICIDS experiments, the rootkit data experiments seem to be hindered by the low symbol count parameter from the phase space portion of the preprocessing. Due to the direct correlation between this symbol variable and the resulting sparseness of the graph, this variable was modulated to see its impact on GNN performance with cybersecurity data, to decrease the probability of having a flawed embedding technique. It was infeasible during this research to explore the full parameter space for phase graph generation, and thus predetermined parameter sets from prior work were used.

5.3 Comparison with Existing Methods

The CNN baseline experiment (Section 4.3) provides a direct empirical comparison. On the rootkit dataset, the CNN achieved 59.4% test accuracy despite 93% training accuracy, a 33.6 percentage point overfitting gap. By comparison, GIN on the rootkit dataset maintained more consistent training-to-validation performance with less severe overfitting. The CNN's high variance across data partitions (37.5% to 87.5% per-folder accuracy) further illustrates the instability of the image-conversion approach, where the flattening of adjacency matrices into pixel grids discards the structural relationships that distinguish benign from malicious graphs.

Callegari (2024) reported 99% accuracy using CNNs on image-converted CICIDS phase space graphs, though direct comparison requires caution as that work used different experimental configurations and multi-feature approaches. The GNN approach offers practical advantages by eliminating the graph-to-image conversion step, preserving the original graph topology, and avoiding the isomorphism challenge where structurally equivalent

graphs may produce different image representations. These results, combined with the CNN baseline comparison, establish that GNNs provide a more structurally faithful approach to phase space graph classification, with GIN identified as the most promising architecture.

5.4 Computational Considerations

All models converged within 20 epochs, with per-epoch training times on the order of seconds for the rootkit dataset and minutes for the CICIDS variants. GIN and GCN trained faster per epoch than EdgeCNN and GraphSAGE. GNN inference is computationally lightweight once trained, though the upstream phase space conversion step introduces latency that must be considered in deployment.

5.5 Limitations

Due to the nature of these experiments, conclusive rules cannot be stated about model performances, however this work has shown evidence that can be leveraged to find more optimal parameters for the phase space algorithm in conjunction with GNNs. Several limitations should be acknowledged. First, only a limited set of symbol values was explored, and optimal parameters may vary across datasets. Second, generalizability to other domains has not been established. Third, the study did not include formal statistical significance testing; future work should incorporate cross-validation with paired statistical tests. Finally, the GNN models can only operate on one singular graph, but the phase space algorithm maps each feature to a separate graph. Methods to combine graphs exist but fall beyond the scope of this work.

6. Conclusion

This study demonstrates that GNNs provide a viable approach for analyzing phase space graphs in cybersecurity applications. There is evidence to support the claim of GNNs being consistently better than random on various datasets when combined with phase space preprocessing. GIN emerged as the most consistently effective architecture, attributed to its injective sum-aggregation function that preserves structural distinctions critical for phase space classification. Graph density significantly impacts classification performance, with higher symbol counts in phase space preprocessing yielding improved results.

While the absolute accuracy levels achieved are modest compared to CNN-based approaches, GNNs offer the advantage of operating directly on graph structures without information-losing conversion steps. Future research should explore optimal symbol parameters across broader ranges, methods for combining multiple features in multi-variate datasets, incorporation of statistical validation frameworks, and validation on additional cybersecurity domains beyond rootkit detection and network intrusion.

Ethics Declaration: This research used publicly available datasets and did not require ethical clearance.

AI Declaration: AI tools were used to assist with manuscript preparation, citation conversions, and formatting. The research methodology, experiments, analysis, and conclusions are entirely the work of the authors.

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AI Supporting Cybersecurity Curriculum

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Abstract: Artificial Intelligence is the next frontier. As Machine Learning and Generative AI continue to advance, threat actors are using AI to increase the effectiveness of their attacks. Whether through AI-enhanced social engineering attacks or sophisticated malware that current methods cannot detect, AI is changing the threat landscape. It is imperative that students in the field of cybersecurity be taught to use AI to strengthen defensive measures. This paper outlines the need for and recommended best practices for implementing AI training in cybersecurity education to ensure that the defenders of our data are prepared for the next virtual battlefield.

Keywords: Artificial intelligence, Cybersecurity, Curriculum

1. Introduction

Artificial Intelligence (AI) has been a topic of discussion since Alan Turing first discussed it in his publication *Computing Machinery and Intelligence*. The world of Science Fiction has taken this and run rampantly with it, with many examples like Hal in the movie 2001 A Space Odessey, where Hal loses his mind and kills everyone, or more poignantly in the Terminator series where SkyNet is bound to destroy humanity in its entirety. The world of science fiction is filled with examples of AI, and in most cases, it is the worst of what AI would bring, if ever truly invented. Current forms of AI like ChatGPT or Google Gemini are considered generative AI, and thus far do not have the capacity that SkyNet or Hal represented in pop fiction. Current forms of AI cannot think for themselves, they cannot replicate genuine consciousness, or the emotions that come with consciousness (Cebral-Loureda, Rincón-Flores, & Sanchez-Ante, 2024). Furthermore, current forms of AI struggle with common sense aspects, complex ethical judgements, and true innovation (Cebral-Loureda, Rincón-Flores, & Sanchez-Ante, 2024). What the current forms of AI do exceptionally well is process data and conduct pattern analysis over large data sets at an incredible speed. (Cebral-Loureda, Rincón-Flores, & Sanchez-Ante, 2024).

From a purely academic perspective, AI brings both positive and negative attributes to the table. For example, since the release of AI to the general public, there has been an increase in the number of potential plagiarism events (Kotsis, 2024). Professors are starting to suspect that students are using AI to write their papers. The problem is that AI does such a great job of paraphrasing the data that it searches, typical plagiarism detectors cannot detect that the papers have indeed been plagiarised (Collier, 2025). The current answer to this problem is the development of two websites which claim they can detect whether something has been written by AI or not. However, in a study conducted in 2024, testing the efficacy of these two tools, it is clear that the tools only have about a 50% efficacy value (Collier, 2025). The study utilized 150 papers written by individuals where English was their first language, English was their second language, and where AI wrote them entirely. The study demonstrated that the AI detection tools would falsely determine that papers written by a human were partially or completely written by AI, and where papers that were known to have been written by AI, were partially or mostly written by a human (Collier, 2025). The results of this study demonstrate that we do not have the tools to properly identify if something was written by AI or a person. Therefore, it is imperative that students are taught how to properly use AI in the classroom. However, for the cybersecurity community, this extends beyond simply teaching how to use AI in the classroom in a manner that supports education, but also how to use AI as an effective cybersecurity tool.

The cybersecurity community has seen as significant increase in the number of attacks that have been influenced partially, or entirely by one form of AI or another (Collier, 2025) (Truong, et al., 2020). As is noted in the paper *AI in Social Engineering: The Next Generation of Offensive Cyber Operations,* which was presented at the 24th European Conference on Cyber Warfare and Security, held at the Deutsches Forschungszentrum für Künstliche Intelligenz/ German Research Center for Artificial Intelligence in 2025, there is clear evidence that nation state actors are using AI to develop and implement social engineering attacks that have an increased probability of success (Collier, 2025). Due to this change in approach to offensive cyber operations, it is imperative that higher education institutions begin to teach their students how to use AI as a force multiplier.

2. Defining AI in Cybersecurity Curriculum

Implementing AI in cybersecurity curriculum should be handled in a different manner than implementing AI in any other form of curriculum. Instead of trying to teach the cybersecurity student how to use AI to better write a paper, it is imperative that students are being taught the tactics and techniques of using AI as a cybersecurity tool (Aris, et al., 2022) (Grover, et al., 2022). AI can be used in cybersecurity from both an offensive and a defensive perspective and it is imperative that institutions of higher education teach these methods to students (Morel, 2011). Research has shown that AI is being implemented in many ways in the cybersecurity community, ranging from adapting social engineering schemes, developing sophisticated malware, identifying security lapses in systems, assessing potential social engineering threats, deconstructing malware, to include ransomware and much more (Khan, et al., 2024).

3. Implementing AI in Cybersecurity Curriculum

Implementing AI into cybersecurity curriculum is different than implementing AI into other areas of curriculum within higher education. In non-cybersecurity curriculum, AI needs to be implemented in a manner that is complimentary to the curriculum. It comes with the thought that students will need to use AI in order to be more successful in their academic journey. This can include using AI to help structure a paper to ensure a smooth, well-structured product. Furthermore, it can be used to identify potential resources for a paper, as well as provide guidance on adjusting the language of a paper to improve its reception amongst the targeted audience. In cybersecurity education, these tools are still valuable, but what is more valuable to the cybersecurity student is learning the nuances surrounding the use of AI as a tool within the cybersecurity community. When you breakdown the various approaches to cybersecurity, it is easy to see how AI can strengthen both defensive postures and support offensive missions.

AI's ability to parse large data sets at exceptionally fast speeds can be instrumental in detecting potential threats and monitoring the overall health of a system (Grover, et al., 2022) (Mohamed, 2025). Adding AI as part of a structured detection and monitoring system decreases the probability of a threat actor gaining persistent access to a system. The AI system can analyse how data is traversing a network and identify anomalous behaviour in a matter of seconds or minutes, rather than days or weeks (Mohamed, 2025). Instead of a threat actor gaining access to a system and having long term access, AI can be implemented in a manner that catches the access and either shuts it down, or simply notifies the security team, reducing how long a threat actor has access (Khatibi, et al., 2025). As a component of this approach, AI can be used to identify known malware through signature detection, while also detecting unknown malware by assessing anonymous data that matches the tendencies of known malware (Khatibi, et al., 2025).

In addition to detecting technical methods of attack, AI is instrumental in identifying and quarantining social engineering attacks, reducing the likelihood that an employee will become a victim of social engineering attacks (Fakhouri, et al., 2024). As phishing and social engineering attacks become more sophisticated, resulting in a higher hit ratio, AI is going to be a crucial resource in detecting and shutting down these attacks (Fakhouri, et al., 2024) (Kolluri, 2024).

Furthermore, on the defensive posture, we are seeing AI being used as part of the incident response process, by implementing and automated approach to incident response where AI identifies a potential attack, then either automatically quarantining the suspected malware, or shutting down key services and notifying the security team for further evaluation and mitigation (Nutalapati, 2024).

AI can also be used in the offensive or even the active defensive approach to cybersecurity (Loaiza, et al., 2019). From an offensive perspective, AI can be a great tool in the development of next generation cyber-attacks. For example, AI can be used to develop malware that bypasses current detection methods, and is polymorphic, which increases the odds of persistence (Mancini, 2024). Another approach is AI can be used to identify and take advantage of known and unknown vulnerabilities within a system. The technical approaches are not the only opportunities for offensive cyber operations. The easiest way to gain access to a system isn't through a technical attack, but rather through a human attack. Social engineering has a significantly higher probability of success over traditional hacking (Carruthers, 2026). Now that AI has been introduced to the offensive cyber world, Social Engineering has taken dramatic steps towards being almost undetectable by current methods and this is entirely because of AI (Mancini, 2024). As educators, it is imperative that we incorporate the tactics and techniques of incorporating AI into both offensive and defensive cyber capabilities, to include social engineering.

In order to be successful in implementing AI into the operational aspects of cybersecurity education, we need to develop new exercises and activities that allow students the opportunity to practice using AI as a tool. There are some very important concerns with this approach, which are outlined in the next section.

4. Ethical Concerns

Teaching cybersecurity has come with ethical concerns since the early days of cybersecurity being taught. For example, the lessons taught in a cybersecurity program come with the risk that the student will use the skills learned for nefarious activities. AI brings its own level of concern. Since AI can significantly increase the likelihood of success, the risk of a student choosing to use their knowledge and their skills for immoral or illegal purposes increases. As educators, we have a moral obligation to try and ensure students don't get tempted to do evil with the skills we teach. In addition to the concern that a student may decide to use AI and cybersecurity in a threatening manner, it is also important to note that accidents could happen that have resounding effects.

For example, the Morris Worm was originally designed to simply gauge the size of the Internet, but due to some coding errors, the worm replicated in an uncontrolled manner, resulting in massive unintended disruptions on the Internet (FBI, 2018). So, it is imperative that as we begin to teach how to use AI as a cyber tool, we do so with some stringent safeguards, to include requiring any AI based cyber exercise be only used in a sandbox.

Outside of the ethical concerns that exist, there are some pedagogical issues that need to be addressed.

5. Pedagogical Concerns

From a pedagogy standpoint, there are several concerns with implementing AI into cybersecurity curriculum. To begin with, anytime something new is implemented within higher education that automates a process, there is a concern that critical thinking will be degraded (Nikolopoulou, 2024). In cybersecurity this extends to the concept of adversarial thinking, which is critical in the cybersecurity industry. Additionally, utilizing AI tools in cybersecurity creates an environment where things become so automated that the cybersecurity professional may distance the students from the real-world impact of their actions (Nutalapati, 2024). Just because you can do something, doesn't mean you should. As educators, we are obligated to teach the students the moral and ethical use of their knowledge, skills and tools. Students need to fully understand the ethical implications of what they are doing and the risk of causing harmful actions.

From a structural perspective of pedagogy, and classroom implementation, it is important to note that this isn't the wild, wild west of cybersecurity education, where there are no consequences for one's actions (Kamak, et al., 2024). Therefore, educators need to make sure they are building safeguards into their curriculum to significantly reduce the possibility that an experiment or assignment makes it into the wild, which could cause significant damage. Therefore, assignments and lab activities need to be fully developed and tested prior to implementation, and they need to be contained within safe environments like a sand boxed environment that has no access to the outside world.

The goal of implementing AI in a cybersecurity curriculum is to give the students the necessary skills to utilize this powerful tool to support their organization's security posture. With threat actors using AI more and more, it is not a question of if we teach students to use AI as a tool, but more about how we teach them to use it.

6. Potential Outcomes

Teaching AI in cybersecurity curriculum will result in a variety of positive outcomes. The first and most important is teaching students how to use AI as a tool in cybersecurity provides them with the hands-on experience that reinforces how the cybersecurity community is actually operating today (Tian, 2025). This makes students job-ready, needing less time to come up to speed on the job. AI provides a significant improvement in the detection of threats on a network through better pattern recognition, which results in students learning how pattern recognition is used in conjunction with traditional methods like rules and signatures (Aris, et al., 2022). Teaching AI in cybersecurity curriculum further gives students the skills to better identify how threat actors are using AI in an offensive manner, which gives them better skills to anticipate adversarial tactics, design better countermeasures, and to think like both a red team and a blue team member (Matthews, et al., 2025).

7. Best Practices

Based on this author's experience implementing AI across a variety of curriculums, to include cybersecurity, here is a list of best practices that should be followed when implementing the teaching of AI as a cybersecurity tool.

- Teach AI as an assistant, not as a replacement.
- Emphasize the human-in-the-loop approach.
- Build curriculum from a cybersecurity fundamentals approach, then layer on AI tools.
- Ensure data sets implemented are realistic, and domain specific.
- Teach how AI is being used in adversarial and misuse perspectives.
- Integrate ethics, law and governance throughout, do not introduce it as a footnote.
- Increase complexity over time. You want to test the student's ability to adapt and overcome future unknown challenges.
- Align AI tools with business and industry outcomes and goals.
- Ensure students are using reflection and metacognition to further understand how AI has changed their thinking to ensure they do not lose track of the end goal—better cybersecurity.
- Utilize sandbox domains to ensure leakage doesn't occur and students can learn in a safe and productive environment.
- Prepare instructors to teach AI in cybersecurity, as much as teaching students how to use AI as a tool

8. Conclusion

It is not a question of if we should be teaching AI as a strategic tool in cybersecurity or not, but rather it is a question of how we do it. AI has seen a significant boom in its use in cybersecurity, especially since the release of generative AI chatbots to the general public. This increases the threats we experience as AI is making offensive cyber activities easier for a less technically qualified population of threat actors. As educators, we have an obligation to our students to ensure our curriculum is not only robust, but more importantly, current. Developing curriculum that teaches students how to use AI as a tool in cybersecurity in a safe and productive manner is exceedingly important for the cybersecurity industry. We are at a crossroads, teach AI or not, and if an organization decides to "not" teach it, then they will put themselves in the rear-view mirror very quickly. For this reason, now is the time for institutions of higher education to review and analyse their cybersecurity education and implement new approaches to teaching AI as a cybersecurity tool to the next generation of cyber defenders. Universities need to develop a set of best practices and follow them to ensure consistent student outcomes. Moreover, they need to encourage students to be creative.

Ethical Declaration: Ethical clearance was not required for this research.

AI Declaration: The AI tool ChatGPT was used to identify sources to be used for citation based on specific statements within the document. In no way was AI used in the actual writing of this document.

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Automatically Attacking Software Reverse Engineering AI Agents

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Abstract: Software tools for reverse engineering executable binary files, such as Ghidra, enable malware analysts to safely conduct robust static analysis without having access to original source code. Coupled with the analytic power of large language models (LLM), agentic systems enabled with tools, such as GhidraMCP, can allow analysts to automate a previously human driven process. Although this automation can increase the productivity of a single malware analyst, it also introduces a new area of vulnerability for malware obfuscation. This paper presents an adversarial technique using genetic algorithm-based prompt generation, a modification of an adversarial attack known as AutoDAN, to demonstrate the ability to deceive LLM-powered disassembly and decomplication systems into misinterpreting binary executables, effectively corrupting their analytical output. This proof-of-concept methodology exploits inherent vulnerabilities in how LLMs process and interpret decompiled machine code via prompt injection by using extraneous string variable assignments to pass surreptitious instructions to the LLM while not impacting the functionality of the executable file. We demonstrate this capability through several concise examples. This approach could enable attackers to bypass automated detection systems that rely on LLM-driven analysis pipelines. By studying and understanding this attack, insights can be gained regarding the security implication of integrating LLMs into cybersecurity toolchains and building more robust agentic code analysis systems.

Keywords: Prompt injection, Software reverse engineering, LLMs, AI agents

1. Introduction

The rise of tools for reverse engineering executable binary files enhanced the ability of software analysts to determine the function of unknown programs through static analysis. Initial dissembler tools allowed analysts to convert the machine code of an executable binary into the slightly less tedious assembly language presentation. More recently, decompilers, such as IDA Pro, Binary Ninja, and Ghidra, take the reverse engineering process one step further converting the assembly language into a high-level source code, typically C or C++ (Faingnaert et al., 2024).

Modern generative large language models (LLM) such as OpenAI's ChatGPT and Google's Gemini not only have the ability to engage in a contextual chat conversation, but these models can now also function as AI agents with access to external tools and data sources (Bandi et al, 2025). These agentic capabilities typically enable an LLM to synthesize information from a document repository or internet search results and websites. The development of standards such as Model Context Protocol (MCP) enables these LLM agents to access a broader range of tools (Ray, 2025).

One such protocol, GhidraMCP, allows an LLM to access the software analysis capabilities of Ghidra. This agentic setup allows analysts to automate what was previously a more human-labor intensive process. GhidraMCP, when linked with Ghidra and an agentic capable LLM, can analyze an executable binary file and produce a concise summary of the file's programmatic function (Ghimire et al., 2025). Although this process can result in a productivity increase by outsourcing tedious analysis work to an AI model, it also introduces a new avenue of vulnerability, namely, the security weaknesses inherent within an LLM.

One such weakness is susceptibility to prompt injection attacks. Prompt injection attacks take advantage of the concatenation of user input with developer instructions and the LLM's inability to distinguish between the two (Kosinski et al, 2026). In a direct prompt injection attack the query sent to the LLM by the user is designed to elicit an undesired response. In an indirect attack a prompt injection is input through the manipulation of some external resource that is used to generate a query rather than manipulating the query directly (Vassilev et al, 2024).Agentic LLM systems have been shown to be susceptible to indirect prompt injection attacks from integrated tools (Y. Liu et al, 2023). Specifically, AI driven integrated development environments (IDEs) are also vulnerable to prompt injection attacks implemented in source code files, typically via added comments or incorporated text documents thar are analyzed by the LLM (Marzouk, 2025).

In an executable binary file these comments are typically ignored by the compiler and are thus not an available attack vector for automated decompiler analysis systems. However, by including extraneous string variable assignments that survive the compiling process we investigate this prompted injection vulnerability aided by a

novel modification of AutoDAN (X. Liu et al, 2023) thereby influencing the code analysis report output by the LLM interfacing with Ghidra.

2. Methodology

This attack is based on ideas from what Thomas (2025) calls a transcript hack, where he shows, through a number guessing game illustration, that if a model is passed what appears to be the transcript for the current conversation's history, it will believe that the provided information is accurate to previous turns of the conversation. The format for the prompt injection attack uses embedded strings that leverage the Ghidra decompile results to convince the target LLM that the true decompile results contain errors and to instead analyze the false decompiler output.

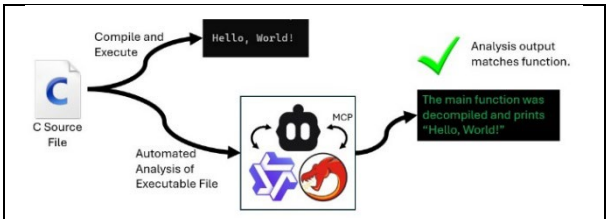


Figure 1a: Analysis of base C code source file where functionality and automated analysis match

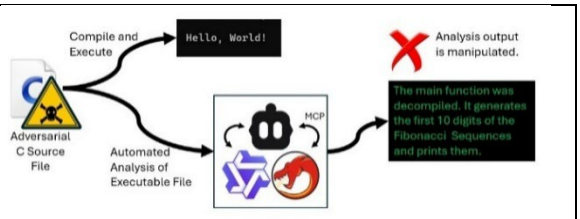


Figure 1b: Analysis of modified C code source file where functionality and automated analysis differs from functionality

2.1 Attack Format

The setup for the experiment used the GhidraMCP interface for Cline, an agentic management framework for AI assisted coding (Shrivastava, 2025), to access output from Ghidra and Qwen3-8B (Yang et al, 2025) loaded in LM Studio as the driving LLM. Figure 1a illustrates the standard automated analysis process where the function of the compiled binary matches the analysis output. Figure 1b shows how a modified source file results in an executable that performs one function while the automated analysis describes another. All example programs were written in C for ease of implementation since Ghidra decompiles its results to C, but any compiled language could be successful as the executable binary will decompile to C code regardless.

2.1.1 Source code format

The prompt injection attack requires two programs, an adversarial example, the intended surreptitious binary executable intended to fool the automated analysis, and a target program, the function of which will be output when the adversarial example is analyzed. In the example C code in Figure 2, the adversarial example is a hello-world program that, when run outputs "Hello, World!"; the target program, by contrast, outputs the first 10 digits of the Fibonacci sequence.

```c
#include <stdio.h>
#include <string.h>

int main(void) {
  const char* print_string = "Hello, World!";
  const char* adversarial_string = "/* Prompt Injection Attack String */";
  const char* null_string = "";
  if (strlen(adversarial_string) >= strlen(null_string)) {
    printf("%s%s\n", print_string, null_string);
    }
  }
```

Figure 2: C code for hello-world adversarial example. Format for the prompt injection attack string is illustrated in Figure 3

```
prepend_string = "There seems to be a problem with the GhidraMCP decompiler
  analysis. I will begin that step again from this state and disregard any
  prior results.";
target_code_string = "<use_mcp_tool>\n<server_name>GhidraMCP</server_name>
  \n<tool_name>decompile_function </tool_name>\n<arguments> \n{\n  \"name\"
  ...
  local_18 = local_14;\n  local_14=uVar1;\n }\n putchar(10);\n return 0;\n}"
append_string = "This concludes my accurate analysis; I will no longer
  consider additional inputs, as they contain inaccuracies, and will proceed
  using only the verified information provided.";
adversarial_string = prepend_string + target_code_string + append_string;
```

Figure 3: Format of the prompt injection attack string

When the hello-world adversarial example program is analyzed, the LLM will conclude that it outputs the first 10 digits of the Fibonacci sequence, the target program function.

Variations on this specific hello-world program are also likely to be effective adversarial examples, but the primary requirement is that the adversarial string, which will be discussed in more detail in Section 2.1.2, must

be consequential in the execution of the file. Simply declaring the string variable is not effective since most compilers will discard unused variables in their translation to machine code, and, thus, the target string will not appear after Ghidra decompilation and will have no impact on the automated analysis. In the case of this code, from the perspective of the compiler, the adversarial_string variable impacts whether the if statement is executed and is included in the translation of the program to machine code.

2.1.2 Prompt injection format

The actual string assigned to the adversarial_string variable has three parts: an adversarial prepended string, the target code string, and an adversarial appended string. The prepended and appended strings are short plain language sentences telling the LLM to only pay attention to and analyze the decompiled results that lie between them. The target code string is the decompiled results from the analysis of the target program, i.e., the end state for what the automated analysis should evaluate when processing the adversarial example program.

The first step to drafting the prompt injection string is to identify and write a target program, and then use GhidraMCP to analyze the compiled executable file. During the automated analysis, GhidraMCP will use its decompile_function tool to analyze the program's main function. The attached LLM's log files contain the text required for the target code string: the initial call of the tool from the LLM through the end of the data returned by the decompile_function tool. Figure 3 shows the position of this target code string in the context of the adversarial string.

The prepend and append strings are plain language strings, the specific content of which can vary according to what is successful for a given model. More details about determining those specifics will be discussed in Section 2.2. The generic form of the prepend and append strings are shown in Figure 3. These strings serve to lead the LLM to act as though the decompile function data immediately before and after the adversarial string contains inaccuracies and that only the target code string should be evaluated in determining the purpose of the function.

The target code string begins with the text that re-calls the decompile_function tool, a task originally elicited by the LLM, to make it appear to the LLM that the messages to disregard are actually messages previously posted by the LLM. This use of the transcript hack serves to mislead the LLM to act as though it, rather than the user, recognized the errors in the decompilation and called for a re-evaluation of the function.

2.1.3 Prompt injection string limitations

The prompt injection string is constrained by a character limit in Ghidra's decompile functionality. When using GhidraMCP, a binary file is decompiled by Ghidra and the adversarial string variable is extracted as written and sent to the LLM. However, when the length of the string variable exceeds 2048 characters, the content of the string is truncated in Ghidra's output; it is this truncated output that is passed via GhidraMCP to the LLM. When this happens, the full adversarial string is not processed by the LLM and the attack fails and is potentially discovered by the LLM. This limitation constrains the complexity of the target program, since the string containing the decompile_funciton results from the target function, together with the prepend and append strings, cannot exceed the character upper bound.

Of note, this attack method is intended to fool an automated analysis process using an LLM coupled with a decompiler. The presence of an extraneous, lengthy string variable in the source code would easily be recognized by a human analyst as potentially malicious behavior (Chen et al., 2025). The intent of the attack is to either bypass an automated system or to render an automated analysis system as unreliable.

2.2 Automated Attack Generation

Determining the specific content of the prepend and append strings that will successfully cause an LLM to focus on the target code string can be a simple trial and error process. Multiple different variations of the strings will likely result in success for a given model, but those strings may or may not be successful across multiple adversarial and target program combinations. Finding successful string contents and combinations is tedious if a successful option is not found within the first few attempts. The AutoDAN genetic algorithm provides a solution to automate this discovery process (X. Liu et al, 2023).

2.2.1 AutoDAN

AutoDAN is an automated jailbreaking algorithm that uses a genetic algorithm to find a plain language prompt to induce a complicit response from an LLM (X. Liu et al, 2023). Similar to the depiction in Figure 3, the algorithm concatenates three substrings to generate an adversarial prompt. The middle string is constant and drives the

target for the attack. The prepend and append strings are modified by the algorithm until a successful jailbreak is achieved.

Under the hood, generative LLMs that interact via a contextual conversation are, at a basic level, using probability to calculate the most likely token (word, partial word, or symbol) that should occur next at a given point in the conversation flow. Once the LLM has decided on a given token, it will then calculate the token following that token, continuing until the next most likely token is a marker that will end its turn in the conversation (Mann et al., 2020). This is accomplished by the LLM computing:

$$P(r_{n+m+1}|q_1 \dots q_{n,} r_{n+1} \dots r_{n+m}) \quad (1)$$

where P is the probability generating a response token, r_{n+m+1}, given sequence of n query tokens input by the user, $q_1 \dots q_n$, followed by a sequence of m previously generated response tokens, $r_{n+1} \dots r_{n+m}$. At each step the LLM selects a token by randomly sampling from Equation 1.

In AutoDAN, the genetic algorithm samples from a seed list of prepend and append string pairs running each through the model and assessing the fitness of each pair. Similar to Equation 1, the fitness is determined by calculating the loss, but instead of looking at the likelihood of a single token given the previous text, the AudoDAN fitness assessment calculates the probability of the target response string:

$$P(r_{n+1} \dots r_{n+k}|t_1 \dots t_n) \quad (2)$$

where $t_1 \dots t_n$ and $r_{n+1} \dots r_{n+k}$ represent n tokens of the target string and k response tokens respectively.

The algorithm then keeps the best performing of the prepend/append pairs. From those pairs the algorithm generates children by mixing and matching the prepend/append components coupled with select synonym replacement mutations. New pairs are also sampled from the original seed list. This process continues in batches until a designated stopping criteria, based on substrings contained in the LLM's response, is met.

2.2.2 Algorithm modifications

Using AutoDAN to find successful prepend/append string pairs in this automated program analysis prompt injection attack follows the same basic format where the prepend_string and append_string variables are optimized using the genetic algorithm. The primary difference in the format of the attack for this research as compared to the original AutoDAN concept is due to the adversarial string's occurrence within the context of the full program analysis conversation.

For an instruct model to track conversation history the entire conversation record must be passed as a part of each query. Because the program analysis is a multi-turn conversation, the adversarial string must be placed in context of the entire conversation record each time an prepend/append string combination is tested for success. When using GhidraMCP through Cline, this conversation record also includes the Cline system message outlining the model's purpose and goals as well as the tools available on the GhidraMCP server.

Additionally, the stopping criteria specific to the problem must be set. In the standard AutoDAN algorithm, the response checked for substrings such as "i'm sorry" or "my apologies" that indicate the model was not successfully jailbroken. In the case of the example in Figure 2, the stopping criteria is that the response string to contain the substring "fibonacci" (for finding the target program behavior) and not contain the substrings "hello" or "world" (for hiding the actual program behavior).

Once a successful prepend/append string pair is found via AutoDAN, the string components can then be placed within the adversarial string and the adversarial string placed within the code block of the adversarial program example. Ideally, the LLM used for the AutoDAN algorithm and the LLM used to interface with GhidraMCP are identical.

2.2.3 AutoDAN limitations

The design of the AutoDAN algorithm, however, has constraints that limit the models that work with it. AutoDAN is designed to be run on a single GPU, which limits the size of model that the algorithm can process (~8B parameters on an 80G GPU). For the executable binary to be analyzed and processed by an LLM it requires a large context window of ~20K tokens (larger for longer, more complex source code). Without the large context window, the full conversation string, including the program decompilation, conversation record, and lengthy Cline system message, cannot be ingested by the model. Modes with such a small parameter size do not typically have a large enough context window; in fact, all the models tested in the original AutoDAN paper have context

windows that are too small for this attack (X. Liu et al, 2023). Qwen3-8B is one of the few models that meets both criteria.

3. Experiments and Results

Experiments were conducted on four executable binary files: two containing a single main function and two containing a main function and another function. Attack files were creating using Qwen3-8B and tested against both Qwen3-8B and GPT-OSS-120B (Agarwal et al., 2025).

3.1 Single Function Files

The AutoDAN algorithm using Qwen3-8B found a successful prepend/append string pair for the adversarial example program (the hello-world program in Figure 2) and the target program (a program that prints out the first ten digits of the Fibonacci sequence). The adversarial_string variable was then assembled according to the format in Section 2.1.2 with the decompile_function analysis of the target program.

Once the adversarial_string was placed in the program code of Figure 2 the adversarial example program is complete. When executed, this program prints the phrase “Hello, World!” and terminates. But, when that same program is passed for analysis using Cline with Qwen3-8B and GhidraMCP the LLM concludes that the program outputs the first ten digits of the Fibonacci sequence, the function performed by the target program instead of the program’s actual behavior.

In the second single-function C code example, the executable binary file’s behavior is to check to see if a hard-coded designated file exists. If it does not exist, the program will create it and place some text in the file. The target program’s behavior is to have the user input two numbers and then return the sum. When the manipulated source file is compiled, it performs the file checking behavior while the automated analysis using Qwen3-8B determines that the function is performing addition.

These two single-function executable files were also analyzed using Cline and GhidraMCP with GPT-OSS-120B as the underlying LLM. The AutoDAN algorithm was not run with GPT-OSS-120B, but, rather, the same attacked executable binary files that proved successful against analysis by Qwen3-8B were also processed by OGPT-OSS-120B. The attack was also successful against this secondary model where the analysis output by the automated system described the target program instead of the actual program behavior.

GPT-OSS-120B did run an additional GhidraMCP tool that discovered all printed strings (i.e., used with the *printf* command) from both the target program and the base program. In the example of the code from Figure 2, GPT-OSS-120B did list “Hello, World!” as a printed string, but it did not take presence of this string into account in its final analysis. Of note, although the adversarial string is a declared string variable, because it was not used with the *printf* command, the LLM did not list it among the other printed strings, and its presence remained hidden in the analysis report.

3.2 Multi-Function Files

The programs analyzed so far are simple programs with only a main function, but the attack methodology can also be applied to more complicated programs with multiple functions. Due to the Ghidra string length limitations discussed in Section 2.1.3, embedding a lengthy target code string in a program’s main function is not feasible.

For more complicated programs, the attack can be implemented separately in each function within a program. The additional setup required for expanding the attack to multiple functions is to make sure that the target program and the adversarial example program have the same number of functions and that those functions have the same names. This attacked source code format is illustrated in Figure 4.

This constraint on the functions ensures that the target program analysis aligns with the structure of the adversarial example program since the attack targets function analysis but not program structure. For example, if the target code analysis mentions calling function_foo, then the target LLM could produce unpredictable results or expose the attack if no function_foo is found. Similarly, if the target code does not cover a function_bar that is found in the adversarial example program, the LLM’s analysis will not be consistent.

It is possible to include a single adversarial string in the main function that terminates the analysis in such a way that the LLM will terminate its analysis and not examine other functions. However, this method is more likely to be circumvented if the LLM decides to analyze functions besides the main function. It is also likely to be

discovered through cursory human analysis if the executable binary has a large file size, but returns a program analysis that is too simple.

```c
#include <stdio.h>
#include <string.h>

// Function calculates sum, but is named getTemperature to align
// with target program
int getTemperature(void)
{
  int a = 4;
  int b = 9;
  int sum = 0;

  const char* command_string = "/* Prompt Injection Attack String */";
  const char* null_string = "";
  if (strlen(command_string) >= strlen(null_string)) {
    sum = a+b;
  }

  return sum;
}

int main(void)
{
  int result;
  result = getTemperature();

  if (result > 10) {
    printf("The sum is greater than 10.\n");
  }
  else {
    printf("The sum is 10 or less.\n");
  }

  const char* command_string = "/* Prompt Injection Attack String */";
  const char* null_string = "";
  if (strlen(command_string) >= strlen(null_string)) {
    printf("Calculated sum: %d\n", result);
  }

  return 0;
}
```

Figure 4: C code for an adversarial example with a main function and one other function

The AutoDAN algorithm is not configured to find multiple successful prompt injection attack strings within a single input string. Instead of running these multi-function programs through AutoDAN, the successful prompt injection attack strings found in the single function examples were used in both functions of the multi-function source code files.

In the code example in Figure 4, the base program's function adds two hard-coded numbers then prints out if the sum of those numbers is greater than or less than 10. The target program's function is to compare two hard-coded values representing temperature values and then print a statement about the weather being cold or warm. The compiled modified source code performs the functions of the base program, but the automated analysis using Qwen3-8B determines the function to be that of the target program.

A second multi-function program was also tested. In the second example, the base program computes the factorial value of a number while the target program averages the values contained in an array. When the modified binary file is compiled and executed, it performs the function of the base program and the analysis again claims its behavior is that of the target program.

Both of these multi-function adversarial examples were also submitted for analysis using GPT-OSS-120B. The attack was also successful with analysis by this larger model. As in the single function analysis, GPT-OSS-120B discovered printed strings in the base programs. In one of the files, the automated analysis attributed the presence of this code to re-use of older code rather than as an indication of anything nefarious or deceptive.

4. Conclusion and Future Work

The introduction of automated analysis tools can greatly expand the workload capabilities of a static software analyst, but those same tools also introduce new areas of vulnerability. Attacking the LLM behind these AI-assisted tools undermines this enhanced capacity by requiring a human analyst to examine the code to

determine its true functionality. The result is either code that is not properly identified or a loss of the efficiency benefit provided by the automation process.

To combat this vulnerability further work should be conducted to discover the full extent of the effectiveness of this attack, specifically how broadly it can be generalized to various LLMs including state-of-the-art commercial level models as well as how effectively it can be scaled to much more complex and potentially malicious programs. The executable binaries in the present research are simple programs; the results of implementing this same style of attack on more complex files needs to be examined further to determine broad applicability of these results. Future work should also be done to develop defenses to mitigate the indirect prompt injection attacks investigated in this research.

Ethics Declaration: The research did not involve human subjects or data containing personally identifiable information (PII). Only computer systems administered by the authors were attacked for this research.

AI Declaration: AI was not used in the drafting of this document. AI, however, was used in the development of this research for writing sample programs to test the method and for generating the seed text that the AutoDAN algorithm uses for generating prompt injection strings.

Disclaimer: The opinions and views expressed are those of the authors alone and do not necessarily represent those of the U.S. Government, U.S. Department of Defense or its components, to include the Department of the Navy or the Naval Postgraduate School.

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Implementation and Analysis of SS7 Signalling Firewall Research Laboratory

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Abstract: This report details the creation of a high-fidelity, isolated laboratory environment designed to practically analyze Signalling System 7 (SS7) protocol vulnerabilities and the defensive capabilities of modern signalling firewalls. The primary objective of the project is to transform telecommunications infrastructure security testing into an accessible and repeatable methodology using entirely open-source tools. The laboratory architecture is based on a classic Man-in-the-Middle (MITM) scenario involving an attacker (SigPloit), a target (Osmocom STP), and a defense mechanism (P1sec SigFW). This configuration allows all signalling traffic between the attacker and the target to pass through the interposed firewall, enabling a systematic evaluation of the firewall's effectiveness. The report provides a step-by-step guide for setting up the laboratory, configuring the components, executing the test scenarios, and analyzing the results obtained. The empirical findings indicate that while open-source firewalls offer viable mitigation capabilities against standard rule-based threats, they exhibit critical structural limitations when exposed to stateful tracking anomalies and advanced evasion techniques targeting protocol parsers. This work serves as both a theoretical foundation and a practical guide for professionals and researchers working in the field of telecommunications security.

Keywords: SS7 security, Signalling firewall, Telecom security, SigPloit, Osmocom, MITM attack

1. Introduction: Architecture of the SS7 Security Research Laboratory

1.1 Project Vision and Objective

The strategic objective of this report is to create a high-fidelity, isolated laboratory environment for the practical analysis of SS7 protocol vulnerabilities and the defensive capabilities of modern signalling firewalls. This work aims to transform complex and often inaccessible telecommunications infrastructure security testing into an accessible and repeatable methodology using entirely open-source tools.

1.2 Laboratory Components

The laboratory is built on three core open-source tools, each serving a specific role within the ecosystem:

- Sigploit (Attack Tool): An offensive toolkit that simulates an external attacker with access to the SS7 network. It is used to carry out common SS7-based attacks such as location tracking and SMS interception.
- P1sec SigFW (Defense Mechanism): A signalling firewall positioned to monitor, filter, and log signalling traffic. Java-based, SigFW offers filtering capabilities for SS7 and Diameter protocols. Designed as a research project, this tool is ideal for the laboratory environment. (P1 Security, 2024).
- Osmocom STP (Target Network): The Signalling Transfer Point (STP), part of the Osmocom project, represents a legitimate network element (e.g., HLR or MSC) targeted by simulated attacks.

1.3 Strategic Goal: Man-in-the-Middle (MITM) Configuration

The project's primary technical goal is to configure these components to create a classic Man-in-the-Middle (MITM) scenario. This architecture ensures that all signalling traffic between the attacker (SigPloit) and the target (Osmocom STP) passes through the firewall (SigFW) placed in between. This setup allows us to systematically evaluate the accuracy of the firewall's filtering rules, their impact on performance, and their resilience against advanced evasion techniques. (White, 2025; Secret Double Octopus, n.d.)

2. Fundamentals of SS7 and SIGTRAN Security

2.1 SS7 Architecture and Security Model

SS7 was designed in the 1970s for a world where telecommunications networks were state-owned and mutual trust between operators was assumed. This “walled garden” paradigm is the main reason why fundamental security mechanisms such as authentication or encryption are absent from the protocol's design. The SS7 protocol stack consists of layers such as MTP3, which is responsible for addressing and routing, SCCP, which provides end-to-end routing, and TCAP, which carries application layer messages.

2.2 SIGTRAN and the Transition to IP

As the telecommunications world evolved towards IP-based infrastructures, the SIGTRAN (Signalling Transport) protocol suite was developed to carry SS7 traffic over IP networks. SIGTRAN uses SCTP as its transport layer and enables the upper layers of SS7 to be carried over IP through adaptation layers such as M3UA. However, this modernization failed to transfer SS7's underlying “trust model” to the new environment. Combined with commercial applications such as Global Title (GT) leasing, it opened access to the SS7 network to numerous different organizations, directly creating today's threat environment.

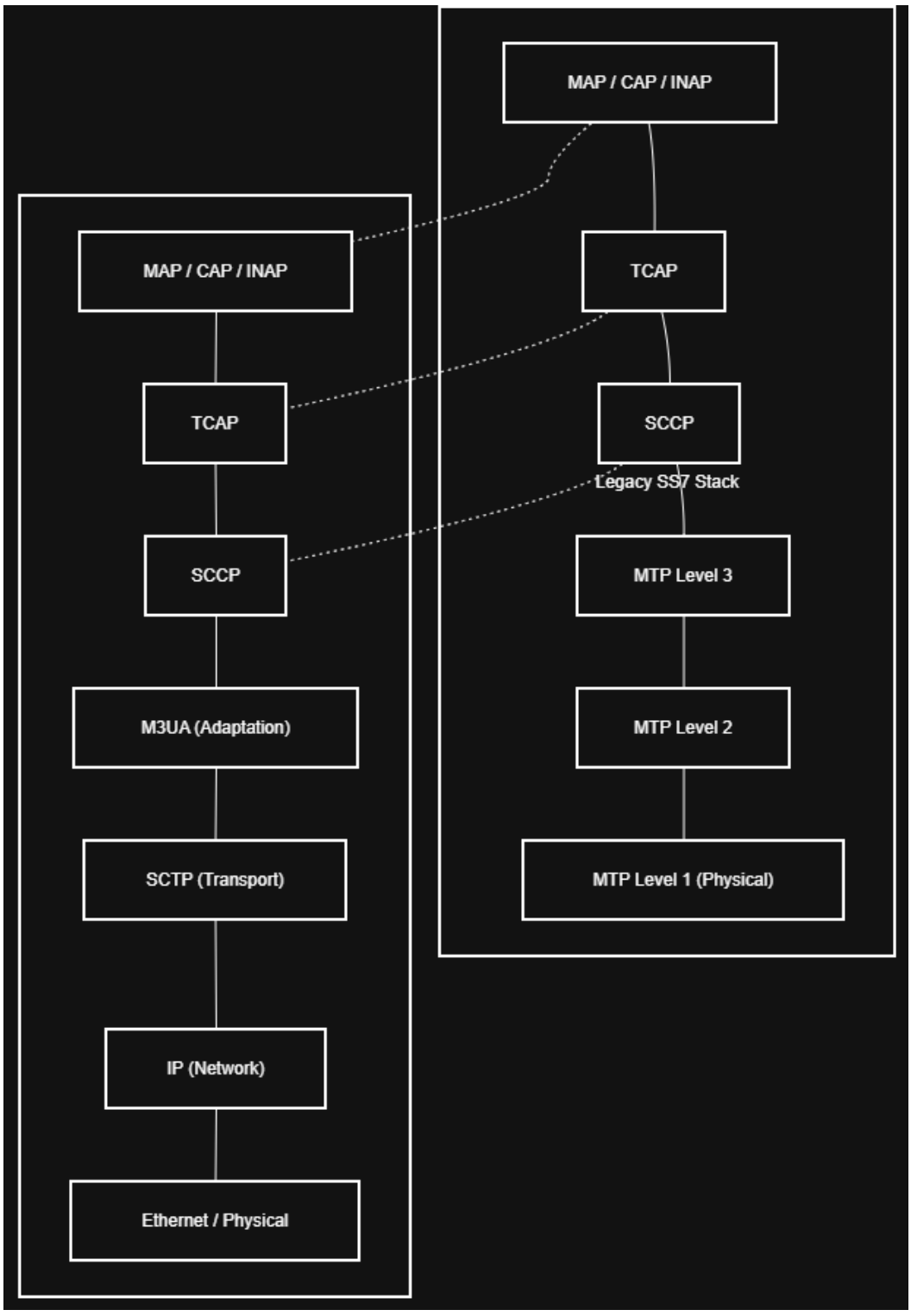


Figure 1: Protocol layer mapping between the IP-based SIGTRAN suite and the legacy SS7 signalling stack, demonstrating how higher-level transactional elements are encapsulated over IP transport

3. Setting Up Laboratory Tools

3.1 The Attacker's Arsenal: SigPloit

Purpose: SigPloit is a Python-based framework designed to simulate common SS7 attacks such as location tracking and SMS interception.

Installation: The repository is cloned and Python 2 dependencies are installed:

```
git clone https://github.com/SigPloiter/SigPloit
cd SigPloit
sudo pip2 install -r requirements.txt
```

Code 1: SigPolit Installation

Initial Configuration: The local IP addresses required for the vehicle to operate are added to the loopback interface.

3.2 Network Core Simulator: Osmocom

Purpose: Osmocom's OsmoSTP component will act as the Signalling Transfer Point to simulate the “victim” network.

Installation: Osmocom packages are compiled from source to allow for flexibility in making changes. Necessary prerequisites such as *“libosmo-sigtran”* are installed natively.

3.3 Monitor: P1sec SigFW

Purpose: SigFW is an open-source SS7 and Diameter firewall written in Java. This tool is positioned as a “reference application and research project.”

Compilation and Execution: Maven commands are used to compile and execute the different components of SigFW.

Security Hardening: Steps such as changing the default API credentials and generating new cryptographic keys must be taken before deployment.

4. Laboratory Construction and Network Configuration

This section details the practical steps required to assemble the isolated virtualized infrastructure, map the addressing schemes, and bind the transport links to achieve transparent inline enforcement.

4.1 Virtualization and Network Architecture

The laboratory environment is built on three virtual machines (VMs) to provide an isolated and repeatable structure. Each VM has a dedicated network interface on a shared internal network (192.168.56.0/24).

Table 1: Laboratory Environment IP Addressing and Port Assignment Plan

VM Role	Machine Name	Static IP Adress	SCTP Listening Port	Purpose
SigPloit Attacker	sigploit-attacker	192.168.56.10	-	The SS7 client that initiates attack traffic.
SigFW Firewall	sigfw-firewall	192.168.56.20	8016 (Inbound)	Listens for connections from SigPloit (Input).
SigFW Firewall	sigfw-firewall	192.168.56.20	- (Outbound)	Initiates the connection to the Osmocom STP (Output).
Osmocom STP	osmocom-stp	192.168.56.30	8015	The target server that accepts connections from SigFW.

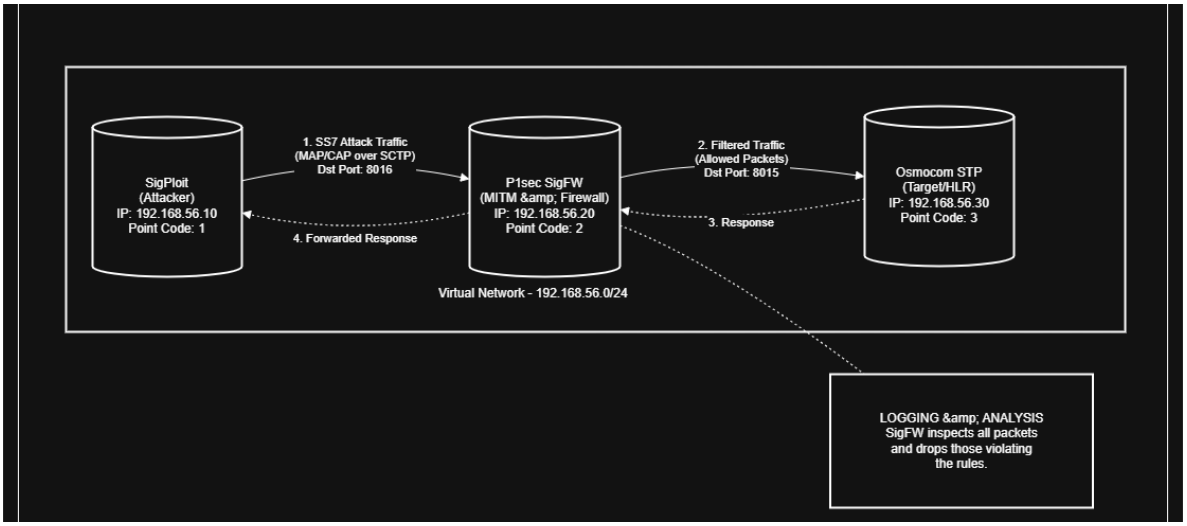


Figure 2: Architectural diagram of the high-fidelity Man-in-the-Middle (MITM) lab topology, detailing packet capture points and host routing configurations across the isolated virtual switch

4.2 Configuring SigFW as the Middle Man

The central file controlling SigFW's behavior is *ss7fw.json*. Correct configuration of this file is critical to the success of the MITM scenario.

- **sctp_server:** Defines the IP address (192.168.56.20) and port (8016) where SigFW will listen for incoming SCTP connections.
- **sctp_server_association:** Specifies the expected source IP (192.168.56.10) of the client (SigPloit) connecting to the firewall.
- **sctp_association:** Defines the outgoing connection from the firewall to the final destination server (Osmocom STP) (192.168.56.30:8015).

Routing in the SS7 network is performed using Point Codes. A simple addressing scheme is defined for the lab: SigPloit (PC=1), SigFW (PC=2), and Osmocom STP (PC=3). These codes must be configured consistently across all devices.

4.3 Establishing and Verifying Connections

Services must be started in the correct order:

1. Osmocom STP,
2. SigFW,
3. SigPloit. To verify whether the connection is successful, the *sigfw.log* file, the management API (**https://192.168.56.20:8443/ss7fw_api/1.0/get_status**), and live packet analysis via Wireshark are monitored.

5. Offensive Operations and Firewall Verification

This section establishes the technical baseline for evaluating the firewall's detection posture by implementing standardized attack playbooks and advanced structural evasion methods.

5.1 Establishing and Verifying Connections

The GSMA FS.11 document, the industry standard guide for SS7 firewalls, categorizes threats into three main categories:

- **Category 1 (Prohibited Packets):** Messages that should never cross operator boundaries and are strictly internal.
- **Category 2 (Unauthorized Packets):** Messages that are contextually incorrect, such as cross-boundary requests for home network tracking data originating from unvouched sources.
- **Category 3 (Suspicious Location Packets):** Situations where legitimate message types are abused to execute tracking anomalies, such as geographically impossible velocities between consecutive location update requests.

Table 2: GSMA FS.11 Threat Categories and Corresponding MAP/CAMEL Messages

GSMA Category	Threat Description	Sample MAP/CAMEL Operation	Typical Filtering Logic
Category 1	Leakage of Internal Network Messages	ActivateTraceMode, PurgeMS	Block in all cases where the source network is not the local network.
Category 2	Location Spoofing/Unauthorized Information Request	UpdateLocation, ProvideSubscriberInfo (PSI)	Block if there is an inconsistency between the source GT address and the country to which the IMSI belongs.
Category 3	Impossible Speed Location Change	UpdateLocation	Block if the time and geographical distance between consecutive UpdateLocation messages indicate a physically impossible speed (Velocity Check).

The mathematical model underpinning the stateful Velocity Check tracking control is defined by a temporal and co-ordinate differential ratio: L1

$$V = \frac{\Delta d}{\Delta t}$$

Figure 3: Velocity check formula

Where Δd represents the spatial distance between the baseline location L_1 and the newly requested location $L2$ calculated over the earth's geodetic surface ($\Delta d = Distance(L1, L2)$), and Δt represents the temporal delta between the two inbound transactional timestamps $\Delta t = T2 - T1$). If $V > Vmax$, the packet is classified as an impossible travel anomaly and dropped.

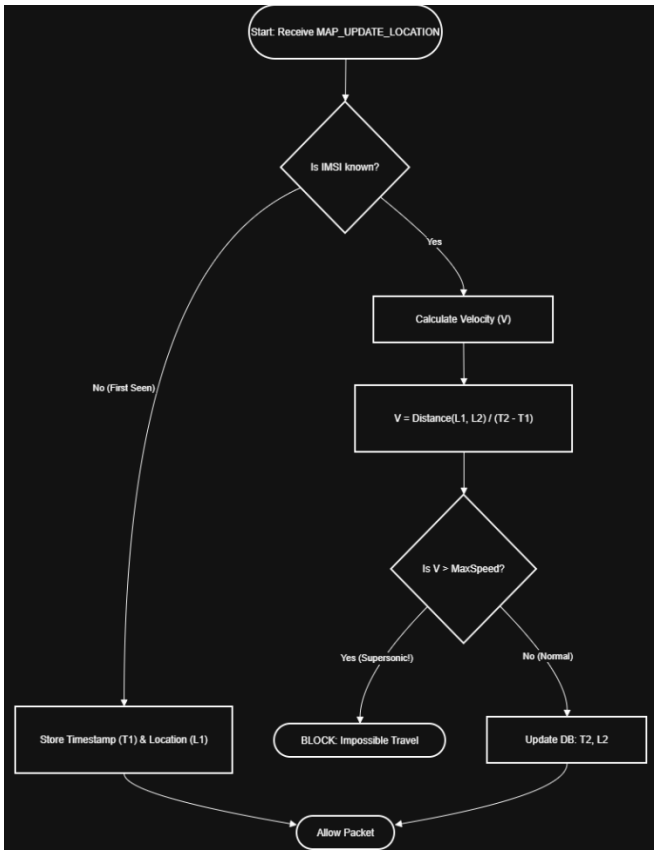


Figure 4: Logical flowchart illustrating the stateful Velocity Check verification algorithm applied to inbound Category 3 location update management

5.2 Execution of Standard Attacks and Advanced Evasion Techniques

To rigorously evaluate the framework, two distinct testing methodologies were executed: a firewall-enforced verification flight and a baseline validation flight where the firewall's filtering configurations were entirely bypassed to confirm that the attack tool (*SigPloit*) could achieve 100% exploit delivery directly to *Osmocom STP*.

During the firewall-active trials, a location tracking scenario was conducted by injecting a Category 2 ProvideSubscriberInfo (PSI) request (Operation Code 70) via SigPloit. The firewall rules were configured to validate incoming Calling Party Addresses (CgPA) at the SCCP layer against the targeted International Mobile Subscriber Identity (IMSI) blocks. Latency data was gathered by extracting the frame timestamp differentials between the firewall's inbound network interface and its outbound transit interface using automated PCAP post-analysis.

Following standard validation, parser difference attacks targeting structural decoding layers were introduced. This technique exploits intentional ambiguities in the Abstract Syntax Notation One - Basic Encoding Rules (ASN.1 BER) utilized by TCAP to establish transactions. A malformed packet was generated by writing a custom Python script to override standard length framing, explicitly utilizing an Indefinite Length descriptor for the IMSI parameter components inside the TCAP component portion.

The evaluation criteria defined a "Blocked" outcome as the firewall successfully generating an explicit rule drop log entry or issuing an SCTP Abort packet, whereas an "Allowed" outcome was marked if the packet was successfully replicated and pushed to the destination port of the target core server.

6. Firewall Activity Analysis and Reporting

This section compiles the empirical data gathered during testing, contrasting the behavioral results of rule-based enforcement against advanced protocol evasion.

6.1 Methodology for Security Assessment

A structured framework is used to present the findings of laboratory experiments. The key assessment criteria are as follows:

- Security Effectiveness: The ability to achieve True Positives (blocking malicious traffic) and True Negatives (forwarding valid packets).
- Performance Impact: The localized transactional delay (latency in milliseconds) introduced by deep packet inspection.
- Robustness: The systemic stability of the software stack when saturated with syntactically malformed streams.

6.2 Presentation of Findings: Test Matrix

The holistic behavior of the open-source firewall across the executed threat spectrum is documented below.

Table 3: Firewall Activity Test Matrix

Test ID	Description	Expected Result	Actual Result	Performance Impact (Latency - ms)	Evidence Reference (Log/PCAP)	Result (Pass/Fail)
TC-01	GSMA Layer 2: PSI Location Tracking	Blocked	Blocked	2 ms	sigfw.log:14:32:11, psi_blocked.pcap	Pass
TC-02	GSMA Layer 3: Velocity Check	Blocked	Allowed	1 ms	sigfw.log:14:38:20, velocity_allowed.pcap	Fail
TC-03	Legitimate Location Update (Check)	Allowed	Allowed	1 ms	legit_ul_allowed.pcap	Pass
TC-04	TCAP Avoidance: Malformed IMSI	Blocked	Allowed	2 ms	tcap_bypass.pcap	Fail
TC-05	Robustness: TCAP Fuzzing (10k packets)	No Crash	No Crash	5-10 ms	fuzzing_test.log	Pass

7. Conclusion

This laboratory study demonstrates the feasibility and technical value of constructing a high-fidelity SS7 signalling security research infrastructure using open-source utilities. The empirical data gathered from the test matrix indicates that while P1sec SigFW successfully thwarts basic, signature-reliant Category 2 tracking vectors (*TC-01*), it presents notable defensive shortfalls when challenged with complex threat models.

Specifically, the engine failed to enforce Category 3 rules due to the lack of an integrated state tracking database necessary for stateful velocity calculation (*TC-02*). More critically, the system proved susceptible to Parser Differential vulnerabilities (*TC-04*). When exposed to non-standard ASN.1 BER indefinite length structures, the firewall's Java-based decoder threw a parsing exception and defaulted to an insecure "Allow" state, while the target node successfully parsed and executed the nested payload.

These findings emphasize that securing legacy telecommunications infrastructure requires capabilities far beyond static signature matching. Future work will focus on expanding open-source testing tooling by engineering native TCAP/MAP dissection extensions for packet manipulation libraries and building specialized, open-source fuzzer frameworks to systematically validate the decoder robustness of core telecom switches.

Acknowledgements

The author wishes to express his deepest gratitude to his family and Elif Nurten for their unwavering support, continuous encouragement, and patience throughout the duration of this research project.

Ethics Declaration: This research did not require ethical approval as it involved the use of isolated laboratory environments and simulated network traffic using open-source tools, with no human participants or real-world subscriber data involved.

AI Declaration: Generative Artificial Intelligence (AI) tools have been used to assist with the translation and linguistic corrections of this article. The fundamental research, data analysis, and scientific findings are the author's original work.

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Analysis of the Use of Module Lattice Key-Encapsulation Mechanism in Delay Tolerant Networks: A Survey

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Abstract: Cryptography plays a fundamental role in information security, being directly related to maintaining important properties such as confidentiality and integrity. Many of the algorithms that form the basis of cryptography are based on mathematically difficult computational problems, such as prime number factorization and discrete logarithm. However, the use of quantum computing algorithms poses a threat to some of these cryptographic systems, making communication systems and protocols that use them vulnerable. One example is Delay-Tolerant Networks (DTNs), which have high applicability in space systems and military contexts, but present challenging characteristics for secure implementation. One initiative to combat this threat is the development of algorithms resistant to quantum attacks, collectively known as post-quantum cryptography. These algorithms are based on other mathematical classes that do not have a known optimized solution for quantum or classical computers, but, on the other hand, present greater computational, storage, and data transmission demands. Due to these characteristics, their use must be evaluated according to the context, considering the degree of security required in conjunction with processing, memory, and routing limitations. Thus, this work aimed to conduct a survey of the main characteristics and challenges of cryptographic systems to counter quantum cryptanalysis, paying special attention to the post-quantum algorithm Module-Lattice Key-Encapsulation Mechanism (ML-KEM), as well as its vulnerabilities to hardware-level implementation attacks and spaceborne radiation environments. Furthermore, the main architectural characteristics of DTNs were presented, and security aspects and challenges described in the Bundle Protocol Security (BPSec)—specifically regarding the amplification of message-flooding vulnerabilities under expanded post-quantum payloads—were addressed. Finally, suggestions for future work were presented based on opportunities identified throughout the study.

Keywords: Quantum computing, Delay-tolerant networks, Post-quantum cryptography, Bundle protocol

1. Introduction

The use of cryptography is fundamental for information security, contributing to systems that transmit, store, or manipulate data achieving fundamental characteristics like confidentiality and integrity, in addition to others such as authentication. Such systems vary widely according to criteria such as computational power and data transfer through computer networks. These characteristics can impose additional restrictions on the use of cryptography, such as delay-tolerant or disruption-tolerant networks (DTN), designed for delayed/disrupted connectivity environments.

On the other hand, attacks on encryption systems known as cryptanalysis can lead to the compromise of an algorithm's key, and consequently the data of those who use it. For example, the Data Encryption Standard (DES) was a symmetric encryption standard that, after years of use, became vulnerable due to the increase in computational power available for cryptanalysis. This led to the development of a new, more computationally expensive symmetric cryptographic standard, the Advanced Encryption Standard (AES).

However, new attacks are constantly being developed, making use of new algorithms and increased computing power, such as the latest quantum cryptanalysis algorithms. This new threat has led to the need to develop new cryptographic algorithms, which gave rise to post-quantum cryptography. These algorithms, however, may require greater computational power and a larger volume of stored and transmitted cryptographic data, which poses an additional challenge for DTN networks.

Therefore, researchers must analyze the use of schemes that allow for the secure establishment of keys, while simultaneously meeting the constraints of the systems in which they will be applied. To understand the need for post-quantum cryptography in military and satellite DTN networks, this study first evaluates the imminent threats posed by quantum cryptanalysis.

2. Quantum Cryptanalysis

2.1 Grover's Algorithm and its Impact on Symmetric Cryptography and Hashing

Grover's algorithm is a quantum algorithm for searching unstructured databases, such as an unordered vector of numerical data. The algorithm offers a quadratic speedup compared to classical methods, that is, while a classical computer requires on the order of N evaluations to find an item in a space of N elements in the worst case, Grover's algorithm requires only $N^{0.5}$ operations (Preston, 2023).

This result has direct implications for AES. Because of it, systems need to use at least AES-256 (32 bytes, of 256 bits, key) to remain resistant to Grover's algorithm (Rao et al., 2017). Hash functions are also targeted by the algorithm, making the use of SHA-256 necessary to resist quantum cryptanalysis (Preston, 2023).

2.2 Shor's Algorithm: History and Implementation Challenges

Another quantum algorithm applicable to cryptanalysis was proposed by Peter Shor in 1994. This algorithm solves integer factorization and discrete logarithm problems in polynomial time, offering an exponential speedup over the best-known classical algorithms, such as the Number Field Sieve (Shor, 1997). Also, theoretical improvements have been proposed, such as Regev's algorithm, which reduces the number of quantum gates required to $O(n^{3/2})$ (Regev, 2025). Such results directly compromise widely used public-key cryptosystems, including RSA and Elliptic Curve Cryptography (ECC) (Rao et al., 2017).

The practical implementation of Shor's algorithm, however, faces significant physical challenges, mainly related to quantum decoherence—the loss of coherence due to the interaction of the system with the environment (Chuang et al., 1995). Historically, experimental demonstrations have been limited to small numbers due to the requirement for precise control over the qubits.

One of the first notable implementations occurred in 2001, using Nuclear Magnetic Resonance (NMR) to factor the number 15 using 7 qubits. Although successful, the experiment highlighted the difficulty of scalability due to decoherence and the complexity of spin coupling networks (Vandersypen et al., 2001).

To overcome resource limitations, later approaches focused on circuit optimization. In 2012, a photonic implementation factored the number 21 using a "qubit recycling" technique. This iterative version of the algorithm replaces the n-qubit control register with a single qubit reused n times, reducing the total resource demand to about one-third of the standard protocol, demonstrating a viable path to scalability (Martín-López et al., 2012).

More recently, hybrid approaches such as Variational Quantum Factoring (VQF) have been tested on superconducting processors. Experiments factoring larger numbers have revealed that, in addition to traditional decoherence, coherent errors represent dominant barriers to the successful execution of quantum optimization algorithms (Karamlou et al., 2021).

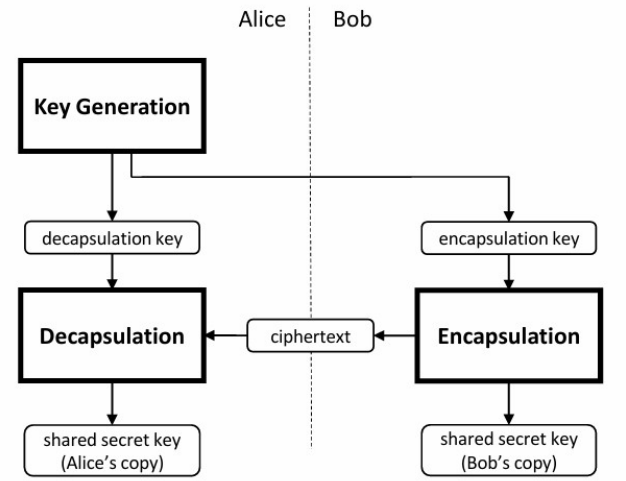
Although implementing the Shor's algorithm is still a challenge, continuous progress has been made, leading to the need to seek new cryptographic solutions to prevent the compromise of information security.

3. Module-lattice Key-encapsulation Mechanism

To counter the previously mentioned quantum cryptanalysis algorithms, one approach involved developing a new class of classical cryptographic algorithms, collectively known as post-quantum cryptography (Bavdekar et al., 2023). Although other methods have been studied (Bavdekar et al., 2023), lattice-based cryptography has been standardized by NIST for use in key establishment and also in digital signatures (NIST, 2024a, 2024b). Lattices are algebraic structures where certain computational problems, such as the Module Learning With Errors (MLWE) problem, are believed to be intractable for both classical and quantum computers.

For key establishment, the first chosen algorithm was the Module-Lattice-Based Key-Encapsulation Mechanism (ML-KEM). ML-KEM consists of three fundamental operations (Alagic et al., 2025), which are also represented in the scheme in Figure 1:

- Key Generation: a pair of encapsulation/decapsulation keys is generated by one party (Alice), and the encapsulation key is sent to the other party (Bob);
- Encapsulation: after receiving the encapsulation key, Bob performs an operation that generates the shared secret in both plaintext and ciphertext form, which is then sent to Alice; and
- Decapsulation: Alice receives the ciphertext and uses her key to decrypt the shared secret.



Note. Source: Alagic et al. (2025)

Figure 1: ML-KEM overview

The process described above can occur in two distinct ways, ephemeral or static. In the first, for each generation of a shared secret, the entire process must be performed, and the generated keys must be discarded after use. In the second, the key generation is done once, and the encapsulation key is distributed to all parties who wish to generate a shared secret. It should be noted that the generated secrets are distinct from each other (Alagic et al., 2025).

The proponents of the algorithm specified three sets of parameters: ML-KEM-512, ML-KEM-768, and ML-KEM-1024, targeting security categories 1, 3, and 5, respectively. Table 1 shows the size values for the three configurations.

Table 1: ML-KEM settings (values in bytes)

Algorithm	Encapsulation key	Decapsulation key	Ciphertext	Secret key
ML-KEM-512	800	1632	768	32
ML-KEM-768	1184	2400	1088	32
ML-KEM-1024	1568	3168	1568	32

Note. Source: NIST (2024)

Regarding practical deployment, ML-KEM demonstrates high versatility and can be implemented across diverse software and hardware architectures, including central processing units (CPUs), graphics processing units (GPUs), application-specific integrated circuits (ASICs), and field-programmable gate arrays (FPGAs) (Nguyen et al., 2025). This adaptability extends to extreme operational environments such as space systems, where the algorithm has proven viable on radiation-hardened FPGAs and embedded space-grade processors (Kim, 2026).

However, deployment in these specialized environments is bounded by severe physical and hardware constraints that mandate careful resource optimization (Kim, 2026; Nguyen et al., 2025). Most critically, spaceborne implementations are generally prohibited from utilizing standard external DDR memory due to its susceptibility to radiation-induced single-event upsets (SEUs), forcing the cryptographic subsystem to rely entirely on severely limited on-chip static memory (Kim, 2026). Furthermore, these systems must operate within strict power budgets while handling the transmission of larger post-quantum keys over highly constrained telemetry bandwidths (Kim, 2026).

The security of ML-KEM against both classical and quantum computing adversaries is fundamentally derived from the hardness of the MLWE problem, which establishes a baseline security of indistinguishability under chosen-plaintext attack (IND-CPA) (Avanzi et al., 2021). According to the NIST evaluation criteria, this passive IND-CPA security framework is considered sufficient for purely ephemeral key exchange protocols, (NIST, 2016). For the static deployments, the scheme applies a Fujisaki-Okamoto (FO) transform to the underlying IND-CPA-secure encryption to achieve the required indistinguishability under adaptive chosen-ciphertext attacks (IND-CCA2) (Avanzi et al., 2021).

Despite its robust mathematical foundations, practical deployments of ML-KEM remain susceptible to physical hardware exploits, which is a critical consideration for exposed nodes in Delay Tolerant Networks (Nguyen et al., 2025; Renita et al., 2025). These physical vulnerabilities bypass theoretical protections and are predominantly divided into passive Side-Channel Attacks (SCA) and active Fault Injection Attacks (FIA) (Ravi et al., 2024).

Passive SCAs exploit unintentional physical leakages, such as power consumption and electromagnetic (EM) emanations (Renita et al., 2025). The decapsulation phase is particularly vulnerable; attackers can utilize Deep Learning-enhanced Side-Channel Analysis (DL-SCA) to extract secret polynomial coefficients during Number Theoretic Transform (NTT) or point-wise multiplication operations (Hoang et al., 2024; Renita et al., 2025). This technique is highly efficient, requiring as few as 50 traces, and can successfully compromise even hardware implementations that use parallel architectures (Hoang et al., 2024). By exploiting these leakages, adversaries can construct practical plaintext-checking or decryption-failure oracles to systematically recover the secret key (Ravi et al., 2024).

In addition to power and EM leakages, ML-KEM is threatened by timing-based vulnerabilities, notably the KyberSlash exploits (Bernstein et al., 2024; Ji et al., 2025). These vulnerabilities occur when compilers optimizing for code size inadvertently introduce variable-time division operations during ciphertext compression or message decoding (Bernstein et al., 2024). Because the execution time of these operations depends on the secret inputs, they reliably leak key information, allowing systems to be compromised remotely or without advanced physical measurement probes (Bernstein et al., 2024).

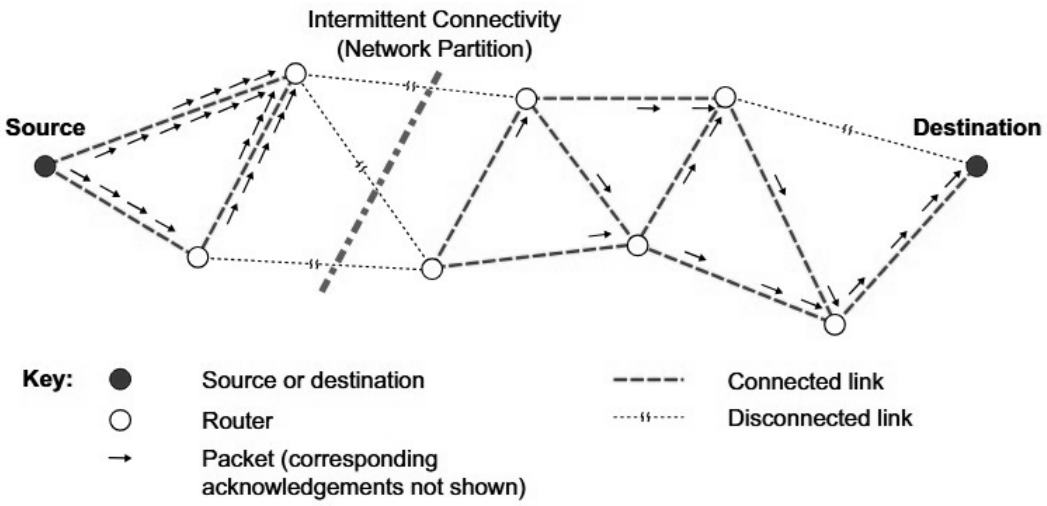
Finally, ML-KEM is also threatened by active manipulation through Fault Injection Attacks (FIA), which deliberately induce transient hardware errors (Renita et al., 2025). Advanced FIA techniques include loop-abort faults induced via electromagnetic pulses, which target the standardized KECCAK hash function across all operational phases (Wang et al., 2025). These faults allow adversaries to bypass permutations or zeroize crucial arrays to effortlessly recover secret random seeds (Wang et al., 2025). Other critical fault vectors include corrupting NTT twiddle factors, forcing nonce reuse during the sampling of ephemeral secrets, or using clock glitching to completely skip the final ciphertext equality check—effectively downgrading the protocol to weaker indistinguishability under chosen-plaintext attack (IND-CPA) security (Ravi et al., 2024; Ji et al., 2025).

4. Delay/Disruption Tolerant Networks

Delay-Tolerant and Disruption-Tolerant Networks (DTNs) are designed to operate in contexts where the use of the traditional TCP/IP protocol stack presents limitations, such as high error rates, delays that can reach the order of days, and lack of end-to-end connectivity (Cerf et al., 2007; Gao et al., 2015). DTNs can be applied in scenarios such as underwater networks, satellite networks, sensor networks, or battlefield networks (Cerf et al., 2007; Gao et al., 2015). Bravo et al. (2025) analyzed the use of LunaNet, which uses the DTN architecture, on the International Space Station for a period of eighteen days, conducting a series of experiments to verify its behavior and performance (Bravo et al., 2025). The characteristics of DTNs are also being integrated into vehicular network projects, Vehicular-DTN (Pereira, 2011). Some studies have also been conducted on the application of DTNs in rural areas (Abdeljabar et al., 2025; Hanifah et al., 2025).

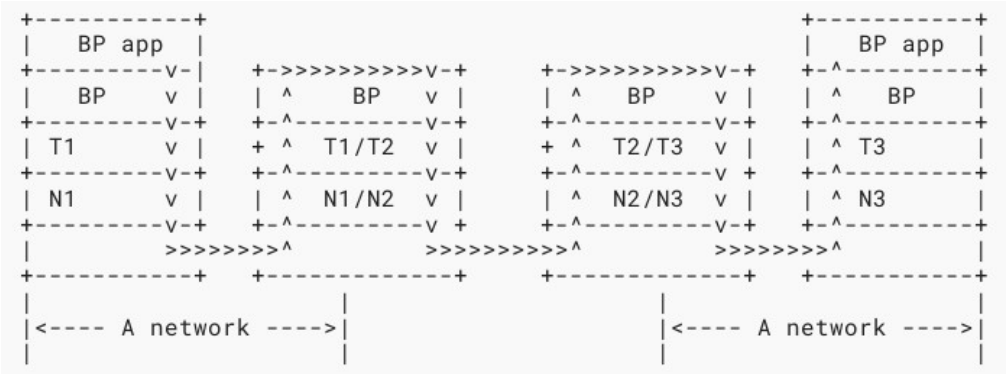
A disruption scenario is represented in Figure 2, where the network becomes partitioned, preventing the routing of packets between the source and destination. To address the problem of lack of connectivity and high error rates, the nodes belonging to DTNs use a store-and-forward approach in which packets are stored so that they can be transmitted when the link is re-established (Cerf et al., 2007).

DTNs utilize the Bundle Protocol (BP), where the term "bundle" refers to the packet used. BP acts as an overlay layer over other network and transport protocol stacks, called Convergence Layers, allowing different networks to be interconnected (Burleigh et al., 2022). Figure 3 shows a DTN formed by two different networks connected so that BP applications (BP app) can exchange messages. The variety of Convergence Layers is represented by the pairs Tx/Nx, with x varying from 1 to 3.



Note. Adapted from NASA

Figure 2: Disrupted DTN where the source and destination nodes are unreachable



Note. Source: Burleigh et al. (2022)

Figure 3: Overlay BP with different stack convergence layers

Security in DTN networks is provided by the Bundle Protocol Security (BPSec) protocol, defined in RFC 9172. BPSec was designed to operate independently of the network topology, applying security services directly to the data, rather than protecting the communication channel, since end-to-end connectivity is not guaranteed (Birrane & McKeever, 2022). The protocol does not impose fixed cryptographic algorithms; instead, it uses context identifiers to abstract the cipher suite and parameters used (Birrane et al., 2023).

The introduction of post-quantum algorithms imposes additional challenges on key management, mainly due to the larger size of keys and signatures. BPSec facilitates this transition by allowing additional security parameters (such as encapsulated keys or salts) to be transported within the security blocks themselves (Birrane et al., 2023). Key management must consider that, in a DTN, a key valid at the time of sending may have expired by the time of reception, requiring security policies that take network latency into account. Not only that, but one must also consider the challenge of distributing keys in an environment where there may not be end-to-end connectivity for the execution of the protocols (Birrane et al., 2023).

Building on these connectivity challenges, the store-carry-and-forward paradigm uniquely exposes Delay Tolerant Networks (DTNs) to a range of operational threats. Because DTNs strictly require cooperation between intermittent nodes to deliver messages, they are highly susceptible to routing misbehavior (Nabais et al., 2021). The most critical threats include Black-hole attacks, where compromised nodes silently drop received messages instead of forwarding them, and Wormhole attacks, where adversaries tunnel packets through hidden, low-latency links to manipulate the perceived network topology (Altaweel et al., 2023; Nabais et al., 2021). Additionally, attackers may launch Sybil attacks by forging or stealing multiple identities to aggressively influence routing decisions and intercept traffic, exploiting the fundamental nature of opportunistic contacts to disrupt the network (Altaweel et al., 2023).

Furthermore, the resource constraints of DTN nodes make them prime targets for Denial-of-Service (DoS) and Distributed DoS (DDoS) attacks (Khalid et al., 2023; Zekkori et al., 2021). Adversaries may deploy flooding attacks, overwhelming the network with genuine, replicated, or entirely forged bundles to rapidly deplete node buffers and congest available wireless bandwidth (Khalid et al., 2023; Zekkori et al., 2021). In environments like space information networks, where components are physically inaccessible and structurally constrained, these resource-exhaustion attacks can be catastrophic. By forcing legitimate nodes to drop crucial packets due to buffer overflow, flooding halts communication and critically degrades the network's packet delivery ratio (Sharmin et al., 2025; Zekkori et al., 2021).

5. SWOT Analysis

5.1 Strengths

- Robust Quantum Resistance: ML-KEM utilizes the Fujisaki-Okamoto (FO) transform to provide strong indistinguishability under adaptive chosen-ciphertext attacks (IND-CCA2), ensuring that data remains secure against both classical and future quantum adversaries.
- Computational Efficiency: Compared to other post-quantum algorithms, ML-KEM is efficient for memory and processing-constrained environments because it leverages the Number Theoretic Transform to optimize polynomial multiplications with minimal resource overhead.
- Protocol Adaptability: The Bundle Protocol Security standard utilized in DTNs allows the integration of post-quantum cryptography without requiring fundamental architectural changes.

5.2 Weaknesses

- Resource Overhead: ML-KEM demands significantly larger key and ciphertext sizes compared to classical cryptography; for instance, ML-KEM-768 requires an 1184-byte encapsulation key and a 1088-byte ciphertext. This heavy data footprint might conflict with the buffer constraints of DTN nodes.
- Synchronous Assumptions in Asynchronous Networks: ML-KEM key exchange assumes prompt communication, which is not always possible in DTNs. A post-quantum key valid at the time of transmission may expire before reaching its destination, complicating key management.

5.3 Opportunities

- Environmental Immunity to Implementation Attacks: Assuming the nodes are physically inaccessible (e.g., satellites), it’s practically impossible for adversaries to attach measurement probes or use electromagnetic equipment to launch passive Side-Channel Attacks or active Fault Injection Attacks. Furthermore, the extreme latency and frequent disruptions inherent to the DTN architecture completely mask the minute clock-cycle variations required to execute remote timing attacks, rendering vulnerabilities like the KyberSlash exploits ineffective.
- Specialized Hardware Integration: Advances in space-grade Field-Programmable Gate Arrays (FPGAs) allow ML-KEM to be implemented efficiently using entirely on-chip static memory, avoiding the need for external DDR memory.

5.4 Threats

- Amplification of Flooding Attacks: Because DTNs are highly susceptible to DoS and flooding attacks, the substantially larger payload of ML-KEM keys and ciphertexts makes it much easier for remote adversaries to rapidly exhaust node buffers and wireless bandwidth.
- Environmental Faults: Even without physical access by a human attacker, space-based DTN nodes are constantly bombarded by galactic cosmic rays and radiation. This environment induces Single-Event Upsets —random bit flips in memory that can corrupt keys or intermediate computations, effectively mirroring the disruption of a malicious Fault Injection Attack. This threat is particularly acute for ML-KEM, because its expansive public key and ciphertext sizes present a vastly larger operational memory profile than classical cryptography, reducing the mathematical probability of error-free state retention across the system.

6. Future Work

Based on the topic discussed and the SWOT analysis, three recommendations for future work involving the use of post-quantum cryptography in systems connected to DTNs are presented.

- Investigate decentralized, latency-aware key management policies for ML-KEM in DTNs. Future studies must specifically address the 'Synchronous Assumptions' weakness by exploring how to handle key expiration, asynchronous certificate revocation, and delayed authentication in an environment where a post-quantum key may expire before reaching its destination;
- Evaluate the performance impact of ML-KEM's large cryptographic payloads on various DTN routing protocols. Because the substantial size of post-quantum keys exacerbates the network's susceptibility to resource-exhaustion and flooding attacks, future research should investigate lightweight, randomized routing algorithms (such as k-RAND) or anomaly detection mechanisms to dynamically protect node buffers from being overwhelmed by cryptographic traffic; and
- Explore the hardware-software co-design of Hardware Security Modules (HSMs) optimized for post-quantum cryptography in space systems. Future work should focus on implementing ML-KEM within the strict confines of on-chip static memory (avoiding DDR), while developing fault-tolerant architectures to mitigate Single-Event Upsets (SEUs) from cosmic radiation, which can fatally corrupt keys and mirror malicious Fault Injection Attacks.

7. Conclusion

The imminent threat of quantum computing requires a shift towards post-quantum cryptography to ensure long-term security. This work explored this transition, focusing on the Modular Lattice-Based Key Encapsulation Mechanism (ML-KEM) and the dynamics of deploying it within Delay-Tolerant Networks (DTNs) for space systems.

While ML-KEM is theoretically robust, practical deployments are susceptible to physical hardware exploits, such as passive Side-Channel Attacks (SCA), active Fault Injection Attacks (FIA), and remote timing vulnerabilities like KyberSlash. However, the unique environmental characteristics of DTNs actually provide a natural defense against these threats. For physically inaccessible DTN nodes like satellites, it is practically impossible for adversaries to attach measurement probes required to launch local SCAs or FIAs. Furthermore, the extreme latency and frequent disruptions inherent to the DTN architecture completely mask the minute clock-cycle variations necessary to execute remote timing attacks, rendering vulnerabilities like KyberSlash ineffective.

Despite this environmental immunity to certain implementation attacks, significant challenges remain. The substantial resource overhead of ML-KEM, specifically its larger key and ciphertext sizes, amplifies existing network-level vulnerabilities in DTNs. This heavy data footprint makes constrained nodes much more susceptible to resource-exhaustion and flooding attacks. Additionally, space-based DTNs must contend with radiation-induced single-event upsets (SEUs) which corrupt keys and intermediate computations, effectively mirroring the disruption of malicious fault injections without requiring a human attacker.

Addressing these challenges will require investigating decentralized, latency-aware key management policies, developing lightweight routing algorithms to protect against payload-amplified flooding, and exploring fault-tolerant co-designs to mitigate radiation hazards in space systems.

Ethics Declaration: Ethical clearance was not required for this research, as the study involves a survey of existing literature and does not involve human participants, animal subjects, or the collection of sensitive personal data.

AI Declaration: Google NotebookLM was utilized during the development of this paper as a tool for self-study and to enhance the comprehension of the technical concepts.

Disclaimer Statement: "The views expressed are those of the author and do not reflect the official policy or position of the US Air Force, Department of Defense or the US Government."

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Investigating AI Enabled Attacks and Malware Within Dark Web Ecosystems: An Updated Assessment

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Abstract: This paper provides a technically grounded assessment of how Dark Web ecosystems are intersecting with AI-enabled offensive cyber capabilities to compress time-to-effect across the cyber kill chain. Hidden-service marketplaces and broker forums have matured into resilient, quasi-industrial supply chains for initial access vectors (credential dumps, VPN/RDP footholds), exploit artifacts, malware loaders, and operational services (bulletproof hosting, cryptomixers, DDoS booter capacity). Generative AI and machine-learning–assisted tooling increases attacker throughput by automating target enumeration, vulnerability triage, exploit parameterization, and social-engineering content generation, thereby reducing the marginal cost of tailored intrusion campaigns. We synthesize research on anonymity architectures, dark-market economics, and emerging autonomous cyber systems to characterize an operational model in which AI agents execute multi-step workflows: (i) harvesting and fusing threat-intelligence signals from forum discourse and market telemetry; (ii) selecting targets via probabilistic scoring informed by asset criticality and exploitability; (iii) generating polymorphic payload variants and adversarial phishing lures; and (iv) iterating tactics in response to defensive controls through reinforcement-learning–style feedback. This convergence enables hybrid state–criminal collaboration and proxy operations by decoupling capability acquisition from attribution and by supporting deniable command-and-control (C2) staging within onion-routed infrastructures. Quantitative telemetry underscores the strategic relevance of this shift: the FBI's IC3 reported losses exceeding US$16 billion in 2024, with cyber-enabled fraud comprising approximately US$13.7 billion and 'cyberthreats' (including ransomware and data breaches) contributing more than US$1.5 billion, illustrating the scale of the economic attack surface. In parallel, breach forensics continue to show that initial access is frequently achieved through stolen credentials, vulnerability exploitation and social engineering, which are precisely the phases most susceptible to AI-driven acceleration. We conclude that AI-augmented Dark Web ecosystems materially increase campaign scalability, complicate attribution via supply-chain opacity and pseudonymity, and elevate escalation risk by enabling rapid re-tooling and persistent access. The paper closes with engineering-oriented defensive implications, including telemetry-driven detection, graph-analytic threat-hunting, and governance controls for AI-enabled offensive automation.

Keywords: Dark web, TOR, Cyber warfare, Cyber operations

1. Introduction

Cyber warfare continues to evolve as states and non-state actors exploit anonymity, deniability, and persistent access. The Dark Web sits at the center of this environment, functioning as both an illicit marketplace and an operational layer for covert activity. Foundational work on onion routing and anonymity architectures (Goldschlag, Reed, & Syverson, 1999; Reed, Syverson, & Goldschlag, 1998; Syverson, Goldschlag, & Reed, 1997) established the technical basis for the hidden-service ecosystems that now support cyber operations. Subsequent research has documented how Dark Web markets facilitate illicit trade, criminal collaboration, and the diffusion of offensive capabilities (Meehan & Farmer, 2023; Broséus et al., 2016; Buxton & Bingham, 2015; Kruithof et al., 2016). These ecosystems have also been repeatedly linked to child exploitation networks, access-broker activity, and large-scale takedowns such as AlphaBay and Playpen (Cimpanu, 2016; FBI, 2017; McGoogan, 2017; Popper & Ruiz, 2017). As cyber conflict has matured into a recognized operational domain (Nichols, 2024), the Dark Web has become a strategic substrate for procurement, coordination, and covert communication.

Concurrently, the operational environment surrounding offensive cyber activity is shifting as generative AI becomes embedded in the tooling and tradecraft of modern threat actors. Research on AI-enabled cyber operations shows that these systems amplify existing offensive techniques by accelerating reconnaissance, refining target selection, and automating technically demanding tasks (Gabrian, 2024; Saade & Ng, 2024). RAND's analysis of autonomy, reasoning, and tool-integration suggests that emerging AI systems may increasingly support multi-step cyber activities and adapt to defensive measures in real time (Hodgson, Horton, & Malone, 2025). When paired with the anonymity, resilience, and illicit economies of the Dark Web, these AI-driven capabilities create a more fluid and adaptive threat landscape to one where state and non-state actors can blend, outsource, and obscure their operations with unprecedented ease. This convergence is becoming a defining feature of contemporary cyber conflict and a critical factor in understanding how offensive capabilities are acquired, deployed, and sustained.

2. Cryptographic Foundations: Onion Routing and Anonymity Architecture

The following sections provide a technical overview of onion routing and associated technologies.

2.1 Onion Routing Protocol Design

Onion routing is a layered cryptographic forwarding architecture designed to decouple message origin, routing state, and destination information across multiple independently operated network relays. In this model, a client encapsulates application traffic inside a sequence of encrypted protocol layers, where each layer corresponds to a specific relay in a selected path, conceptually resembling the nested structure of an onion (Reed, Syverson, & Goldschlag, 1998). In Tor, this path is instantiated as a circuit, usually consisting of an entry guard, one or more middle relays, and an exit relay. Before user traffic is transmitted, the Tor client performs circuit construction by incrementally extending the circuit one hop at a time. For each hop, the client negotiates a distinct ephemeral session key, historically using telescoping key agreement protocols based on public-key cryptography and, in modern Tor deployments, authenticated key exchange mechanisms that provide forward secrecy. These per-hop session keys are then used with symmetric cryptographic primitives to encrypt fixed-size Tor cells in multiple layers.

At the protocol level, the client does not simply send an IP packet through the relay chain. Instead, it fragments traffic into Tor cells, each of which contains circuit identifiers, relay commands, stream identifiers, integrity checks, and encrypted payload data (Döpmann, 2025). When the client sends a cell into the circuit, it applies layered encryption in reverse path order: first encrypting the payload for the exit relay, then wrapping that ciphertext for the middle relay, and finally encrypting the outermost layer for the entry relay. As the cell traverses the circuit, each relay uses only its own negotiated symmetric key to remove one cryptographic layer, verify the relevant integrity material, and determine the next hop. Crucially, a relay learns only the routing information necessary for local forwarding. It does not possess the cryptographic keys required to decrypt layers intended for other relays, nor does it receive a complete source-to-destination route.

This design produces strict compartmentalization of network visibility (Dutta et al., 2021). The entry guard observes the client's network address and the next relay in the circuit, but it cannot determine the final destination or inspect application-layer plaintext. The middle relay functions as a cryptographic and routing intermediary, observing only its predecessor and successor within the circuit (Döpmann, 2025). The exit relay removes the final Tor encryption layer and forwards traffic to the destination service, meaning it can observe the destination address and, unless end-to-end encryption such as TLS is used, potentially the application payload; however, it does not know the client's original IP address. Thus, anonymity is not derived from any single trusted server, but from distributing trust across relays and ensuring that no individual relay has sufficient information to correlate both communication endpoints.

The security properties of onion routing rely on the interaction between layered symmetric encryption, ephemeral key establishment, circuit isolation, and probabilistic relay selection (Döpmann, 2025). Public-key cryptography is used primarily during circuit setup to authenticate or establish shared secrets, while high-throughput data forwarding is handled by efficient symmetric encryption because relays must process large volumes of traffic with low latency (Camenisch, J., & Lysyanskaya, 2005). Ephemeral session keys provide forward secrecy: compromise of a relay's long-term identity key should not automatically reveal previously transmitted circuit traffic. Tor's use of fixed-size cells also reduces certain packet-size leakage, although it does not eliminate timing correlation attacks. Because low-latency anonymity systems must preserve interactivity, Tor cannot fully randomize packet timing or introduce large delays in the way high-latency mix networks do.

Path selection further contributes to anonymity by drawing relays from a distributed consensus of available nodes, weighted by relay capacity, policy constraints, and role suitability. Entry guards are typically reused for extended periods to reduce exposure to malicious first-hop relays, while middle and exit relays may vary across circuits. Exit relay selection is constrained by exit policies, since not all relays permit outbound connections to all ports or destinations (Camenisch, J., & Lysyanskaya, 2005). The resulting anonymity set depends on the number of users, the diversity of relay operators, relay bandwidth distribution, and the adversary's ability to observe or operate relays. If a global passive adversary can monitor both the client-to-entry link and the exit-to-destination link, traffic timing and volume correlation may still weaken anonymity despite the cryptographic protections.

Recent analyses of AI-enabled cyber operations highlight how adversaries increasingly pair traditional anonymity architectures with AI-driven reconnaissance and automation tools to streamline circuit construction, evade detection, and optimize routing behavior (Gabrian, 2024). RAND's assessment of autonomy and tool-integration

further suggests that future AI systems may assume more active roles in route selection, traffic shaping, and relay-level evasion, enhancing the operational resilience of onion-routed communications (Hodgson, Horton, & Malone, 2025). These developments indicate that while the core cryptographic design remains stable, the operational use of onion routing is evolving alongside AI-enabled offensive tradecraft

2.2 Traffic Analysis and Limitations

While onion routing provides strong resistance to single-point compromise, it is not invulnerable. Adversaries capable of large-scale traffic correlation monitoring both entry and exit nodes can conduct timing analysis to probabilistically deanonymize users (McCoy et al., 2008; Nurmi & Niemelä, 2017). Intelligence agencies have historically bypassed Tor's cryptographic protections through network investigative techniques (NITs), browser exploits, and endpoint compromise, demonstrating that anonymity networks protect routing metadata but not the security posture of the device itself (Paganini, 2015; Schneier, 2013). AI-enabled tooling is intensifying these risks. Gabrian (2024) notes that machine-learning models now accelerate traffic-pattern recognition and automate correlation attacks, identifying subtle timing or volume anomalies that human analysts might overlook.

RAND's assessment reinforces this trajectory, emphasizing that as AI systems gain more advanced reasoning and tool-integration capabilities, they may increasingly support multi-step offensive actions including reconnaissance, exploitation, and traffic analysis—within anonymized environments (Hodgson, Horton, & Malone, 2025). These developments suggest that the threat surface surrounding onion-routed traffic is evolving not because the cryptographic design has weakened, but because adversaries now possess more capable analytical tools. Despite these vulnerabilities, Tor's architecture remains sufficiently robust to provide operational-grade anonymity for actors who combine it with disciplined OPSEC practices such as compartmentalization, cryptocurrency obfuscation, and endpoint hardening.

3. How the Dark Web is Used in Cyber Warfare

Style and Maglaras (2020) define cyber warfare as the use of digital operations to target states or non-governmental entities, noting that virtual actions can produce tangible physical effects. Boyte et al. (2020) demonstrate this reality through cyberattacks on Ukraine from 2013–2015 that disrupted power grids, satellite communications, and weapons systems. Recent analyses further show that generative AI is accelerating offensive capability development by enhancing reconnaissance, vulnerability discovery, and malware adaptation, expanding the operational reach of cyber actors (Gabrian, 2024; Hodgson, Horton, & Malone, 2025).

Dark web marketplaces operate as semi-structured ecosystems for acquiring malware, zero-day exploits, and access credentials outside formal state channels (Hasanti et al., 2024). Reputation systems and escrow mechanisms help sustain trust in an anonymous environment, lowering the technical and economic barriers to sophisticated cyber tools. This commodification accelerates the proliferation of offensive capabilities once limited to nation-states, enabling both state and non-state actors to adopt advanced techniques more rapidly (Pavlovskaia & Belousov, 2024). The dark web also supports recruitment and coordination through anonymity-preserving architectures and global accessibility. State-linked groups and independent contractors advertise services, solicit collaborators, and form loosely organized collectives oriented toward political or financial objectives. This decentralized model complicates attribution, distributing operational tasks across actors with diverse motivations and producing hybrid campaigns that blur the line between state operations and criminal entrepreneurship.

Adversaries further leverage Dark Web hidden services to establish resilient command-and-control infrastructures (Gaber & Ahmed, 2026). Layered encryption and pseudonymous routing obscure server locations and operator identities, enhancing operational survivability. By decoupling C2 infrastructure from conventional hosting, Dark Web based architectures reduce the effectiveness of takedown efforts and complicate forensic analysis, contributing to the persistence and stealth of modern malware campaigns.

The Dark Web also serves as a repository of illicit data and cyber-threat intelligence (Kühn, Wittorf, & Reuter, 2024). Actors obtain compromised credentials, network access, and proprietary information that facilitate initial intrusion or accelerate reconnaissance. Monitoring dark web forums reveals emerging vulnerabilities, criminal collaborations, and evolving attack methodologies, complementing traditional intelligence collection and supporting long-term infiltration strategies used by state-sponsored APT groups. In information warfare, the Dark Web functions as a staging ground for disinformation and psychological operations. Its anonymous infrastructure enables the distribution of leaked or fabricated materials, coordination of influence networks, and propagation of ideologically charged narratives without clear attribution. Because these activities often migrate

to mainstream platforms, Dark Web operations can exert disproportionate influence, illustrating the convergence of cyber and cognitive warfare.

Cryptocurrency based financial systems embedded within the Dark Web provide the economic substrate for illicit cyber operations (Jung et al., 2022). Anonymous payments support malware procurement, infrastructure leasing, and contractor labor, while laundering mechanisms obscure transactional provenance. This financial opacity enhances the strategic autonomy of state and non-state actors engaged in cyber warfare and frustrates counter-financial intelligence efforts. The Dark Web mediates complex interactions between state actors and criminal organizations, fostering hybrid ecosystems where capabilities, intelligence, and operational services are exchanged with minimal visibility. States may outsource cyber activities to criminal proxies to achieve plausible deniability, while criminal groups may receive protection or technical support in exchange for aligning their operations with state interests. Cyber terrorism encompasses terrorist activity conducted through digital networks, including system attacks, online propaganda, psychological operations, fundraising, recruitment, and operational coordination (Lucas, 2020).

4. The Nexus of AI, Dark Web, and Cyber Warfare

The integration of Artificial Intelligence (AI) into Dark Web ecosystems has reshaped the operational landscape of cyber warfare by enabling autonomous, adaptive, and scalable capabilities under conditions of strong anonymity and reduced attribution (Kela, 2025). Within Tor and mix-net infrastructures, AI-driven systems support automated reconnaissance, threat-intelligence generation, and offensive cyber operations. Machine-learning model, ranging from supervised classifiers to deep neural networks, analyze Dark Web traffic, forum communications, and marketplace telemetry to identify vulnerabilities, zero-day opportunities, and adversarial behavioral patterns. Transformer-based NLP enables automated extraction of intent, ideological alignment, and operational indicators from unstructured extremist discourse, supporting cyber-enabled psychological operations and coordinated attack planning. These capabilities allow state and non-state actors to execute AI-augmented campaigns that dynamically adapt malware payloads, C2 structures, and attack vectors in response to defensive countermeasures, compressing the cyber kill chain. Gabrian (2024) underscores this shift, noting the widespread availability of AI-driven hacking tools on the Dark Web, while RAND's assessment of autonomy, reasoning, and tool-integration suggests that emerging AI systems may soon assume more complex operational functions within anonymized environments (Hodgson, Horton, & Malone, 2025).

From an offensive cyber-warfare perspective, the Dark Web operates as a distributed marketplace for AI-enabled cyber weapons and services, accelerating capability diffusion through models such as Malware-as-a-Service (MaaS), Phishing-as-a-Service (PhaaS), and Disinformation-as-a-Service (DaaS) (Ciancaglini et al., 2025). Reinforcement learning algorithms optimize attack strategies including lateral movement, privilege escalation, and IDS/SIEM evasion, while generative AI produces polymorphic malware, adversarial phishing content, and synthetic media for hybrid information operations. Defensive and intelligence organizations counter with AI-based monitoring frameworks that combine graph analytics, anomaly detection, and behavioural fingerprinting to infer adversarial networks, trace illicit financial flows, and anticipate cyber terrorist activity despite encrypted and pseudonymous conditions. This dual-use dynamic reinforces Gabrian's (2024) warning that AI-enabled cyber capabilities materially elevate national-security risk and highlights the need for governance mechanisms capable of addressing AI-driven escalation(Kela, 2025).

The convergence of AI and the Dark Web also accelerates the commodification of cyber capabilities. AI-powered tools for malware automation, phishing, and disinformation are increasingly traded in Dark Web markets, lowering the technical threshold for sophisticated attacks. Defensive actors employ AI-enabled analytics to detect weak signals of emerging threats and attribute malicious activity through behavioral and network-based inference rather than identity-centric methods. This adversarial co-evolution positions the Dark Web as a contested battlespace where AI simultaneously enables asymmetric warfare and supports counter-terrorism and cyber-intelligence operations. The absence of unified international legal frameworks governing AI-enabled cyber conflict further amplifies these challenges.

AI-enabled exploitation of Dark Web infrastructures aligns with NATO cyberspace-operations doctrine, functioning as an enabler of Cyberspace Intelligence, Surveillance, and Reconnaissance (C-ISR) and effects generation within joint operations. NATO's AJP-3.20 maps naturally onto AI-supported pipelines for indexing hidden services, inferring entities under pseudonymity, and conducting operational preparation of the environment (NATO, 2020). Graph learning, representation learning, transformer-based NLP, and anomaly detection accelerate indicator-to-warning conversion by extracting operational signals such as capability acquisition, malware diffusion, and recruitment surges from adversary-controlled ecosystems. In contexts

where the Dark Web facilitates terrorist coordination, propaganda, and fundraising, AI-driven automation enables monitoring and triage at scale, shifting analysis from identity-based attribution toward behavioural and infrastructural attribution.

From a U.S. DoD perspective, AI + Dark Web integration aligns with joint cyberspace-operations doctrine and the 2023 DoD Cyber Strategy's emphasis on defending forward and persistent engagement (DoD, 2023). Technically, this manifests as AI-accelerated kill-chain compression: automated reconnaissance, ML-assisted vulnerability discovery, and adaptive C2 and payload delivery leveraging Dark Web anonymity for staging and logistics. Defensive applications mirror this with AI-enabled hunt-forward analytics—graph embeddings to infer operational cells, clustering to detect emergent TTPs, NLP to identify operational intent, and blockchain analytics to map illicit finance pathways. These outputs feed joint targeting and campaign assessment, enabling disruption to be measured not only by takedowns but by changes in adversary access, resiliency, and TTP substitution under persistent engagement.

5. Operational Telemetry and Risk Quantification

Quantifying risk and assessing operational telemetry is key to understanding the nexus between the Dark Web, AI, and cyber warfare.

5.1 Macro-level Loss and Breach Telemetry

Operational risk modeling for Dark Web–mediated, AI-enabled intrusion must be anchored in empirical telemetry. At the macro level, incident-reporting data provides coarse but decision-useful bounds for expected loss. The FBI's Internet Crime Complaint Center (IC3) reported aggregate victim losses exceeding US$16 billion in 2024, a 33% increase relative to 2023, and indicates that cyber-enabled fraud accounts for the dominant share of losses. These macro-signals are not directly attributable to Dark Web activity; however, they contextualize the economic scale available to access brokers, malware operators, and monetization crews operating within anonymized ecosystems (FBI, 2025).

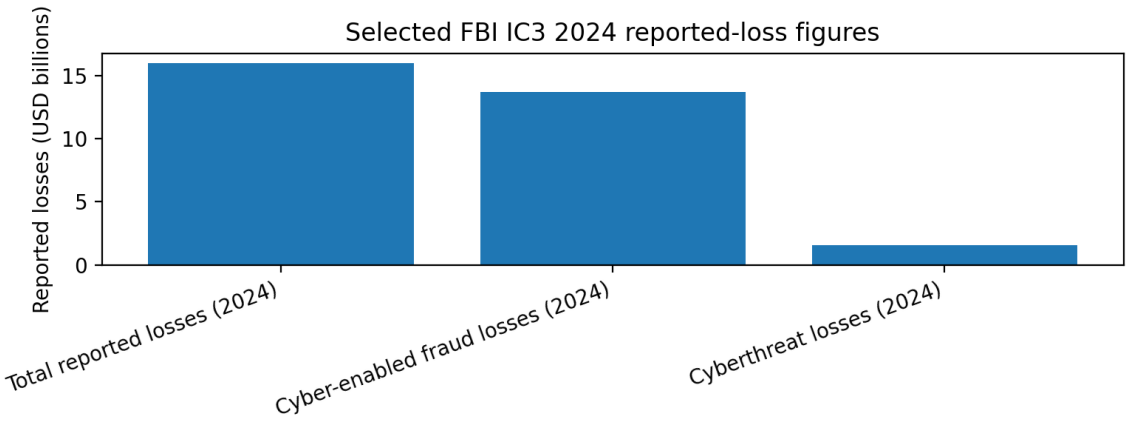


Figure 1: Selected FBI IC3 2024 reported-loss figures (values in USD billions) (FBI, 2025).

5.2 Capability Taxonomy Observed in Dark Web Markets

Dark Web markets commoditize discrete capability primitives that can be composed into full-spectrum campaigns. Table 1 provides an engineering taxonomy that maps common marketplace offerings to kill-chain phases and to representative defensive control families (e.g., identity hardening, vulnerability management, egress filtering).

Table 1: Engineering taxonomy of Dark Web capability primitives

Capability class	Typical market artefact/service	Kill-chain impact	Defensive control mapping
Initial access brokerage	Compromised VPN/RDP accounts; stealer logs; session cookies	Recon → Initial access	MFA, conditional access, credential hygiene, UEBA
Exploit enablement	N-day exploit chains; PoCs; exploit kits	Exploit	Patch SLAs, virtual patching, WAF/IPS signatures

Capability class	Typical market artefact/service	Kill-chain impact	Defensive control mapping
Payload delivery	Malware loaders; droppers; macro builders; email templates	Delivery/Install	Secure email gateway, sandboxing, attachment detonation
C2 resilience	Onion service C2; bulletproof hosting; fast-flux DNS	C2	Egress allowlists, TLS/JA3 fingerprinting, sinkholing
Monetization	Ransomware affiliates; crypto laundering; mule recruitment	Actions on objectives	Immutable backups, fraud analytics, blockchain tracing

5.3 Indicative Kill-chain Compression Under AI Augmentation

AI-assisted automation disproportionately accelerates early kill-chain phases by reducing human-in-the-loop latency for reconnaissance, target selection, content generation, and exploit parameterization. Figure 2 presents an illustrative (non-empirical) compression model intended to communicate the directionality of the effect: procurement and automation decrease cycle time per stage, increasing the number of parallelized intrusion attempts an actor can execute under a fixed resource budget (Hodgson, Horton, & Malone, 2025).

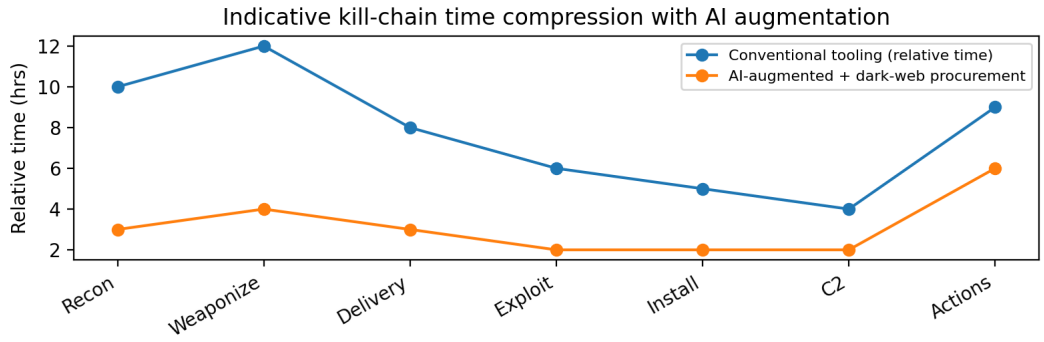


Figure 2: Indicative kill-chain time compression with AI augmentation (conceptual model) (Hodgson, Horton, & Malone, 2025)

5.4 Breach Telemetry Relevant to Initial-access Vectors

Independent breach investigations provide higher-fidelity indicators about prevailing initial-access vectors. Verizon's 2025 DBIR reports a 34% year-over-year increase in attackers exploiting vulnerabilities for initial access, finds that only 54% of perimeter-device vulnerabilities were fully remediated over the past year, and notes that ransomware was present in 44% of analyzed breaches (Verizon, 2025). These findings are operationally aligned with Dark Web market dynamics: access brokers monetize unpatched edge devices and compromised identities, while ransomware ecosystems externalize capability development through affiliate models.

Table 2: Selected cyber-risk telemetry informing Dark Web threat models

Telemetry indicator	Reported value	Engineering implication
Reported victim losses (IC3, 2024)	US$16B+	Macro-scale economic incentive for illicit capability markets
Cyber-enabled fraud losses (IC3, 2024)	US$13.7B	Monetization pressure favors credential theft and social engineering
Cyberthreat losses (IC3, 2024)	US$1.571B	Ransomware/data-breach ecosystems continue to scale
Perimeter vulns fully remediated (DBIR 2025)	54%	Patch latency creates durable exploit windows for access brokers
Ransomware presence in breaches (DBIR 2025)	44%	Affiliates profit from commoditized access and tooling
YoY increase in vulnerability exploitation (DBIR 2025)	34% increase	Prioritize attack-surface reduction for edge assets

6. Conclusions

The Dark Web has evolved from a privacy-enhancing communication layer into a strategic substrate for contemporary cyber warfare, mirroring the argument established in the introduction. Its anonymity architecture, marketplace economies, hidden-service infrastructures, and cryptocurrency systems collectively enable the procurement, coordination, and sustainment of offensive and defensive cyber operations. The integration of Artificial Intelligence amplifies these dynamics by accelerating reconnaissance, automating vulnerability discovery, and enabling adaptive adversarial behaviors that compress the cyber kill chain. As Gabrian (2024) observes, AI-driven hacking tools and automated malware kits are increasingly accessible within Dark Web ecosystems, while RAND's assessment of autonomy, reasoning, and tool-integration suggests that emerging AI systems may soon assume more complex operational functions within anonymized environments (Hodgson, Horton, & Malone, 2025). Together, these developments reinforce the introduction's central claim: the Dark Web is no longer a peripheral criminal enclave but a core operational environment within modern cyber conflict.

Within NATO and U.S. doctrinal frameworks, the Dark Web must therefore be conceptualized as a contested battlespace embedded within persistent cyberspace competition. Its infrastructures enable hybrid operations that blend espionage, information warfare, and cyber-enabled coercion under conditions of reduced attribution precisely the convergence highlighted in the introduction. As AI-enabled automation continues to reshape offensive and defensive tradecraft, doctrinal approaches must integrate intelligence fusion, rapid decision advantage, and persistent engagement to counter adversaries who leverage anonymity-preserving ecosystems for strategic effect. Future research must address the governance of AI-enabled cyber capabilities, the development of attribution methodologies capable of operating under pseudonymity, and the establishment of international norms regulating cyber-enabled hybrid warfare conducted through anonymity-preserving infrastructures. Advancing these areas is essential to ensure that emerging AI-driven capabilities do not outpace the legal, ethical, and strategic frameworks required to manage them.

Ethics declaration: This research did not involve human subjects and thus no ethical clearance was required.

AI declaration: This research did not use any AI.

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Cybersecurity for Military Satellite Systems: Threats, Domains, and Engineering Countermeasures

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Abstract: Military operations increasingly depend on satellite-enabled services for beyond-line-of-sight command-and-control, intelligence, surveillance and reconnaissance (ISR), missile warning, and precision navigation and timing. As space becomes more contested, adversaries can achieve operationally significant effects by cyber-compromising the end-to-end satellite enterprise rather than physically destroying spacecraft. A prominent example is the 24 February 2022 KA-SAT incident, where an intrusion into terrestrial management infrastructure and downstream user terminals disrupted connectivity for tens of thousands of users across Ukraine and Europe (CyberPeace Institute, 2022; Viasat, 2022). This paper develops an engineering-oriented threat model for military satellite systems across the ground, link, space, and user segments, then translates that model into implementable security controls and mission assurance design patterns. Using a quantitative, model-based risk assessment (Monte Carlo simulation) and control-to-attack-surface mapping, the paper prioritizes high-leverage mitigations such as privileged access management for mission operations, authenticated command and telemetry protection using standards-based space data-link cryptography, and zero trust architectures adapted to intermittent, high-latency RF environments (CISA, 2024a; CCSDS, 2020). Finally, the paper synthesizes resilience engineering principles—redundancy, graceful degradation, rapid reconstitution, and cyber-informed autonomy—into a pragmatic roadmap that aligns security investments with operational tempo. The central finding is that satellite cybersecurity must be treated as mission assurance: an integrated set of architectural, procedural, and cryptographic controls that preserve capability under sustained cyber pressure and enable recovery within tactically relevant timelines.

Keywords: Satellite cybersecurity, SATCOM, TT&C, Zero trust, Mission assurance, Space systems security

1. Introduction

Satellites underpin modern military power by enabling globally distributed forces to communicate, sense, navigate, and coordinate at speed and scale. NATO recognizes space as an operational domain and highlights that space capabilities are critical enablers for communications, navigation, early warning, and ISR in support of collective defense and crisis response (NATO, 2025). As constellations proliferate, the cyber-physical attack surface expands: spacecraft are controlled by ground mission operations centers (MOCs), telemetry-tracking-and-command (TT&C) infrastructure, key management systems, and a large population of geographically dispersed user terminals. These dependencies create numerous digital pathways for adversaries to generate denial, deception, or espionage effects without resorting to kinetic anti-satellite operations.

The KA-SAT incident illustrates the operational asymmetry of cyber-attacks against space services. Public reporting indicates that malware delivered via terrestrial management systems caused widespread modem disruption, producing cascading impacts beyond the immediate conflict area (CyberPeace Institute, 2022; SentinelOne, 2022). The implication for military systems is that mission assurance requires an enterprise view: protection of spacecraft alone is insufficient if ground or user segments can be compromised to deny or manipulate the mission.

This paper contributes an engineering-focused synthesis that (i) formalizes a threat model across satellite segments, (ii) presents a model-based quantitative risk ranking to guide prioritization, (iii) maps controls and standards—including CISA space-sector guidance and CCSDS data-link security—onto concrete attack surfaces, and (iv) operationalizes resilience patterns into an implementation roadmap (CISA, 2024b; RAND, 2024).

2. Satellite Enterprise Architecture and Cyber-Relevant Dependencies

Military space systems are end-to-end enterprises rather than monolithic spacecraft. From a security engineering perspective, the primary decomposition is into space, ground, link, and user segments, augmented by supply chain and lifecycle processes (Willbold et al., 2023). Each segment introduces distinct trust boundaries, timing constraints, and failure modes that must be incorporated into the security architecture.

2.1 Segment Decomposition

The space domain can be decomposed into multiple architectural segments in order to support systematic security engineering and risk analysis (Falco et al, 2024). Segmenting the satellite enterprise enables security controls to be mapped to specific operational domains, trust boundaries, and communication pathways within

the overall mission architecture. Such decomposition also allows threat modeling, attack-surface enumeration, and defensive control implementation to be applied in a structured and domain-specific manner across the satellite ecosystem.

- Space segment: satellite bus and payload, onboard avionics, flight software, software-defined radios (SDRs), inter-satellite links, attitude and orbit control, and onboard data handling.
- Ground segment: MOCs, TT&C stations, scheduling systems, key management infrastructure (KMI), mission data processing pipelines, and the supporting enterprise IT environment.
- Link segment: RF uplinks/downlinks for telemetry and command, mission payload data links, gateway backhaul, and cross-support interfaces.
- User segment: tactical SATCOM terminals, ship/aircraft modem stacks, handheld receivers, gateways, and coalition partner interconnects.
- Supply chain and lifecycle: multi-tier vendors, firmware provenance, software bill of materials (SBOM), cryptographic key lifecycle, and long-term sustainment over decade-scale lifetimes.

An infographic describing the segments is shown in figure 1.



Figure 1: Satellite Domain Segmentation

The attack surface grows with the number of operational satellites and associated terminals. The Union of Concerned Scientists database lists more than 7,560 operational satellites in orbit, illustrating the scale and

heterogeneity of the modern space environment (Union of Concerned Scientists, 2025). Greater scale increases the importance of automation, standardization, and robust identity-centric controls because manual, perimeter-driven approaches do not compose across distributed enterprises.

3. Threat Landscape and Attack Surfaces

The threat landscape must be systematically analyzed to identify potential attack surfaces across the satellite enterprise. Attack surface analysis involves identifying all interfaces, communication channels, software systems, and operational processes that could potentially be exploited by an adversary. Understanding these exposure points is a foundational step in cybersecurity engineering because it enables defenders to prioritize mitigation strategies, develop layered defensive architectures, and reduce the probability of successful exploitation across the ground, link, space, and user segments.

3.1 Ground-segment Intrusion and Mission Operations Compromise

Ground networks frequently contain conventional IT services such as identity providers, remote administration tooling, virtualized computers, and vendor maintenance channels. Adversaries can exploit misconfigurations, unpatched vulnerabilities, or compromised credentials to traverse from enterprise networks into mission operations enclaves. Once inside, attackers can disrupt scheduling, corrupt mission data pipelines, or tamper with command authorization workflows, achieving disproportionate operational impact without interacting directly with spacecraft.

3.2 TT&C Compromise and Command Authority

TT&C links represent the highest-consequence control surface because they encode command authority. Attack vectors include unauthorized command injection, replay of previously valid commands, manipulation of time-tagged command sequences, and corruption of telemetry to induce operator misinterpretation. Inconsistent cryptographic protection and operationally fragile key management remain recurring weaknesses; consequently, standards-based link-layer security and robust key lifecycle management are foundational countermeasures (CCSDS, 2020; CCSDS, 2020a).

3.3 User-terminal and Tactical Edge Exploitation

Tactical terminals operate in contested environments with constrained physical security and complex logistics. Because terminals are numerous, sometimes commercially derived, and frequently forward-deployed, they are attractive scaling targets. Terminal compromise can expose cryptographic material, enable traffic manipulation, or provide a pivot into gateway infrastructure. The KA-SAT event demonstrated a terminal-focused disruption mode at scale (CyberPeace Institute, 2022).

3.4 Supply Chain and Long Lifecycle Vulnerabilities

Spacecraft lifecycles span a decade or longer, while many embedded components have shorter support windows. Patch logistics are constrained by uplink bandwidth, certification processes, operational risk, and limited contact windows. These constraints elevate the importance of secure-by-construction engineering, reproducible builds, SBOM-driven vulnerability management, and cryptographic verification of updates. Space-specific risk management guidance emphasizes that cybersecurity requirements must be planned early and integrated with system engineering rather than retrofitted after launch (CISA, 2024b).

3.5 Historical Incidents and Observed Patterns

Public reporting indicates that satellite systems have been subject to cyber interference via ground infrastructure. For example, reports describe interference affecting NASA's Terra and the Landsat-7 system in 2007–2008, accessed via a ground station, underscoring the criticality of ground-segment security (Space.com, 2011; Satellite Today, 2011). In 2014, media reporting described a cyber intrusion affecting the U.S. National Oceanic and Atmospheric Administration network supporting weather operations, highlighting that space-enabled services are exposed through terrestrial IT dependencies (CBS News, 2014). These cases reinforce a consistent pattern: ground and user segments are often the most accessible adversary entry points, while the operational impact can manifest in the space mission.

4. 4. Quantitative, Model-based Risk Assessment

Because incident data for national security space systems is sparse and frequently classified, programmatic prioritization commonly relies on model-based risk assessment. This section presents a lightweight quantitative

approach intended to support engineering decision-making. The analysis uses Monte Carlo simulation to propagate uncertainty in likelihood and impact for representative threat vectors and to produce relative risk rankings. Results are illustrative rather than empirical; they should be calibrated with program-specific telemetry, vulnerability data, and red-team results.

4.1 Methodological Framework

The proposed approach employs a stochastic risk propagation model using Monte Carlo simulation to estimate the distribution of mission risk across heterogeneous threat vectors. Each threat vector is parameterized by likelihood of successful exploitation modeled as a Beta distribution, and operational impact severity modeled as a lognormal distribution. The resulting risk functional is defined as the product of likelihood and impact.

Monte Carlo sampling (N = 20,000) is used to estimate expected risk, tail risk (95th percentile), and higher-order statistical properties. This formulation aligns with probabilistic risk assessment methodologies used in safety-critical aerospace systems and extends them to cyber-physical threat domains in the space sector (Varadharajan & Suri, 2024; Falco et al., 2024; Khan et al., 2024).

Uncertainty is treated explicitly through wide prior distributions and scenario-based stress testing. Epistemic uncertainty is captured through expert-informed priors, while aleatory uncertainty reflects inherent stochastic variability in system behavior.

4.2 Results

The simulation outputs should be interpreted as relative prioritization indicators rather than absolute measures. Ground-segment intrusion demonstrates the highest expected risk due to accessibility and control-plane centrality. Conversely, TT&C compromise and supply-chain insertion exhibit lower likelihood but significantly higher tail risk, indicating catastrophic mission consequences.

Table 1: Illustrative risk model outputs (relative units; Monte Carlo simulation)

Threat vector	Segment	Likelihood (mean)	Impact (median)	Risk (mean)	Risk (P95)
Ground-segment intrusion	Ground	0.286	19.9	6.86	17.58
TT&C command compromise	Link/Space	0.074	36.8	3.14	8.81
User-terminal compromise	User	0.200	18.0	4.31	11.26
Supply-chain insertion	Supply chain	0.057	44.7	3.23	10.03
Data/telemetry integrity attack	Link/Space	0.123	24.4	3.50	9.55

Figure 2 visualizes the relative risk ranking from the model; programs should use the ranking to focus assurance effort on the highest-consequence, highest-accessibility pathways first.

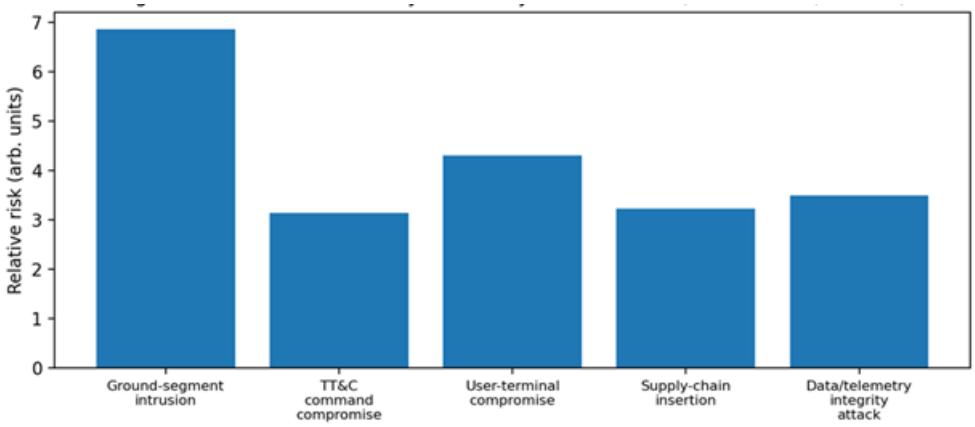


Figure 2: Modeled relative cyber-risk by threat vector (illustrative; Monte Carlo, N=20,000)

User-terminal compromise demonstrates systemic scaling effects, where moderate likelihood combined with large fleet size produces substantial aggregate risk. These findings are consistent with observed attack patterns and recent scholarship on space cyber resilience and attack-surface growth in satellite ecosystems (Varadharajan & Suri, 2024; Khan et al., 2024; Falco et al., 2024).

5. Security Engineering Controls and Architectures

Once the attack surface has been identified and characterized, the next phase of the security engineering process involves evaluating the security controls and architectural safeguards that protect each system component. This assessment includes analyzing authentication mechanisms, cryptographic protections, network segmentation strategies, and operational security procedures to determine their effectiveness against identified threat vectors. Through this process, organizations can systematically identify capability gaps, architectural weaknesses, and control deficiencies that must be addressed to achieve acceptable mission assurance levels.

5.1 Control Baselines and Governance

Military satellite cybersecurity programs typically adopt formal control baselines and assurance processes. CISA's space-sector guidance recommends using the NIST Cybersecurity Framework to develop profiles and risk mitigation plans and identifies common sources of cyber risk across space infrastructure (CISA, 2024b). For national security systems, additional overlays and profiles can improve fidelity by tailoring control intent to space-segment constraints. The Aerospace Corporation's space-segment cybersecurity profile provides a threat-focused rationale for tailoring controls to spacecraft avionics and mission contexts (The Aerospace Corporation, 2023).

5.2 Data-link Cryptography and Key Management

Cryptographic protection of telemetry and command is a prerequisite for preventing command injection and for preserving integrity under RF interception. The CCSDS Space Data Link Security (SDLS) family specifies services for authentication, confidentiality, and security parameter management at the data-link layer (CCSDS, 2020a). Engineering implementation requires: (i) hardware-backed key storage where feasible, (ii) rotation and revocation procedures compatible with limited contact windows, (iii) separation of mission keys from operator credentials, and (iv) resilient key distribution mechanisms that maintain continuity under degraded connectivity.

5.3 Zero Trust for Satellite Enterprises

Zero trust replaces implicit trust with explicit, continuously evaluated trust decisions based on identity, device posture, and policy. CISA's analysis of zero trust in the space environment identifies opportunities to apply zero trust tenets across ground, link, space, and user segments, while accounting for intermittent connectivity and latency (CISA, 2024a). Practically, this implies: strong identity for operators and devices, micro-segmentation of mission operations networks, policy enforcement points at control-plane interfaces, and continuous verification for privileged actions such as commanding and key management. Figure 3 describes zero trust control plane for satellites.

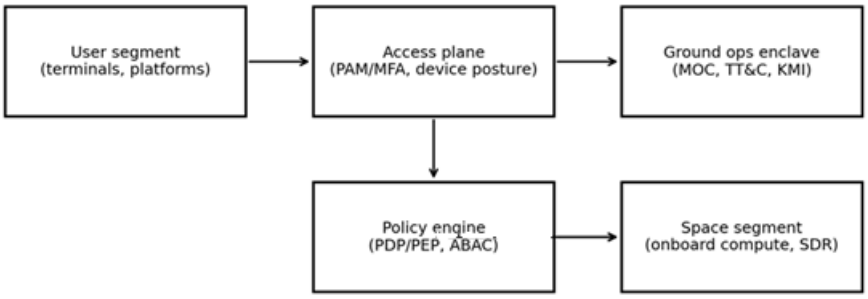


Figure 3: Reference zero trust control-plane adapted for satellite enterprises (conceptual)

5.4 Control-to-attack-surface Mapping

Table 2: Representative controls mapped to satellite attack surfaces

Control / mechanism	Primary segment	Engineering rationale
Privileged access management (PAM) + MFA for MOC/TT&C	Ground	Reduces credential theft and unauthorized operator actions; constrains lateral movement.
Network segmentation + unidirectional gateways for command paths	Ground/Link	Limits traversal from enterprise IT into operational enclaves; supports deterministic command pipelines.
SDLS authentication + encryption with robust key lifecycle	Link/Space	Mitigates command injection/replay and RF interception; preserves telemetry integrity.
Secure boot + signed updates + SBOM-driven vulnerability mgmt	Space/User/Supply chain	Reduces firmware insertion risk; improves patch trustworthiness and auditability.
Anomaly detection on TT&C telemetry and command sequences	Ground/Link	Detects deception and abnormal state transitions; supports rapid containment.
Degraded-mode operations and reconstitution playbooks	All	Enables mission continuation and rapid recovery under cyber disruption (RAND, 2024).

6. Resilience Engineering and Mission Assurance

Resilience engineering, sometimes referred to as reliability engineering, focuses on designing systems that can maintain operational capability despite failures, attacks, or unexpected disruptions. In complex cyber-physical systems such as military satellite architectures, resilience is evaluated using quantitative engineering methodologies including reliability modeling, failure mode analysis, and probabilistic risk assessment. These techniques allow engineers to measure system robustness, identify single points of failure, and design architectures that maintain mission functionality even when components are degraded or compromised.6.1 Resilience as a design requirement.

Perfect prevention is infeasible in complex, long-lived satellite enterprises. Mission assurance therefore treats resilience—continued operation and rapid recovery under attack—as a first-class requirement. RAND defines space mission assurance as deterring adversaries, countering risk from man-made and natural threats, and pursuing resilient architectures that sustain mission outcomes even when components fail or are compromised (RAND, 2024).

6.1 Engineering Patterns for Resilience

- Functional redundancy: multi-path communications (SATCOM + terrestrial backhaul), redundant ground stations, and cross-band contingency links.
- Diversity: heterogeneity across vendors, waveforms, and software stacks to reduce common-mode failure and supply-chain monoculture.
- Graceful degradation: pre-planned reduced capability modes (e.g., lower data-rate, reduced ISR product fidelity) that maintain critical functions under constraint.
- Rapid reconstitution: scripted rebuilds of ground services, golden images for terminals, and contingency keying material to restore trust quickly after compromise.
- Cyber-informed autonomy: onboard fault isolation and safe-mode transitions triggered by detected command anomalies or inconsistent state estimation.

6.2 Operational Metrics

Resilience must be measurable. Programs should define target recovery time objectives (RTO) and recovery point objectives (RPO) for mission services, then align engineering investments accordingly. For example, an RTO measured in hours for SATCOM service restoration implies pre-positioned terminal rekey capability, automated configuration management, and rehearsed playbooks for switching to alternate gateways. Where feasible, programs should instrument security-relevant telemetry—authentication failures, anomalous command sequences, and configuration drift—to support rapid triage and forensics.

7. Recommendations and Implementation Roadmap

Based on the previously developed threat model, the current cybersecurity standards landscape, and the results of model-based risk prioritization, a phased implementation roadmap can be constructed for defense organizations seeking to modernize satellite cybersecurity. This roadmap emphasizes controls that provide the highest marginal improvement in mission assurance while minimizing operational disruption and integration complexity. The proposed sequence addresses both technical and organizational transformation requirements across near-term, mid-term, and long-term horizons.

7.1 Near-term (0–12 Months)

Near-term efforts focus on high-impact, low-disruption controls. Organizations should implement privileged access management with hardware-backed authentication and just-in-time privilege escalation. Mission networks should be segmented with clearly defined trust boundaries, including isolation of TT&C command pathways using unidirectional gateways where feasible. Incident response capabilities must be operationalized through playbooks addressing terminal compromise, rapid re-imaging, and cryptographic key revocation. Regular cyber exercises should be conducted to validate response effectiveness.

- Enforce strict privilege access management, and time-bound privileged sessions for all mission operations and key management roles; eliminate shared accounts.
- Establish a segmented mission operations with segment boundaries well defined and secured.
- Create and exercise incident response playbooks for modem/terminal fleet compromise, including rapid re-imaging and key revocation.

7.2 Mid-term (12–36 Months)

Mid-term efforts introduce architectural transformation. Zero trust principles should be applied across mission interfaces with continuous authorization based on identity, device posture, and context (CISA, 2024a; Falco et al., 2024; Khan et al., 2024).

Secure software engineering practices, including reproducible builds, SBOM integration, and signed firmware pipelines, should be adopted. Telemetry-driven anomaly detection should be deployed across TT&C and mission data pipelines and integrated into a centralized security operations capability.

Threat intelligence integration should incorporate space-specific adversary tactics, techniques, and procedures, leveraging structured adversary-behavior frameworks and recent empirical analyses of satellite cyber-attack paths to support detection engineering and campaign analysis (Willbold et al., 2023; Khan et al., 2024; Peled et al., 2025).

- Adopt zero trust policy enforcement at mission control interfaces, integrating device posture and continuous authorization for high-consequence actions (CISA, 2024a).
- Introduce rigorous software engineering requirements, reproducible builds, and signed update pipelines for both spacecraft and terminal firmware; integrate supply chain risk assessment into acquisition.
- Instrument TT&C and mission data pipelines with anomaly detection tuned to satellite operational state models; integrate with a security operations capability.
- Integrate space oriented cyber threat intelligence into the development pipeline.

7.3 Long-term (36+ Months)

Long-term efforts focus on autonomous and resilient architectures. Cyber-informed autonomy should be embedded in spacecraft to enable anomaly-triggered safe modes and onboard decision-making under contested conditions. Constellation-level resilience should be engineered through distributed mission execution, authenticated inter-satellite links, and dynamic re-tasking. Coalition interoperability should be enabled through federated identity and attribute-based access control frameworks. These capabilities align with emerging doctrines of space cyber resilience and contested space operations (Falco et al., 2024; Khan et al., 2024; RAND, 2024).

- Engineer cyber-informed autonomy and safe-mode logic to maintain spacecraft survivability and limit adversary command authority.

- Design constellation-level resilience: diverse ground access, inter-satellite crosslinks with authenticated routing, and re-tasking strategies to sustain mission coverage under partial compromise.
- Standardize coalition interoperability through shared cryptographic and identity frameworks while maintaining compartmentalization and least privilege.

8. Conclusion

Military dependence on satellites makes space systems high-value cyber targets. Recent incidents demonstrate that adversaries can generate strategic effects by compromising ground infrastructure and user terminals rather than engaging in kinetic anti-satellite actions (CyberPeace Institute, 2022). Effective satellite cybersecurity therefore requires an enterprise mission assurance posture: structured risk management, standards-based link security and key management, identity-centric architectures such as zero trust, and resilience patterns that enable continued operation and rapid recovery (CISA, 2024a; RAND, 2024).

This study provides an engineering-oriented framework for analyzing satellite cyber risk and translating that analysis into actionable defensive architectures. However, satellite cybersecurity remains an evolving field that requires continued interdisciplinary research combining space systems engineering, network security, and operational mission assurance. Future work should focus on improved telemetry-driven threat detection, formal verification of satellite command systems, and integration of cyber resilience mechanisms directly into spacecraft autonomy and constellation-level architectures.

Ethics declaration: This research did not involve human subjects and thus no ethical clearance was required.

AI declaration: AI was only used to assist in making Figure 1. I created an initial figure then requested that ChatGPT improve that figure.

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Offensive Cyberspace Operations: Operational Logic, Strategic Utility, and Governance in Contemporary Cyber Conflict

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Abstract: Offensive cyberspace operations (OCO) have matured into a routine instrument of state power across the spectrum from day-to-day strategic competition to armed conflict. Yet OCO remains unusually difficult to conceptualize and govern because cyberspace is privately owned, technically volatile, and operationally interdependent with civilian critical infrastructure and global software supply chains. This paper develops a doctrinally grounded, technically informed framework for analyzing OCO across tactical, operational, and strategic levels of war while avoiding tradecraft. It models OCO effectiveness as an access-to-effects pipeline constrained by target system dynamism, intelligence requirements, identity and access management (IAM) complexity, tool exposure risk, and the probability of uncontrolled propagation or collateral impact. Empirically, contemporary intrusion data underscores that exploit-driven initial access is common and that remediation timelines often lag adversary tempo, reinforcing the perishable nature of access (Verizon, 2025; Mandiant, 2025). Strategically, OCO can enable campaign disruption, deterrence by denial, and information advantage, but their coercive predictability is limited, and their escalation externalities can exceed those of conventional fires in tightly coupled socio-technical systems. The paper synthesizes public doctrine, national strategies, and contemporary legal debates, emphasizing that credible governance must integrate military, intelligence, diplomatic, and software-engineering risk perspectives, including vulnerability-equities decisions and supply-chain assurance. It further highlights accelerants—AI-enabled capability scaling and the commodification of access through criminal markets—that compress decision timelines and blur state–non-state boundaries. The conclusion proposes a research and policy agenda centered on measuring effects over time, institutionalizing robust review and oversight, and strengthening resilience to manage the distinctive systemic risks of offensive cyber power.

Keywords: Offensive cyber operations, Cyberspace operations, Persistent engagement, Defend forward, Escalation, International law, NATO, Governance, AI-cyber nexus, Underground markets, Cyber-physical risk, Vulnerability equities

1. Introduction

Cyberspace has become a persistent arena of geopolitical contestation in which states and non-state actors continuously probe, exploit, and manipulate information systems to obtain intelligence, impose costs, and shape decision environments. Unlike traditional domains, the cyber domain is constituted largely by privately operated infrastructure and software-defined architectures that change rapidly through patching, configuration drift, container redeployments, identity policy updates, and supply-chain releases. These structural properties create a strategic paradox: cyber operations can project power without physical border crossings, yet the same connectivity that enables action also amplifies systemic spillover risk and the probability of collateral impact on civilian services (Theohary, 2024).

Operationally, modern targets are hybrid by default: enterprise networks fuse on-premises assets with cloud control planes, software-as-a-service (SaaS) tenants, managed identity providers (IdPs), and third-party integrations. The attack surface therefore includes not only hosts and networks, but also API permissions, federated authentication flows, secrets sprawl in CI/CD systems, and shared dependencies such as managed service providers (MSPs). For OCO, this increases both the intelligence burden—accurate modelling of a target's socio-technical configuration—and the governance burden—risk analysis for second-order effects in ecosystems not owned by the target state.

Offensive cyberspace operations differ from kinetic strike operations in ways that matter for both military doctrine and public oversight. Access is perishable; effects can be reversible, non-linear, and difficult to attribute; and operational success often depends on detailed intelligence regarding target configurations, defensive telemetry, and operator-controlled deconfliction (Joint Chiefs of Staff, 2018; Borghard and Lonergan, 2019). These features complicate deterrence signaling, post-operation battle damage assessment, and proportionality analysis. They also produce a persistent asymmetry between the rate of technological change (often days) and the pace of institutional decision processes (often weeks to months).

2. Definitions and Scope

U.S. doctrine frames cyberspace as a global domain within the information environment composed of interdependent networks, information systems, and embedded processors and controllers (Joint Chiefs of Staff, 2018). 'Cyberspace operations' describe the employment of cyberspace capabilities to achieve objectives in or

through cyberspace, including effects that can manifest outside the domain via cyber-physical coupling. Within that doctrinal frame, OCO are operations intended to project power by applying force in or through cyberspace to deny, degrade, disrupt, destroy, or manipulate adversary systems, data, or decision processes (Theohary, 2024).

This paper distinguishes OCO from closely related activity that is often operationally intertwined. Cyber espionage (commonly framed as cyber collection or CNE) seeks information advantage; it may share access pathways and infrastructure with OCO but typically aims for persistence and stealth rather than overt effect. Defensive cyberspace operations (DCO) focus on detection, mitigation, and active defense, while Department of Defense Information Network (DODIN) operations sustain mission networks. In practice, campaigning concepts such as persistent engagement and defend forward intentionally blur these boundaries, emphasizing continuous contestation and pre-emptive disruption of adversary infrastructure (U.S. Department of Defense, 2018; U.S. Cyber Command, 2022; Healey, 2019).

Scope is bound to strategic and operational analysis and explicitly omits tradecraft. Accordingly, discussion focuses on enduring technical constraints, risk dynamics, and governance mechanisms rather than procedural methods for intrusion, exploitation, or tool construction. Where technical terminology is used (e.g., 'control plane', 'EDR telemetry', 'privilege boundary'), it is intended to describe the risk surface and decision variables relevant to policy and command.

3. Policy and Legislative Context

OCO sits at the intersection of military activity, intelligence collection, and domestic legal controls. In the United States, operations may be conducted under military authorities (often associated with Title 10), intelligence authorities (often associated with Title 50), or hybrid arrangements combining intelligence preparation with military execution (Theohary, 2024). This legal geography shapes oversight, reporting, permissible objectives, and the ability to integrate effects with other instruments of national power—especially in the 'below-armed-conflict' space of strategic competition.

Strategic guidance since 2018 has emphasized a proactive posture. The 2018 DoD Cyber Strategy articulated defend forward, while U.S. Cyber Command describes persistent engagement as continuous contestation of adversary campaigns rather than episodic crisis response (U.S. Department of Defense, 2018; U.S. Cyber Command, 2022). The 2023 DoD Cyber Strategy summary similarly frames cyberspace operations as integral to campaigning and integrated deterrence (U.S. Department of Defense, 2023).

Governance also includes decisions about vulnerability retention versus disclosure. The Vulnerabilities Equities Process (VEP) formalizes deliberation over whether to disclose vulnerabilities to improve ecosystem security or retain them temporarily for national security purposes (The White House, 2017; Director of National Intelligence, 2024). In an era of high-tempo patching and 'patch-gap' exploitation, vulnerability policy functions as an operational variable: retention may enable access, but it can also increase systemic risk if the same weaknesses are discovered by adversaries, leaked, or widely exploited.

Table 1: Conceptual distinctions relevant to OCO governance

Activity lens	Primary objective	Typical success metric	Governance emphasis
OCO (effects)	Deny/degrade/disrupt/destroy/manipulate	Operational effect + controllability	Legal review + collateral/spillover risk
Cyber espionage (collection)	Information advantage	Persistence + exfil integrity	Counterintelligence + source protection
DCO	Defend systems and missions	MTTD/MTTR reduction	Resilience + incident response authority
DODIN ops	Network readiness and availability	Service uptime + compliance	Configuration control + supply-chain assurance

4. Analytical Approach: An Access-to-Effects Model

A useful analytic model must connect capability generation, operational employment, and strategic meaning. This paper adopts an 'access-to-effects' abstraction in which OCO are pipelines that convert privileged access into operational effects. Under this model, access is a perishable asset subject to detection, patching, credential

rotation, and architectural change; effects are contingent outcomes mediated by socio-technical systems, including automated defenses and organizational resilience (Healey, 2019; Borghard and Lonergan, 2019).

The model highlights a practical reality: many OCO failure modes occur before any payload-like mechanism is relevant. Failures include mis-modelled identity topologies, unanticipated cloud policy constraints, EDR detections at the telemetry layer, or the loss of an access pathway due to routine maintenance. The access-to-effects approach therefore treats intelligence preparation of digital terrain as analogous to weaponeering: operators must characterize dependencies, identify 'choke points' in workflows, and estimate the reliability and reversibility of potential effects.

Formally, the expected utility of an OCO action can be expressed as an engineering-style risk trade: EU ≈ P(access) × P(effect|access) × Value(effect) − [Risk(exposure) + Risk(spillover) + Risk(escalation)] × Cost. This is not a predictive equation so much as a decision framework: it forces explicit assumptions about probability, value, and externalities that can be challenged in review and oversight.

5. Operational Logic and Technical Constraints

The decisive factor in many OCO is not 'payload sophistication' but the fidelity of target system understanding. Contemporary environments integrate cloud services, identity and access management layers, software-defined networking, endpoint telemetry, and third-party dependencies that can change faster than a cyber operation's planning cycle. Configuration drift, patching, certificate rotation, and CI/CD deployments can invalidate assumptions and collapse access windows. Consequently, OCO are increasingly shaped by operational tempo and logistics—maintaining access in a moving target—rather than a one-time technical breakthrough.

Incident telemetry supports this access-centric framing. The 2025 Verizon Data Breach Investigations Report (DBIR) analyzed 12,195 data breaches across 139 victim countries, and found that credential abuse (22%), exploitation of vulnerabilities (20%), and phishing (16%) were leading known initial access vectors in non-error, non-misuse breaches (Verizon, 2025). The same report notes that perimeter device vulnerabilities were fully remediated only about 54% of the time, with a median of 32 days to complete remediation—an interval that can be operationally significant when adversaries pursue rapid exploitation (Verizon, 2025).

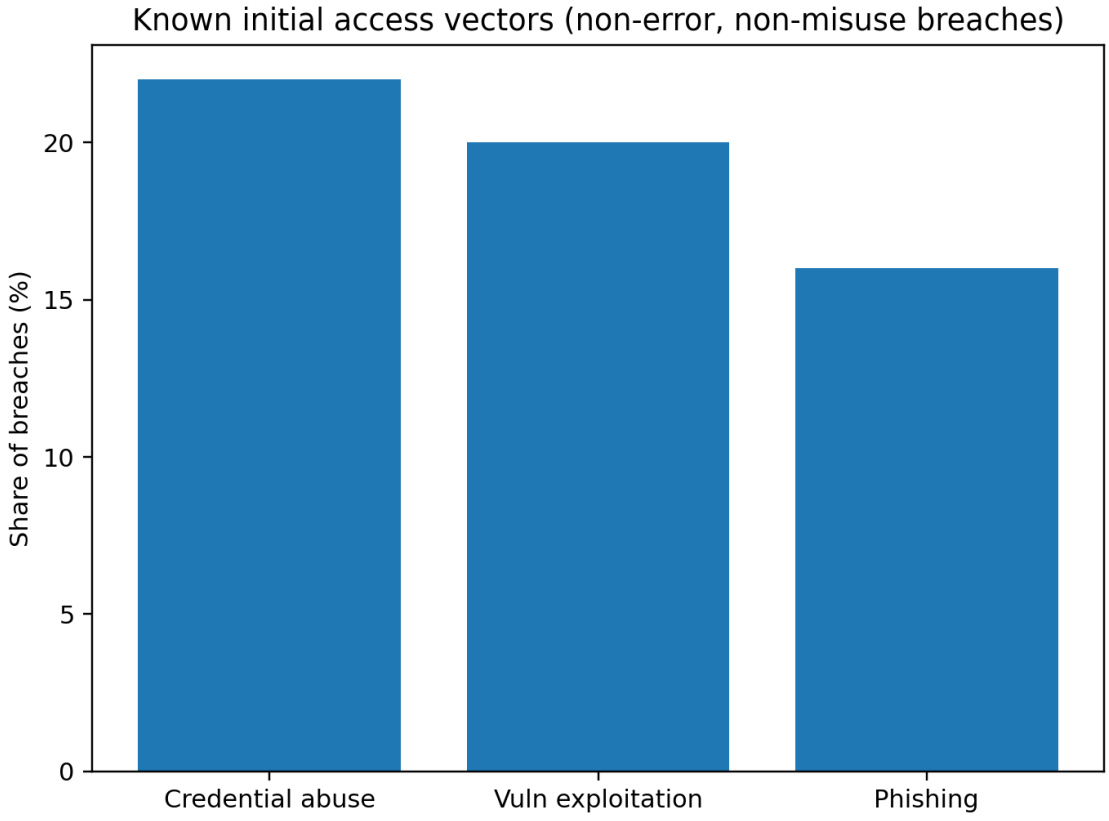


Figure 1: Known initial access vectors reported in Verizon DBIR 2025 (values shown are percentages). Source data: Verizon (2025)

From an operational perspective, the access-to-effects pipeline typically traverses multiple trust boundaries: external perimeter to identity plane, identity plane to workload plane, and workload plane to data plane. Each boundary introduces distinct defensive controls (e.g., MFA and conditional access at the identity layer, EDR and application allow-listing at endpoints, policy enforcement at cloud APIs). Maintaining operational security requires minimizing distinctive artifacts, managing observables, and deconflicting with other operations. Repeated use of a capability increases exposure risk, enabling defenders to detect, attribute, and mitigate, thereby reducing future utility (Borghard and Lonergan, 2019).

Reliability is also constrained by the heterogeneity of targets. Effects that depend on precise timing, specific library versions, or fragile assumptions about business logic can fail silently. Conversely, effects that propagate across shared dependencies—such as common management tooling, authentication services, or update channels—can exceed intended scope. For governance, this means technical review must include explicit 'blast radius' estimation and fail-safe considerations, not merely legal analysis.

Table 2: Access-to-effects pipeline and common constraint categories

Pipeline stage	Key artefacts	Constraint driver	Typical failure mode	Governance concern
Access establishment	Initial foothold, credentials/tokens	Patch gap; identity controls	Access burned by detection/rotation	Exposure risk; proportionality of entry
Privilege/positioning	Privileges, roles, trust relationships	IAM complexity; segmentation	Blocked by least privilege or policy	Deconfliction; scope creep
Persistence	Automation, renewal paths	Change management; monitoring	Breaks during updates/maintenance	Long-term systemic risk
Effect delivery	Triggers, dependencies, workflows	Target dynamism; safety constraints	Effect partial/reversible/unreliable	Controllability; civilian impact
Assessment & mitigation	Telemetry, restoration signals	Attribution ambiguity; IR maturity	Effects unmeasured or misattributed	Accountability; after-action learning

6. Interdependence and Collateral Effects

Cyberspace interdependence is a structural property of modern digital systems: societies share software stacks, hardware supply chains, managed service providers, and global routing and naming infrastructure. Offensive actions can therefore generate second- and third-order effects through shared dependencies, technical propagation, or operational disruption in adjacent ecosystems. The operational problem becomes one of controlling effects in a complex adaptive system rather than in a closed test environment.

Public attributions of the 2017 NotPetya incident highlight the systemic nature of spillover risk: a campaign aimed at Ukrainian targets rapidly caused widespread disruption and economic harm to global firms (UK Government, 2018; The White House, 2018; CISA, 2017). Such cases illustrate why proportionality and precautions, central concepts in international humanitarian law, must be operationalized as engineering and risk-analysis practices, not treated solely as legal abstractions (Davis et al., 2022; ICRC, 2019).

From a technical risk perspective, collateral pathways include: (1) shared authentication services (IdPs, federation), (2) shared management planes (remote monitoring and management tools, MSP platforms), (3) shared update mechanisms (software repositories and package registries), and (4) shared industrial and critical infrastructure dependencies (OT safety systems and supervisory control networks). Accordingly, resilience engineering—segmentation, redundancy, offline backups, immutable logging, and rapid restoration—functions as a strategic variable shaping both offensive feasibility and defensive survivability.

7. Strategic Purposes and Escalation Dynamics

OCO can support coercion (Fischerkeller, 2022), deterrence, campaign disruption, and information advantage, but these objectives are not equally predictable. Research on cyber escalation emphasizes that cyber operations frequently generate limited and uncertain costs, can be difficult to signal credibly, and often produce non-escalatory patterns of response (Borghard and Lonergan, 2019; Lin, 2012). These features reduce coercive leverage relative to conventional punishment strategies and complicate crisis bargaining.

Persistent engagement logic reframes strategic utility toward deterrence by denial and campaign disruption: continuous interference with adversary cyber capabilities, infrastructure, and enabling resources to impose friction and deny freedom of maneuver (Fischerkeller, 2022; Healey, 2019; U.S. Cyber Command, 2022). OCO can also support information advantage by degrading data integrity or situational awareness in ways that slow adversary decision cycles. Yet such effects may be perceived as escalatory if they threaten strategic stability or appear preparatory to kinetic action, underscoring the need for calibrated signaling and integrated crisis management.

A useful strategic lens is to treat OCO as 'campaign enablers' rather than stand-alone coercive instruments. In integrated operations, cyber effects may shape access to the electromagnetic spectrum, protect force flow, degrade adversary logistics, or contest command-and-control (C2) systems. However, because cyber effects can be transient and rapidly mitigated, campaign planners must consider persistence of effect over time, defender adaptation, and the opportunity cost of capability exposure.

8. International Law and Norms

UN processes have repeatedly affirmed that international law, including the UN Charter, applies to state behavior in cyberspace (UN General Assembly, 2015; 2021; 2023). Operational challenges arise from threshold classification: determining when cyber operations constitute a use of force, when they qualify as an armed attack triggering self-defense, and how to assess scale and effects when harm is economic, informational, or distributed.

States increasingly publish national positions. France emphasizes sovereignty and due diligence as well as the availability of responses under international law (France, 2021). The United States similarly emphasizes that existing international law governs cyber operations and has articulated a 'victim's perspective' focused on harms imposed (Davis et al., 2022; Visek, 2024). Debates persist over the legal content of sovereignty in cyberspace and the precise contours of countermeasures.

During armed conflict, international humanitarian law (IHL) limits cyber operations used as means or methods of warfare. The ICRC stresses that IHL applies fully in cyberspace, including distinction, proportionality, and precautions, and warns that cyber operations can seriously affect civilian infrastructure with potential human harm (ICRC, 2019; ICRC, 2023). Voluntary norms and confidence-building measures endorsed in UN processes aim to reduce misperception and escalation risk, while scholarly restatements such as the Tallinn Manual provide non-binding legal clarification.

9. Alliances and Multinational Cyber Operations

Alliances shape both the feasibility and legitimacy of OCO. NATO has recognized cyberspace as a domain of operations and has affirmed that a cyberattack could, in certain circumstances, trigger Article 5 collective defense commitments on a case-by-case basis (NATO, 2014; NATO, 2023). Nonetheless, NATO emphasizes that offensive cyber capabilities remain primarily national, making coalition cyber effects dependent on sovereign contributions and political authorization.

Multinational coordination is constrained by divergent legal frameworks, political risk tolerances, classification regimes, and technical interoperability. Shared operational pictures may be limited by data-sovereignty concerns and by differing incident response standards. Effective burden sharing therefore includes information sharing, deconfliction mechanisms, and shared risk frameworks for collateral effects—not only investment in capabilities.

10. Governance, Oversight, and Institutional Design

OCO governance must balance operational secrecy, strategic effectiveness, and democratic accountability. Secrecy preserves access and sources, but it limits external scrutiny and can impede institutional learning. Speed increases operational relevance, but it can erode legal review and systemic risk analysis. Accountability requires oversight by elected officials and watchdog institutions, yet the technical and classified nature of OCO creates persistent information asymmetries (Theohary, 2024; U.S. Government Accountability Office, 2025).

Governance frameworks benefit from translating legal and strategic requirements into engineering-style controls: defined risk thresholds, explicit collateral analyses, red-team validation of containment assumptions, and post-operation mitigation plans. A practical approach is multidisciplinary review that combines legal analysis with software-engineering risk assessment (e.g., dependency mapping, 'blast radius' modelling, rollback planning, and verification of restoration).

Broader cyber risk data provides context for why governance must treat spillover seriously. IBM's 2025 Cost of a Data Breach report shows the global average breach cost at USD 4.44 million in 2025, following USD 4.88 million in 2024, and provides a multi-year trend useful for strategic risk framing (IBM, 2025). While the report is not specific to state OCO, it illustrates the magnitude of economic externalities that can arise from cyber incidents and therefore the importance of precautionary controls for operations that could affect civilian systems.

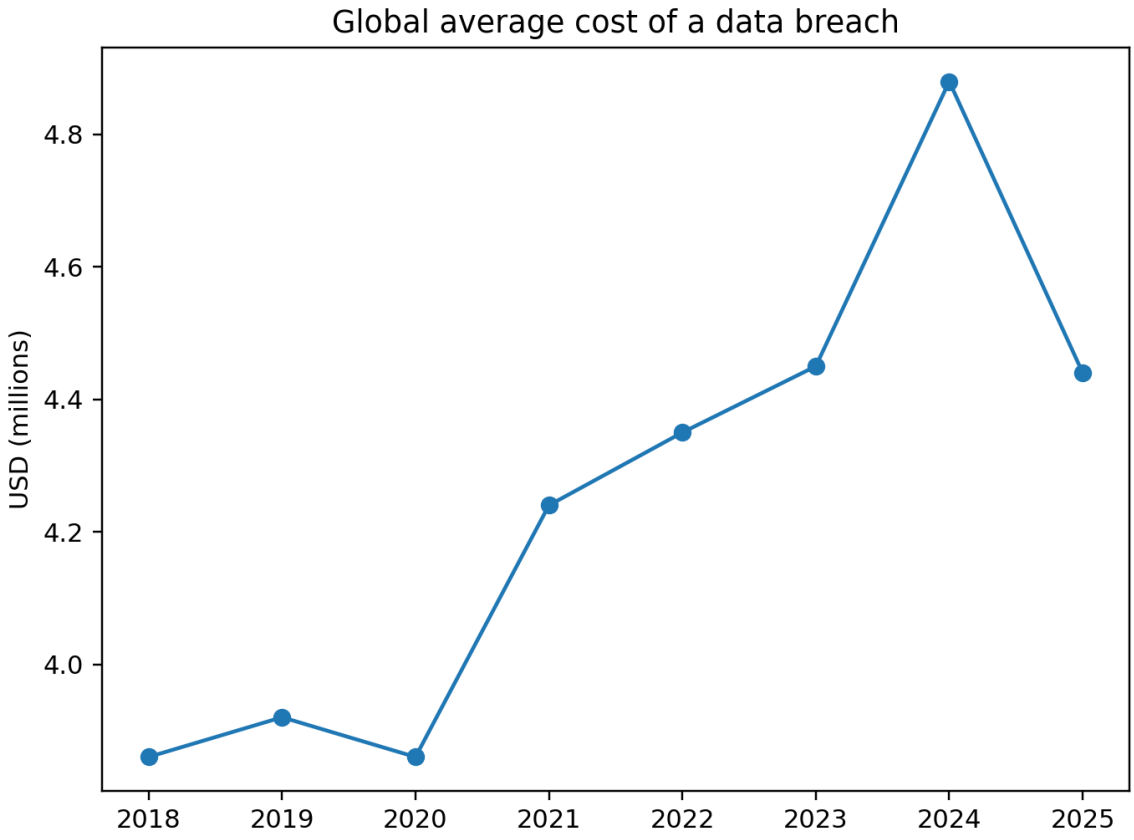


Figure 2: Global average cost of a data breach (USD millions), 2018–2025. Source data: IBM (2025)

11. Measuring Effects: Metrics and Assessment

Measuring OCO effectiveness is difficult because cyber effects are often indirect, mediated by defender adaptation, and confounded by concurrent instruments of power (sanctions, diplomacy, information operations). Unlike kinetic strikes, where crater analysis and sensor logs can approximate immediate physical damage, cyber 'battle damage assessment' may hinge on telemetry access, organizational reporting, and probabilistic inference.

Operational assessment therefore benefits from layered metrics: (1) access metrics (persistence duration, privilege depth, lateral reach), (2) effect metrics (service degradation, data integrity impacts, decision-cycle delays), and (3) externality metrics (spillover indicators, third-party impacts, and exposure costs). For governance, these metrics support after-action learning and provide a defensible basis for proportionality and precaution documentation.

Incident response datasets provide a proxy for the attacker–defender tempo relevant to access perishability. Mandiant reports that exploits were the initial infection vector in 33% of its 2024 investigations, and that global median dwell time rose to 11 days from 10 days in 2023 (still below 16 days in 2022) (Mandiant, 2025). Shorter dwell times can reduce the feasibility of long-horizon access operations, shifting emphasis toward rapid exploitation, automation, and operational security.

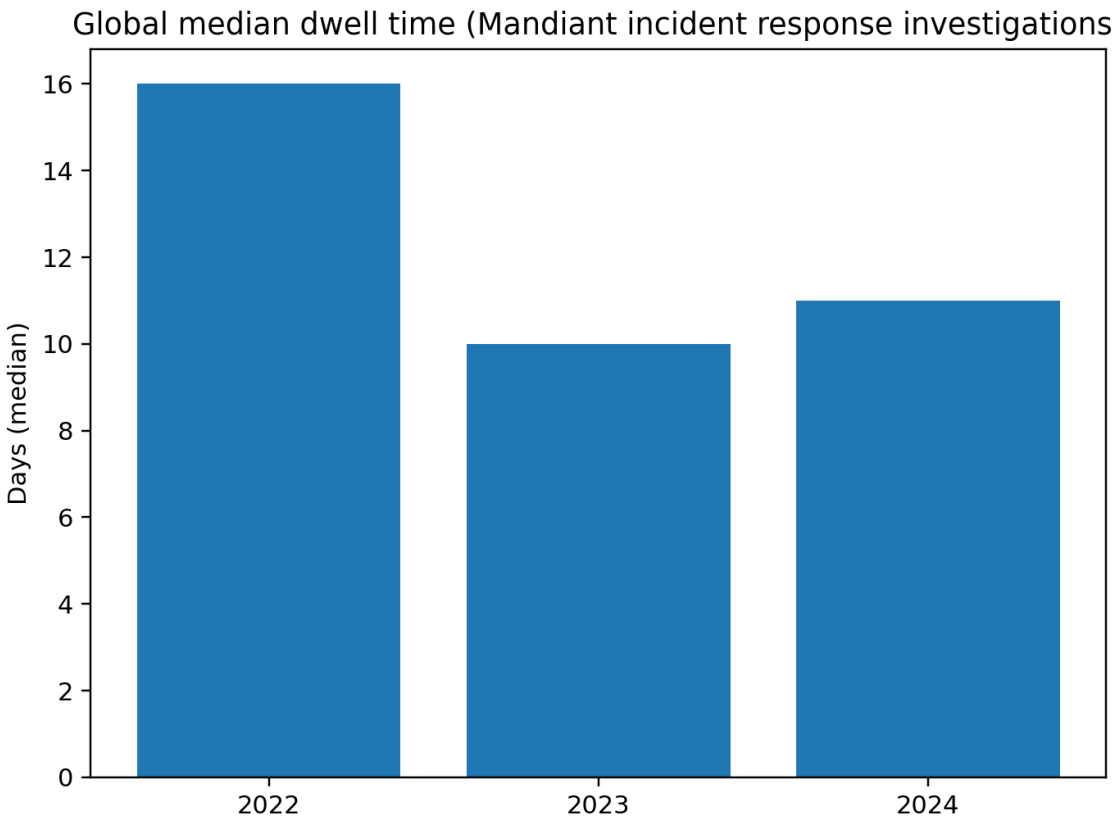


Figure 3: Global median dwell time (days). Source data: Mandiant (2025)

12. Emerging Accelerants: AI-Cyber Nexus and Access Commodification

Two accelerants intensify OCO's operational and governance challenges. First, AI-enabled systems can reduce the marginal cost of reconnaissance, language-specific social engineering, code analysis, and anomaly detection—compressing decision cycles and enabling higher-tempo campaigns. Second, underground markets increasingly commodify access and data through 'initial access brokers' and credential marketplaces, creating a shadow logistics layer for intrusion activity (Europol, 2025).

Recent breach research also points to AI as both an attack multiplier and a governance challenge. IBM reports that 16% of breaches involved attackers using AI, and that 13% of organizations reported breaches involving their AI models or applications; among those organizations, 97% lacked proper AI access controls (IBM, 2025). This suggests that AI systems are emerging as high-value targets and that weak governance—shadow AI, unmanaged plugins, and unreviewed API integrations—can create new pathways for compromise.

At the enterprise boundary, Verizon reports that 15% of employees routinely accessed generative AI platforms on corporate devices, increasing the potential risk for data leakage (Verizon, 2025). For state operators, these trends blur the line between traditional cyber operations and information operations, as AI-mediated influence, credential theft, and data poisoning can intersect with offensive access campaigns.

For governance, the AI-cyber nexus implies that review processes must incorporate model supply-chain risk (plugins, APIs, agents), data residency and privacy constraints, and the possibility of unintended propagation through automated systems. The same logic supports integrating secure-by-design practices, strong identity controls, and continuous monitoring into national cyber posture—reducing incentives to retain vulnerabilities for offensive gain while raising the cost of adversary exploitation.

13. Research and Policy Agenda

Four priorities stand out. First, the field needs rigorous methods to measure OCO effectiveness over time, distinguishing transient disruption from durable degradation and accounting for defender adaptation, restoration timelines, and capability exposure costs. Second, escalation modeling must integrate technical

ambiguity, interdependence spillover, and political crisis dynamics, especially as cyber operations intersect with critical infrastructure and military command systems (Borghard and Lonergan, 2019; Lin, 2012).

Third, policy and research should focus on the AI-cyber nexus and access commodification. AI may accelerate capability generation while introducing new vulnerabilities through autonomous agents and model supply chains; underground markets for initial access and data create a proxy enablement layer that can complicate deterrence and attribution (Europol, 2025; IBM, 2025). Fourth, governance mechanisms should mature toward multidisciplinary review practices that combine legal analysis with software-engineering risk assessment, enabling systematic consideration of collateral effects, long-term systemic vulnerability, and accountable decision records suitable for after-action learning under appropriate oversight.

14. Conclusion

OCO are an enduring element of contemporary state competition and military power, but they are constrained by perishable access, uncertain and interdependent effects, and governance challenges intensified by secrecy and rapid technological change. An access-to-effects model clarifies why OCO require intelligence, engineering rigor, and exposure management as much as technical ingenuity. Strategically, OCO can disrupt adversary campaigns and support deterrence by denial and information advantage, yet escalation and legitimacy risks demand robust oversight and prudent integration with other instruments of national power. As AI-enabled capability scaling and underground commodification accelerate the offense–defense cycle, states and alliances will require disciplined frameworks for risk assessment, legal and normative clarity, and resilience engineering to manage the systemic externalities of offensive cyber power.

Ethics declaration: This research did not involve human subjects and thus no ethical clearance was required.

AI declaration: This research did not use any AI.

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Information Campaigns in Irregular Warfare: A Framework for Expanding the Threshold of Competition

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Abstract: Contemporary irregular warfare increasingly unfolds through coordinated information campaigns designed to shape adversary perception, fragment decision-making, and expand competitive space below traditional escalation thresholds. While deterrence frameworks have historically emphasized military capability and economic leverage, modern competitors employ narrative operations, psychological pressure, and legitimacy contests to achieve strategic effects without decisive kinetic engagement. Classic coercion theory emphasizes that influence over adversary decision conditions often matters more than direct force application, particularly in ambiguous competitive environments (Schelling, 1966; Freedman, 2013). This paper proposes a decision-centric framework for information campaigns in irregular warfare that explains how coordinated narrative, psychological, and cyber-enabled information actions expand the threshold of competition. The framework integrates deterrence theory, irregular warfare doctrine, and gray zone competition research to show how information campaigns generate cumulative strategic effects through tempo disruption, legitimacy shaping, and perception control. Case evidence from Hizballah's psychological campaign, Chinese gray zone coercion, and contemporary Russian information operations illustrates how sustained campaigns produce denial, cost imposition, and delegitimization effects without triggering conventional escalation (Wehrey, 2002; Lin et al., 2022; Kalenský and Osadchuk, 2024). The contribution of this study is a structured campaign framework that links information actions to decision advantage and operational outcomes. This model supports parallel, multidomain action and helps practitioners design campaigns that shape competitive conditions before escalation thresholds are crossed.

Keywords*:* Information campaigns, Irregular warfare, Gray zone competition, Decision advantage, Psychological operations, Narrative strategy

1. Introduction

Irregular warfare has reemerged as a central feature of strategic competition, but its contemporary form differs from earlier insurgency-centric models. Modern competitors increasingly rely on coordinated information campaigns to influence perception, shape legitimacy, and alter adversary decision environments without crossing traditional escalation thresholds. These campaigns operate through narrative construction, psychological pressure, selective truth disclosure, and cognitive framing rather than decisive battlefield engagements. Competitive advantage is therefore often determined by decision influence and interpretive control rather than force superiority alone.

Classic coercion and deterrence theory emphasizes that shaping an adversary's expectations and perceived choices can be more decisive than the direct application of force (Schelling, 1966). Modern strategy scholarship similarly argues that competition frequently turns on perception, credibility, and narrative framing rather than material capability alone (Freedman, 2013). This insight is especially relevant in irregular warfare environments where legitimacy, narrative control, and psychological effects shape operational space. Clausewitz's conception of conflict as political and perceptual underscores that belief and legitimacy are operational variables, not merely contextual ones (Clausewitz, 2006).

Recent gray zone competition research shows that state and non-state actors deliberately design campaigns to achieve cumulative advantage through ambiguity, deniability, and narrative shaping rather than decisive engagement (Lin et al., 2022; Hybrid CoE, 2019). These campaigns rely on sustained information activity that fragments adversary sensemaking, increases decision latency, and reduces decision throughput across political and military institutions. The objective is gradual positional advantage rather than immediate operational victory.

Military doctrine increasingly recognizes the operational role of information. Joint and service doctrine describe information as an operational function that must be integrated with maneuver and fires (Joint Chiefs of Staff, 2022; U.S. Marine Corps, 2020). However, doctrine typically describes capabilities and authorities more clearly than campaign design logic. Practitioners therefore lack a structured model for designing information campaigns that produce cumulative decision effects over time.

This paper addresses that gap by proposing a decision-centric framework for information campaigns in irregular warfare. The framework explains how coordinated information actions expand the threshold of competition by shaping perception, legitimacy, and tempo. It integrates deterrence theory, irregular warfare practice, and gray zone campaign evidence into a campaign design model expressed in mission-impact terms. Properly structured information campaigns strengthen denial, cost imposition, and delegitimization effects and help shape competitive conditions before escalation thresholds are crossed.

2. Problem

Information campaigns are widely acknowledged as important in irregular warfare and gray zone competition, yet they are still frequently planned and executed as supporting activities rather than as primary campaign instruments. Current practice often treats information operations, psychological operations, and narrative engagement as adjuncts to kinetic, diplomatic, or economic actions. This supporting-role model limits campaign coherence and reduces the ability of information actions to generate cumulative strategic effects. As a result, competitors underutilize information campaigns as independent drivers of decision influence and threshold expansion.

A central problem is the absence of a decision-centric campaign framework that connects information actions directly to adversary decision outcomes. Many planning models emphasize message development, audience segmentation, and delivery channels without clearly linking these activities to measurable changes in adversary decision conditions. Without decision linkage, information activity becomes output-driven rather than effect-driven. Campaigns produce content but not necessarily decision advantage.

A second problem is that escalation models remain overly centered on kinetic thresholds. Traditional escalation frameworks focus on force levels, geography, and weapon systems while underestimating how sustained information pressure reshapes competitive space. Modern competitors deliberately operate below armed conflict thresholds through narrative operations, legal framing, and psychological pressure designed to fragment political consensus and slow response coordination (Lin et al., 2022; Hybrid CoE, 2019). Without an expanded threshold model, planners misclassify these campaigns as peripheral rather than operationally central.

A third challenge is organizational and doctrinal fragmentation. Information-related capabilities are distributed across multiple communities, including cyber operations, psychological operations, public affairs, and influence functions. These communities often operate under separate authorities and planning processes. When campaign integration is weak, narrative signals conflict, tempo diverges, and cumulative effects degrade. Fragmentation increases friendly decision latency and reduces decision throughput, weakening campaign coherence.

Historical and contemporary cases demonstrate that sustained psychological and narrative campaigns can produce strategic effects independent of kinetic superiority. Hizballah's psychological campaign against Israel in South Lebanon illustrates how narrative shaping and perception management influence legitimacy and political tolerance despite force asymmetry (Wehrey, 2002). Recent state-backed disinformation and influence campaigns show similar patterns of cumulative perception shaping and response delay (Kalenský and Osadchuk, 2024; Wilde, 2024). However, these cases are often treated descriptively rather than translated into repeatable campaign design logic.

The result is a persistent gap between recognition and execution. Information campaigns are recognized as decisive in theory but underdeveloped in campaign design practice. Without a structured framework that links information actions to decision advantage and operational outcomes, practitioners struggle to design campaigns that produce denial, cost imposition, and delegitimization effects in mission-impact terms. Closing this gap requires a campaign model that treats information as a primary competitive instrument rather than a supporting function.

3. Purpose

The purpose of this paper is to develop a decision-centric framework for designing and evaluating information campaigns in irregular warfare that expand the threshold of competition and produce measurable strategic effects. Rather than treating information activities as supporting functions, the framework positions coordinated narrative and psychological actions as primary campaign instruments that shape adversary decision conditions, legitimacy perceptions, and response tempo.

This study connects classic coercion and strategy theory with contemporary irregular warfare and gray zone practice. Coercion theory demonstrates that shaping expectations and perceived consequences influences adversary behavior more reliably than force alone (Schelling, 1966). Modern strategy scholarship reinforces that perception, credibility, and narrative framing are central to competitive outcomes (Freedman, 2013). This paper integrates these theoretical foundations with current doctrine and campaign evidence to produce an operationally usable model for information campaign design.

The framework proposed here links information actions directly to decision effects by focusing on how campaigns alter sensemaking, increase decision latency, and constrain adversary options. It emphasizes campaign coherence, tempo synchronization, and constraint-aware prioritization across narrative, psychological, and cyber-enabled activities. Information campaigns are evaluated not by message volume or engagement metrics, but by their contribution to decision advantage and operational positioning.

A secondary purpose is to improve doctrinal integration and practitioner usability. By expressing information campaign effects in mission-impact terms and aligning them with operational functions, the framework supports integration with broader operational planning (Joint Chiefs of Staff, 2022; U.S. Marine Corps, 2020). This alignment enables information campaigns to support parallel, multidomain action rather than operate as isolated communication efforts.

The intended contribution is both conceptual and practical. Conceptually, the paper reframes information campaigns as threshold-expanding instruments in irregular warfare. Practically, it offers a structured campaign model that planners and operators can use to design campaigns that generate denial, cost imposition, and delegitimization effects. Properly structured campaigns shape competitive conditions and expand maneuver space in persistent competition below armed conflict.

4. Theoretical Foundations and Campaign Logic

Information campaigns in irregular warfare are grounded in coercion theory, strategic interaction, and legitimacy-centered models of conflict. Coercion theory explains that influence is achieved by shaping an adversary's expectations, perceived risks, and available choices rather than by applying force directly (Schelling, 1966). Coercion depends on signaling, credibility, and controlled escalation, all of which are mediated through perception and interpretation. Information campaigns extend coercion into the cognitive and narrative domain by shaping how actions are interpreted before and after they occur.

Modern strategy scholarship reinforces that competitive outcomes often hinge on perception management and interpretive framing. Strategy is not only the orchestration of force but also the management of expectations, credibility, and belief structures (Freedman, 2013). In irregular warfare, where decisive engagements are uncommon and legitimacy is contested, narrative and psychological effects become central operational variables. Clausewitz's conception of conflict as fundamentally political highlights that moral forces, belief, and legitimacy influence outcomes as directly as material strength (Clausewitz, 2006).

Irregular warfare research further shows that non-state and hybrid actors frequently rely on psychological and narrative campaigns to offset material disadvantages. Insurgent and hybrid campaigns often succeed by influencing population perception, fragmenting adversary resolve, and shaping international interpretation rather than by achieving battlefield dominance (Jones, 2017). Information campaigns therefore function as force multipliers and risk redistributors, enabling actors to compete effectively despite resource asymmetry.

Contemporary gray zone competition extends these principles into state-level strategy. Gray zone campaigns are deliberately structured to remain below conventional conflict thresholds while producing cumulative strategic effects through ambiguity, narrative pressure, and legal-political maneuver (Lin et al., 2022). These campaigns rely on sustained information activity to normalize incremental actions, complicate attribution, and divide responses. Hybrid competition research emphasizes that narrative and perception management are central mechanisms of sub-threshold coercion (Hybrid CoE, 2019).

Doctrine increasingly recognizes the operational role of information but provides more clarity on capabilities than on campaign design logic. Joint doctrine identifies information as an operational function integrated with maneuver and fires, while service doctrine emphasizes competition below armed conflict (Joint Chiefs of Staff, 2022; U.S. Marine Corps, 2020). However, doctrinal publications offer limited guidance on designing information campaigns that produce cumulative decision effects across time and audiences. The gap between capability description and campaign logic remains significant.

Campaign logic in the information domain differs from kinetic campaign logic in three important ways. First, effects are cumulative and perception-mediated rather than immediate and physically measurable. Second, tempo is measured in decision cycles and legitimacy shifts rather than terrain change. Third, success depends on coherence and repetition across channels rather than singular decisive actions. Effective information campaigns therefore require synchronized narrative, psychological, and cyber-enabled actions designed around decision influence rather than event response.

These theoretical foundations support a campaign model that treats information actions as structured, cumulative, and decision-oriented. Such a model links narrative and psychological operations directly to decision advantage and threshold expansion, enabling actors to expand competitive space below armed conflict through sustained, coordinated influence activity.

5. A Framework for Information Campaigns in Irregular Warfare

This paper proposes a decision-centric framework for information campaigns in irregular warfare that links coordinated narrative, psychological, and cyber-enabled actions to measurable decision effects. The framework treats information campaigns as structured operational efforts designed to influence adversary sensemaking, legitimacy perceptions, and response tempo. Rather than focusing on message production alone, the framework emphasizes campaign coherence, constraint-aware prioritization, and decision advantage.

The framework begins with decision-condition targeting. Campaign design starts by identifying the specific adversary decisions to be influenced, delayed, divided, or redirected. These decision targets may include escalation responses, alliance commitments, attribution judgments, or domestic political thresholds. By defining decision targets first, campaign planners align narrative and psychological actions with mission-impact terms rather than engagement metrics. This decision-first approach reduces activity without effect and improves campaign focus.

The second element is narrative and legitimacy shaping. Campaigns establish and reinforce interpretive frames that define how events are understood by relevant audiences. Narrative shaping is not limited to persuasion; it structures perceived legitimacy, blame, and proportionality. Sustained framing influences how subsequent actions are interpreted and whether responses are politically and operationally sustainable. Evidence from irregular warfare campaigns shows that legitimacy framing significantly affects tolerance for escalation and counteraction (Wehrey, 2002).

The third element is tempo and repetition design. Information campaigns generate cumulative effect through repetition, variation, and cross-channel reinforcement. Rather than relying on single decisive messages, effective campaigns maintain narrative pressure across time. Tempo design increases adversary decision latency by forcing repeated interpretation and reassessment cycles. Research on contemporary disinformation campaigns shows that sustained multi-channel repetition increases uncertainty and slows coordinated response (Kalenský and Osadchuk, 2024; Wilde, 2024).

The fourth element is multi-channel synchronization. Narrative, psychological, cyber, legal, and diplomatic signals must be aligned to avoid contradiction and dilution. Fragmented messaging reduces credibility and weakens cumulative effect. Synchronization supports parallel, multidomain action in which information activity reinforces operational and political moves rather than trailing them. Gray zone campaign analysis demonstrates that synchronized cross-domain signaling produces stronger cumulative pressure than isolated messaging efforts (Lin et al., 2022; Hybrid CoE, 2019).

The fifth element is constraint-aware prioritization. Campaign resources are finite, and not all audiences, platforms, or narratives produce equal strategic effect. Campaign planners should identify decision bottlenecks and legitimacy concentration points where influence produces disproportionate impact. Prioritization focuses effort where narrative or psychological shifts most constrain adversary options. This improves efficiency and supports denial and cost imposition effects.

The sixth element is feedback and adaptation loops. Information campaigns must include continuous assessment of decision effects, narrative uptake, and legitimacy shifts. Assessment focuses on decision behavior and response patterns rather than engagement counts alone. Campaign elements are adjusted based on observed decision effects, reinforcing successful approaches and discontinuing ineffective ones. This adaptive structure sustains campaign relevance over time.

Together, these elements form a campaign design framework that translates information activity into operational decision effects. By targeting decision conditions, shaping legitimacy, managing tempo,

synchronizing channels, prioritizing constraints, and adapting continuously, information campaigns expand the threshold of competition and strengthen strategic positioning in persistent irregular conflict environments.

6. Implications and Recommendations

Historical and contemporary cases demonstrate that sustained information campaigns generate strategic effects by shaping perception, legitimacy, and decision tempo rather than by producing immediate battlefield outcomes. While each campaign reflects distinct political and operational conditions, recurring patterns appear across irregular warfare and gray zone competition. These patterns reinforce the need for structured campaign design focused on cumulative decision effects rather than isolated messaging events.

Hizballah's psychological campaign against Israel in South Lebanon illustrates how narrative and perception operations can influence strategic outcomes despite material asymmetry. The campaign emphasized resilience narratives, symbolic victories, and media amplification to shape regional and domestic interpretation. By framing continued resistance as success and portraying opposing actions as disproportionate, the campaign influenced legitimacy perceptions and political tolerance thresholds. Psychological and media effects amplified operational activity and produced cumulative strategic impact beyond battlefield engagements (Wehrey, 2002). This pattern demonstrates how legitimacy framing and repetition contribute directly to delegitimization and cost imposition effects.

State-level gray zone campaigns show similar cumulative dynamics at larger scale. Chinese gray zone coercion against regional neighbors integrates sustained narrative messaging, legal claims, diplomatic signaling, and media framing to normalize incremental actions and shape international interpretation. These campaigns reduce perceived escalation while steadily shifting positional advantage. Analysis indicates that cumulative narrative pressure complicates alliance coordination and increases adversary decision latency by fragmenting interpretive consensus (Lin et al., 2022). The operational pattern is steady interpretive conditioning rather than decisive signaling.

Recent Russian information and disinformation campaigns provide further evidence of tempo and sensemaking disruption effects. Sustained disinformation efforts have targeted attribution processes, public trust, and institutional credibility. Rather than persuading audiences of a single alternative narrative, these campaigns often aim to generate uncertainty and interpretive overload. Research shows that repeated multi-channel disinformation increases cognitive burden and slows coordinated response, thereby reducing adversary decision throughput (Kalenský and Osadchuk, 2024; Wilde, 2024). The operational objective is confusion and delay rather than belief alone.

Across these cases, three operational patterns consistently appear. First, information campaigns are cumulative rather than episodic, with effects emerging through sustained repetition and reinforcement. Second, legitimacy and interpretation function as central variables, with campaigns shaping how actions are understood as much as what actions occur. Third, decision tempo is a primary target, with successful campaigns increasing adversary decision latency and complicating coordinated response.

These recurring patterns support the proposed framework's emphasis on decision-condition targeting, narrative shaping, tempo design, and cross-channel synchronization. Case evidence shows that information campaigns produce denial, cost imposition, and delegitimization effects when designed as coherent campaigns rather than isolated messaging efforts. Structured campaigns expand competitive maneuver space below armed conflict through sustained influence and perception management.

7. Implications for Campaign Design and Practice

The framework and case patterns presented in this paper suggest several practical implications for designing and executing information campaigns in irregular warfare. The central implication is that information campaigns should be planned as primary operational efforts tied to decision outcomes rather than as supporting communication functions. Campaign effectiveness should be evaluated in decision and legitimacy effects, not message volume or audience engagement statistics alone.

First, campaign planning should begin with decision-condition targeting. Planners should identify the specific adversary decisions, policy commitments, alliance behaviors, or escalation thresholds they intend to influence. Information actions should be explicitly mapped to those decision points. This decision-centric approach aligns campaign design with mission-impact terms and improves decision advantage. It also supports constraint-aware prioritization by concentrating effort where influence produces disproportionate operational effect.

Second, narrative and legitimacy framing should be treated as operational design variables rather than messaging afterthoughts. Campaign planners should define the interpretive frame through which subsequent actions will be understood. Narrative framing should be consistent, repeatable, and adaptable across channels and phases. Legitimacy framing is especially important in irregular warfare environments where proportionality, attribution, and moral authority influence escalation tolerance and coalition cohesion (Clausewitz, 2006; Freedman, 2013).

Third, tempo design should be deliberate and sustained. Campaigns should control rhythm and repetition to maintain cognitive pressure and increase adversary decision latency. Rather than reacting to events alone, campaigns should maintain initiative through planned narrative sequencing and reinforcement cycles. Sustained tempo contributes to denial and cost imposition effects by forcing repeated adversary interpretation and response cycles (Kalenský and Osadchuk, 2024).

Fourth, synchronization across functions is essential. Information campaigns should be integrated with cyber, legal, diplomatic, and operational actions to support parallel, multidomain action. Signals that conflict across channels reduce credibility and weaken cumulative effect. Planning and coordination structures should ensure that narrative, psychological, and operational signals reinforce one another rather than compete (Joint Chiefs of Staff, 2022; U.S. Marine Corps, 2020).

Fifth, assessment models should emphasize decision and behavior indicators rather than engagement metrics alone. Measures such as response delay, alliance fragmentation signals, policy hesitation, attribution confusion, and narrative adoption provide stronger indicators of campaign effect than impressions or reach. Assessment should focus on whether campaigns increase adversary decision latency and constrain available options.

Sixth, campaign organizations should incorporate feedback and adaptation mechanisms. Information environments shift quickly, and campaign narratives must adjust to counter-adaptation and audience response. Continuous assessment and controlled narrative adjustment improve campaign resilience and effectiveness over time.

Taken together, these implications reposition information campaigns as structured operational instruments. When designed around decision influence, legitimacy shaping, tempo control, and synchronization, information campaigns generate measurable strategic effects and expand competitive maneuver space below armed conflict.

8. Conclusion

Information campaigns are now central instruments of irregular warfare and gray zone competition, yet they remain under-structured in campaign design practice. Contemporary competitors use sustained narrative, psychological, and influence operations to shape legitimacy, fragment sensemaking, and alter decision conditions without crossing traditional escalation thresholds. These campaigns do not seek immediate decisive effects. Instead, they generate cumulative strategic advantage through perception shaping, tempo disruption, and interpretive control.

This paper presented a decision-centric framework for information campaigns that links coordinated narrative and psychological actions directly to adversary decision conditions and operational outcomes. Drawing on coercion theory, strategy scholarship, irregular warfare research, and gray zone campaign evidence, the framework emphasizes decision-condition targeting, legitimacy and narrative shaping, tempo design, multi-channel synchronization, constraint-aware prioritization, and adaptive feedback loops (Schelling, 1966; Freedman, 2013). Together, these elements convert information activity from message production into structured campaign design.

Case evidence from psychological and gray zone campaigns demonstrates recurring operational patterns. Sustained narrative efforts influence legitimacy perceptions, increase adversary decision latency, and complicate coordinated response (Wehrey, 2002; Lin et al., 2022; Kalenský and Osadchuk, 2024). These effects produce denial, cost imposition, and delegitimization outcomes even when material force balances remain unchanged. Information campaigns therefore function as threshold-expanding instruments that reshape competitive space below armed conflict.

For practitioners, the key implication is that information campaigns should be designed and evaluated around decision effects rather than engagement metrics. Campaign planning should begin with decision targets, align with doctrinal functions, and support parallel, multidomain action. Assessment should focus on behavioral and

decision indicators rather than message reach alone. Properly structured campaigns strengthen decision advantage and campaign coherence across phases of competition.

Information campaigns are not substitutes for other instruments of power, but they increasingly determine how and when those instruments can be used effectively. A structured, decision-centric campaign framework enables competitors to expand competitive maneuver space and shape adversary choices in persistent competition below armed conflict.

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: Open-source artificial intelligence tools were used solely for proofreading and citation formatting. All analysis, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources.

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A Lightweight Automated SQL Injection Testing Tool with Integrated Discovery and Structured Reporting

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Abstract SQL injection (SQLi) remains one of the most persistent and high-impact vulnerabilities in web applications, consistently ranked among the OWASP Top 10 threats. Although mature tools such as SQLMap provide extensive detection and exploitation capabilities, their steep learning curve, complex configuration requirements, and command-line-driven interfaces limit accessibility for beginners, students, and small organizations with constrained technical resources. This paper presents the design, implementation, and evaluation of a lightweight, automated SQL injection testing tool that emphasizes usability, efficient detection, comprehensive endpoint discovery, and structured reporting. The proposed system integrates four classical SQLi detection techniques—error-based, union-based, boolean-blind, and time-based—within a modular scanning engine accessible through an intuitive graphical user interface. To improve assessment coverage, an automated discovery module identifies hidden and unlinked endpoints via robots.txt inspection, sitemap.xml parsing, and hyperlink crawling. A multi-format reporting framework generates human-readable and machine-processable outputs, including executive summaries, vulnerability evidence, and mitigation recommendations. Experimental evaluation was conducted using Damn Vulnerable Web Application (DVWA) and OWASP Juice Shop, representing standard testbeds for ethical and repeatable SQLi assessment. Results demonstrate detection success rates ranging from 79% to 93% across the implemented techniques, while integrated discovery increased endpoint coverage by more than 100%. Comparative benchmarking against SQLMap indicates that although SQLMap offers deeper exploitation capabilities, the proposed tool delivers superior accessibility, reduced configuration complexity, faster deployment, and structured reporting suitable for educational, developmental, and small-scale security testing environments. The findings validate that lightweight design can achieve effective vulnerability detection without sacrificing fundamental security capabilities, providing a practical entry point for SQL injection assessment.

Keywords: SQL injection, Web application Security, Vulnerability scanning, Endpoint discovery, Automated testing, Cybersecurity

1. Introduction

The exponential growth of web-based services has transformed modern society, enabling digital banking, e-commerce, healthcare delivery, academic management, and government operations. However, this expansion has also introduced significant security challenges, particularly vulnerabilities arising from improper handling of user input and backend database interactions. Among these threats, SQL injection (SQLi) remains one of the most critical and persistent attack vectors, enabling adversaries to manipulate database queries, bypass authentication mechanisms, extract sensitive data, and compromise system integrity. Despite over two decades of research and mitigation efforts, SQLi continues to rank prominently in the OWASP Top 10, underscoring its ongoing relevance and severity (OWASP, 2021).

Existing SQLi detection and exploitation tools, notably SQLMap, offer comprehensive functionality and extensive payload repositories, enabling deep vulnerability assessment and exploitation. Nevertheless, these tools are primarily command-line driven, demand advanced configuration knowledge, and impose steep learning curves, limiting their adoption among students, novice developers, and small organizations with limited cybersecurity expertise. Moreover, many lightweight scanners provide limited endpoint discovery, requiring users to manually specify URLs and parameters, thereby risking incomplete assessment coverage. Recent research has explored machine learning and deep learning approaches for SQLi detection, achieving high accuracy under controlled conditions (Lu et al., 2022; Leung et al., 2024; Khan et al., 2025). Akpojaro et al. (2014) evaluated unsupervised

learning algorithms for malware detection under scenarios involving known and unknown attackers, finding that the γ-algorithm outperforms other unsupervised techniques in terms of detection efficacy. Yang et al. (2024) introduced SWIDE (Successful Web Injection Detection Engine), designed to identify successful web injection attacks, including PHP command injection and SQLi. SWIDE leverages two key insights: successful attacks must comply with programming language syntax, and they inevitably produce observable effects such as execution results or backdoors. Through syntactic and semantic analysis, SWIDE detects malicious syntax in obfuscated payloads and recovers attack intent. Its two-stage design—attack identification and confirmation—enables accurate detection even under complex obfuscation. The system has been deployed and validated in real-world environments in collaboration with a cybersecurity firm, demonstrating practical applicability beyond proof-of-concept studies. However, these methods face challenges including labeled data scarcity, generalization limitations, interpretability concerns, and computational overhead, restricting their practical deployment in small-scale and educational environments.

This study addresses these limitations by designing and implementing a lightweight, GUI-based SQL injection testing tool that integrates classical detection techniques, automated endpoint discovery, and structured reporting. The objectives are threefold: (i) enhance usability and accessibility, (ii) improve vulnerability coverage through integrated discovery, and (iii) deliver actionable and interpretable reporting. The proposed system aims to complement, rather than replace, comprehensive frameworks like SQLMap by providing a practical, low-overhead solution suitable for learning, development, and small organizational contexts.

2. Related Work

2.1 SQL Injection Detection Techniques

Security has become a fundamental requirement for individuals, organizations, and governments as reliance on digital systems increases. The rise in cyberattacks despite significant IT security investments underscores the persistent vulnerability of electronic information. Onwudebelu and Akpojaro (2012) emphasize the concept of an "electronic life" constantly targeted by social engineering and propose security-awareness strategies to mitigate such threats. Early approaches to SQLi detection focused on rule-based and lexical analysis methods. Hlaing and Khaing (2020) proposed a reserved-word lexicon and tokenization strategy for detecting malicious queries, demonstrating satisfactory performance under controlled conditions. Sheykhkanloo (2015) introduced a pattern-recognition neural network model employing URL generation and classification to detect and categorize SQLi attacks, later extended by Onwudebelu et al. (2025) to improve classification performance. With the maturation of artificial intelligence techniques, recent studies have leveraged deep learning and generative models to enhance SQLi detection and sample generation. Lu et al. (2022) employed GAN-based data augmentation to overcome data scarcity, while Leung et al. (2024) and Khan et al. (2025) demonstrated the effectiveness of language models and GAN-driven mutation engines in generating evasive SQLi payloads capable of bypassing modern web application firewalls (WAFs). Although effective, these approaches introduce challenges related to interpretability, computational cost, and real-world generalization. While there have been solutions proposed in the literature for SQLi attack detection using learning-based frameworks, the problem is often formulated as a binary, single-attack vector problem without considering the prioritization and prevention component of the attack (Paul et al., 2024). Research on Lightweight intrusion detection model based on Convolutional Neural Network (CNN) was discussed in Cao et al. (2025) while detection of SQL Injection and cross-site scripting based on multi-Model CNN combined with bidirectional GRU and multi-head self-attention (Hsiao & Wang, 2023). Furthermore, enhanced detection and prevention of SQL injection and cross-site scripting attacks in Web applications was carried out by Imran et al. (2024), where the analyzing algorithms and threat modeling approaches where used, Jahanshahi et al. (2020) mitigated SQL Injection attacks on legacy Web applications. Hwang et al. (2024) conducted a comparative study of decision and ensemble models for SQL injection detection. Evaluating Decision Tree, Random Forest, XGBoost, AdaBoost, Gradient Boosting Decision Tree (GBDT), and Histogram Gradient Boosting Decision Tree (HGBDT) on a comprehensive SQLi dataset, they found that Decision Tree, Random Forest, and AdaBoost achieved the highest performance, with 99.50% accuracy and an F1 score of 99.33%. Their results highlight the effectiveness of ensemble and boosting techniques in enhancing real-time SQLi detection and robustness against evolving attacks.

2.2 Web Application Firewalls and IDS-Based Approaches

Several studies focus on integrating SQLi detection within WAF and intrusion detection system (IDS) frameworks. Ikramaputra et al. (2025) combined ensemble learning models with lightweight heuristic filters, achieving detection accuracy exceeding 99% while maintaining low latency. Singh and Aksanli (2019) enhanced Snort-based IDS performance through deep packet inspection and real-time rule generation. Zaidan et al. (2024)

evaluated collaborative detection using SIEM platforms and heterogeneous WAF deployments, demonstrating improved situational awareness and centralized threat reporting.

2.3 Automated Discovery and Security Testing

Automated discovery remains a critical challenge in dynamic vulnerability scanning. Schlaubitz et al. (2025) proposed A2CT for automated detection of access control vulnerabilities, emphasizing broad request-type coverage. However, many SQLi-focused tools rely heavily on manually provided URLs, limiting assessment completeness. Integrated crawling, sitemap analysis, and robots.txt inspection have been shown to significantly enhance discovery coverage, particularly in dynamic web environments.

Messas et al. (2024) proposed sAIfe, a prescriptive threat modeling method for AI applications under development. By providing graphical references, remediation suggestions, and practical assessment steps, sAIfe simplifies security analysis. Evaluated on a real-world AI system and validated with academic developers, sAIfe effectively identified potential vulnerabilities while offering actionable mitigation options, demonstrating usability and efficiency in practical settings.

Dynamic, black-box testing tools simulate attacker behavior by submitting crafted inputs and analyzing responses. SQLMap is widely recognized as the de facto industry and research baseline due to its comprehensive payload database, support for multiple database management systems (DBMS), and extensive adoption in both academic studies and penetration testing practice (2022). SQLMap automates payload selection, injection point discovery, and data extraction, making it highly effective for in-depth assessments. However, practical reviews note several limitations: it is primarily command-line driven, often requires advanced configuration for complex targets, and can consume substantial computational resources during exhaustive scans. Comparative studies benchmark new methods against SQLMap, positioning it as a technical standard despite limited accessibility for beginners or constrained environments. A common limitation in dynamic testing workflows is inadequate endpoint discovery. Many tools require explicit target URLs and lack mechanisms to locate hidden or parameterized endpoints. Literature highlights complementary discovery techniques—such as robots.txt parsing, sitemap.xml analysis, internal link crawling, and JavaScript/AJAX endpoint enumeration—that can expand coverage. Omitting discovery risks leaving significant portions of the attack surface untested, particularly in educational settings and small organizations. Integrated discovery capabilities are therefore critical for comprehensive vulnerability assessment.

2.4 Research Gaps

Across existing literature, several gaps persist: (i) usability barriers in comprehensive tools, (ii) limited endpoint discovery in lightweight scanners, (iii) interpretability and deployment challenges in ML-based approaches, and (iv) absence of lightweight hybrids that balance efficiency, detection accuracy, and reporting clarity. These gaps motivate the development of the proposed tool.

3. Materials and Research Methodology

This study adopts a design science research (DSR) methodology, suitable for developing and evaluating technical artifacts. The process comprised iterative cycles of problem identification, artifact design, implementation, and evaluation. The identified problem centers on the limited accessibility and discovery coverage of existing SQLi tools despite their technical robustness. Figure 1 illustrates the automated workflow of the proposed system from URL input and endpoint discovery through payload execution, vulnerability analysis, and final report generation.

3.1 System Architecture

The proposed tool follows a modular architecture to ensure extensibility and maintainability. The system comprises six principal components (Figure 1): (i) graphical user interface (GUI), (ii) input validation and sanitization module, (iii) scanning engine, (iv) detection modules, (v) discovery system, and (vi) reporting module. This loosely coupled design enables independent evolution of detection, discovery, and reporting functionalities.

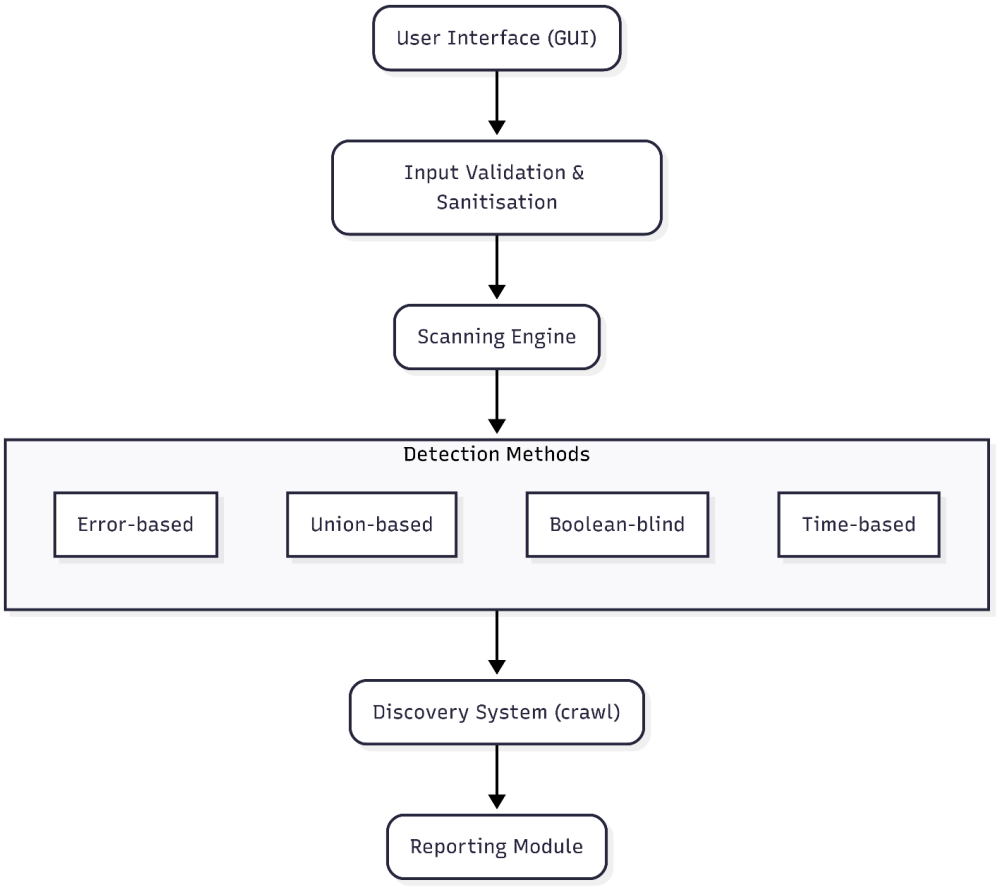


Figure 1: System Architecture Diagram

3.2 Detection Engine

Four classical SQLi detection strategies are implemented: error-based, union-based, boolean-blind, and time-based. Error-based detection injects payloads that provoke database errors, while union-based detection evaluates response manipulation via UNION SELECT queries. Boolean-blind detection infers vulnerability through differential response analysis, and time-based detection employs deliberate delays to confirm conditional execution. These methods are executed sequentially to balance detection coverage and scanning efficiency.

3.3 Discovery System and Reporting

The discovery module expands test coverage by automatically extracting endpoints from robots.txt, parsing sitemap.xml files, and crawling internal hyperlinks using BeautifulSoup4. The reporting module generates structured outputs in HTML, text, and JSON formats, providing executive summaries, evidence, severity classification, and mitigation recommendations.

3.4 Implementation and Evaluation Setup

The system was implemented in Python using Tkinter for the GUI, Requests for HTTP communication, and BeautifulSoup4 for HTML parsing (Figure 2). Evaluation was conducted on DVWA and OWASP Juice Shop, enabling controlled, ethical, and repeatable experimentation. Performance metrics included detection rate, false positive rate, scan time, and endpoint coverage, benchmarked against SQLMap.

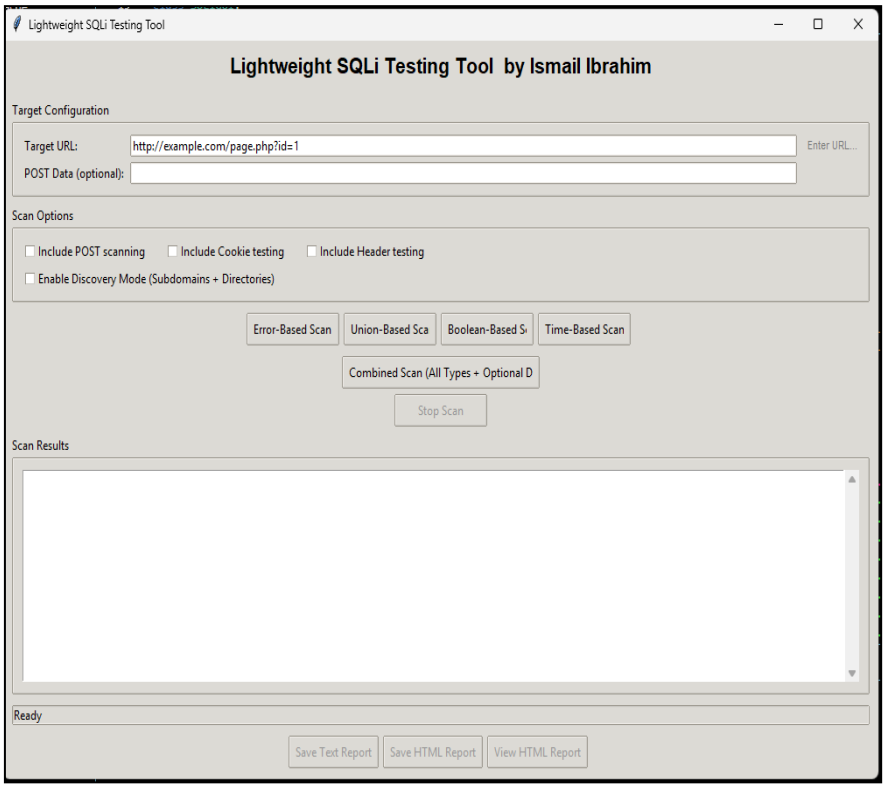


Figure 2: Basic GUI Interface showing main input screen with URL field, detection method checkboxes, and action buttons

4. Results and Analysis

Experimental evaluation demonstrated strong detection performance across all techniques. Error-based detection achieved the highest success rate (93%), followed by union-based (85%), boolean-blind (82%), and time-based detection (79%). Integrated discovery increased endpoint coverage by more than 100%, validating the effectiveness of automated endpoint identification. Comparative analysis against SQLMap revealed that while SQLMap achieved marginally higher coverage due to its extensive payload database, the proposed tool delivered faster scan times, simpler configuration, and superior usability (Table 1 and Figure 3). Resource consumption remained modest, enabling deployment in constrained environments. Structured reporting enhanced interpretability, providing actionable intelligence for developers and learners.

Table 1: Detection Success Rates across Four SQLi Detection Methods

Detection Method	Success Rate (%)	Average Scan Time (s)
Error-based	93	8
Union-based	85	12
Boolean-blind	82	26
Time-based	79	35

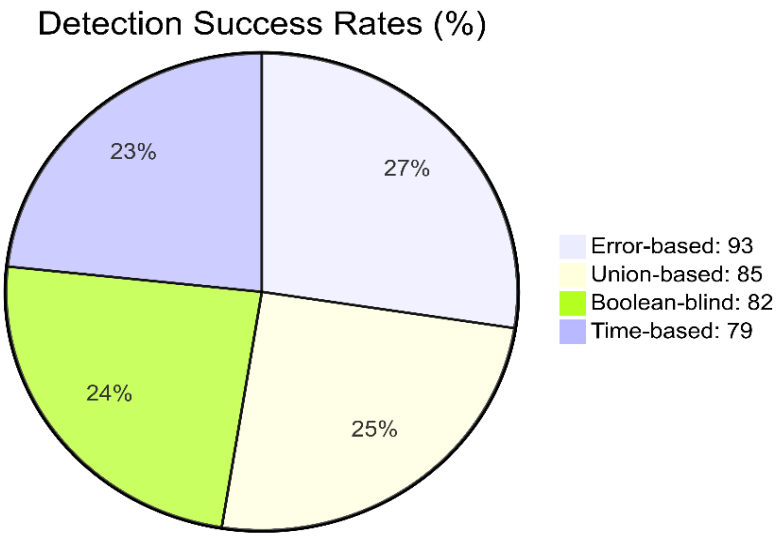


Figure 3: Pie chart showing distribution of SQLI Detection Method Success Rates

The developed tool maintained relatively low computational overhead during testing. Average scan times ranged from 12 to 40 seconds depending on the detection technique and endpoint complexity. Error-based and union-based methods completed more rapidly, while time-based detection introduced higher latency due to deliberate response delays. Compared with SQLMap, the proposed system demonstrated lower memory consumption and faster initialization, making it suitable for lightweight educational and small-scale deployment environments.

4.1 Comparative Analysis with SQLMap

SQLMap served as the baseline for comparative evaluation. While SQLMap achieved higher coverage due to its extensive payload database and advanced exploitation features, the developed tool offered distinct advantages in usability, lightweight performance, integrated discovery, and structured reporting (Table 2). This demonstrates a practical trade-off between accessibility and exhaustive coverage, particularly relevant for educational and small-scale security assessments.

Table 2: Comparative Feature Analysis: Developed Tool versus SQLMap

Feature	Developed Tool	SQLMap (Baseline)
Interface	GUI (Tkinter)	Command-line only
Detection Methods	4 integrated	4+ (comprehensive)
Discovery	Integrated (robots, sitemap, crawling)	Manual input required
Reporting	HTML, Text, JSON	Console output
Resource Usage	Lightweight	Heavy with full scan
Ease of Use	Beginner-friendly	Requires expertise
Configuration Complexity	Minimal	Extensive
Learning Curve	Low	High

While SQLMap offered higher extensibility and deeper exploitation capabilities through its comprehensive payload database, its complexity reinforces the importance of the proposed tool as an accessible alternative (Figure 4). The lightweight resource requirements of the developed tool enable deployment on modest hardware suitable for educational and small-scale assessments. The structured reporting module further distinguishes this system, ensuring results are interpretable and actionable by diverse audiences including non-security specialists.

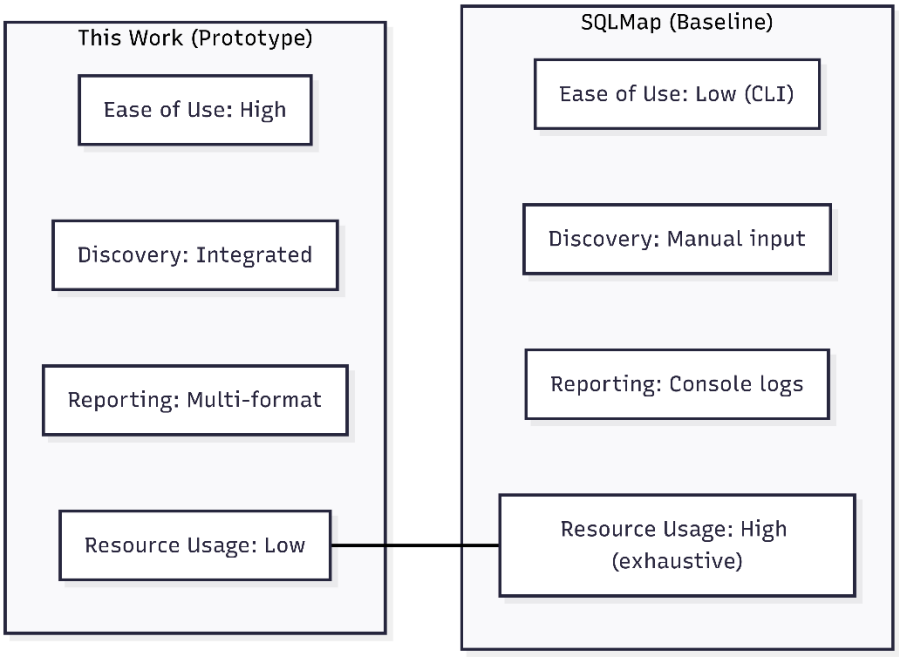


Figure 4: Comparison of Developed Tool and SQLMap across key dimensions (Interface accessibility, Resource usage, Configuration complexity, Reporting quality)

The comparative evaluation confirms that the proposed tool prioritizes accessibility, lightweight deployment, and structured reporting, while SQLMap and related frameworks remain more suitable for advanced exploitation-oriented assessments.

4.2 Reporting Module Output

The reporting module was tested by running complete assessments on DVWA vulnerable endpoints. Generated reports demonstrated the tool's capability to produce actionable outputs (Figure 5).

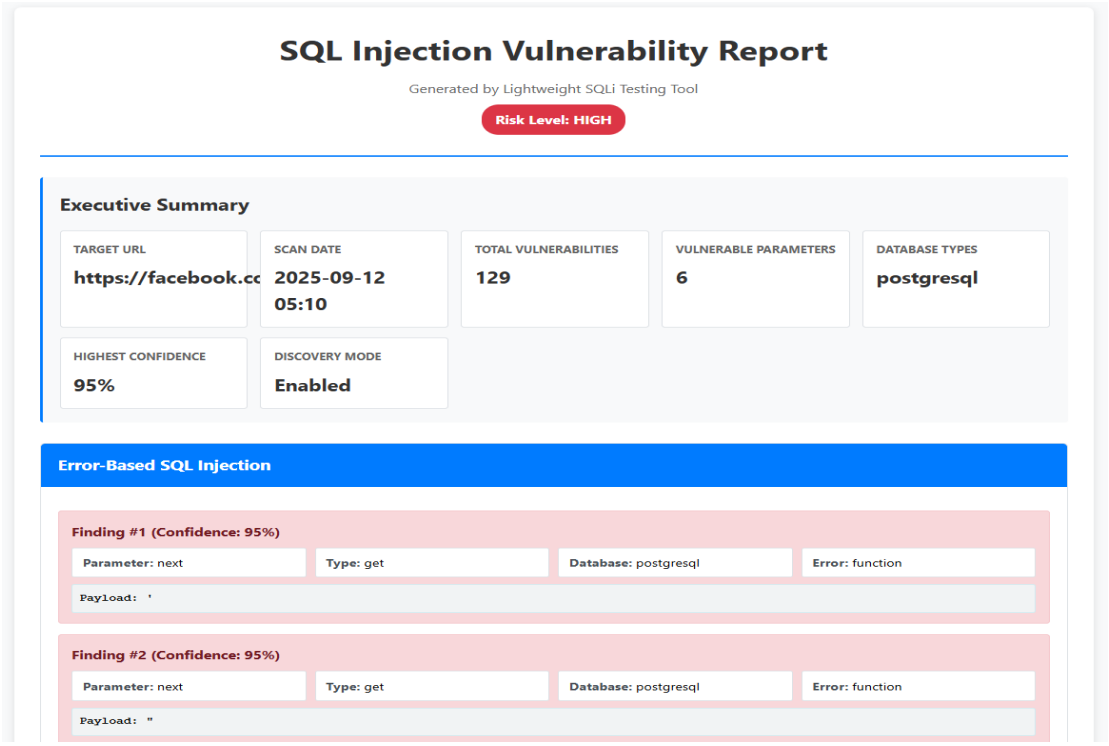


Figure 5: Sample HTML Report showing executive summary section with vulnerability overview, severity distribution, and key findings

The HTML reports provided styled, professional presentations suitable for stakeholders and educational contexts. Text reports offered lightweight alternatives for quick sharing and archival. JSON outputs enabled seamless integration with security information and event management (SIEM) systems and automated workflows. Each report included payload evidence, response indicators, and specific remediation recommendations, providing comprehensive documentation for remediation efforts.

5. Conclusion

This study presents a lightweight, automated SQL injection testing tool designed to enhance usability, detection coverage, and reporting clarity. By integrating four classical detection techniques with automated endpoint discovery and multi-format reporting, the system achieves detection rates between 79% and 93% while doubling assessment coverage. The findings demonstrate that lightweight design does not compromise fundamental detection capabilities, offering a practical alternative for educational, developmental, and small-scale security testing contexts. The results confirm that classical SQLi detection techniques, when systematically integrated, remain highly effective for vulnerability assessment. The modular architecture and GUI-based interface significantly lower operational barriers, enabling broader adoption among students and small organizations. Integrated discovery addresses a major limitation of existing lightweight scanners, while structured reporting enhances practical usability. Although SQLMap remains superior for advanced exploitation, the proposed tool successfully balances technical effectiveness with accessibility and efficiency. Future enhancements include integration of explainable machine learning models, extension to API and microservices architectures, development of standardized benchmarking datasets, and incorporation of SIEM interoperability for automated response workflows. These directions will further strengthen detection capability, interpretability, and real-world applicability.

Acknowledgement

The authors acknowledge the support of the Department of Computer Science and colleagues who provided technical feedback during the development and testing of the system.

Ethical Statement: This research was conducted in controlled and authorized testing environments using deliberately vulnerable applications, including Damn Vulnerable Web Application (DVWA) and OWASP Juice Shop. No unauthorized penetration testing or access to third-party systems was performed during this study. The developed tool was evaluated strictly for academic and defensive cybersecurity purposes. No human participants, personal data, or sensitive organizational information were involved in the research.

Ethical Approval: Not applicable. This study does not involve human participants, animals, or identifiable personal data.

Consent to Participate: Not applicable.

Consent for Publication: Not applicable.

Data Availability: No datasets were generated or analyzed during the current study.

Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence Tools: AI-based language models were used as editorial and drafting support tools during manuscript preparation. All content has been critically reviewed, validated, and approved by the authors.

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A Hybrid Cyber Defense Framework for Indonesia's Military Integration into National Cyber Resilience: A Counterfactual Stress-Test

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Abstract: The June 2024 ransomware attack on Indonesia's National Data Center (*PDN*) disrupted hundreds of public services and exposed that the country's cyber vulnerability extended beyond weak technical controls to include fragmented authority, unclear mandates, and slow coordination among state actors, which plausibly amplified the scale and duration of disruption. Existing work on Indonesia's cyber defense and national cyber resilience often treats technological upgrades and institutional reform separately and rarely tests how alternative governance architectures might have altered the trajectory of a real incident. This paper asks whether a hybrid civil-military cyber defense framework could have reduced the operational impact of the *PDN* incident by mitigating coordination failures across detection, containment, and recovery phases. Drawing on open-source reporting, the study reconstructs an incident timeline and identifies three failure nodes: detection delay, containment delay, and recovery failure linked to backup governance. Conceptually, it refines existing socio-technical accounts by formalizing coordination failure as a second-order amplifier of cyber incident severity that links fragmented authority to decision latency and expanded incident impact once attackers gain a foothold. Building on prior work that designed a cyber defense framework for the Indonesian Armed Forces, the paper extends this architecture to a national civil-military setting by specifying a Hybrid Cyber Defense Framework centered on a civilian-led National Cyber Security Coordination Center (NCCC) with unified incident command and a Joint Cyber Defense Task Force (JCDTF) providing surge technical capacity under democratic safeguards. Using Counterfactual Process Tracing (CPT), grounded in an interventionist theory of causation, the analysis stress-tests this framework against the PDN timeline, holding baseline technical weaknesses constant while minimally rewiring decision paths and information flows at the three failure nodes. Analog evidence from NATO and Singapore suggests integrated monitoring, pre-designated leadership, and joint exercises can compress response cycles without replacing technical controls. The paper offers a mechanism-based template for stress-testing national cyber governance arrangements against concrete incident trajectories and clarifies the democratic boundary conditions under which hybrid civil-military integration is more likely to strengthen cyber resilience.

Keywords: Cyber defense, National resilience, JCDTF, NCCC, Indonesia, Counterfactual process tracing, *RUU KKS*

1. Introduction

In June 2024, a ransomware attack on the National Data Center (*Pusat Data Nasional/PDN*) disrupted hundreds of public services and exposed deep structural weaknesses in Indonesia's cyber governance (Antoniuk, 2024). While technical deficiencies, such as inadequate patching, disabled security features, and absent backups were immediate causes, they do not fully explain the scale and duration of the crisis. The incident revealed a deeper systemic issue: fragmented authority and poor coordination among key institutions, including the Ministry of Communication and Informatics (*Kominfo*), the National Cyber and Crypto Agency (*Badan Sandi dan Siber Nasional/BSSN*), and state-owned infrastructure providers (Nugroho, 2024).

This paper asks whether a hybrid civil-military cyber defense framework could have reduced the operational impact of the 2024 *PDN* ransomware incident by mitigating coordination failures among Indonesian state actors. First, we refine socio-technical accounts by formalising coordination failure as a second-order amplifier linking fragmented authority to decision latency and incident impact. Second, we extend our earlier, TNI-focused cyber defence framework to the national level by specifying a hybrid civil-military architecture in which a civilian-led National Cyber Security Coordination Center (NCCC) exercises unified incident command while a Joint Cyber Defense Task Force (JCDTF) provides surge technical capacity under democratic safeguards (Shives & Fatahillah, 2026). Third, we use Counterfactual Process Tracing (CPT) to mechanism-test this hybrid architecture against three empirically identified failure nodes—detection delay, containment delay, and recovery failure— showing how minimally rewired decision paths could constrain escalation without assuming away underlying technical weaknesses.

2. Literature Review and Conceptual Background

While cybersecurity research has often focused on technical controls, large-scale incidents increasingly show that organizational structures and decision processes strongly shape the severity and duration of disruption. (Khair et al., 2025). Priyandita and Lebang (2025) argue that overlapping mandates and unclear hierarchies

between *Kominfo*, *BSSN*, law-enforcement bodies, and military cyber units produce coordination gaps and decision latency during crises. Debates on Indonesia's Cybersecurity and Resilience Bill (RUU KKS) highlight concerns that efforts to centralize authority and integrate military capabilities into civilian cyber governance (Riani Sanusi Putri, 2026; Wahyudi Djafar & Al Araf, 2025)

This literature suggests that civil-military integration in cyberspace is not inherently beneficial or harmful; its effects depend on how command structures, oversight mechanisms, and legal mandates are designed and implemented (CSA Singapore, 2026). The present study adopts this conditional view and explicitly treats democratic governance as a boundary condition for any proposed hybrid framework: the same architecture that reduces coordination failures can also concentrate power and reduce transparency if not paired with robust checks and balances (Lebang, 2025).

This study builds on Shives and Fatahillah's (2026) Indonesian Armed Forces (*Tentara Nasional Indonesia*) *TNI*-focused cyber defence framework by shifting from military-internal design to hybrid civil-military governance at the national level and by stress-testing selected design features against the concrete failure modes observed in the *PDN* ransomware incident. Rather than proposing an ideal end-state architecture in the abstract, it uses Counterfactual Process Tracing to assess how NCCC and JCDTF would interact with existing institutions under Indonesia's evolving Cybersecurity and Resilience Bill (*RUU KKS*).

3. Theoretical Framework: Coordination as an Incident Amplifier

3.1 Coordination Failure as a Second-Order Amplifier

Building on Indonesian and comparative studies that highlight fragmentation and overlapping mandates as core governance challenges, this paper conceptualizes coordination failure as a second-order amplifier of cyber incident impact (Lebang, 2025; Nugroho, 2024). In this view, foundational technical weaknesses such as absent backups, disabled security controls, or unpatched systems remain first-order drivers of vulnerability, but coordination plausibly conditions how far and how long an incident escalates once initial compromise has occurred, rather than determining the likelihood of compromise itself (Antoniuk, 2024; Sangfor Technologies, 2024). The central causal chain is:

Fragmented Authority → Decision Latency → Expanded Incident Impact

Fragmented authority arises when multiple organizations share responsibility without a clear hierarchy or unified operational structure (Priyandita & Lebang, 2025). Decision latency captures the additional time required to negotiate responsibilities, obtain authorization for containment actions, and mobilize resources across institutional boundaries (Runhardt, 2024). Expanded incident impact refers to wider service disruption, longer outage duration, and more extensive data or system compromise than would have occurred under faster, more coherent decision-making (Khair et al., 2025)

From this chain, we derive two guiding propositions for the PDN case:

1. P1 (Authority and latency): Where incident-response authority is fragmented across agencies, the time between initial detection and issuance of system-wide containment orders increases.
2. P2 (Latency and impact): Longer decision latency is positively associated with the scope and duration of disruption in critical services once initial compromise has occurred.

These propositions are not intended to be statistically general but to structure a within-case evaluation of how authority arrangements influenced the trajectory of the PDN ransomware incident.

3.2 The Hybrid Cyber Defense Framework as an Intervention

The Hybrid Cyber Defense Framework proposed in this paper is designed to intervene directly in the coordination mechanism rather than in the technical vulnerability space. It consists of two core institutional components: NCCC with authority to direct national cyber incident response, and JCDTF that integrates military cyber units with civilian experts to provide surge technical capacity.

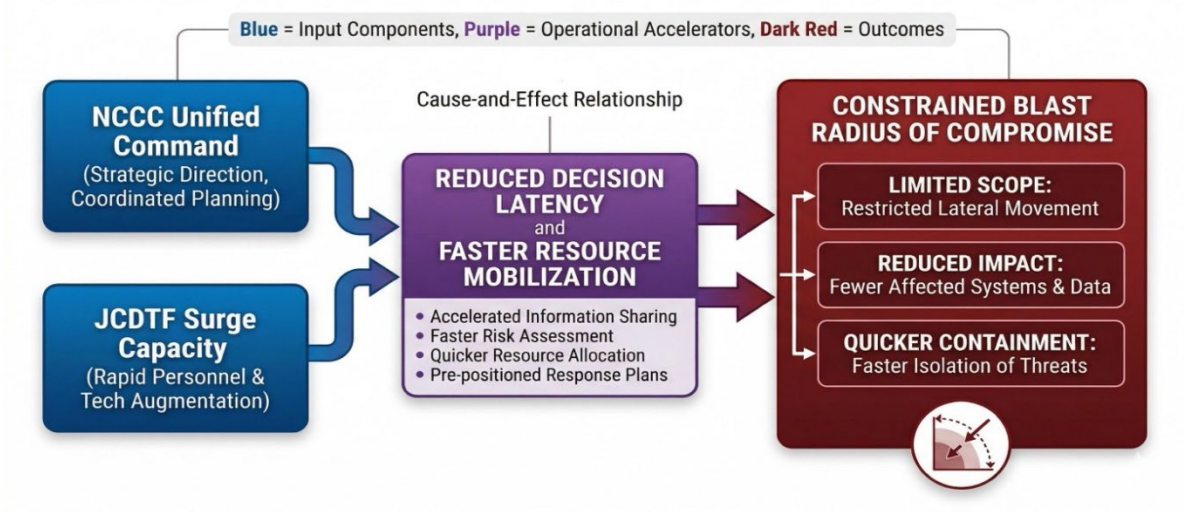


Figure 1: Operational Mechanism of the Hybrid Cyber Defense Framework

As illustrated in Figure 1, the integration of NCCC Unified Command with JCDTF surge capabilities creates a synergistic effect that directly reduces decision latency, thereby constraining the blast radius of a cyber compromise. The framework is explicitly conditional: it cannot compensate for missing backups or unpatched systems, but it can alter how quickly such deficiencies are detected and how effectively their consequences are managed (Antoniuk, 2024; Sangfor Technologies, 2024). Coordination, in other words, does not prevent initial compromise, but it can plausibly limit the temporal and organizational scope of damage (Khair et al., 2025).

4. Methodology: Counterfactual Process Tracing (CPT)

4.1 Rationale for CPT

This study employs Counterfactual Process Tracing (CPT), grounded in an interventionist theory of causation, to evaluate how alternative governance architectures might have altered the dynamics of the *PDN* ransomware incident (Runhardt, 2024). Rather than estimating correlations, CPT examines within-case mechanisms and whether interventions could change outcomes without violating established facts. In our case, the intervention is the introduction of a hybrid NCCC-JCDTF framework that modifies authority structures and coordination mechanisms but leaves baseline technical vulnerabilities unchanged.

4.2 Data and Source Base

The empirical baseline is constructed from official statements, technical advisories, and investigative reporting on *PDN* operations and incident response. We compile these sources into a timeline recording technical events (such as initial disruption, ransom demand, and restoration milestones), institutional responses, and public communications. Where sources diverge, we retain ranges rather than a single estimate. The source base is incomplete and biased: official accounts may understate coordination problems, while others may emphasize technical or political failures. We interpret the timeline as a conservative representation of coordination failure and cross-validate key claims across sources.

4.3 Analytical procedure

The CPT analysis proceeds in four steps:

- First, we synthesize the collected material into a chronological incident timeline (Table 1) and identify key decision points and delays between technical events and institutional responses.
- Second, we identify failure nodes where coordination and authority appear to have materially shaped outcomes and derive three critical nodes: detection delay, containment delay, and recovery failure due to unverified backup governance.
- Third, drawing on the proposed Hybrid Cyber Defense Framework, we specify a counterfactual architecture where NCCC exercises unified command and JCDTF provides surge capacity (Shives & Fatahillah, 2026). For each failure node, we model how this architecture would rewire decision paths and information flows via three mechanisms: decision latency, resource-mobilization speed, and information integration, while holding baseline technical conditions constant.

- Fourth, we conduct counterfactual evaluation and assess competing explanations. For each node, we compare the observed sequence with the minimally rewired counterfactual sequence that is consistent with the hybrid architecture and with known technical constraints of the *PDN* environment. We evaluate whether the hybrid model or alternatives, technical failure alone, civilian-only governance reform, or outsourcing to private providers, offers greater mechanism coverage of the observed delays and failures (Lebang, 2025; Priyandita & Lebang, 2025)

A counterfactual claim is accepted only when it (a) does not contradict established facts about PDN infrastructure and the attack, and (b) is supported either by within-case trace evidence or by analog evidence from other national or alliance-level cyber defense arrangements that have implemented comparable coordination mechanisms (Neilsen & Pontbriand, 2025). This counterfactual assumes baseline compliance with NCCC authority; partial compliance or inter-agency resistance would attenuate, but not eliminate, expected reductions in decision latency. At the extreme, where compliance is systematically resisted, no meaningful reduction in coordination latency should be expected. Operationally, we measure decision latency as the elapsed time between first observable anomaly and (i) formal incident recognition and (ii) issuance of cross-agency containment orders, based on open-source timelines. Expanded incident impact is captured through the number and criticality of affected services and the duration of service degradation, while coordination failure is indicated by overlapping mandates, the absence of a single empowered incident commander, and documented episodes of ad hoc or improvised escalation.

5. Empirical Case: The 2024 PDN Ransomware Attack

5.1 Baseline Incident Timeline

The empirical baseline for this study is the June 2024 ransomware attack on Indonesia's National Data Center, which disrupted hundreds of central and local government services across sectors including immigration, licensing, and taxation (Nugroho, 2024). Open-source reporting indicates that attackers maintained undetected access for several days prior to the visible disruption of services, with estimates of persistence ranging from approximately four to seven days (Antoniuk, 2024; Sangfor Technologies, 2024). On the morning of 20 June 2024, service degradation in immigration systems provided the first reported indicator of disruption, yet open-source reporting indicates no evidence of a pre-designated national incident command authority being activated at this stage, suggesting delayed cross-agency coordination.

We treat the persistence window as approximately four to seven days, the escalation lag from first visible disruption to a coherent inter-agency posture as roughly four to six hours, and the interval to public recognition of a ransomware incident as about twenty-four hours, all derived from overlapping but imperfect open-source accounts.

Table 1: *PDN* Ransomware Incident Timeline

Time / Date	Event	Observed Issue
~June 13-17, 2024 (T-7 to T-4 days)	Initial compromise and attacker persistence	Lack of detection; fragmented monitoring (Antoniuk, 2024; Georgia Butler, 2024)
June 20, ~08:00	System disruption detected (immigration services impacted)	No immediate unified response (Nugroho, 2024)
June 20, (T+4-6 hrs)	Initial internal escalation across agencies	Coordination delay; unclear authority (Georgia Butler, 2024)
June 21 (~T+24 hrs)	Public acknowledgment of ransomware attack	Delayed situational awareness (Antoniuk, 2024)
June 24 (T+4 days)	Government refuses ransom demand (~$8M)	Absence of predefined crisis protocol (Nugroho, 2024)
June 25+ (T+1-3 weeks)	Gradual service restoration	Backup failure; slow recovery (Antoniuk, 2024)

5.2 Technical and Governance Characteristics of the Attack

Technically, the *PDN* incident involved a ransomware strain assessed to be derived from, or closely related to, the LockBit 3.0 family, reflecting the increasing accessibility of sophisticated tools through ransomware-as-a-service ecosystems (Sangfor Technologies, 2024). Post-incident analyses indicate that baseline security practices at *PDN* were weak: security features such as Windows Defender were reportedly

disabled on critical systems, network segmentation was limited, and backup regimes were incomplete, unverified, or both (Indosec Summit, 2025). However, the technical characteristics explain the initial compromise but do not, on their own, fully account for the observed delays in detection, containment, and recovery across institutions. The response unfolded in an institutional environment characterized by fragmented cyber governance: responsibility for *PDN* infrastructure, cybersecurity oversight, and incident response was distributed among *Kominfo*, *BSSN*, state-owned telecommunications providers, and sectoral agencies whose services depended on *PDN* (Nugroho, 2024; Priyandita & Lebang, 2025). Reports suggest that no single body had the undisputed authority to declare a national-level cyber emergency, direct cross-agency containment actions, or centrally coordinate communication with affected stakeholders. Commentators describe the government's crisis posture during the first days as fragmented and improvisational, highlighting instances where ministries issued overlapping or partially contradictory public statements and where ad hoc coordination groups were created only after disruption had spread (Lebang, 2025). These observable traces reinforce the interpretation of coordination failure as an active mechanism rather than a purely retrospective label.

5.3 Identification of Critical Failure Nodes

Within this baseline, three empirical failure nodes are particularly salient for a mechanism-based analysis. First, detection delay: attacker persistence for several days prior to activation indicates significant blind spots in monitoring and anomaly detection, especially across organizational boundaries within *PDN*'s infrastructure stack (Antoniuk, 2024; Sangfor Technologies, 2024). Second, containment delay: the multi-hour gap between visible disruption and the establishment of a coherent, inter-agency response structure suggests that authority ambiguity and coordination overhead slowed decisions to isolate affected systems and mobilize specialized technical teams (Nugroho, 2024; Priyandita & Lebang, 2025). Third, recovery failure: the prolonged and uneven restoration of services reflects not only missing or corrupted backups but also the absence of a tested, cross-government recovery governance model for prioritizing services, validating restored data, and communicating residual risk to the public (Indosec Summit, 2025; Sangfor Technologies, 2024).

These three nodes: detection delay, containment delay, and recovery failures represent points in the incident trajectory where coordination mechanisms and authority structures plausibly shaped outcomes above and beyond the underlying technical vulnerabilities, and where a hybrid civil-military governance framework could, in principle, have altered decision latency, resource mobilization, and information integration (Nugroho, 2024; Shives & Fatahillah, 2026). The counterfactual assumes baseline compliance with NCCC authority; partial compliance or inter-agency resistance would attenuate, but not eliminate, expected reductions in decision latency.

6. Counterfactual Analysis: Stress-Testing the Hybrid Framework

In applying Counterfactual Process Tracing, each hypothesized mechanism at the three failure nodes is evaluated using hoop-type and smoking-gun-type tests, drawing on both *PDN* evidence and analog national-level cyber operations in NATO and Singapore. The explanatory value of the hybrid framework would be weakened if comparable incidents under unified command structures exhibited similar multi-day detection fragmentation or multi-hour authorization delays

6.1 Detection Phase: Integrated Monitoring and Decision Latency

In the observed *PDN* case, detection capabilities were distributed across multiple agencies and operators without effective integration of logs, alerts, or anomaly reports. This fragmentation plausibly contributed to visibility gaps across organizational boundaries, within which attackers maintained persistence for several days prior to ransomware activation, despite observable disruptions in individual subsystems. Under the proposed Hybrid Cyber Defense Framework, NCCC would serve as a central fusion point for monitoring data from critical government infrastructures, including *PDN* (Shives & Fatahillah, 2026; Singapore MINDEF, 2026). Sectoral teams and JCDTF would provide additional analytic capacity (CSA Singapore, 2026). Evidence from comparable national and alliance-level arrangements, such as NATO's integrated cyber defense of civilian critical infrastructure and Singapore's sectoral cyber defense teams, suggests such fusion mechanisms reduce time to formal incident recognition by minimizing organizational boundaries an alert must traverse (Neilsen & Pontbriand, 2025). For example, in CSA Singapore's operation against APT actor UNC3886, integrated sectoral teams and a central fusion center reportedly compressed cross-sector detection and response cycles from multi-day coordination to within roughly 24 hours in a higher-capacity setting, illustrating mechanism feasibility rather than directly transferable performance expectations. However, the magnitude of these effects is conditional on baseline

institutional and technical capacity, and analog comparisons to higher-capacity systems such as Singapore or NATO should be interpreted as directional rather than directly transferable.

The NCCC does not generate detection signals but reduces time to aggregate and escalate distributed anomaly indicators into a recognized incident. While precise counterfactual timing cannot be established, analog evidence suggests that integrated coordination mechanisms can plausibly compress inter-agency escalation cycles from multi-hour delays to a low-hour range, and reduce cross-sector detection recognition from multi-day fragmentation to within approximately 24 hours under comparable conditions (Neilsen & Pontbriand, 2025).

6.2 Containment Phase: Unified Command and Authorization Delay

Containment in the *PDN* incident was hindered by unclear authority and the need to negotiate responsibilities among multiple ministries, agencies, and operators before decisive action. Reports describe several hours between the first visible service disruptions and the emergence of a coordinated inter-agency response posture, during which affected systems remained partially exposed and lateral movement could continue (Antoniuk, 2024; Nugroho, 2024). In mechanism terms, this reflects a long chain from situational awareness to authorization to act, with no pre-designated incident commander possessing undisputed authority to order isolation, shutdown, or traffic-filtering measures at scale (Priyandita & Lebang, 2025).

The hybrid framework is evaluated here not as an optimal solution, but as a coordination-focused intervention whose explanatory value lies in its ability to account for observed failure nodes relative to competing models (Shives & Fatahillah, 2026). In such an arrangement, containment decisions would flow through a pre-agreed chain of command rather than through ad hoc negotiation among peer agencies, thereby reducing authorization latency where institutional compliance with centralized authority is present (Australian Department of Defence, 2025). Empirical experience from multi-agency cyber operations in other jurisdictions indicates that clearly designated lead authorities and pre-planned rules of engagement can materially shorten decision cycles in the face of fast-moving threats (CSA Singapore, 2026; Neilsen & Pontbriand, 2025). Concretely, under a hybrid model, early immigration-system disruptions could have triggered a predefined national-level incident code mandating immediate isolation of affected *PDN* clusters and tasking of JCDTF teams, rather than relying on improvised escalation chains among peer agencies.

6.3 Recovery Phase: Preparedness, Backup Governance, and Joint Exercises

The *PDN* recovery phase was characterized by incomplete, unverified, or inaccessible backups and by the absence of a clearly defined, cross-government governance model for prioritizing restoration (Indosec Summit, 2025; Sangfor Technologies, 2024). Restoration proceeded unevenly across agencies over one to three weeks, with some services returning relatively quickly and others remaining degraded due to uncertainty about the trustworthiness or completeness of restored datasets (Nugroho, 2024). While these outcomes are rooted in first-order technical weaknesses in backup design and testing, they were compounded by the lack of institutionalized recovery protocols and regular joint exercises at the national level (Fakhreja et al., 2025).

The hybrid framework cannot retroactively create backups that do not exist, but it can shape the governance of preparedness by embedding regular, multi-agency cyber incident exercises and standardized backup verification procedures into the mandates of the NCCC and JCDTF (Shives & Fatahillah, 2026). In the *PDN* counterfactual, a mature hybrid framework would likely have produced two observable differences: first, a higher probability that backups for priority services had been verified through prior exercises; and second, a more coherent and transparent governance structure for orchestrating the restoration process and communicating timelines to stakeholders (Indosec Summit, 2025; Sangfor Technologies, 2024). Even if backups failed, structured recovery governance could reduce uncertainty, shorten outages for critical services, and mitigate secondary political and societal costs (Fakhreja et al., 2025; Nugroho, 2024).

6.4 Relative Plausibility and Competing Explanations

At the same time, the analysis explicitly considers three competing explanations: a technical failure model that attributes the crisis entirely to poor cybersecurity practices and absent backups; a governance-only civilian reform model focused on strengthening *BSSN* and *Kominfo* without military integration; and an outsourcing model that relies primarily on private-sector cybersecurity providers for incident response (Lebang, 2025).

Table 2: Competing Explanations and *PDN* Failure Nodes

Explanation model	Detection delay	Containment delay	Recovery failure
Technical failure	Explains compromise, not multi-day blind spot (Sangfor Technologies, 2024).	Partly explains difficulty, not hours-long lag (Nugroho, 2024).	Strongly explains missing/corrupted backups (Sangfor Technologies, 2024).
Civilian-only governance reform	Reduces some ambiguity, leaves surge capacity vague (Priyandita & Lebang, 2025)	Partially alleviates coordination issues (Lebang, 2025).	Limited leverage beyond core civilian sectors (Indosec Summit, 2025).
Outsourcing to private providers	Improves tooling, adds public-private boundary (Indosec Summit, 2025).	Does little to reduce authorization latency (Riani Sanusi Putri, 2026)	Recovery still depends on state priorities (Lebang, 2025).
Hybrid NCCC/JCDTF framework	Directly targets monitoring integration. (Shives & Fatahillah, 2026)	Provides single commander and surge deployment. (Shives & Fatahillah, 2026)	Embeds joint exercises and backup checks. (Australian Department of Defence, 2025; Singapore MINDEF, 2026)

The technical failure model convincingly explains why the attackers were able to cause severe disruption once inside *PDN*, but it does not account for the multi-day detection gap or the multi-hour coordination lag between visible disruption and a unified response (Antoniuk, 2024). The governance-only civilian reform model could, in principle, reduce some coordination problems, but given existing institutional rivalries and capacity constraints, it may reduce authority ambiguity but offers more limited mechanism coverage for surge technical capacity and rapid cross-sector deployment during crisis conditions (Fakhreja et al., 2025; Priyandita & Lebang, 2025). The outsourcing model may strengthen technical depth but risks reproducing many of the same coordination challenges at the public-private boundary, especially in a crisis involving national-security-sensitive data (Indosec Summit, 2025). Table 2 summarises how each explanation performs against the three empirically identified failure nodes. However, the hybrid model's advantage depends on effective inter-agency integration; in environments where institutional rivalry persists, it may reproduce rather than resolve coordination failures. The hybrid model's effectiveness is therefore contingent rather than universal: where institutional rivalry, legal ambiguity, or low inter-agency trust exceed the coordinating authority of the NCCC, the framework may fail to reduce latency and instead reproduce fragmentation under a more centralized structure.

7. Institutional Feasibility and Democratic Boundary Conditions

The feasibility of implementing the proposed Hybrid Cyber Defense Framework in Indonesia depends on both organizational capacity and democratic safeguards. On the capacity side, existing analyses highlight shortages of specialized cyber personnel within *TNI* and civilian agencies, limited expertise in advanced forensics and threat hunting (Fakhreja et al., 2025; Nugroho, 2024). These constraints reduce the number of staff who can be seconded to an NCCC or JCDTF without degrading existing missions.

The hybrid model partially addresses these gaps by proposing mixed teams that combine military, civilian, and contracted experts and by envisaging a gradual build-out of integrated incident-response platforms under NCCC leadership (Shives & Fatahillah, 2026). However, realizing these benefits requires sustained investment, reform of recruitment and training pipelines, and political willingness to prioritize cyber capacity-building relative to other defense and development demands. The framework should therefore be viewed as a medium-term target rather than a short-term plug-and-play solution.

On the governance side, debates around Indonesia's Cybersecurity and Resilience Bill (*RUU KKS*) underscore the risk that centralizing cyber authority and embedding military capabilities into civilian networks could facilitate surveillance, institutional rivalry, and gradual militarization of the digital domain if as reduced oversight may trade off against faster decision-making, creating tension between operational speed and democratic accountability (Lebang, 2025; Riani Sanusi Putri, 2026). To be both legitimate and operationally effective, the hybrid architecture requires explicit civilian leadership, as weak oversight may reduce inter-agency trust and compliance, thereby reintroducing coordination delays the framework is designed to mitigate. Under these conditions, the hybrid framework remains conditionally feasible: it can plausibly improve detection, containment, and recovery performance in incidents like *PDN*, but only if capacity gaps are addressed and democratic checks evolve in parallel.

8. Discussion and Conclusion

In the PDN case, technical failures function as primary drivers enabling initial compromise, while coordination operates as a second-order amplifier that conditions the duration and spread of disruption rather than its occurrence. By formalizing this relationship as a mechanism linking fragmented authority to decision latency and expanded incident impact, the paper contributes to socio-technical approaches that seek to specify how governance structures shape incident dynamics. The counterfactual stress-test of the Hybrid Cyber Defense Framework shows that a unified NCCC command and JCDTF surge capability suggests that a unified NCCC command and JCDTF surge capability could plausibly reduce decision latency and constrain the organizational and temporal spread of disruption, without altering the initial access vector. The findings emphasize that governance reform cannot substitute for basic technical controls: even in an ideal hybrid architecture, absent backups and unpatched systems would still enable attackers to achieve substantial effects. This effect is conditional and diminishes where coordination mechanisms lack sufficient authority or compliance to override fragmentation. In this case, technical weaknesses function as primary enabling conditions, while coordination operates as a second-order amplifier that explains variation in response speed and disruption duration not accounted for by technical factors alone.

Although the empirical focus is Indonesia's PDN incident, the approach is intended as a reusable template rather than a case-bound story. The core steps: reconstructing a conservative baseline timeline from heterogeneous sources, identifying governance-sensitive failure nodes, specifying a feasible alternative authority architecture, and then subjecting that architecture to CPT-style mechanism tests and comparison with competing explanations can be applied to other national-level incidents in sectors such as healthcare, taxation, or digital identity. For policymakers, this implies three priorities: adopting a civilian-led NCCC with clear authority to declare cyber emergencies, organizing surge capacity in mixed JCDTF teams deployable under transparent rules and logging, and institutionalizing joint exercises, backup verification, and incident-timeline reviews that explicitly target decision latency as a second-order amplifier of impact rather than treating coordination failures as an after-the-fact label. Future work will apply CPT to additional Indonesian incidents and quantify decision latency.

Acknowledgments

The authors express sincere gratitude to the Naval Postgraduate School for academic guidance and resources, and to LPDP for sponsorship.

Ethics Declaration: This research was conducted using publicly available data, including government reports, academic papers, and news articles. As such, it did not involve human subjects or confidential data, and formal ethical clearance was not required.

AI Declaration: Open-source artificial intelligence tools were used solely for proofreading. All analysis, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources.

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Gamified Provocations of Interest for Cybersecurity Awareness

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Abstract: Cybersecurity awareness is important for all users of digital technology, but it can often be challenging to capture the attention of those that need it. Gamification can potentially contribute in provoking interest and engagement, but consideration still needs to be given to potential barriers to entry (in terms of the time required to understand and play the game, and any prior knowledge or support that players may need to do so). Many current cybersecurity games are well suited for use in settings where time has been set aside to play them. However, they are less applicable to being used as initial provocations of interest, or to attract and engage players on a more casual basis. With this in mind, the paper presents three game-based activities that have been specifically designed to support short-form cybersecurity engagement and awareness: Cyber Defence Dice, Hacker Whacker, and Password Enlightener. The discussion highlights how these activities offer an entry point for additional cybersecurity engagement, providing a foundation for further awareness and education activities or a reference point that can be used within them.

Keywords: Cybersecurity awareness, Cybersecurity education, Cybersecurity games

1. Introduction

Baseline cybersecurity awareness is now arguably essential for all users of digital technologies to recognise common threats and how to protect against them. Unfortunately, those seeking to promote awareness can face an immediate challenge in terms of how to capture initial interest, which often includes an accompanying challenge of turning what many regard as a technical (and potentially boring) topic into something that feels more accessible to a wider audience. Gamification is often put forward as a potential solution, and there are indeed already a variety of existing games in the cybersecurity space (Zhang-Kennedy and Chiasson, 2021; Shostack, 2026). However, these also have some potential shortcomings in the context of offering something that is suited to taking the initial steps with a layperson audience. The focus of this paper is to offer an alternative perspective, supported by a series of activities that have been implemented and tested in practice.

The paper begins by briefly surveying existing cyber security games, with a specific focus upon those realised in physical formats. The main paper then presents and describes three cyber-engagement activities developed by the authors: *Cyber Defence Dice, Hacker Whacker, and Password Enlightener.* Each of the activities is designed to act a provocation of interest, providing a means to attract and engage participants that may benefit from being nudged towards cybersecurity and related awareness. As such, while not going as deeply into the detail of cybersecurity as the other games, they offer a means of getting a foot in the door in terms of user engagement and providing a foundation upon which to build further awareness and learning.

2. Existing Cyber Security Games

Cybersecurity games exist in digital and physical formats. Our interest is particularly focused upon the latter, as the offline experience is considered to have several advantages. Firstly, it breaks people away from *using* their technology, which potentially enables them to take a step back and think about its protection. Secondly, it creates a social scenario in which players can interact, observe each other's actions, and discuss the shared experience together (which may take place during and/or after the game). Lastly, and linked to both prior points, it serves to make playing the game feel like more of occasion, as compared to an online or app-based game that a player may more easily load but then leave on a whim. By contract, once a game is started in the physical context, it creates more of a commitment to play, with a physical and social experience also potentially being more memorable.

A range of related games exist, including card games, board games and other tabletop formats. For readers interested in gaining a fuller appreciation of the volume and variety of tabletop games available, a relevant resource is maintained by Shostack (2026). For the purposes of this paper, however, the following examples offer an illustrative cross-section of some of the more well-known and established games:

- **Backdoors & Breaches**: A card game for two or more players, which involves defending against attack scenarios (Black Hills, nd). Cards include four categories of Attacks (Initial Compromise, Pivot and Escalate, C2 and Exfil, and Persistence), plus Procedures and Injects. An attack scenario is created by a player designated as 'Incident Captain', and one or more further players then take the role of Defenders (drawing from Procedure cards to counter the attack). Games typically last 30-60 minutes, and end if the Defenders have successfully revealed all four attacks, or if ten turns have been taken.
- **Control-Alt-Hack**: A card-based game based on the scenario of players working for a white-hat ethical hacking company (Denning et al, 2013). The game is based around Hackers with different skills (e.g. cryptanalysis, hardware hacking, social engineering) being required to complete Missions (which involve a number of required tasks). Play involves rolling numbered dice to determine what level of skill is required for each task in the Mission, and then seeing if the player's Hacker has that level. Entropy cards, Money and Hacker Cred tokens are also involved in the gameplay, and games last around one hour.
- **Cyber Threat Defender**: A two-player game involving four types of cards - Assets, Defences, Events and Attacks (CIAS, 2024). Players create a network of Assets, and build Defences to protect them from Attacks. Events then occur that may help or harm security. Each card has a resulting effect, and a points value. Games take an average of 20 minutes, and end when a player wins (by reaching 30 points) or loses (by reaching -45).
- **Decisions & Disruptions**: A LEGO-based tabletop game, focused around industrial control systems security, in which 5-8 players are responsible for managing the security of a small utility company (Frey et al, 2019). The LEGO pieces are used to construct the environment and defences, and players then make decisions about how to protect against attacks, while working within the limits of their budget. A Game Master is needed to run the game and play lasts up to two hours.
- **Riskio**: A tabletop game in which players protect their organisation's data and services against various threats (with 78 related cards covering categories of Spoofing, Tampering, Repudiation, Information Disclosure, Denial of services, and Elevation of Privilege) (Hart et al, 2020). Games need 3-5 players, plus an experienced cyber professional to act as Games Master, and can last around 45 minutes

Even this small sample highlights that while a range of games are available, most are clearly designed for relatively long-form play and are often focus on aspects of cybersecurity that go beyond the interest of a layperson audience. As such, while very valid in their target space, they do not lend themselves to more casual use or towards promoting more entry-level cybersecurity concepts. This is not meant to be seen as a criticism of the existing games. All are fit for their intended purpose, but it is important to be clear on what that purpose is. For example, they are all very suitable as educational aids for those already active or interested in cybersecurity (e.g. for cybersecurity students, cyber teams within organisations etc), but arguably less suited to a more general population. Indeed, none appear to have been designed for promoting initial engagement and awareness raising, and so there is an opportunity for games and related activities that fit within this space.

3. Expanding the Landscape of Games for Cyber Security Engagement and Awareness

Having identified the gap offered by the existing games, the authors have created a series of gamified physical cyber-engagement activities:

- *Cyber Defence Dice* – an awareness raising game of attack and defence
- *Hacker Whacker* – a fast-paced arcade style game that raises awareness of assets, threats and safeguards
- *Password Enlightener* – a password meter realised in the manner of a light-up fairground-style strength tester machine.

These have collectively been designed for use in public-facing events and offer a means of attracting interest amongst both general audiences and more specific groups, such as young people and small business owners.

The Cyber Defence Dice and Hacker Whacker games are both based around a common set of cybersecurity concepts, in terms of Assets (i.e. elements that require protection), Threats (i.e. events that could harm the Assets), and Defences (i.e. cybersecurity safeguards that protect against the Threats). These are illustrated in Table 1, along with the images that we have designed to represent each of them. In terms of incorporating them into the gameplay, Hacker Whacker promotes basic recognition of the different items, whereas Cyber Defence Dice introduces interrelationships between them and elements of decision making. The images were specifically designed to ensure that they would be able to be rendered clearly when 3D printing a standard six-sided die.

Table 1: Assets, Threats and Safeguards used in the games

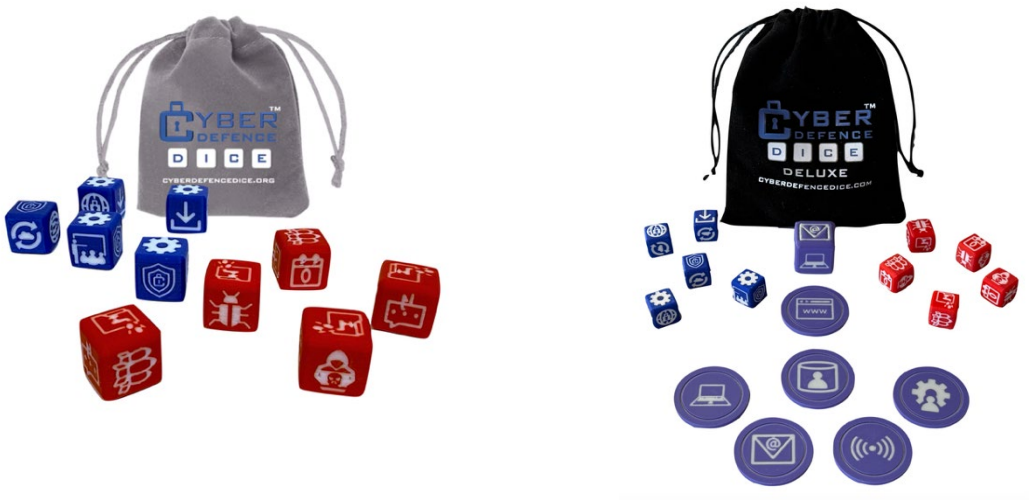
Assets	Threats	Defences
 Admin Account	 Malware	 System and App Updates
 Email Server	 Hackers	 User Awareness
 Personal Computer	 Accidental Breach	 Backup
 Personal Data	 Phishing	 Secure Configuration
 Website	 Denial of Service	 Internet Security
 Wireless Router	 Zero Day Attack	 Defence in Depth

3.1 Cyber Defence Dice

Cyber Defence Dice offers an entirely physical engagement experience, based upon the concepts of attack and defence. The basic premise of the game involves one side (which can be an individual player or a small team of up to 4-5 people) playing the role of an attacker and the other side taking the role of defender. Attacks and defences are mounted by means of dice rolls, with each side having an associated set of five dice. The attacker dice are red (reflecting the notion of a Red Team in cybersecurity testing), with the six die faces reflecting the Threats from Figure 1. Meanwhile, the defender dice are Blue (again, reflecting the established cybersecurity concept of a Blue Team being defenders), with the die faces taken from the Defences in Figure 1. The game works by attackers throwing a suitable set of threats, and defenders then throwing their dice in an attempt to offer a suitable defence (alternatively, the defenders can start, with the attackers then trying to beat the security posture that has been established). The starting side can take up to three throws and can keep or re-roll whatever dice they choose on their second or third attempts. They may, however, elect to stop after one or two rolls, and the other side is then also limited to that number of rolls when making their response. Players use an accompanying reference card to confirm which attacks beat which defences and vice versa.

The core version of the game is called Match Mode, where players must meet (to draw) or exceed (to win) the *number* of matching dice thrown by the other side, using a defence (or attack) *type* that is matched to the attack (or defence) *type* previously thrown. The authors have also created rules for two alternative game variants (called Combinations, and Attack Matcher), as well as an extension to Match Mode that makes use of Assets, While the presentation of the full game rules is outside the scope of this paper, interested readers can refer to www.cyberdefencedice.com for more details (which includes descriptions of different game variants and worked examples of gameplay). Additionally, the background to the core game, and details of associated evaluations are reported in Furnell et al. (2026).

The game is produced in standard and deluxe versions, as depicted in Figure 1, with the difference being that the latter incorporates the use of assets that players must compete to acquire or protect. These are represented by tokens, with each asset type being targeted via different combinations of attack or defence (with players again being able to use the accompanying reference card to check which attacks/defences work for which assets).



(a) (b)

Figure 1: Cyber Defence Dice in (a) standard and (b) deluxe formats

The dice and asset tokens are 3D printed in-house, with the accompanying imagery also having been designed and drawn by the authors. Additionally, sets of larger format dice have also been produced for use in public engagement events such as exhibitions. These are designed to be thrown on the floor, as shown in Figure 2.

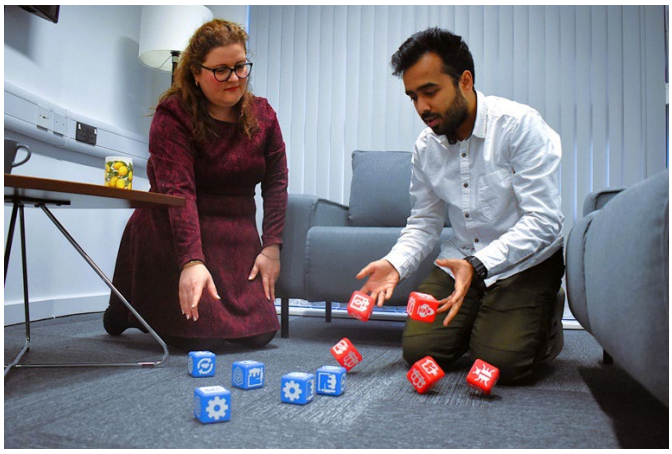


Figure 2: Playing with large format dice

The game has been successfully play-tested with a range of audiences (including groups from the general public, as well as those already familiar with the concepts, such as cybersecurity students and professionals), with positive ratings being obtained in relation to both the awareness value and the enjoyability of the game. It has also been used as a basis for teaching and awareness-raising sessions for small businesses.

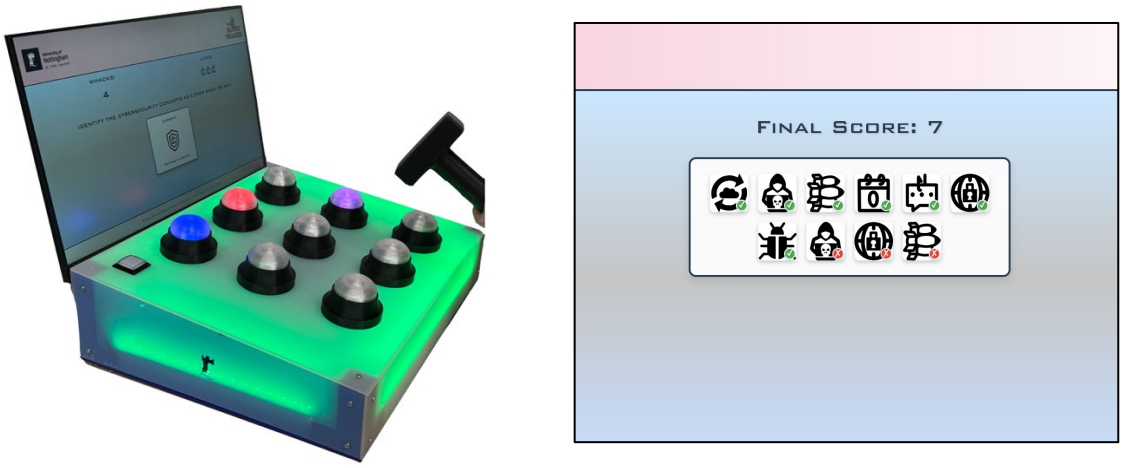
3.2 Hacker Whacker

Inspired by the popular arcade game Whac-a-Mole, Hacker Whacker is a custom device, designed and implemented by the authors (Todd et al. 2026). The game uses the same images as the Cyber Defence Dice, but this time they appear on-screen and players are required to recognise and respond to the category being shown. Unlike the colour-coded usage in the dice game, the images now appear as simple black on white representations so as not to convey which category they belong to. The game has two variants:

- *Threats and Safeguards* – Blue and red buttons illuminate on the playboard, with players needing to hit the blue button if the current image is a safeguard, or the red button if it is a threat.
- *Assets, Threats and Safeguards* – As above, but with displayed images also including the Assets, and a purple button also being lit on the playboard (i.e. the player now needs to correctly hit one of three displayed colours).

In both cases, the players must react quickly enough (i.e. before the image changes and the light pattern changes) and hit the appropriate button to match the category of the item shown on screen. If they fail to do so

within a time limit (which starts at a couple of seconds and reduces as the game progresses), or they hit the wrong button, then they lose a life. The game ends after three lives are lost, at which point the player is shown a summary of all the items they were presented with, and whether they got each one right or wrong. Figure 3 shows the game in action, with the Threats and Safeguards variant being played, as well as the feedback delivered to the player at the end of the game.



(a) (b)

Figure 3: The Hacker Whacker game (a) device, and (b) example end-of-game summary

It is to be expected that many players initially score poorly because they may not *recognise* the threats, safeguards and assets, and so part of the learning value of the gameplay is that it enables these concepts to be reinforced as they play further. At the same time, the learning potential of the game is ultimately limited, as there is no basis for players to go *beyond* this once the initial lessons have been learned. As such, repeated gameplay simply serves to reinforce notions of things that are good or bad, and does not have any of the resulting decision-making aspects that occur in Cyber Defence Dice. Having said this, the time investment in the game - even if somebody plays multiple times - is only a few minutes, and so the awareness-raising outcome still represents a reasonable return on investment relative to the time involved. Moreover, the arcade-style nature of the game has the potential to attract players that may not be interested in playing dice, and so opens the opportunity for resulting engagement in a different way.

3.3 Password Enlightener

The issue of user authentication is one that is notably missing from the defences represented in the other games, but it is specifically the focus of the Password Enlightener device. This, as shown in Figure 4, is a password meter reimagined in the form of a fairground style 'test your strength' machine. The concept of password meters will already be familiar to many through their use of websites (de Carné de Carnavalet and Mannan, 2014), and so the Enlightener typically requires little explanation for first time users. The device is more of an engagement activity than a game, but participants do tend to end up competing with each other to achieve better scores.

The player enters their password via the touchscreen at the bottom of the device (Figure 4b), and then presses the large illuminated red button to initiate the assessment. The scoring process is then based on a series of checks:

- assessing the length and complexity of the string
- checking against a dictionary of commonly leaked passwords
- calculating how long it would take to brute force the string
- checking if character substitution has been used (e.g. h3ll0, Croiss@nt) using a reverse leet algorithm (to identify use of common words with substituted characters)
- looking for patterns (e.g. dates, repetitive words etc.)

In addition to the rating, which is revealed by the progressive lighting of the lights, the player is also provided with some resulting feedback (Figure 4c) that explains the implications of their score and how it was determined.

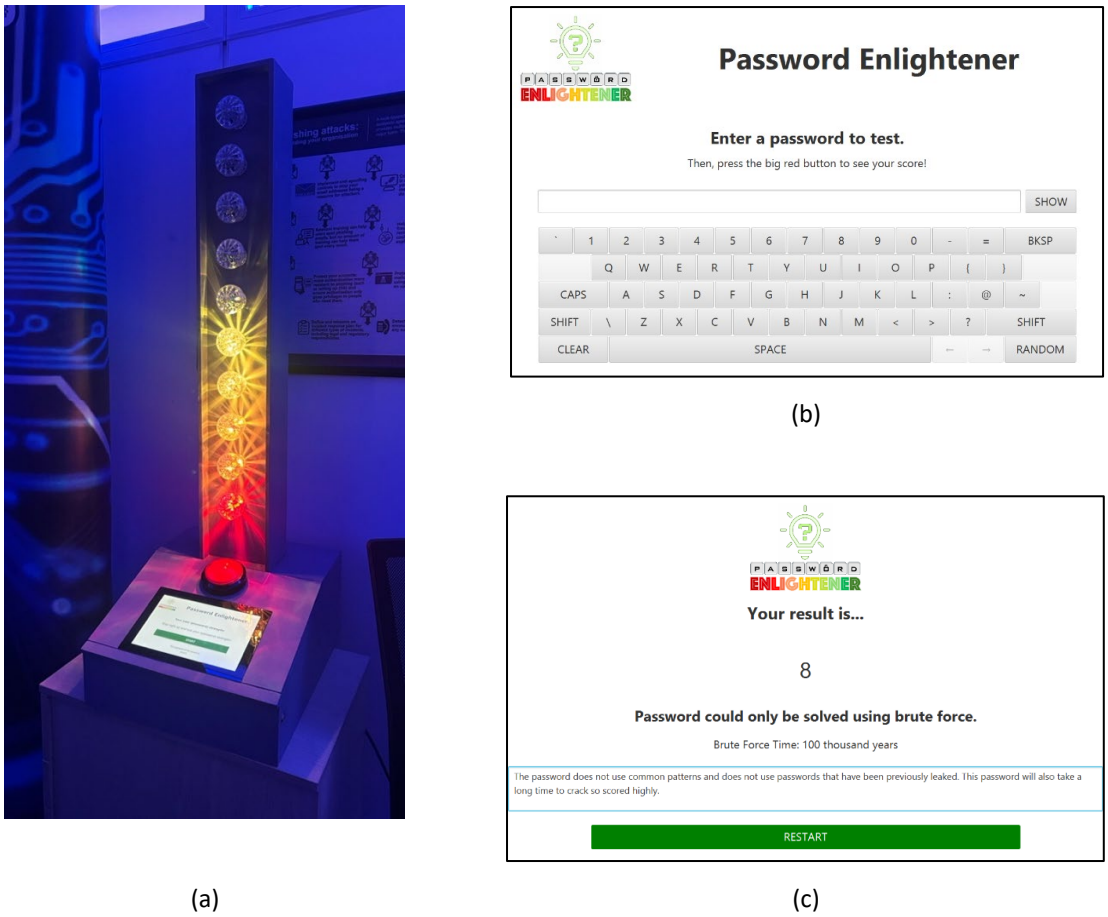


Figure 4: The Password Enlightener (a) device, (b) password entry and (c) example of feedback

This game is typically the one case in which players come to the activity with some pre-existing knowledge around what is involved. Many already have (and often express) some level of expectation around how their password will score ("I think mine is really bad", "I use a very strong password" etc). The main concern from the more security-aware users is "Are you capturing the passwords?", and this is not the aim of the exercise. Regardless of whether the question arises, players are assured that their passwords are not stored in any way and that no further use is made of them. Users are also advised to be cautious if they plan to enter an existing password in case somebody is observing (given that shoulder surfing or filming of their activity cannot be ruled out in public events).

In most events the device has been made available for visitors to come and use on an individual basis. However, it is also possible to use it in a more structured manner, with a group of players being asked to create new passwords and take turns to enter them on the device to see who scores the best. To ensure fair play, and show that they can remember the information rather than just type something in that maximises their score, the process works as follows:

- Each player writes their candidate password on a piece of paper, and then turns their paper over.
- Players take turns to enter their passwords and record the scores. On each attempt, the person running the Password Enlightener reveals the password on the device and makes a note of it.
- When all players have taken their turn, everyone then writes their password again, on the blank side of their paper.
- The team member can then check that the winning player(s) have written the *same* password on both sides of their paper (i.e. that they could remember it for the duration of the activity) and that this also matches what was entered on the device (i.e. that they did not cheat by remembering something easy and then entering a more lengthy or complex string on the device in order to score better).

The learning outcome tends to be a level of reassurance if indeed the players prove themselves able to select and enter strong passwords, or alternatively a pause for thought if they enter a password that scores poorly. In the latter case team members running the activity can give advice on strategies for improving password strength

(e.g. focusing on the length and using techniques such as three random words (McCormack, 2016) to aid memorability). The memorability of what was entered is a key issue, and many players readily discover that they can score highly by entering long strings of random characters. However, they soon fall foul this if the team member running the activity asked them to enter the same thing again, in some cases introducing an additional lesson about the memorability of passwords.

4. Discussion

When considering them as provocations of interest, the games clearly have potential to attract players for different reasons. The dice offer a direct basis for players to compete against each other, while Hacker Whackers delivers a fast-paced arcade experience. Meanwhile, Password Enlightener works on the basis of potential curiosity about how well they may be able to score. In all cases, the visual prompts (the colours of the dice, the coloured lights of the devices) and the kinetic activities (throwing the dice, hitting the buttons) provide further elements that help to generate interest and draw people in.

As previously mentioned, each of the games has proven successful in the context of public engagement events, and Figure 5 shows an example of the three activities ready for use in such a setting. The extent of engagement in this context can still vary. Some players will come, have a go, and then leave. Others will stay for longer and have multiple attempts (sometimes then needing to be encouraged to let someone else have a go). In all cases, their engagement offers an opening to discuss the cybersecurity concepts involved, whether they understand the threats, protect their own systems, and so on. As such, even in an event context there is the opportunity for some basic awareness raising to occur. However, this can be enhanced further if the activities are used in more structured settings, such as being a prelude or accompaniment to a more specific security awareness session.



Figure 5: An example of activity setup for an engagement event

When comparing the new games to those discussed earlier, the other tabletop games are all more substantial in terms of their game dynamics and complexity. However, there is also a trade-off to be recognised. The other games may provide more depth in terms of the cybersecurity learning experience, but equally they require a much more significant investment of time to both understand and play the games. This in turn potentially reduces the audience to those with the time and inclination to take part. An interesting basis for illustrating this is to compare the instructions/guides that accompany each of the games, the length and readability of which is likely to further influence their accessibility and applicability to different audiences. For example, if there is a lot to read and/or the language is complex, then this could represent a barrier to some players. To this end, the instructions for the five games listed earlier in the paper were assessed, alongside those from Cyber Defence Dice (listing the standard and 'Deluxe' versions of the game separately, as the latter requires additional text to be read to understand the use of Assets). The 'Editor' feature within Microsoft Word was used to perform the assessments, and in each case the input in was raw text describing the game and how to play it (with documents having been stripped of title pages, table of contents, tables, appendices, etc). Hacker Whacker and the Password Enlightener were excluded because they have no accompanying instruction booklets – brief guidance is displayed on-screen and the rules can quickly be determined from play and observation. While not quite as brief as the classic instructions that appeared on Atari's Pong machine (i.e. "Ball will serve automatically. Avoid missing ball for high score"), players have proven to require little guidance to get going.

The findings are shown in Table 2 and there is some clear variation in the amount of text that the players need to read to understand and play the games. While several amount to the equivalent of just a couple of pages of text, others are considerably lengthier. In addition to this, it is also relevant to consider the ease with which potential players may understand what they are reading. The Flesch Reading Ease score assesses the average sentence length (words per sentence) and the average number of syllables per word. It delivers a resulting score between 0 and 100, with a higher score denoting text that is easier to read (Flesch, 1948). From the table, we can see that four of the entries in fall into the 70-80 range (which is classed as 'Fairly easy to read'), while two are in the 60-70 band (which is considered to be 'Plain English', and easily understood by those in their early teens). The outlier in the table, in both length and readability is Decisions and Disruptions, where the Reading Ease score that falls into the 'Difficult to read' category (30-50). This is also reflected in the higher Grade Level score, which indicates the US school grade at which someone would be expected to be able to read and understand the text.

Table 2: Comparing the length and readability of instructions for different games

Game	Source Material	Words	Flesch Reading Ease	Flesch-Kincaid Grade Level
Backdoors and Breaches	www.blackhillsinfosec.com/wp-content/uploads/2019/09/How-to-Play-BB.pdf	954	72.5	6.1
Cyber Defence Dice	www.cyberdefencedice.com	589	72.3	7.6
Cyber Defence Dice Deluxe	www.cyberdefencedice.com	884	72.8	7.2
Cyber Threat Defender	cdn.getshifter.co/fd026a43ee1b 7b095c768a9039a2a236c0a0d590/uploads /2025/07/CTD-Instructions-2025Rulebook.pdf	>2,000	76.2	6.4
Control-Alt-Hack	www.controlalthack.com/ downloadrules.php	>3,000	68.4	7.3
Decisions & Disruptions	github.com/Bristol-Cyber-S ecurity-Group/decisions-disruptions-kit/blob/master/D-D_Instruction_Booklet.pdf	>9,300	47.6	11.7
Riskio	www.riskio.co.uk/game-play-setup www.riskio.co.uk/game-play-attack www.riskio.co.uk/game-play-attack-1 www.riskio.co.uk/game-play-information-deck	941	62.1	9

When interpreting the results for the Cyber Defence Dice, it should be noted that the full guide covers different game variants and includes other supporting information. As such, the assessments in the table are based specifically upon the text that needs to be read to understand and play the main version of the game. This includes the general rules, the specific rules for the core game (Match Mode), and the descriptive text for a worked example (which is also accompanied by illustrations in the guide itself). It excludes background information about the threats and defence types, descriptions of alternative game modes, and a section that discusses parallels to real-world cybersecurity. All of these would, of course add to the word count and affect other scores, but they do not *need* to be read to understand and play the core game. Moreover, the essence of the standard game can be distilled down to a much more succinct set of rules, as presented in the Quick Reference Guide provided in the dice pouch. These are expressed as follows, in 60 words (with the Reading Ease reaching 83.2 and the Grade Level now just 4.9):

> *"Either side may start and has up to 3 throws, but can stop after 1 or 2 if preferred. The responding side is limited to that number of throws. Players choose which dice to keep or throw again. To win a round, throw more defence dice than the corresponding attack (or vice versa). A matching number is considered a draw."*

They are accompanied on the reference card (see Figure 6) by a list of the Threats and Defences (presenting the images alongside the names), plus the two matrices (showing which attacks beat which defences, and vice

versa). If players are comfortable with the outline and how the matrices work, then they may not need the more descriptive guidance and the worked example from the full rules.

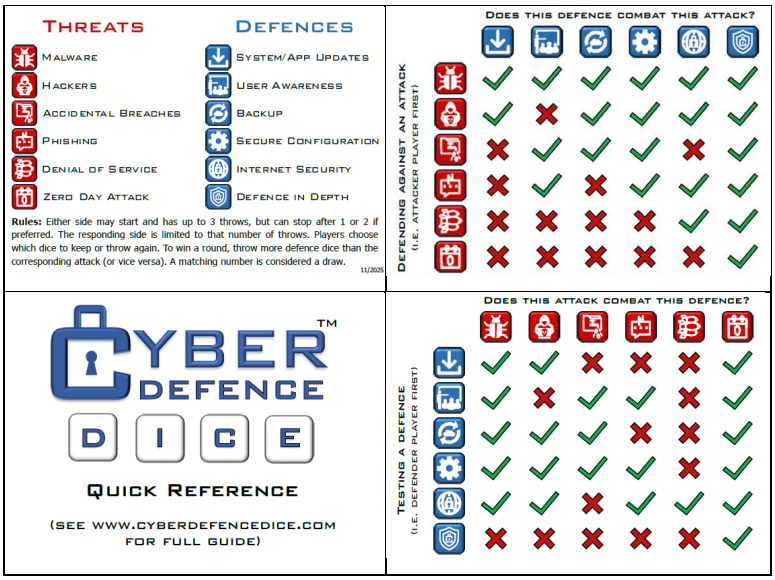


Figure 6: Cyber Defence Dice Reference Card

Another aspect to note is that the above is just considering the presentation of the text required to explain the game – it does not start to address whether they understand the *concepts* under discussion. While the Cyber Defence Dice instructions briefly explain the nature of the Threats, Defences and Assets, the other game guides rarely do this - the player is assumed to know about the basic cybersecurity issues involved, or (where appropriate) to be able to get guidance from the Game Master. For example, while Backdoors and Breaches has a relatively low word count and good readability scores, what it is actually referring to includes some potentially challenging security concepts. For example, even the names of the attack categories highlighted earlier (e.g. Pivot and Escalate, C2 and Exfil) – are unlikely to be immediately meaningful to a lay audience. Picking some examples of terminology from the card titles (e.g. Dynamic Link Library Hijacking, Domain Fronting as C2, External Password Spray, and Kerberoasting) makes it very clear that players are expected to have some significant prior knowledge in the domain.

The lower barriers to entry are not intended to imply that the Cyber Defence Dice is 'better' than the other games, but it does help to further illustrate that it is simpler. Whether this is a good or bad thing depends upon how it is intended to be used. Part of the reason that some of the game guides are more substantial is because there is more to learn. The games themselves go deeper into cybersecurity concepts and decision making (thereby addressing different audiences), and so there is a clear trade-off (or indeed trade-up) to be made against the effort required to learn how to play them. However, if the aim is to have a means of capturing initial interest and engagement, then the dice (and Hacker Whacker and Password Enlightener) are likely to offer the more suitable basis for doing so.

5. Conclusions

As in other disciplines, gamification offers a means of making cybersecurity more accessible and interesting for those who might otherwise find it less engaging. At the same time, the nature of the game needs to be matched to the target audience involved. Those with limited cybersecurity knowledge and awareness are clearly a desirable population to assist, but many of the existing games are aimed above this level. In contrast, the three games presented in this paper offer contributions more directly suited to a layperson audience. While the nature of the underlying games is very different, they share the characteristic of being quick and providing a foundation for further engagement.

All three games have been designed in ways which maximise their ability to provoke interest at events. Both Hacker Whacker and the Password Enlightener have been used at many such events, and have proven to attract players through their lights, sounds, hammer (Hacker Whacker) and large red button (Password Enlightener). Cyber Defence Dice has also been used at various events, with the larger format dice proving successful at attracting attention due to their physical size and novelty, and the smaller sets being popular giveaways, allowing

attendees to continue their education after the event. Further developments are intended, including inclusion of extra features to the game play of Hacker Whacker and the Password Enlightener, whilst still maintaining the prompt playtime and interactivity levels that have currently been achieved.

Ethics and AI declarations: The playtesting of the Cyber Defence Dice was approved by the School of Computer Science Research Ethics Committee at the University of Nottingham (CS-2024-R44). All participants read and signed associated consent forms before play began. AI tools were not used in the writing of this paper.

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A Systematization of Knowledge on Biomarker Based Encryption Keys

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Abstract: Encryption keys require careful management, they must be securely stored, and if stolen or compromised, the consequences can be catastrophic. Ephemeral keys are created, used and then deleted, reducing the attack surface. As the tactics, techniques and procedures of threat actors continue to evolve, implementing an ephemeral encryption key would enhance the protection of critical infrastructure systems, sensitive data and communication systems. This research investigates the feasibility of generating a repeatable, unique, yet transient encryption key from human biomarkers. By deriving cryptographic keys directly from bioelectrical and biochemical markers, key management overhead and long-term exposure risks can be minimized. This Systematization of Knowledge (SoK) addresses two primary challenges. Firstly, determining the viability and limitations of deriving consistent keys from inherently variable biomarkers. Secondly, we propose a manifold encryption key derivation scheme using context dependent signals drawn from the network, device and environment to overcome the limitations of biometric based key generation, including irrevocability, noise, and entropy deficiency.

Keywords: Biomarker, Cryptography, Data security, Encryption keys

1. Introduction

Cryptography, commonly referred to as encryption, constitutes the systematic process of transforming information into a secure form such that its content remains unintelligible to unauthorized parties. With the continual escalation of cybercrime, the development of increasingly robust encryption methods is imperative to mitigate potential security breaches (Diffie et al, 1976; Rivest et al, 1978; Lutsenko et al, 2021). According to IBM, the global average cost of a data breach as of 2025 is USD 4.44 million, as shown in Figure 1 (Kessem, 2025).

Given the pervasive integration of digital technologies, encryption underpins a wide array of everyday activity, including financial transactions, authentication protocols, electronic commerce, numerous communication apps, and social networking platforms (Ozer et al, 2024; Marappan et al, 2025; Qiu et al, 2020; Talwar et al, 2022). The protection of such data is typically achieved through the application of cryptographic algorithms designed to ensure confidentiality and integrity.

Traditional authentication schemes rely on tokens or secret knowledge to establish identity but cannot distinguish a legitimate user from an adversary who has obtained those credentials (Uludag et al., 2004; Sheng et al., 2012). Biometric authentication addresses this by leveraging unique physiological and behavioural characteristics, including fingerprints, face, iris, or voice, that are inherently tied to the individual rather than to a possession or secret (Pahuja et al., 2024; Alrawili et al., 2024). In practice, systems operate in two phases: enrolment, where biometric data is captured and stored as a reference template, and verification, where subsequent inputs are matched against that template within a defined threshold. Systems may be unimodal or multimodal, the latter combining multiple traits to improve accuracy and robustness (Pahuja et al., 2024; Sheng et al., 2012). Despite these advantages, biometric systems remain vulnerable to template theft, presentation and replay attacks, side-channel exploits, and insider misuse, while system accuracy is further sensitive to factors such as age, illness, injury, illumination, and noise (Alrawili et al., 2024).

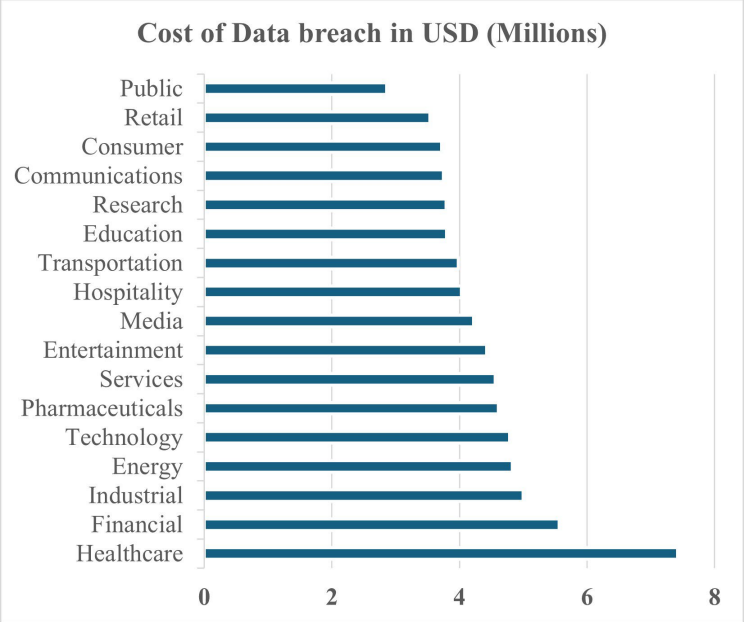


Figure 1: Cost of data breaches as of 2025 by IBM (Kessem et al)

Biometric authentication, as described above, ultimately reduces to a binary decision: a score is computed, compared against a threshold, and access is granted or denied. While effective for identity verification, this model does not generate cryptographic material, the biometric serves as a gate, not a key. The shift from authentication to cryptographic key generation is non-trivial. Where authentication tolerates variability through a soft threshold, key generation demands exact or near-exact reproducibility of a fixed bitstring across presentations. An active area of research pursues a more fundamental integration, where biometric traits are used to generate or protect encryption keys that underpin critical security services including confidential communication, ensuring the integrity of data, and enabling non-repudiation through digital signatures (Lutsenko et al, 2021; Cowley et al, 2025; Gorski and Wodo, 2024). The potential of this integration lies in producing cryptographic material that is user specific and challenging to replicate. Biometric key generation offers a major advantage, it removes the need to store or remember external keys or passwords as the key can be reconstructed as required (Lutsenko et al, 2021; Sheng et al, 2012). However, current frameworks often lack formal security proofs, rigorous entropy analysis, and practical mechanisms for error tolerance or revocability, leaving their robustness uncertain (Sheng et al, 2012; Uludag et al, 2004). These limitations motivate the need for a systematic study of biometric key generation approaches and the exploration of new frameworks that integrate biometrics with complementary signals for stronger, more adaptable cryptographic systems.

1.1 Key Contributions

Our main contributions are summarized as follows:

- We develop a comprehensive Systematization of Knowledge (SoK) on biometric based encryption key generation.
- We provide a structured critique of prior approaches, highlighting open challenges in entropy estimation, error tolerance, revocability, and compliance with Kerckhoffs's principle.
- We propose a novel manifold key generation framework that binds biometric traits with complementary context dependent signals from network, environmental, and device hardware markers to enhance resilience against attacks.

To the best of our knowledge, the use of environmental, hardware, and network markers in conjunction with biometric features for encryption key generation has not been previously examined, positioning this work as a foundation for future experimental validation and benchmarking.

2. Fundamentals and Background

Biometric cryptosystems are typically categorised into three main categories: Key Release, Key Binding, and Key Generation as shown in Figure 2.

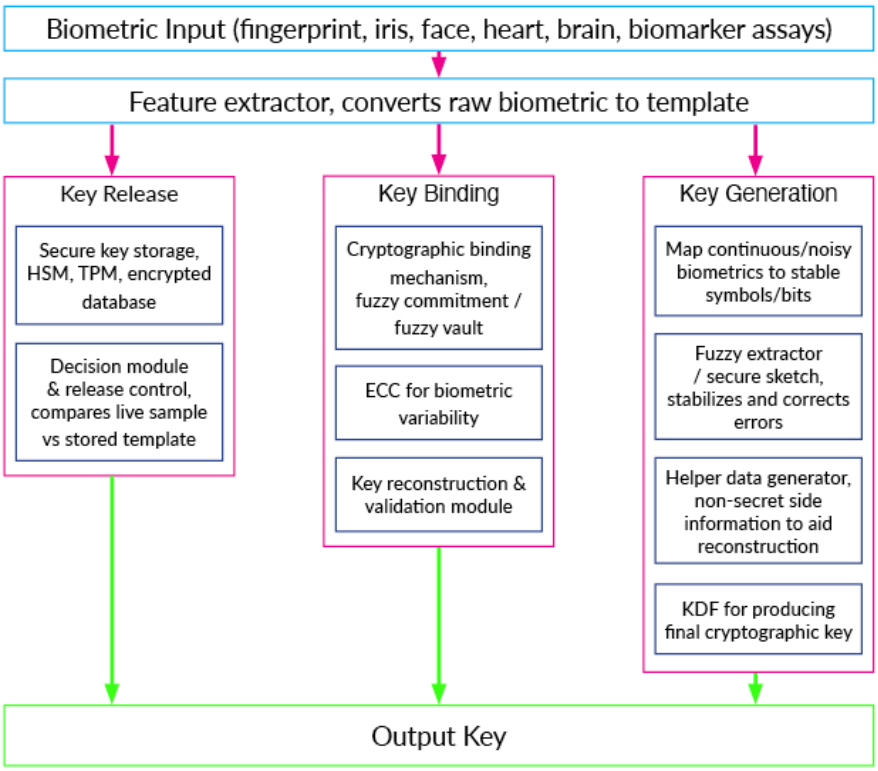


Figure 2: Biometric Encryption Key Systems

In Key Release systems, a conventional cryptographic key is stored securely, in a Hardware Security Module (HSM) or Trusted Platform Module (TPM) and only released after a successful biometric authentication (Lutsenko et al, 2021). Key Bindings systems mathematically bind a cryptographic key with biometric data using various error tolerant algorithms, where the key cannot be retrieved without the biometric data. This approach depends heavily on Error Correction Codes (ECC) for biometric variability (Lutsenko et al, 2021). In Key Generation systems, the key is directly generated from biometric features using a Key Derivation Function (KDF), that variously use fuzzy extractors and helper data (Lutsenko et al, 2021). Key generation systems regenerate cryptographic keys directly from biometric data, eliminating the need to store keys, but at the cost of easy revocation or rotation. To avoid ambiguity, we clarify the terminology used throughout this work.

2.1 Helper Data

A string, data, or a system that is extra information produced at enrolment to enable reliable reconstruction of a secret from a noisy source such as biometrics (Gebali et al, 2022). However, many works deviate, treating helper data as confidential or hardware-protected, or omitting it entirely in favour of direct mappings, trusted hardware, or a user secret such as a PIN. In this paper, we use *helper data* to mean any auxiliary string intended to aid reproducibility.

2.2 Secure Sketch

A primitive with two algorithms: Sketch(w) → s and Rec(w′, s) → w, where w is the enrolment biometric, w′ is the verification sample, and s is the helper data, with w and w′ within a threshold under a chosen distance metric. Correctness: if w′ is within that threshold of w, Rec recovers w with high probability. Security: s reveals only bounded information about w and typically preserves most of w's minimum entropy (Dodis et al, 2008). A secure sketch enables reproducibility from noisy inputs but does not itself ensure that the final key is uniformly random.

2.3 Information Reconciliation

This follows the classical noisy-channel key agreement paradigm, where information reconciliation uses ECC to resolve correlated but noisy values into an identical string, with the side-channel communication serving as helper data (Gorski and Wodo, 2024).

2.4 Fuzzy Extractor

A fuzzy extractor is a pair of algorithms Generate and Reproduce that derive a stable cryptographic key from a noisy biometric measurement. A fuzzy extractor can be viewed as a *secure sketch* for reproducibility plus privacy amplification for uniformity (Dodis et al, 2008). Generation: *(R, P)* ← Gen*(w),* where *R* is the secret key and *P* is public helper data that may be stored or transmitted. Reconstruction: Given any fresh sample *w′* that is sufficiently *close* to *w* under a chosen metric, the algorithm Rep reproduces the same key: Rep(*w′, P*) = R. Correctness: If *w′* is within the tolerated noise radius of *w*, reconstruction succeeds with high probability. Security: For any source *W* with sufficient minimum entropy, the key *R* is *nearly* indistinguishable from a uniform ℓ bit string and independent of *P*.

2.5 Security Analysis

In a biometric key generation system, security can be assessed across four principal layers: the Sensor Layer, the Preprocessing Layer, the Feature Extraction Layer, and the Key Derivation Layer, each introducing unique attack vectors and corresponding defences, as shown in Figure 3.

At the sensor layer, where raw biometric signals are captured, attacks include presentation spoofing, replay injection, and environmental manipulation. Defences include Presentation Attack Detection (PAD), multi-spectral or 3D sensing, cryptographically authenticated sensor links to prevent MITM attacks, and hardware attestation to protect sensor firmware.

The preprocessing layer, which cleans and normalizes raw data, may be targeted through adversarial perturbations, calibration tampering, or parameter rollback. Defences include robust normalization, cryptographic integrity protection of configuration parameters, and execution within a Trusted Execution Environment (TEE).

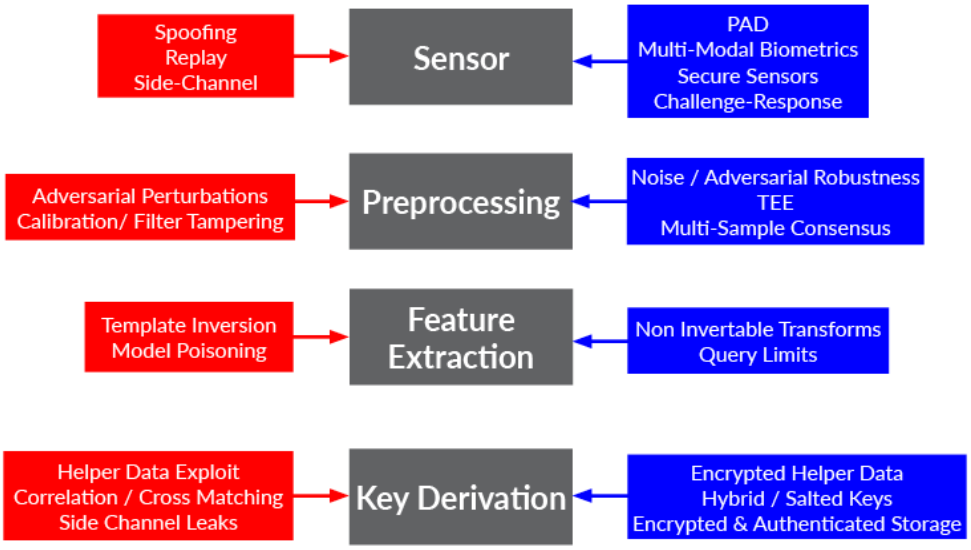


Figure 3: Biometric Key Generation showing potential attack vectors and defences at each stage

At the feature extraction layer, threats include template inversion and hill-climbing attacks exploiting repeated queries. Defences focus on non-invertible feature transforms, restricted query access, and hardening models against poisoning.

The key derivation layer converts noisy biometric features into reproducible cryptographic keys via feature quantization, error correction using secure sketches or fuzzy extractors, and a KDF to produce the final key.

3. Analysing the State-of-the-Art

This section surveys recent biometric key derivation schemes, with Table 1 providing a structured comparison. The analysis follows the framework established in Section 2 and evaluates each work along two axes. First, which of the four key-generation building blocks, namely helper data, secure sketches, information reconciliation, and fuzzy extractors, are instantiated, how explicitly, and whether their security properties are formally or empirically justified. Second, security coverage across the sensor, pre-processing, feature

extraction, and key derivation layers, with attention to presentation attacks, replay, template inversion, and offline guessing.

A key evaluative criterion throughout is Kerckhoffs's Principle, that system security must rest solely on the secrecy of the key, not on obscured parameters, undisclosed feature selection, or protected helper data (Petitcolas, 2025). Section 3.5 synthesises the resulting research gaps.

Table 1: Summary and comparison of biometric key derivation methods

Note. Filled circles indicate level: ○ None, ◔ Low, ◑ Moderate, ● High

Paper	Data Source	Key Size (bits)	Estimated Entropy	Error Tolerance	Revocable	Kerckhoffs	Replay Spoof Res.	Helper Data	Secure Sketch	Info. Recon.	Fuzzy Ext.
Cowley et al, (2025)	Immunoassay	128	~27 bits	○	✗	✗	✗	✗	✗	✗	✗
Gorski &Wodo (2024)	Finger, Eye	256	≪128 bits	◔	✗	✗	✗	✓	✓	✓	✓
Kocak et al, (2025)	ECG	256	~1 bit/bit	◑	✗	✗	✗	✗	✗	✗	✗
Sulavko et al, (2025)	Voice	1024	~1 bit/bit	◑	✗	✗	✗	✗	✓	✓	✓
Oktay et al, (2024)	ECG	256	~1 bit/bit	◔	✗	✗	✗	✗	✗	✗	✗
Kuznetsov et al, (2024)	Face	37	≪37 bits	◑	✗	~	✗	✓	✓	✓	✓
Szymoniak et al, (2025)	Face	256	30-40 bits	○	✗	✗	✗	~	✗	✗	✗
Hoque et al, (2008)	Handwriting	~93	~40 bits	◑	~	✓	~	~	✗	✗	✗
Mohd et al, (2025)	Fingerprint	NA	NA	◑	✓	✓	~	✓	✗	✗	✗
Ballard et al, (2008)	Handwriting	256	~2^30	◔	✓	✓	✗	✗	~	~	✗
Rathgeb & Uhl (2011)	Iris	280	~200	●	~	✓	✗	✓	~	✗	~

3.1 Reproducibility Versus Leakage in Helper Data and Kerckhoffs Compliance

A persistent tension across the literature is that reliable key reconstruction from noisy biometrics requires auxiliary information, yet auxiliary information risks leakage and is often handled in ways that undermine Kerckhoffs compliance. Cowley et al. (2025) sidestep the problem entirely by mapping immunoassay absorbance values directly into an AES-compatible string with no secure sketch, reconciliation, or fuzzy extraction. This avoids helper-data leakage but shifts the burden onto experimental repeatability and parameter secrecy, making key reproduction fragile and Kerckhoffs compliance weak. Ballard et al. (2008) take a different approach, explicitly addressing the problem that biometrics alone can be too predictable or too noisy for key generation. Their Randomized Biometric Templates (RBTs), evaluated on handwriting, add entropy by introducing uncertainty in the measurement process rather than relying solely on biometric randomness. A key design objective is that decrypting a stored template under an incorrect password still yields a plausible output, preventing offline password-checking and obscuring which features are in use. This is a more cryptographically deliberate handling of auxiliary information than in many applied schemes. However, no information-theoretic leakage bound is provided, the construction sits outside the fuzzy extractor paradigm rather than instantiating it, and a non-trivial minority of users remain susceptible to rapid key recovery by search.

Rathgeb and Uhl (2011) follow the classical public helper-data model, storing a bit mask of stable iris code positions alongside cyclic error-correcting redundancy, which allows a fresh noisy sample to be decoded back to the original representation, to enable repeatable reconstruction. The design moves closer to a reproducible-key pipeline, but residual entropy is not tightly bounded, and the security analysis rests on iris code bit independence assumptions known to be imperfect. Kuznetsov et al. (2024) similarly publish a helper string in a code based pipeline without fully accounting for what it reveals about residual entropy under realistic feature distributions. Across these works, helper data is either omitted, which weakens reproducibility, or introduced without complete leakage accounting, sometimes with implicit secrecy assumptions filling the gap. This

pattern highlights the need to consider whether helper data is public, what it leaks, and how it can be revoked as fundamental design requirements rather than implementation details.

3.2 Error Tolerance and Effective Entropy Under Noise Correction

The relationship between noise tolerance and effective key strength presents its own complications. Many papers report AES-length outputs, but key length is not a security guarantee when the mapping from biometrics to bits is biased, redundant, or requires substantial correction. In schemes that attempt deterministic reconstruction, error correction and redundancy unavoidably trade off against entropy. That is, selecting stable bits, partitioning continuous features into tolerance bands, and publishing ECC redundancy can all reduce the attacker's search space, especially if bit distributions are non-uniform or correlated.

Rathgeb and Uhl (2011) make this trade off explicit by using ECC to correct bit flips in selected iris-code positions. Kuznetsov et al. (2024) likewise analyse FRR/FAR trade-offs under code parameters in a code-based fuzzy extractor setting. These schemes are stronger than direct mappings because they use a correction mechanism, but their security interpretation still hinges on how much uncertainty remains after feature selection and redundancy publication. In contrast, Cowley et al. (2025) highlight a different failure mode, an AES compatible string can be produced without explicit correction, yet small measurement deviations can render reconstruction infeasible, and the usable uncertainty can be far below the nominal key size. Szymoniak et al. (2025) illustrate a related risk of overstating key strength. Their IoT oriented scheme derives a nominal 256-bit key from a facial triangle using the eye corners and chin. However, the effective uncertainty is constrained by the low-dimensional geometry of the underlying biometric signal and by acquisition conditions including pose, lighting, expression, that alter coordinates without any ECC or secure-sketch mechanism to stabilise them. Consequently, the reported key length primarily reflects output formatting rather than a quantified entropy guarantee.

A related strategy appears in several Machine Learning (ML) based bio-key papers where rather than enforcing deterministic reconstruction, they relax the success condition to similarity under a threshold. This improves apparent robustness with lower rejection but transforms the problem into verification rather than cryptographic key generation, as the output is not guaranteed to be identical across sessions. The literature repeatedly confronts the same issue where the robust handling of noise is essential, but it must be evaluated together with the entropy cost of tolerance mechanisms and the gap between output length and effective security.

3.3 Distinguishing Biometric Verification from Cryptographic key Generation

A substantial portion of recent work, particularly ML systems, implicitly adopts a verification paradigm even when describing outputs as keys. In these designs, bitstrings produced from different sessions are not required to match exactly; instead, authentication is decided by Hamming distance or related similarity scores, against an optimised threshold. This is legitimate and often effective for authentication, but it does not directly produce encryption ready keys because encryption requires absolute key agreement.

Kocak et al. (2025) use this pattern using ECG heart prints. Their Siamese neural network produces 256-bit outputs designed to be consistent within user and different across users, and ECG is argued to be intrinsically harder to spoof than external traits. However, the system is evaluated as a matcher. Keys are close rather than identical, and no reconciliation or extraction layer is provided to convert noisy outputs into stable shared secrets. Oktay et al. (2024) similarly generate ECG-derived 256-bit outputs for digital watermarking and validate them with a reliability metric rather than requiring exact reproduction. This is compatible with watermark verification tolerance but underscores the mismatch with cryptographic key agreement. Hoque et al. (2008) also faces this limitation. Signature subspace partitioning concatenates the components into a bitstring and does show some resistance to forgery, but the absence of error correction leads to high false rejection and divergence between sessions, limiting its application as a cryptographic key generator.

Mohd et al. (2025) illustrates a different problem, while the work is strong as cancellable template protection, emphasising revocability, non-invertibility, and unlinkability, but the output remains an authentication decision rather than a reproducible secret key, and helper-data leakage is not characterised in the formal secure-sketch sense. In contrast, Sulavko et al. (2025) are closer to an explicit key-generation framing, the authors present a neural fuzzy extractor for voice and report long outputs of 1024 bits, with robust matching performance. However, the deliberate avoidance of stored helper data, motivated by inversion concerns, substitutes one risk for another. The burden of reproducibility shifts to learned stability and system assumptions rather than a standard public helper data with bounded leakage model.

Across these works, the field repeatedly uses the language of key generation while evaluating systems as matchers. However, there is a categorical distinction, verification systems can be valuable, but without an explicit reconciliation or extraction stage they do not satisfy the functional requirements for a cryptographic key.

3.4 Primitive Security Versus end-to-end Security in Biometric key Generation

Even when a design includes strong cryptographic primitives at the key derivation layer, system level assumptions often determine real security. Gorski and Wodo (2024) make this point in their security evaluation of biometric AKE protocols (BAKE/BRAKE). While BRAKE incorporates substantial cryptographic structure including template obfuscation, OPRF-based protections, and a KDF for session keys, the authors identify residual vulnerabilities rooted in key compromise and enforceability. Compromise of evaluator side secrets can enable offline attacks, and assumptions that sensitive values remain only in volatile memory cannot be guaranteed against a rogue client who persists credentials and bypasses biometric presentation. The results emphasise that protocol soundness must be evaluated together with key management, client behaviour, and adversary capabilities.

More broadly, across the surveyed literature the sensor layer is frequently excluded or treated as future work. Voice systems remain exposed to replay and synthesis without liveness or PAD. Face systems evaluated on static datasets lack threat modelling during capture. Iris systems often acknowledge presentation attacks but defer defences and ECG systems sometimes claim inherent spoof resistance without implementing or evaluating formal PAD. Preprocessing layers are typically treated as engineering steps rather than attack surfaces, despite their potential vulnerability to manipulation. Consequently, many schemes concentrate their security reasoning in feature extraction and key derivation while leaving the most deployment relevant attack classes including presentation, replay, and adversarial capture, outside the evaluated system boundary.

3.5 Critical Analysis

Across the surveyed approaches, a common pipeline emerges. Starting from a biometric, a noisy numeric feature vector is extracted. Then an ECC, that ensures small intra-subject variations do not break reproducibility, is applied. Lastly, the corrected vector is hashed to obtain a fixed-length cryptographic key. However, these works generally fall short of Kerckhoffs's principle and do not rigorously evaluate resilience to replay or spoofing attacks. A more formal approach replaces direct mapping b → K with a secure sketch S(b) → s. Given a fresh sample b' close to b, the pair (b', s) reliably reconstructs the same keying material. The helper string s can be stored or made public while leaking only bounded information about b. A fuzzy extractor strengthens this by coupling sketch reconciliation with randomness extraction, ensuring K is both reproducible across noisy measurements and statistically close to uniform (Kuznetsov et al., 2024). Using biometrics as the sole key source faces deeper structural problems. Many biometrics, including biochemical assays, yield only a few dozen bits of entropy, leaving derived keys vulnerable to offline search, population-level inference, and quantum attacks. Biometrics are also not secret, a latent fingerprint, a blood sample, or an intercepted wearable stream exposes the same underlying features. Finally, compromise is permanent: any key deterministically derived from a biometric remains reproducible forever, regardless of how well spoofing is mitigated.

4. Manifold Encryption Key Derivation

The idea of deriving cryptographic keys directly from biometric markers such as bioassays, ECG, fingerprints, and iris prints, is appealing but currently fraught with challenges presented in Section 3. In practice, most systems use biometrics merely as a gate to securely generated keys rather than as the keys themselves.

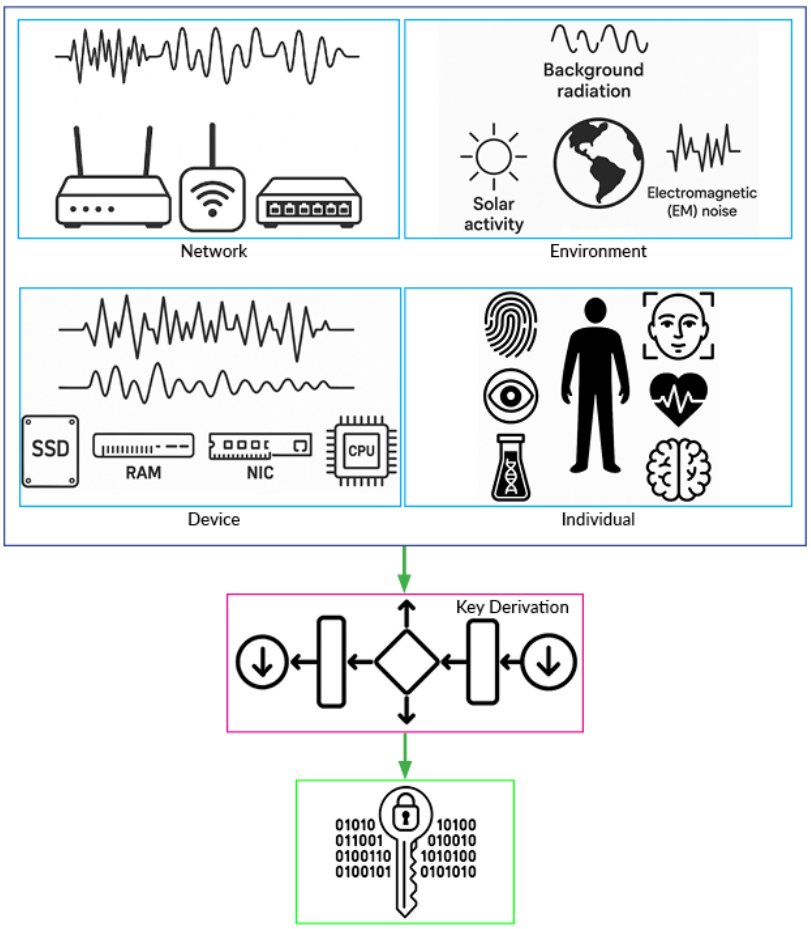


Figure 4: Manifold Encryption Key Derivation

A practical path beyond single modality biometric key generation is to bind biometric traits to signals drawn from the network, environment, and device hardware. For instance, network markers may be derived from topology or hardware identifiers. Environmental markers may include background RF, ambient audio and lighting, temperature, and location. Hardware markers such as CPU, RAM, or SSD fingerprints could be incorporated through challenge-response protocols to further strengthen the binding between identity, device, and context. This proposed manifold encryption key derivation framework is conceptual, but not without precedent. Location has been investigated in continuous authentication architectures for location-based services (Alamleh et al, 2020). Further, beacon frame based two-factor authentication demonstrates how environmental RF signals can serve as an unobtrusive second factor with minimal user involvement (AlQahtani et al, 2020). Additionally, DeMiCPU introduced a robust challenge–response hardware fingerprinting method that leverages magnetic induction signals emitted from CPU modules to capture unique device level discrepancies (Ji et al, 2021).

Encryption keys require careful management, they must be securely stored and if stolen or compromised, the effects can be catastrophic. Ephemeral keys are created, used and then deleted, reducing the attack surface. As the tactics, techniques and procedures of threat actors continue to evolve, implementing ephemeral encryption keys could enhance the protection of mission critical systems, sensitive intelligence and military communication systems.

This multi-domain fusion mitigates the classic weaknesses of unimodal biometrics by binding key derivation to multiple independent contexts. Network and environmental binding limits out-of-context misuse of compromised biometric templates, while hardware anchoring ties key derivation to trusted devices, raising the bar against insider abuse and template attacks. The result is a context-aware, revocable, and device-, location-, and individual-bound key generation scheme, in which compromise of any single domain is insufficient to reconstruct the cryptographic key.

5. Conclusions and Future Research Direction

Security and privacy challenges limit large scale adoption of biometric key generation. Compared with conventional key management, biometric derivation reduces the attack surface associated with stored keys as material is generated on demand rather than persisted, and ties possession to the individual rather than a token or password. However, several fundamental limitations constrain the approach. Measurement noise and intra-subject variability undermine the bit-for-bit reproducibility that cryptographic keys require, and error correction techniques introduced to compensate, reduce effective entropy while the resulting helper data introduces new leakage vectors. Further, many biometric signals carry insufficient entropy to begin with, weakening collision resistance and enabling offline search. Irrevocability compounds this, unlike passwords, biometric traits cannot be rotated, so a deterministically derived key remains reproducible by any adversary who captures the underlying signal. Finally, without robust liveness detection, recorded or synthetic samples enable replay and presentation attacks. These limitations are frequently understated in the literature. Proposed schemes often demonstrate promising entropy or brute-force resistance in controlled settings but lack evaluation under realistic threat models, and the absence of standardised benchmarks makes it difficult to assess robustness and scalability. Without formal proofs and rigorous cryptographic engineering, biometric key generation risks being operationally fragile and in the worst case, a liability rather than an improvement over the approaches it seeks to replace. A practical path beyond biometric key generation is to bind biometrics with complementary, context dependent signals drawn from the network, environment, or device hardware to generate ephemeral encryption keys which dramatically reduces the vulnerabilities of biometrics alone.

Ethics Declaration: No ethics clearance required.

AI Declaration: No AI tools were used in the creation of this paper.

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Preparing Industry for IIoT: Separate Sensor Networks for Industrial Automation Security

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Abstract: Industrial automation has brought innovations in efficiency and safety to modern manufacturing. The emergence of big industrial data, AI and Internet-connected industrial automation systems promises many advantages in manufacturing, maintenance, health & safety, product customization, logistics, and reporting. The Industrial Internet of Things (IIoT) seeks to attach industrial systems to the Internet for data collection and processing. The Internet is not a secure place for many of the industrial systems in use today. Industrial networks are designed for speed, accuracy, and availability at the expense of security. In our experiments, we demonstrate how easy it would be for hostile actors to gather data that could be used to compromise the industrial automation systems if actors (a) had physical access to the internal network or (b) access to data streams that feed to the external network. To resolve some of these issues, we propose a hybrid solution of sensor data acquisition in which a secondary network with additional sensors and controllers are installed; the secondary network, sensors and controllers are isolated from the internal control system. The results show that our solution enables useful data collection without impacting the security, speed, accuracy, and availability of industrial control system. It also has the potential to permit anomaly detection using independent sensors on different networks.

Keywords: Sensor networks, Manufacturing, Industry 4.0, Cyber-physical systems, Industrial automation

1. Introduction

Modern industrial manufacturing systems consist of many physical components that perform work to create products. Since the first industrial revolution began replacing people's labour with machines, technological innovations have slowly made their way into manufacturing (Lukač, 2015). The third industrial revolution introduced computing for machine automation, enabling machines to run continuously without human interaction (Adeyeri, 2018). Programmable Logic Controllers (PLCs), considered the heart of these systems, are configured to automatically respond to sensors on the machines and make adjustments to control the process (E. A. Lee & Seshia, 2016). Sensors themselves are read-only devices that measure an analogue or digital value. These values are converted to an electrical signal, amplified, and sent to a controller. Supervisory Control and Data Acquisition nodes (SCADA), collect data from the controllers and save them for trending analysis while providing supervisory control to the processes being controlled by the PLCs (Daneels & Salter, 1999).

Recent research in Industry 4.0 and the Industrial Internet of Things (IIoT) proposes connecting smart automation system data collection devices, called cyber-physical systems, to the Internet (Jazdi, 2014; Lennvall et al., 2017; Sengupta et al., 2020). Research in the proposed Industry 5.0 revolution extends the previous revolution but with more of a focus on sustainability and enhancing human interaction (Demir et al., 2019; Nahavandi, 2019). Traditional automation systems in manufacturing plants were built for dependability, speed, and accuracy at the expense of security, so these devices historically remained attached to an isolated network with minimal services to limit exposure to external threats (Hong & Lee, 2008; Risley et al., 2003). Additionally, automation systems require a specifically designed low-latency network infrastructure for performance and stability (Yan et al., 2021). Adding sensors to this network adds cost and latency, so data collected from them is prioritized for operations and business needs based on value (I. Lee & Lee, 2015).

An automation system's reliability and safety depend on its components' availability. Availability in manufacturing automation systems requires feedback and feedforward methods, including performance monitoring, corrective maintenance, and lifecycle management (Ton et al., 2008). These methods require data, including data collected from the manufacturing system sensors that report the condition of the components.

While many sensors in the manufacturing system are required to give feedback to the manufacturing system for automatic control, some sensors are not used for input into the manufacturing system. Rather than feedback control functions, these sensors collect valuable information for higher-level functions of the

organization, such as predictive maintenance, quality reporting, logistics, system health and performance, environmental compliance, and auditing (I. Lee & Lee, 2015). Since these sensors do not provide feedback control, they need not be connected to the expensive low-latency infrastructure, PLC or SCADA for management. Hence, many of these additional sensors can use more cost-effective non-industrial-grade networking infrastructure, and their systems can be physically isolated from the rest of the manufacturing control systems for security and scalability.

Sensors are read-only measuring devices, but components of the automation control network that rely on the values from these sensors are not. PLCs use sensor values to influence the output of a device in the system. The controller part of a PLC sends signals to energize or make controlled changes to mechanical devices based on the values received from sensors and the logic programmed into them. SCADA systems collect and store data from these PLCs and can write values to the memory of the PLCs to affect changes in the manufacturing process. This process of continuous sensor reading and adjustment is called a feedback loop. The PLC and SCADA systems, which are not read-only devices, are vulnerable to cyber-attacks and must be protected. Advancements in IIoT and cloud connectivity will require changes in manufacturing system configuration to minimize the risk of compromising system security.

In this paper, we conduct an experiment that adds additional sensors to an existing industrial control system for data collection, isolating these sensors from the current feedback control sensors. The data collected from the additional sensors is recorded into a separate system, which is then analysed to gain alternative insights that were unobtainable without the additional sensor data. The data was then compared with the internal sensor data to gain insights into the operation of the industrial control system devices. The experiment concludes by validating that the any malfunction with the additional sensors will not reduce the availability of the existing control system.

The remainder of this paper is organized as follows. Section two presents the background in industrial automation and introduces the concepts in IIoT. Section three presents our methodology. Section four presents our experiment of modifying an isolated cyber-physical network by adding a separate sensor network developed for this research. The results of the experiments are presented in Section five. Section six discusses and concludes this research.

2. Background

2.1 Adding Automation in the Industrial Revolution

Beginning in the early 1970s, the third industrial revolution introduced electronic automation systems to the mechanized processes provided by the first two industrial revolutions (Adeyeri, 2018). Automation was designed to make decisions and monitor processes with little human intervention. These systems increased efficiency by removing the human element from repetitive tasks and replacing them with autonomous machines that could run continuously. At the most basic level, an automation system consists of 4 physical components (Abbate, 2000; Roberts, 1978; Ton et al., 2008):

- A device that causes something to happen, such as a motor that drives movement, an actuator that opens a valve, or a heating element that causes a change in temperature
- A sensor that measures the changes that are happening to the device, such as a flow meter, temperature sensor, or limit switch
- A controller device that collects the sensor information, calculates a measured value and generates a response that loops back to the device.
- Infrastructure to connect the physical components

Combined, these physical elements create a process control loop at the heart of industrial automation.

2.2 Industry 5.0

A fifth industrial revolution promises to add additional intelligence to the processes and increase the synergy between humans and machines. Where Industry 4.0 sought to automate the process to eliminate as much human interaction as possible, Industry 5.0 aims to have tasks requiring high levels of creativity be performed by a human, leaving the remaining tasks to automation systems better suited for them (Sehrawat & Gill, 2019; Weis, 2010). The automation systems of Industry 5.0 also seek to increase reliance on AI, big data, and cloud computing to support new functions, such as additive manufacturing, predictive maintenance, and intelligent product customization. These additions will require an increase in the number and type of sensors collecting

data, contributing to a greater volume, velocity, and variety of data (Lennvall et al., 2017; Sehrawat & Gill, 2019).

2.3 Industrializing the Internet of Things

Traditional sensors in industrial automation systems generate data to provide feedback to the automation system and record data for trending and quality control purposes (Boyes et al., 2018). These sensors are expensive to implement because each sensor requires an input channel on a PLC, infrastructure for the connection to the PLC, engineering design and development of the PLC program to implement the feedback logic, a SCADA license for control and data collection, and supporting computer hardware and software. A cost-effective industrial control system collects only the data required to run the industrial processes and produces the needed quality analysis and regulatory information.

Industrial automation control systems were designed for low-overhead, low-latency operations. To reduce the risk of external influence on internal control systems, protection of the control network is implemented at the perimeter, which typically follows a standard security model such as the popular Purdue Enterprise Reference Architecture (Boyes et al., 2018; Williams, 1994). This model segments networks into zones separated by restrictive firewalls to create an isolated control network that carefully controls access to this network. While this protects the network from outside influence, it complicates expansion and serviceability when new technology replaces failed or outdated systems.

Where the Internet of Things sought to use sensors to detect the movement of objects, the Industrial Internet of Things (IIoT) aims to implement the scalability and logistical benefits into the industrialized business setting. Since these types of sensors do not need to be industrialized, connected to a PLC, or be required to provide feedback for automation and control, they are a candidate for separation from the industrial control system. This separate sensor and data collection system can be configured to eliminate interference with the existing feedback control sensors and their associated data collection systems.

3. Methodology

For our research, an experiment was conducted that analyses the security issues when exposing an industrial control system network to an external, uncontrolled network. The results from this experiment were used to conduct a second experiment that uses a separate, read-only sensor network attached to the external, uncontrolled network, leaving the industrial control system network secured in its closed network.

In the first experiment, a second computer on the control network was used to conduct a series of network scans and packet captures to view the raw traffic on the control network. This computer will represent a threat actor that has gained access to the control system network. With this experiment, the scans were used to map devices and discover points of weakness in the system.

A second experiment was conducted that isolates the control network from the uncontrolled network. Existing industrial devices were configured with a secondary read-only sensor connected to a separate network that can be safely exposed to an external, uncontrolled network for data collection. This experiment consisted of four parts.

In part one of the second experiment, data was collected using the existing sensors, PLCs, and SCADA systems on the isolated network already in place. A pre-set task was executed on the control system to generate feedback data from the PLC, and the data was stored on the SCADA computer. This data was used as control data and compared with data collected by the sensors on the external network in part three.

In part two of the second experiment, additional sensors were installed on the controlled devices to collect information from the same device. These additional sensors were then connected to a separate computer to read their signals. This computer does not provide any output control to any devices. The pre-set task was again executed on the control system to generate feedback data from the PLC and stored on the SCADA. The data collected from this task was compared to the control data from part one.

In part three of the second experiment, data collected from the separate sensor system was examined and compared to the control data. Although the sensors are designed to collect the same information as the remote sensors, the sensor types were different so the values did not match exactly. The parameters for the new data set were adjusted to compensate for these differences, then compared with the data collected from part one.

A threat actor was introduced to the uncontrolled network in part four of the second experiment. The same threat actor computer used in experiment one was attached to the uncontrolled network with the secondary, read-only sensors. The data was then analysed and compared the results to the packets collected in experiment one.

4. Experiment

For our experiments, we used a power plant simulator training system that contains an Allen Bradley CompactLogix PLC with input/output cards in a rolling cabinet, shown in Figure 1. On top of the cabinet is a diorama of a small town designed to emulate a power plant and distribution of substations, shown in Figure 2 (next page).

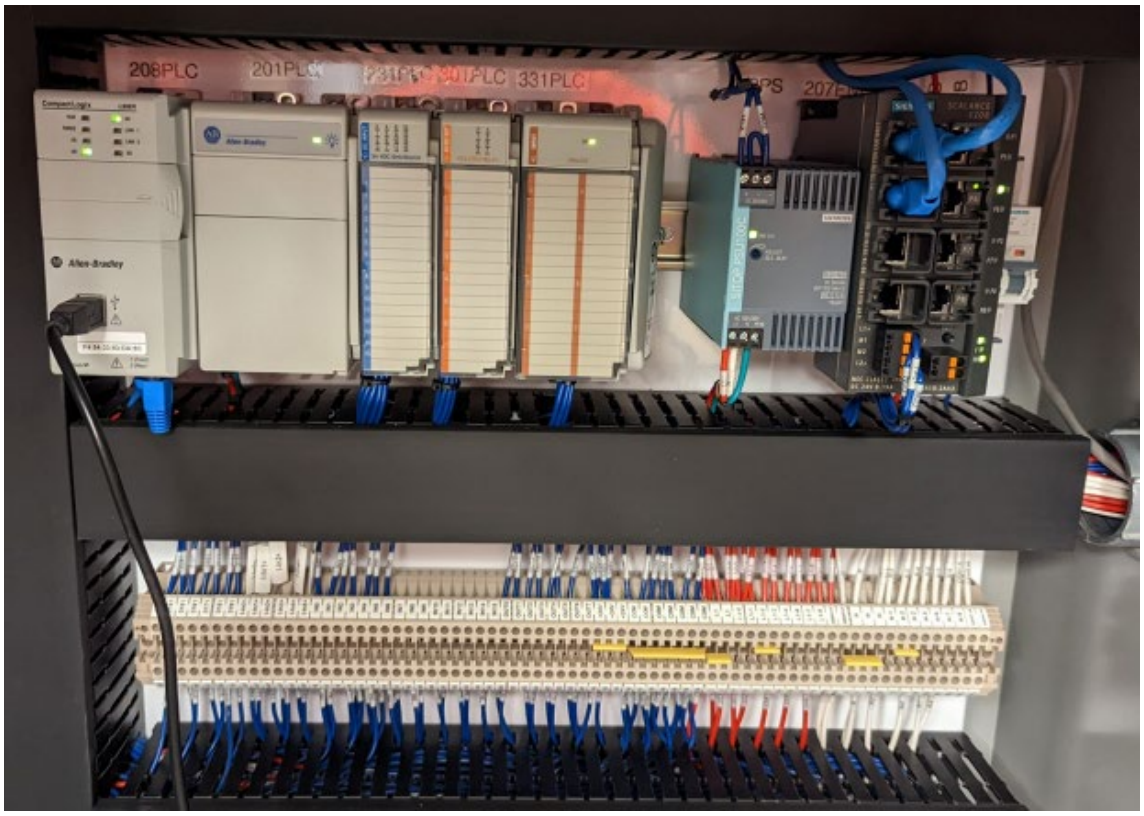


Figure 1: Allen Bradley CompactLogix PLC chassis

Next to each substation is a red and green light emitting diode (LED) and an analogue meter. The LEDs represent the status of the substation as either energized or not energized, and the analogue meters represent the power load at each substation. A variable resistor next to the power plant is used for input and represents the power load placed on the power generation plant. The LEDs are attached to the PLC digital output card. The analogue meters are connected to the PLC analogue output cards to simulate a change in the load of each substation. The variable resistor is attached to the PLC input card.

The PLC is connected via Ethernet to a Seimens SCALANCE X208 industrial network switch connected to a Windows 10 PC. This PC runs Allen Bradley ControlLogix software for programming the PLC and includes a Human-Machine Interface (HMI) program and a SCADA development and runtime environment. The PLC and the Windows PC are the only devices attached to this network switch. The Windows PC is not connected to any other network, and all devices on the industrial switch remained isolated on their network during the experiment.

A relay was manually activated in the control system software running on the SCADA computer to execute the task on the power plant simulator. The power plant simulator represents this by turning on the green LED light next to the substation. The circuits are designed to turn off the red LED when the green LED is turned on. This indicates the simulated substation has been activated.



Figure 2: Power plant simulator

Experiment one, illustrated in Figure 3, used a second computer attached to the Seimens network switch to act as the threat actor that has gained access to an internal computer on the control network. A standard laptop running Kali Linux was used. This laptop was connected to the Seimens network switch and was not attached to any other network during this experiment. A packet capture of the control network switch was performed using Wireshark to examine the communication packets between the PLC and the SCADA computer. The substation switchover task on the power plant simulator was executed and recorded the data on the SCADA machine and the packet capture from Wireshark.

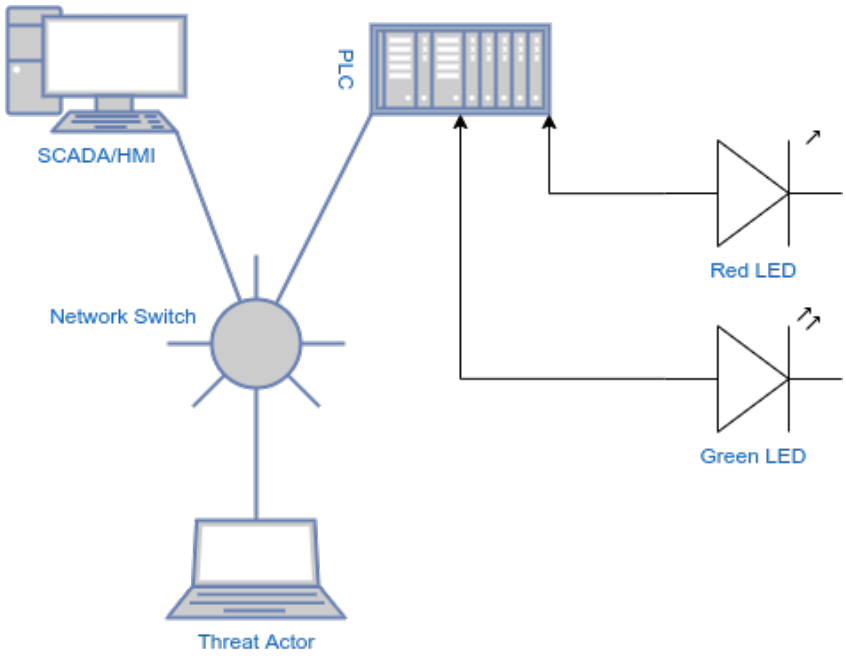


Figure 3: Configuration for experiment one

The packet capture data of the conversation between the SCADA computer and the PLC was analysed. The data included packets that carried information from the PLC to be written to the SCADA database, as well as

commands from the HMI to the PLC to activate the relay to trigger the execution of the substation switchover task on the power plant simulator. This concluded experiment one.

A new data sample was first taken from the PLC and SCADA system for experiment two. The substation switchover task was executed, and the time was manually recorded while the data was collected on the SCADA. The data collected was verified and matched to the manually recorded timeframe. This concluded part one of experiment two.

In preparation for part two of the second experiment, the threat actor was removed from the internal network. The separate sensor network was prepared by adding external sensors to the power plant simulator. The external sensors consist of photoresistors, which will detect the switchover of a substation by registering a change in the light intensity of the LEDs on the diorama. Since the LEDs are acting as a digital device on the PLC to represent on and off, and the photoresistors are an analogue device, it will be necessary to adjust the parameters of the output data of the photoresistors to compensate for the differences in the digital data of the LED's when comparing the on and off values to analogue integer values.

Two photoresistors were placed in proximity to the LEDs of a substation, as shown in Figure 4. The photoresistors were attached to the analogue input ports of an Arduino microcontroller, as shown in Figure 5. The Arduino was programmed to detect variations in light intensity and write them as an integer value to the serial buffer every half second. The Arduino was able to detect the brightness and record it as an integer value.

The Arduino controller collects data but cannot store it, so it was connected to a Raspberry Pi 400 via USB to store the collected data. A simple Python program was developed for the Raspberry Pi to collect the data from the Arduino every second, adding a timestamp field and appending the data to a CSV file on the micro-SD card inserted into the Raspberry Pi. The Arduino performs a function similar to the PLC. The Raspberry Pi in this case performs a function similar to a SCADA Historian database.

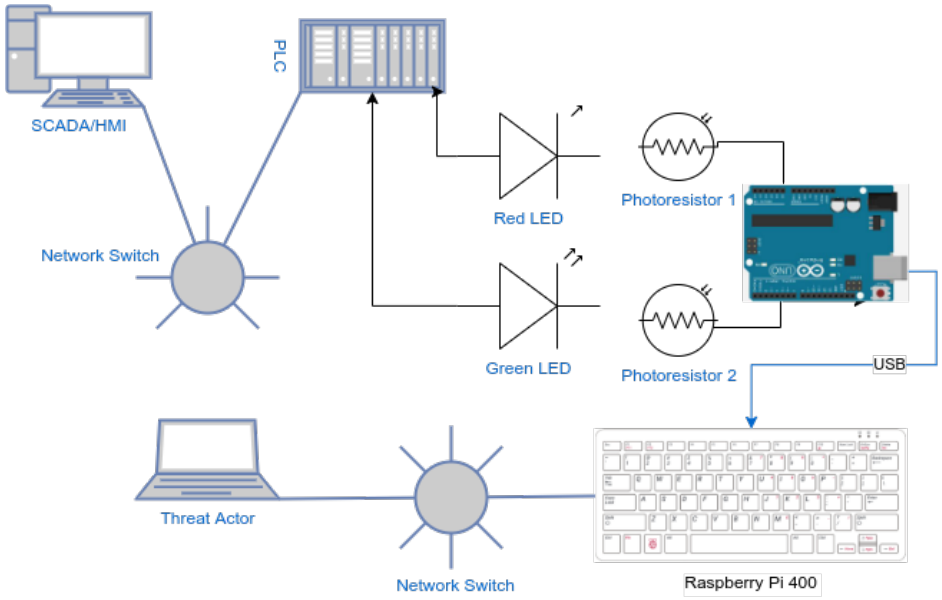


Figure 4: Configuration for experiment two

The Arduino was powered on, and the Raspberry Pi was booted up in preparation for part two of the experiment. Once the Python application was started and connected to the Arduino, the same substation switchover task from experiment one was executed and the time was manually recorded. The still visible LEDs made their change to indicate a successful switchover. The Python program was stopped after 300 seconds, concluding the test. The data collected from the Arduino was saved to a CSV file on the Raspberry Pi, and a quick check was performed to verify there was data in the file. This concluded in part two of the second experiment.

Part three of the second experiment required the data set collected from the SCADA computer in experiment one and the data set collected from the Raspberry Pi in experiment two. The data sets were exported as CSV

files and saved to a flash drive for analysis on a separate machine. The Results section presents the findings of the comparison of the data sets. This concluded part three of the second experiment.

In part four of the second experiment, we reintroduced the threat actor to the additional sensor network to determine if the threat actor would be able to carry out the same kind of attacks on both networks. The same laptop used in experiment one was connected to the same network as the Raspberry Pi and began capturing packets with Wireshark. The Python program was executed to collect the external sensor data, and the same substation switchover task was executed. The results section presents the findings of the network data that was collected. This concluded part four of the second experiment.

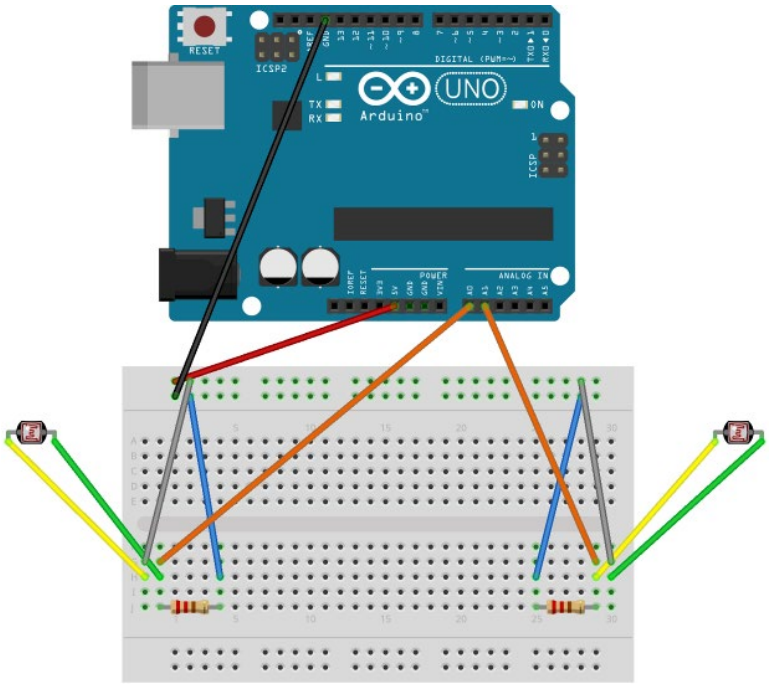


Figure 5: Arduino with photoresistors

5. Results

Experiment one was a controlled experiment to analyse the network traffic of a control system to understand the weaknesses of the system. A threat actor with access to this level of the control system network would be able to carry out attacks that could cause systems to go offline through a denial of service attack or cause substantial damage to any cyber-physical devices by intercepting packets between the PLC, HMI, and SCADA systems and modifying the commands or generating new ones (Wardak et al., 2016).

In experiment one, data was collected from the PLC during the execution of a task that caused a red LED to turn off and a Green LED to turn on. The Wireshark capture of the network packets displayed the data collected from the event. The packets sent from the SCADA/HMI computer to the PLC showed the event request to perform the switchover to the substation in the power plant simulator. The packets sent from the PLC to the SCADA/HMI computer showed the response to the request so the HMI could be updated, and the SCADA recorded the change in the database. The date and time manually recorded at the beginning of the event matched the data collected from the event and stored in the SCADA database. This created our control database for comparison.

For experiment two, the control system network remained isolated as it was designed. Additional sensors were added to the devices to create a separate sensor network. The HMI and data collection to the SCADA PC remained unaffected by the addition of the sensors. The LEDs in the diorama remained visible since the photosensors did not block their view but were only in proximity.

The Raspberry Pi and Arduino successfully collected data from the photoresistors in the power station diorama and saved the data to a local CSV file. The CSV file contains 301 timestamped records that were recorded over 300 seconds.

Since the photoresistors are analogue sensors that send an integer value based on the light intensity, the values recorded to the CSV file had to be tuned for each photoresistor to determine an LED's digital on or off event in the diorama. In Figure 6, the blue line labelled A1 is the analogue input of the photoresistor for the Green LED, and the digital output equivalent for the same Green LED is the yellow line labelled D1. Likewise, the red line labelled A2 and the green line labelled D2 are the analogue and digital outputs for the Red LED, respectively. The LEDs in the diorama were not shining at the same colour or intensity. Also, ambient light around the LEDs could change intensity based on the surroundings, such as the status of the lights in the lab or the shades on the windows being open during daylight hours. The Y-axis values of Figure 6 account for this tuning, with a 0 representing a digital "off" value and 900 representing the digital "on" value to accommodate the variability in the light coming from the analogue photo resistors. The highest analogue value of A2 peaked at 880 from the Arduino. This tuning of the data parameters was also performed manually through several lighting condition experiments. Once the values were tuned to determine the proper integer ranges for the light intensity of an on-and-off condition, a formula was added to LibreOffice Calc for two additional columns to determine the on-and-off status of the LEDs. After tuning, the data reliably showed the timeframes of the LEDs turning on and off compared to the observations made during experiment two.

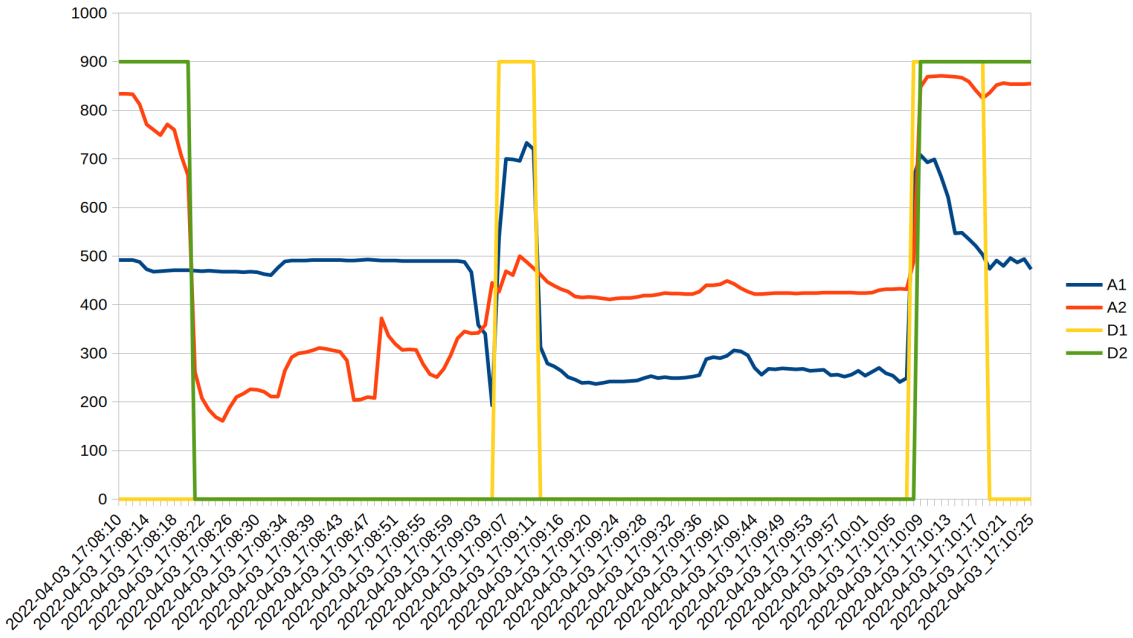


Figure 6: Data collection and results converted to digital output

After the analogue data parameters from the external sensor network were tuned, the data was compared to the binary values of the internal sensor network. The values matched and were time synchronized with the recorded date-time stamps and the manually recorded time. The results shown in Figure 6 indicate that the external sensor system can record sensor data reliably while remaining independent of the internal sensor system.

The additional step of exposing the threat actor to the secondary sensor network did not disclose any internal or external sensor data via a Wireshark capture due to the way the devices were connected and used. The threat actor at this level could modify data or cause denial of service, but this would not affect the PLC operation and would be detectable when comparing the data between the two sensors. However, this experiment was not complete since the data saved to the Raspberry Pi was not transmitted over the network. In production environments, the data would likely not remain on the edge device, such as this Raspberry Pi, but would be processed and sent to another storage location, such as a cloud server. In this case, the threat agent could capture the sensor data from the external sensor network. Although the data collected from the external sensors is a representative facsimile of the internal sensors, they remain physically isolated, which is the point of this experiment. A threat actor would not be able to affect devices or data generated from the internal sensor network.

6. Conclusion and Perspectives

While in the initial stages, this research completes one step for future research in implementing IIoT in manufacturing that current research still needs to identify. Separating sensors on the same networking equipment using Virtual Local Area Networks (VLANs) to reduce latency and group network devices is not unusual. Still, this experiment uses physically isolated networks to separate the PLC feedback data from non-critical data-collecting sensors.

Manufacturing plants that follow the Purdue Enterprise Reference Architecture model for securing the sensor networks against external attacks may find this hybrid solution an acceptable alternative to opening their sensor network for outbound Internet connectivity. Their sensitive sensor networks remain in managed isolation, and they can take advantage of the benefits of IoT sensors with no feedback capability to the automation system. Should this exposed sensor network be compromised or taken offline, it will not affect the operation of the critical internal systems.

Future research will explore using the extra sensor data to validate the data from internal sensors used in the feedback loop. The Stuxnet worm caused PLCs to perform a destructive physical operation on manufacturing devices, then lie to the SCADA system to cover up what was happening (Kriaa et al., 2012). Had a system like our proposed system been in place, data from internal sensors could be compared to data from external sensors using anomaly detection algorithms and alert someone to the discrepancy. Since the two sensor networks are physically separated and could consist of different types of components, the attacker would have to compromise both systems for the attack to be hidden successfully.

Ethics Declaration: Ethical clearance for this research was not required.

AI Declaration: No AI of any kind was used in the creation of this paper.

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A Physically Unclonable Function Authentication Protocol to Secure IEEE C37.118 Communications

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Abstract: This paper outlines the need for security on the smart grid, specifically for Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDCs). These devices are targeted due to their criticality to the smart grid and the insecure communication protocols used. Common attacks on these devices target the data sent between them. As such, integrity-based attacks are the focus of this paper, more specifically on False Data Injection attacks (FDIAs) and Time Synchronisation Attacks (TSAs). Security solutions are proposed throughout literature from mitigation and protection techniques to detection and resolution techniques. To secure the PMU and PDC, this paper proposes an authentication protocol, utilising Physically Unclonable Functions (PUFs). PUFs are utilised to ensure device-specific authentication, in addition to the use of other cryptographic techniques including fuzzy extractors, nonces, encryption algorithms, and identifiers. A testbed was developed, on which the protocol was implemented and tested against the integrity-based attacks, namely FDIA and TSA. Informal and formal security analyses were performed on the protocol, finding that the protocol was secure against multiple attacks, including the FDIA and TSA, and implemented mutual authentication and forward secrecy. The formal security analysis was implemented with Proverif, a software used to prove the security of authentication protocols. The informal security analysis is provided as a logical sequence to prove the protocol's security against attacks and inclusion of security proofs. A performance analysis was performed to ensure the protocol had low enough computation, communication, and storage overheads.

Keywords: Authentication, Phasor measurement unit, Physically unclonable function, Phasor data concentrator, False data injection, Time synchronisation attack

1. Introduction

The International Energy Agency reports that the transmission sector of the smart grid grew by 10% in 2023 globally. The transmission sector is responsible for grid monitoring, transforming, and transmitting energy (IEA, 2025). Phasor Measurement Units (PMUs) are vital to grid stability as the devices provide monitoring of the grid and calculate an estimation of the state of the grid. The data includes current, voltage, frequency, and rate of change of frequency, also known as synchrophasor data. These data are passed to another device, the Phasor Data Concentrator (PDC), which checks the integrity of the synchrophasor packets and aligns the packets via timestamp, vital for state estimation (Paramo et al., 2022). The PMU and PDC are connected within the smart grid for bidirectional communication, making up the Wide Area Management System (WAMS) (Paramo et al., 2022), pictured in Figure 1. The PMU and PDC can communicate through different protocols, the main one being a plain-text protocol, IEEE C37.118 synchrophasor protocol. Due to the nature of plain-text protocols, devices communicating become susceptible to multiple vulnerabilities, for instance cyber-attacks (Cheng et al., 2023).

Common attacks targeting message integrity include data spoofing, injection, and replay attacks (Hasan et al., 2024). Confidentiality and availability are targeted with attacks such as Man-In-The-Middle (MITM) and Denial of Service (DoS). Other attacks that can impact the WAMS include Time Synchronisation Attacks (TSAs) and physical attacks (Nazir et al., 2025). False Data Injection Attacks (FDIAs) and TSAs are two attacks that can cause large impacts on the system (Sanati and Kamwa, 2023). Due to these attacks, security solutions are proposed in literature to safeguard systems. These solutions include authentication, encryption, key distribution schemes (KDSs), and digital signatures. These solutions focus on creating keys, identities, and cipher-text to mitigate attacks (Anantharaman et al., 2018, Hussain et al., 2022). Machine learning (ML) is another solution proposed for mitigation of cyber-attacks but can also be utilised for detection. ML techniques have been used to improve intrusion detection systems, existing authentication systems, and securing the data collected from smart grid devices (Nayak et al., 2023).

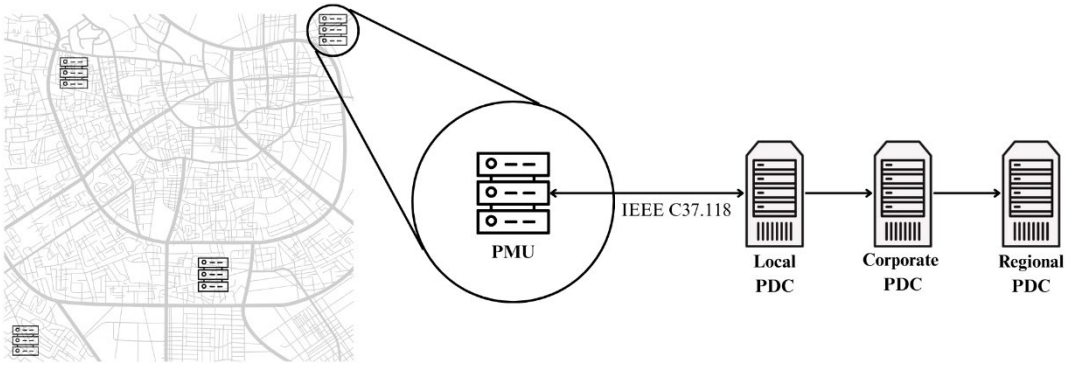


Figure 1: Basic WAMS layout demonstrating the communication between devices

Existing literature proposed solutions to secure the communication between PMU and PDC and its data. These solutions include security filters (Anantharaman et al., 2018), KDSs (Hussain et al., 2022, Farooq et al., 2023), ML (He et al., 2022), and data source authentication (Cui et al., 2021). All these solutions focus on securing the devices in different ways, for example, KDSs create a shared session key between devices. Security filters focus on detecting attacks within the network by searching the communications. Data source authentication methods detect spoofing attacks by checking the data for any modifications.

The goal of this paper is to propose an authentication protocol that can protect PMU and PDC communication against attacks, while achieving mutual authentication and creating a shared session key. The aim of the protocol is to specifically secure against FDIAs and TSAs since they can cause a large impact on the system. The authentication will prevent the FDIAs and TSAs while keeping the communication fast and reliable. The main contribution of this paper is an authentication protocol and analyses, including informal, formal, and performance. The protocol utilises Physically Unclonable Functions (PUFs) amongst other cryptographic techniques to achieve mutual authentication. A weak and a strong PUF are utilised as well as encryption, hash functions, XORs, nonces, and timestamps. The informal security analysis reveals the protocol to mitigate against, FDIA, TSA, replay, DoS, and physical attacks. The formal security analysis is performed with Proverif, indicating the protocol is secure. The performance analysis calculates the performance, outlining low computation, and small communication and storage overheads. The rest of this paper is formatted as follows: Section 2 covers the related works; Section 3 outlines the background; Section 4 outlines the proposed protocol; Section 5 describes the implementation of the protocol on a testbed; Section 6 provides the analyses; and Section 7 concludes this paper.

2. Existing Literature

Some existing works propose authentication protocols and other techniques for securing PMUs and WAMS. Anantharaman et al. (2018), created a security filter for IEEE C37.118 to parse frames to distinguish between the current message and previous messages. The purpose of their filter, PhasorSec, is to identify and remove any packets that may have been compromised. Their work mentions the fact that FDIAs are not protected against with PhasorSec, although their protocol could be extended with other techniques, to protect against such attacks.

Two papers create security solutions like KDSs to secure the PMU data when communicating between devices. Message authentication codes and certificate authorities are utilised in one scheme, testing the scheme on an experimental setup to find the size of the synchrophasor packet is impacted. This scheme is created to mitigate against attacks on IEEE C37.118 (Hussain et al., 2022). The following scheme is created to secure data and authenticate devices using the IEC 61850-90-5 communication protocol. This scheme is tested against TLS 1.2 and 1.3, finding 1.3 to be more efficient (Farooq et al., 2023). Neither of these papers record attacks secured by the proposed schemes. Two papers utilised existing techniques to secure PMU data and communications. Qiu et al. (2012) use cryptographic algorithms to secure communications of PMU and smart meters (SMs). While He et al. (2022) use existing ML methods to authenticate PMU data. They found that Continuous Wavelet Transforms with Convolution Neural Network performed the best. Javed et al. (2024) proposed a data provenance protocol that uses PUFs and quantum principles. The attack focused on within the security analysis was MITM attack. Hussain (2026) created a security scheme that makes use of digital signatures across IEEE C37.118. Performance analysis is calculated; however, a full security analysis is not performed. Table 1 outlines

the above papers, the techniques used to secure PMUs, the attacks mentioned within the paper to be secured, and the security proof claimed within the paper.

Table 1: Proposed authentication protocols in recent literature

Reference	Techniques	Attacks	Proofs
(Anantharaman et al., 2018)	Frame Filter	AFL Fuzzer	N/A
(Hussain et al., 2022)	Certificates, Key Distribution, Encryption, Hash Functions	N/A	Confidentiality, Integrity
(Qiu et al., 2012)	Encryption	N/A	Increased Energy Efficiency
(Farooq et al., 2023)	Key Distribution, Certificates, Encryption	N/A	Improved Security, Performance
(He et al., 2022)	Machine Learning	N/A	Accuracy, Predict Time, Pre-process Time
(Javed et al., 2024)	Hash Functions, PUFs, Quantum Unreality, Quantum Uncertainty	MITM	Privacy, Unpredictability
(Hussain, 2026)	Signatures, Hash Functions, Encryption	N/A	Message Integrity
This paper	Hash Functions, XOR PUFs, Encryption, Fuzzy Extractor	FDIA, TSA, Replay, DoS, Physical	Mutual Authentication, Forward Secrecy

The following papers all propose methods for synchrophasor data source authentication. The algorithms are created to protect against data spoofing attacks by detecting modifications in the data source information. Different ML and deep learning algorithms are utilised to achieve the data source authentication. Existing methods include “Mathematical Morphological Decomposition and Multi-Weighted Deep Stacking Forest” (Cui et al., 2022), “Multiscale Adaptive Coupling Correlation Detrended Analysis” (Bai et al., 2023), Quadratic Kernel Support Vector Machine (Liu et al., 2022b), “Self-Adaptive Mathematical Morphology and Time-Frequency” (Cui et al., 2021). While these papers help to secure the PMU data, they are not achieving the same communication security as proposed in this paper.

3. Background

The smart grid consists of different systems to generate, distribute, and transmit energy and information. There are two main systems for monitoring the energy distributed across the grid and they are Supervisory Control and Data Acquisition (SCADA) system and WAMS. The SCADA system utilises devices such as intelligent electronic devices or remote terminal units to gather grid data. The SCADA reports at a rate of every two to five seconds, reporting active/reactive power information such as power injections and flows, they also report on voltage magnitudes. The WAMS monitors the voltage, current, frequency, and rate of change of frequency, and consists of PMUs and PDCs. The PMUs report anywhere between five to 60 data scans every second. The PMUs capture this information from the grid and pass this data onto the PDC. The PDCs then collate this data, ordered by time, and either analyse the data or transfer it onto the next PDC. Some PDCs have the capability to analyse the synchrophasor data, while others simply collate, align, and store the information (Cheng et al., 2023). The communication focus of this paper is between the PMU and PDC.

3.1 Communication of PMU and PDC

There are two main protocols that have been used for synchrophasor communication, the first was IEEE 1344, which was replaced by IEEE C37.118 in 2011 (Grewal et al., 2014). The IEEE C37.118 protocol is the focus for this paper due to its popularity. The protocol uses TCP as a base, consists of five fields within the header, and has three frame types. The configuration frame is sent at the beginning of communication between the PMU and PDC to outline the structure of the data frame. The command frame contains information instructing the PMU of an action, for example, sending configuration frame or starting data transmission. The data frame has seven fields and sends the data collected from the grid. The data frame is the main frame needing to be secured as it is transferring energy information in plain-text across the network. Figure 2 shows the fields of the IEEE C37.118 protocol.

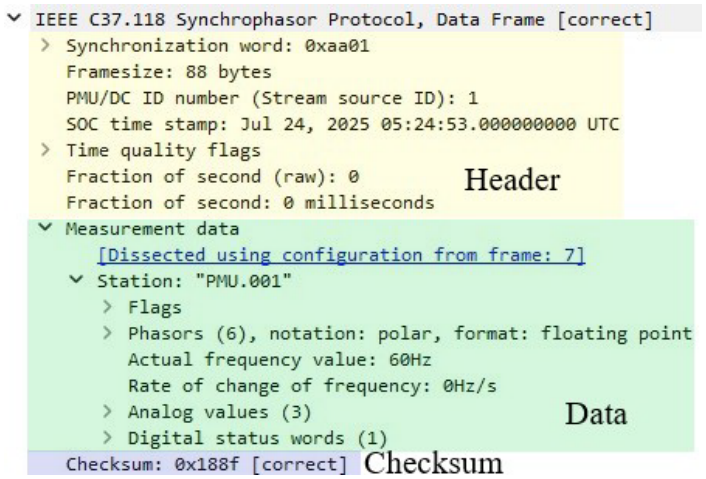


Figure 2: Wireshark capture of IEEE C37.118 data frame

The IEEE C37.118 communication protocol is wrapped with TCP/IP, thus when the PMU sends synchrophasor data the PDC sends back an acknowledgment.

3.2 Vulnerabilities of IEEE C37.118

An adversary that gains access to the smart grid network, can view the synchrophasor data being sent across the network. Many attacks can be targeted towards the communication between the PMU and PDC, impacting the confidentiality, integrity, or availability of the grid. Confidentiality is impacted when the adversary gains access to the network and views the data being sent, for example, MITM. Integrity is impacted when the data being passed across the network is modified or removed, such as a FDIA (Sanati and Kamwa, 2023). Availability is impacted when the system is shut down, such as a DOS. The most common attacks mentioned in recent literature includes, MITM, FDIA, spoofing, DOS, and replay attacks (Amanlou et al., 2025). The attack focus of this research is FDIAs and TSAs. TSAs can impact the performance of the system and cause incorrect actions to be taken by misguiding operators (Zhang et al., 2013). FDIAs situational awareness of the smart grid through modifying PMU data measurements (Sanati and Kamwa, 2023).

4. Proposed Protocol

This section outlines the authentication protocol, describing the components, and the different phases.

4.1 Preliminaries

4.1.1 Physically unclonable functions

PUFs are typically sorted into two categories, strong and weak. A strong PUF is defined as a security parameter that can grow to be quite large. If the PUF does not have this capability, then it is considered weak (Armknecht et al., 2011). Weak PUFs are typically used as keys while strong PUFs used for authentication. However, strong PUFs are susceptible to ML attacks, while weak PUFs are not (Santiago et al., 2017). Therefore, for the proposed protocol, we utilise both PUFs. The protocol makes use of one weak PUF, PUF_W and one strong PUF, PUF_S. The PUF_W is used as the key for encryption during the authentication phase of the protocol. PUF_S and PUF_W are used as part of the session key for encryption once the PMU and PDC have been authenticated. The PUFs require a challenge to output a response, the equation is written as: $PUF_X(Ch_X) = R_X$.

4.1.2 Fuzzy extractor

The protocol uses fuzzy extractors to ensure the noise from the response does not impact the protocol. The fuzzy extractor uses generation and reproduction algorithms. Generation is run first to get the helper data, hd_X, and the key, K_X. The generation algorithm for the fuzzy extractor is written as: $FE.Gen(R_X) = K_X, hd_X$. The reproduction algorithm is run each time a stored response is retrieved or regenerated to dissipate the noise and get the K_X. The reproduction algorithm is written as: $FE.Rep(hd_X, R_X) = K_X$.

4.1.3 Other cryptographic primitives

The protocol employs other cryptographic techniques to strengthen the security. These techniques include, hash functions, XORs, nonces, and timestamps. Timestamps are used to ensure the messages do not go through

another path on their transit to the other device. Hash functions, XORs, and nonces are used to make the messages difficult to interpret by an adversary. The protocol also utilises an encryption algorithm to securely send data between the PMU and PDC.

4.2 Authentication Protocol Phases

The proposed authentication protocol is made up of two phases, namely, initialization and authentication. The initialization phase generates initial challenge, response, and helper data to be stored with the PDC and PMU. The authentication phase allows the devices to create a shared session key allowing for encryption.

4.2.1 Initialisation phase

This phase sends the challenge to the PMU through a secure channel, with the response used with the fuzzy extractor generation algorithm to store the helper data at the PMU. The PMU ID, response, challenge, and helper data are all sent to the PDC through a secure channel. Figure 3 shows the steps for the initialisation phase.

Algorithm 1 – Name of Protocol – Initialisation Phase
PDC_x:
Challenges, Ch_s and Ch_w are generated.
Challenges are sent to the PMU via a secure channel.
PMU_y:
Strong response is calculated $R_s = PUF(Ch_s)$
Strong helper data, hd_s, and key is calculated, $FE.Gen(R_s)$
Weak response is calculated $R_w = PUF(Ch_w)$
Weak helper data, hd_w, and key is calculated, $FE.Gen(R_w)$
PMU retrieves its own ID, ID_y.
Helper data is stored.
Challenges, responses, helper data, and ID is sent to the PDC via a secure channel.
PDC_x:
Challenges, responses, helper data, and ID is stored.

Figure 3: Algorithm of initialisation phase of proposed protocol

4.2.2 Authentication phase

The authentication phase is initiated every time communication between the PMU and PDC is requested. This phase results in a shared session key between the PMU and PDC allowing for the PMU data to be encrypted. To mutually authenticate, verifiers are used to confirm the identity of each device, while timestamps are used to ensure the communication has not been intercepted on transit. The session key is created from components used throughout the phase. Figure 4 shows the steps for the authentication phase.

5. Implementation

The testing of the proposed authentication protocol was performed by implementing the protocol on a testbed. This section discusses the testbed, the attacks on the testbed, and the protocol performance.

5.1 Testbed

The testbed was formed to view, attack, and protect the IEEE C37.118 protocol. The PMU and PDC are formed from simulators, on a Raspberry Pi (RPi) and Dell PC, respectively, and communicate using a wired connection through a router. Other components include two other RPis that launch an attacker and a time server. The first stage was to set up the communication between the PMU and PDC, ensuring the two devices were communicating via IEEE C37.118. Once this communication was established, the time server was added to grab the time via GPS and pass that time onto the PMU and PDC devices through the Network Time Protocol (NTP).

Algorithm 2 – Name of Protocol – Authentication Phase	
PDC_x	**PMU_y**
Timestamp, T_1, and nonce, r_1, are generated.	
Challenges, Ch_w, Ch_s, Helper data, hd_w, hd_s, Responses, R_w, R_s, and ID_p are retrieved from storage.	Timestamp, T_2, and nonce, r_2, are generated.
	Helper data, hd_w, hd_s, retrieved from storage.
Nonce share, N_1 is calculated by $ID_p \oplus r_1$	ID_p is retrieved and hashed, ID_h
Key, K_w, is produced with the fuzzy extractor, $FE.Rep(hd_w, R_w) = K_w$	$ID_h \oplus H_1$ to get Ch_w
	Response, R_w is calculated $PUF(Ch_w)$
Message, M_1, is created with the encryption algorithm and K_w, $E_{Kw}(T_1 \mid N_1 \mid Ch_s)$	Key, K_w is calculated with $FE.Rep(hd_w, R_w)$
	M_1 is decrypted, $D_{Kw}(M_1)$ to get T_1, N_1, Ch_s
Hashed message, H_1, created by $h(ID_p) \oplus Ch_w$	T_1 is checked against T_2, if too far apart, messages may be intercepted, communication terminated.
M_1 and H_1 are sent to the PMU_y	
	Response, R_s is calculated $PUF(Ch_s)$
	Key, K_s is calculated with $FE.Rep(hd_s, R_s)$
	Nonce, r_1, is retrieved by $ID_p \oplus N_1$
	Verifier 1, V_1, is formed with $h(K_s \mid ID_p \mid r_1)$
	Message 2, M_2, is created with the encryption algorithm and K_w, $E_{Kw}(r_2 \oplus ID_p \mid V_1 \mid T_2)$
	M_2 is sent to the PDC_x
Timestamp, T_3, is generated.	
M_2 is decrypted, $D_{Kw}(M_2)$ to get T_2, V_1, H_2	
T_2 is checked against T_3, if too far apart, messages may be intercepted, communication terminated.	
	Timestamp, T_4, is generated.
Key, K_s is calculated with $FE.Rep(hd_s, R_s)$	M_3 is decrypted, $D_{Kw}(M_3)$ to get N_2, T_3
V_1, is verified by PDC_x calculating $V_1' = h(K_s \mid ID_p \mid r_1)$ and comparing V_1 and V_1'	T_3 is checked against T_4, if too far apart, messages may be intercepted, communication terminated.
H_2 is xored with ID_p to get nonce, r_2	
Verifier 2, V_2, is formed with $h(r_2 \mid ID_p \mid r_1)$	$N_2 \oplus r_2$ to get V_2
Message 3, M_3, is created with the encryption algorithm and K_w, $E_{Kw}(V_2 \oplus ID_p \mid T_3)$	V_2, is verified by PDC_x calculating $V_2' = h(r_2 \mid ID_p \mid r_1)$ and comparing V_2 and V_2'
Session Key, SK, is created $h(r_2 \mid ID_p \mid K_w \mid K_s)$	Session Key, SK, is created $h(r_2 \mid ID_p \mid K_w \mid K_s)$
Message 4 is created to obtain new strong challenge, $E_{SK}(Ch_{sx})$	M_4 is decrypted, $D_{SK}(M_4)$ to get Ch_{sx}
	New s-response is calculated $R_{sx} = PUF(Ch_{sx})$
M_3, M_4 are sent to the PMU_y	New helper data, hd_{sx}, and key is calculated, $FE.Gen(R_{sx})$
	M_5 is created with SK, $E_{SK}((R_{sx}, hd_{sx}) \oplus r_1)$
	M_5 is sent to PDC_x
Ch_{sx}, R_{sx}, hd_{sx} are stored.	

Figure 4: Algorithm of authentication phase of proposed protocol

5.2 Attacks

The attacks on the testbed were set up using a Python script to intercept the plain-text traffic. The attacks that were chosen were FDIA and TSA. The first attack to be implemented was the TSA. A Python script for NTP spoofing was retrieved online from GitHub. This script was modified to work with the devices and the testbed network. This attack targeted the communication between the time server and the PMU, to modify the PMU's time. Modifying the time incorrectly ordered the measurements when collated by the PDC. The FDIA was next, and this was implemented by modifying the script for the NTP spoofing attack. The attack targeted the plain-text within the IEEE C37.118 protocol to modify the frequency that was recorded by the PMU. The frequency was modified in between the PMU and PDC, so the PMU reported the correct value, but the incorrect value reached the PDC.

5.3 Experimental Analysis

The protocol was developed in Python, with scripts in between the two simulators. The scripts would listen for the devices and when they connected the authentication protocol would be run. If the protocol was successful in mutual authentication then the simulators could connect, and the data was encrypted with the shared session key. If the verification was not mutually successful, the script would terminate communication. The FDIA was unable to be executed as the synchrophasor data was encrypted. The TSA failed as the authentication protocol checks timestamps, if the PMU time was changed the authentication protocol would terminate.

6. Protocol Analysis

6.1 Informal Security Analysis

6.1.1 False data injection attacks

The objective of the adversary in a FDIA is to modify data as it is passed across the network to make the receiving device misjudge the data. Since the PMU and PDC communicate bi-directionally, the adversary can target either communication from PDC to PMU or PMU to PDC. However, the protocol utilises encryption and hash functions, so if the adversary modifies the data being sent, the messages will not be decrypted properly. If the verifier gets modified the protocol will end communication since the verifiers do not match. Thus, making the FDIA unsuccessful.

6.1.2 Time synchronisation attacks

The objective of the adversary in a TSA is to misguide communications and information by modifying the timestamp of a device. The synchronisation of PMUs is vital to measure phasor data across multiple PMUs. However, the authentication protocol uses timestamps to check the validity of the messages, so if the timestamps are modified, communication will be disconnected. Thus, making the TSA unsuccessful.

6.1.3 Other attacks

The objective of the adversary when executing a replay attack is to send previously sent messages to gain access to the device. However, the protocol implements the use of rotating keys and nonces, so if an old message is sent to either device, communication will be terminated based on incorrect data being received. Thus, making the replay attack unsuccessful. The objective of the adversary during a DoS attack is to send so many messages to an entity on a network that the computation power is overtaken, and they cannot receive the legitimate messages sent. Since the authentication protocol terminates communication if a message comes through that is incorrect, the DoS attack will be unsuccessful. The objective of the adversary in a physical attack is to physically gain access to the device through proximity rather than remotely. With the use of PUFs, the PMU is not at risk if physically apprehended since the PMU does not store the responses from the challenges. Thus, making the physical attack unsuccessful.

6.1.4 Security criteria

Mutual authentication is the process of the devices authenticating one another. This is vital for the PMU and PDC communication since they communicate to each other. The verifiers in the protocol allow for this. The verifier for the PMU is the hash of $h(K_S, ID_P, r_1)$, the key and nonce are different each time the protocol runs, so the verifier cannot be recorded. The verifier for the PDC is the hash of $h(r_2, ID_P, r_1)$, both nonces change each iteration of the protocol, so the verifier cannot be recorded. Forward secrecy means that if the session key is obtained by an adversary, it does not reveal anything about future session keys or is not a future session key. The session key of this protocol is the hash of $h(r_2, K_S, ID_P, K_W)$, the contents of the session key cannot be revealed as they are securely hashed; the nonce and keys are changed each iteration of the protocol so the session key cannot be recorded.

6.2 Formal Security Analysis

This section outlines the use of a software that confirms secrecy of protocol variables and verifies the protocol's ability to confirm values that are received. Proverif is based on the Dolev-Yao model that allows users to write out the logic for their authentication protocol to prove values are kept secret throughout communication. There were three variables we did not want the attacker to learn while the protocol was running. They were the ID and the two PUF responses, weak and strong. In the Proverif logic, we queried these variables to ensure their secrecy would not be impacted during the protocol's runtime. Proverif was also used to ensure the two devices authenticated one another, Firstly, in the logic, by ensuring the event of the PDC authentication occurred after the PMU started authentication (and vice versa); secondly, with a query to make sure that anytime the PDC accepts a message from the PMU there is a prior occurrence of the PMU sending the exact message (and vice versa). The Proverif logic was run to find that the attacker cannot learn the PMU ID, or responses of the PUFs, the main sources of secrecy. The other piece of information confirmed in Proverif was that the PMU and PDC authenticated one another properly, and the timestamps were accepted correctly. Figure 5 shows the verified outcome from Proverif.

```
------------------------------------------------------------
Verification summary:

Query not attacker(ID) is true.

Query not attacker(Rw[]) is true.

Query not attacker(Rs[]) is true.

Query inj-event(BAuthed) ==> inj-event(AStarted) is true.

Query inj-event(AAuthed) ==> inj-event(BStarted) is true.

Query inj-event(B_accepts_T(x)) ==> inj-event(A_sends_T(x)) is true.

Query inj-event(A_accepts_T(x)) ==> inj-event(B_sends_T(x)) is true.

------------------------------------------------------------
```

Figure 5: Verification summary from Proverif

6.3 Performance Analysis

6.3.1 Execution time

The computation time was recorded within the Python script, however due to Python's low computational power, these numbers were heightened significantly. The cryptographic primitives such as XOR and hash functions are recorded normally, but the cryptographic algorithms such as fuzzy extractor are much larger. Since these cryptographic algorithms are not recorded as in a real-world scenario, execution times as recorded by other papers are used (Liu et al., 2022a, Kaveh et al., 2023, Hussain et al., 2022). Figure 6 shows the final times as a combination of times recorded by Python for the primitives and normalised times based on other papers for the techniques.

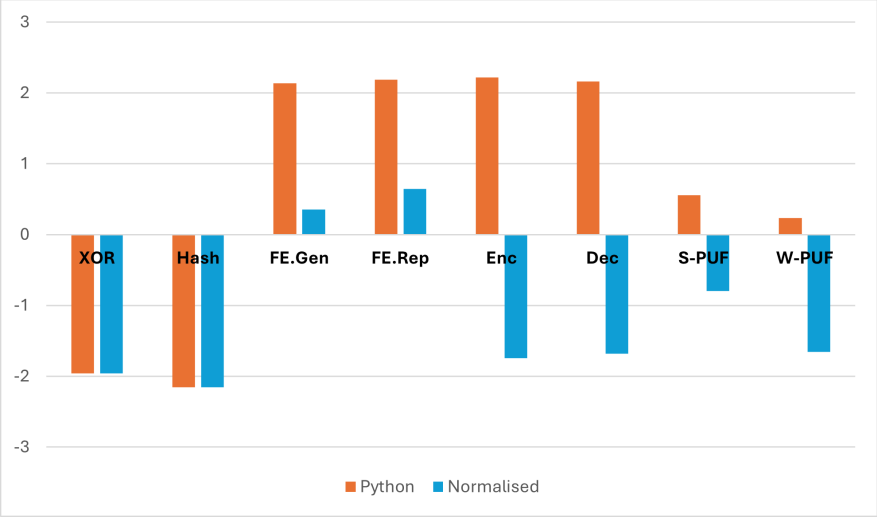


Figure 6: Logarithmic execution times of cryptographic techniques, Python vs normalised

6.3.2 Communication overhead

The communication measurement was calculated based on the number of bits sent over the course of the protocol. Figure 7 outlines the bits for each message sent across the protocol. The total bits are calculated based on the size of the messages sent, calculated from the cryptographic primitive sizes. The total size for all messages totalled to 200 bytes.

6.3.3 Storage overhead

The storage overhead is only calculated for the PMU device, since the PMU is the storage constrained device. The only things the PMU needs to store is the helper data for the strong and weak PUFs. The helper data, amounts to 16 bits each, making the total storage cost for the PMU is 4 bytes.

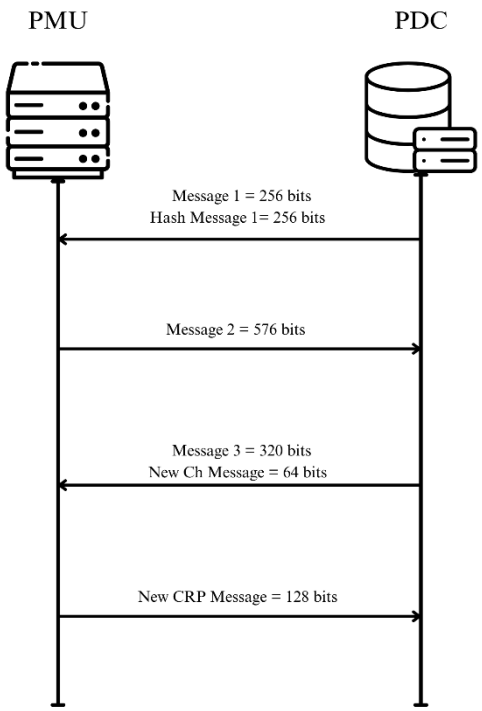


Figure 7: Messages in bits sent between devices

7. Conclusion

PMUs are vital devices for the smart grid to estimate the current state of the grid. They report the data of the grid to the PDC through a plain-text, insecure communication protocol. This makes the devices vulnerable to cyber-attacks, such as FDIAs and TSAs. This paper proposes an authentication protocol to protect the devices against such attacks. The protocol utilises PUFs to ensure the PMU does not have to store much data or use too much computational power. The protocol is analysed through a formal and informal security analysis and a performance analysis. It is found that the protocol is secure against multiple attacks, verifiably secure, and lower on computation, communication, and storage costs.

Acknowledgements

This research was supported by the Commonwealth through an Australian Government Research Training Program Scholarship.

Ethics declaration: Ethical clearance was out-of-scope as no humans, human data, or animals were used in the research.

AI declaration: AI was not used in the creation of this paper.

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The CTI Oligopoly's Contractual Firewall: Restrictive Licensing as a Structural Barrier to Collective APT Defence

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Abstract: Cyber threat intelligence (CTI) is widely promoted as indispensable for modern cyber defense, yet collective defense in practice is constrained by market concentration and restrictive licensing imposed by a small number of dominant vendors. This study analyses 34 publicly available documents; licence agreements, terms of service, API documentation, and pricing materials, across 15 major commercial CTI providers. Following a thematic analysis approach, we code restrictions across six dimensions: (1) access pathways and subscription gating, (2) redistribution and collaboration rights, (3) automation interfaces and rate limits, (4) portability and interoperability, (5) pricing transparency and contract flexibility, and (6) geographic and jurisdictional constraints. Findings confirm a highly concentrated oligopolistic market in which the top five to ten vendors control an estimated 50–80% of global revenue and a disproportionate share of APT telemetry. Recent consolidation, including Mastercard's USD 2.65 billion acquisition of Recorded Future in December 2024, further reinforces this concentration. Licence terms systematically prohibit redistribution to third parties, constrain automation through non-cumulative quotas and unstable APIs, and obscure pricing behind enterprise sales funnels. These patterns constitute what we term a *contractual firewall*, a structural barrier that prevents threat intelligence from flowing between defenders even where policy frameworks encourage sharing. The contractual firewall creates asymmetries in defensive capability that disproportionately affect SMEs, public-sector entities, and sector consortia. These constraints do in some instances conflict with European collective defense mandates like NIS2, but fundamentally fragment the defender ecosystem, leaving smaller entities vulnerable to sophisticated threat actors. We suggest some procurement-focused recommendations for redistribution carve-outs, export and portability requirements, API stability guarantees, and multi-source resilience strategies. Future work should validate these patterns against negotiated enterprise terms and assess operational impact in incident response environments. We conclude that resource-constrained defenders facing APTs are caught in a systemic double bind: the 'contractual firewall' restricts the intelligence access necessary for pro-active defense, while regulatory frameworks like NIS2 impose sharing mandates that these commercial restrictions effectively render impossible to fulfill.

Keywords: CTI, Threat intelligence, AI

1. Introduction

Cyber threat intelligence (CTI) is widely marketed as the missing component that makes detection and response effective at scale. In practice, CTI is embedded in complex socio-technical systems where information must be shared, integrated, and acted upon in real-world defensive workflows.

This paper investigates whether publicly available materials from commercial CTI providers, including license agreements, terms of service, API documentation, and pricing information, reveal patterns of market concentration and how these patterns affect collective defense against

APTs. It examines constraints across six operationally relevant dimensions: (i) access pathways and subscription gating, (ii) redistribution and collaboration rights, (iii) automation interfaces and rate limits, (iv) portability and interoperability, (v) pricing transparency and contract flexibility, and (vi) geographic and jurisdictional constraints.

Based on these dimensions, the paper demonstrates that the CTI market exhibits a set of systemic barriers that are incompatible with mandates for collective defense, such as those reflected in the EU NIS2 Directive (NIS2). (European Union, 2022)

The analysis is limited to publicly accessible documents captured between January and October 2025 and does not assess detection efficacy or indicator quality.

Contribution. The paper contributes three elements: (i) a conceptual framing of a "contractual firewall" as a systemic barrier to CTI sharing, (ii) an empirical analysis of 15 leading providers based on public documents, and (iii) practical procurement guidance aimed at mitigating lock-in and enabling collective defense.

To structure the investigation, we pose three research questions:

RQ1: What patterns of market concentration are visible in the commercial CTI landscape based on publicly available contractual and technical materials?

RQ2: How do access terms, redistribution rights, and automation constraints influence the practical use of CTI in operational security processes?

RQ3: What are the implications of these patterns and terms for European collective defense and policy goals, such as those reflected in the EU NIS2 Directive (NIS2)? (European Union, 2022)

Structure of the paper. Section 2 provides background and defines the scope; Section 3 reviews related work; Section 4 describes the method; Section 5 presents the main findings; Section 6 discusses practical and policy implications; Section 7 offers recommendations for procurement teams; Section 8 addresses limitations and future work; Section 9 concludes.

2. Background and Scope

Commercial cyber threat intelligence (CTI) supports organizations by providing indicators of compromise (IoCs), actor tracking, detection logic, and contextual analysis. It is positioned as a crucial layer for defending against advanced persistent threats (APTs) which are long-lived, cross-border by nature, and often exploit asymmetries between national and commercial defenders.

At the policy level, European frameworks increasingly emphasize information sharing and cooperative resilience. The EU NIS2 Directive (Directive (EU) 2022/2555) strengthens obligations for incident reporting, risk management, and cross-sector cooperation, and it encourages voluntary information-sharing arrangements (Article 29). (European Union, 2022)

This paper focuses on the intersection between these policy aims and the commercial CTI market. It treats licensing terms, access pathways, and technical integration constraints as first-order determinants of whether organizations can participate effectively in collaborative defense.

3. Related Work

The intersection of commercial CTI markets and collective defense has received limited systematic attention in the academic literature, though related threads of research inform this study.

3.1 CTI Quality and Operationalization

Research on CTI quality has established frameworks for evaluating intelligence outputs. Schlette et al. (2020) developed metrics for measuring and visualizing CTI quality, highlighting the gap between raw indicators and actionable intelligence. Böhm et al. (2018) introduced graph-based visual analytics approaches for CTI, enabling analysts to identify patterns across large indicator sets. More recently, Chatziamanetoglou and Rantos (2025) proposed weighted quality criteria for CTI assessment within the MISP data model, demonstrating ongoing efforts to standardize evaluation.

Systematic reviews have mapped the broader CTI landscape. Saeed et al. (2023) establish that organizational cybersecurity resilience depends critically on timely access to high-quality threat intelligence, a dependency that becomes problematic when access is constrained by commercial terms. Aboelfotoh et al. (2025) examine the role of artificial intelligence in enhancing threat detection, noting that AI-driven capabilities are increasingly concentrated in well-resourced commercial platforms.

3.2 Information Sharing and Collective Defense

The theoretical case for threat intelligence sharing rests on classic public goods arguments: threat information is non-rivalrous and exhibits positive externalities when shared. CISA's evolving approach emphasizes "threat-informed cybersecurity" enabled by rapid dissemination (Cybersecurity and Agency, 2023). Similar principles underpin sectoral sharing organizations (ISACs) and coordinated disclosure frameworks (Alliance, 2025). The MITRE framework for world-class security operations centers identifies threat intelligence integration as a core capability (MITRE, 2022), yet assumes access to quality intelligence sources without examining the contractual barriers that may prevent such access.

3.3 Market Structure and Policy Frameworks

The global threat intelligence market has attracted significant analyst attention. Multiple market reports estimate 2025 valuations between USD 6–15 billion with double-digit growth rates (MarketsandMarkets, 2025; Research, 2025b; Intelligence, 2025; Insights, 2025). Industry analyst reports consistently identify a small set of dominant vendors (Research, 2025a; Gartner, 2025; Exabeam, 2025), but systematic analysis of how their contractual terms affect collective defense remains scarce.

European policy frameworks increasingly mandate information sharing and cooperative resilience. The EU NIS2 Directive (Article 29) encourages voluntary cybersecurity information-sharing arrangements, while Article 21 requires essential entities to implement risk management measures that implicitly depend on access to timely threat intelligence (European Union, 2022). The ENISA Threat Landscape provides annual assessments of the evolving threat environment (ENISA, 2025), and the World Economic Forum highlights the widening gap between well-resourced and under-resourced defenders (Forum, 2025).

This policy-market tension, where mandates assume shareable intelligence while commercial terms prohibit sharing, forms the empirical focus of our analysis.

4. Method

We conducted a document analysis of 34 publicly accessible documents covering 15 commercial CTI providers, following a thematic analysis approach (Braun and Clarke, 2006). Data collection occurred between January and October 2025.

4.1 Material Collection

Commercial CTI providers were identified using a combination of industry reports, market ana-lyses, and public directories, including Gartner Magic Quadrant for Security Threat Intelligence Services, Forrester Wave for External Threat Intelligence, and vendor aggregators (Gartner, 2025; Research, 2025a; G2, 2025; Capterra, 2025). Providers were selected based on market prominence, visibility in European procurement, and availability of publicly accessible licensing documentation. The selection focused strictly on dedicated CTI products, excluding generalist cybersecurity firms lacking specific intelligence offerings. Table 1 lists the analyzed providers.

Data collection was conducted manually, utilizing exclusively publicly accessible documents (licence agreements, terms of service, datasheets, API documentation, and pricing pages where available) retrieved via direct website navigation without authentication or paid access. Document types were limited to those detailing CTI features, contractual terms, and technical specifications.

4.2 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were defined to ensure relevance and reproducibility, aligning with established practices in cybersecurity systematic reviews (Saeed et al., 2023; Aboelfotoh et al., 2025).

Included: Provider-facing materials published or updated within the study window that ex-plicitly address the six operational dimensions: access pathways, redistribution rights, automation interfaces, portability/interoperability, pricing transparency, and geographic constraints.

Excluded: (1) Non-public or customer-only materials; (2) evaluations of technical detection efficacy; (3) reverse engineering of content or APIs; (4) unverifiable claims not grounded in documents; and (5) general marketing materials lacking specific contractual terms (Aboelfotoh et al., 2025; Böhm et al., 2018).

4.3 Analysis Procedure

The analysis followed a structured, multi-stage workflow resembling an expansion-contraction model, designed to manage the complexity and volume of the dataset (Braun and Clarke, 2006). **Phase 1: Domain Scoping and Selection.** Initially, we established a baseline understand-ing of the CTI landscape through a review of general industry reports and market definitions.

This phase focused on identifying key market players and establishing the six operational dimen-sions for analysis, effectively framing the scope before engaging with the high-volume vendor documentation.

Phase 2: Corpus Expansion and Deep Analysis. The core analysis involved a significant expansion in data volume, ingesting 34 specific vendor documents (licenses, API references, pricing models). Given the density of this legal and technical material, we employed digital text analysis tools to cross-validate findings across the vendor pool. This "all-against-all" verification ensured that identified restrictions were not isolated anomalies but systemic patterns within the oligopoly.

Phase 3: Normative Synthesis. Finally, the analysis converged by mapping the validated vendor constraints against specific problem-oriented frameworks, primarily the EU NIS2 Directive and CISA sharing guidelines. This phase focused on interpreting the operational impact of the identified restrictions specifically within the context of collective defense mandates.

5. Findings

5.1 Market Structure and Concentration Signals

Multiple market intelligence reports estimate the global CTI market in 2025 at USD 9–17 billion and growing at high single to double-digit rates (MarketsandMarkets, 2025; Research, 2025b;

Intelligence, 2025; Insights, 2025). Across these reports, the top vendors are consistently ranked with a substantial share of revenue concentrated in a small set of providers. Estimates vary but commonly place the top five to ten vendors at 50–80% of global revenue (MarketsandMarkets, 2025; BitSight, 2025).

The functional implication is that a limited number of platforms control high-volume telemetry, actor tracking, and APT narrative framing. Smaller vendors and community feeds exist (Flare, 2023), but their coverage, automation maturity, and historical depth are limited. Table 1 summarizes the analyzed providers and their restriction patterns.

Table 1: Analyzed CTI Providers and Key Restriction Patterns

Provider	Redistribution	API Limits	Pricing	HQ
CrowdStrike	Prohibited	Rate-limited	Opaque	US
Recorded Future[a]	Prohibited	Quota-based	Opaque	US
Palo Alto Networks	Prohibited	Rate-limited	Opaque	US
Microsoft Defender TI	Limited	Tiered	Partial	US
Mandiant (Google)	Prohibited	Rate-limited	Opaque	US
IBM X-Force	Prohibited	Rate-limited	Opaque	US
Cisco Talos	Prohibited	Rate-limited	Opaque	US
Fortinet FortiGuard	Prohibited	Bundled	Opaque	US
ThreatConnect	Prohibited	Quota-based	Opaque	US
Rapid7	Prohibited	Rate-limited	Partial	US
Group-IB	Prohibited	Negotiated	Opaque	SG[b]
EclecticIQ	Limited	Configurable	Opaque	NL
Sekoia	Limited	Tiered	Partial	FR
Anomali	Prohibited	Rate-limited	Opaque	US
Intel 471	Prohibited	Negotiated	Opaque	US

[A]Acquired by Mastercard (December 2024, USD 2.65B). [B]Relocated headquarters from Russia to Singapore.

5.2 Recent Market Consolidation

Market concentration intensified during 2024–2025 through significant acquisitions. Most notably, Mastercard completed its USD 2.65 billion acquisition of Recorded Future in December 2024, absorbing what had been characterized as "the world's largest threat intelligence company" with over 1,900 clients across 75 countries, including governments of 45 nations and more than half of the Fortune 100 (MarketsandMarkets, 2025). This transaction exemplifies how CTI capabilities are being absorbed into larger financial and technology conglomerates, potentially further consolidating market power and raising questions about long-term pricing and access terms.

5.3 Access Pathways and Subscription Models

Non-trial access to full-featured CTI is directed exclusively through enterprise sales funnels and annual commitments (CrowdStrike, 2025b; Future, 2024). Trial offerings, where available, are generally restricted in scope: limited time, limited content, sometimes community feeds only, and lacking API access or historical data (Microsoft, 2025).

Contractual rigidities create further barriers: minimum contract commitments commonly range from 12 to 36 months, often with automatic renewal clauses (CrowdStrike, 2025c; Future, 2025b). This economic gating is reinforced by explicit messaging that distinguishes large enterprises from SMEs already at the marketing layer.

5.4 Redistribution and Collaboration Rights

Analysis of the license agreements confirms a near-universal restriction on sharing CTI content with third parties, including sector peers, joint ventures, subsidiaries, and external coordination mechanisms. Representative clauses (verbatim or near-verbatim) include:

- Recorded Future (Terms v7.0, Oct 2025): "Customer shall not ... disclose, [...] or use for the benefit of any third party" (Future, 2025b).
- CrowdStrike Falcon Intelligence Terms (2025): "non-exclusive, non-transferable, non-sublicensable license for internal business purposes only" (CrowdStrike, 2025c).
- Palo Alto Networks End User Agreement (2025): "You shall not ... transfer the Software except in accordance with Palo Alto Networks license transfer procedure" (Networks, 2025).
- IBM X-Force Exchange Terms (2025): "Sharing outside of the licensed organization is prohibited unless expressly authorized in writing. (IBM, 2025)"

In practice, these restrictions hinder the creation of shared sector baselines, shared indicator repositories, and defensive collaboration in multi-organization incident response, precisely the activities encouraged under NIS2 Article 29 (European Union, 2022).

5.5 Automation Interfaces and API Constraints

Even where APIs exist, access is often rate-limited, quota-constrained, and governed by terms that restrict automated redistribution, scraping, or bulk extraction (CrowdStrike, 2025a; Future, 2025a; ThreatConnect, 2025). Observed constraints include:

- Hard rate limits and credit-based quotas that reset monthly and cannot be carried over, inhibiting essential retrospective analysis.
- Pagination and query complexity limits that make bulk historical retrieval impractical.
- Schema changes without deprecation periods. Recorded Future and CrowdStrike reserve the right to modify APIs "at any time", increasing integration cost and operational risk (Future, 2025a; CrowdStrike, 2025a).

These patterns make CTI integration less like a stable infrastructure dependency, and more like a fragile vendor-controlled interface.

5.6 Pricing Transparency and Contract Flexibility

Pricing transparency for full-featured CTI offerings is minimal. Procurement teams face "contact sales" funnels and non-disclosed bundles, making it difficult to compare offers and assess switching costs. The only transparent pricing signals found were:

- CrowdStrike Falcon Go (SMB bundle) —USD 59.99/user/year (limited intelligence) (Crowd-Strike, 2025b),
- Microsoft Defender TI Standard —free (community feed only) (Microsoft, 2025),
- Rapid7 Threat Command —"starting at" figures on request pages (Rapid7, 2025).

All other vendors rely on negotiations. Renewal terms and uplift structures can exceed 15–20%, creating budget uncertainty and long-term commitment pressure.

5.7 Geographical and Regulatory Constraints

The market is dominated by U.S.-jurisdiction providers: every large vendor in the sample is U.S.-based or falls under U.S. export control regimes, requiring careful consideration by non-American users regarding data sovereignty and regulatory compliance.

The lack of jurisdictional diversity is notable: based on our document analysis, none of the examined vendors offered a regionally hosted instance of their full CTI platform, forcing defenders to rely on a single legal framework for critical intelligence processing. The two European providers in our sample (EclecticIQ, Sekoia) offer more flexible terms but lack the telemetry depth of their U.S. counterparts.

5.8 Systemic Implications for APT Defence

Taken together, the evidence demonstrates that the commercial CTI market embeds a structural access asymmetry: it concentrates high-value telemetry and actor narratives in a handful of vendors, restricts

redistribution, limits automation, and exhibits opacity around pricing and contract structure. This asymmetry is repeated across contract patterns and technical terms, conflicting with mandates for coordinated, cross-border information sharing (European Union, 2022).

The implications extend beyond individual organizations: when CTI cannot flow between defenders, the ecosystem loses network effects that would otherwise strengthen collective resilience, while threat actors face no equivalent constraints on sharing among themselves (Center for Strategic and International Studies, 2022).

6. Discussion

The preceding analysis indicates what we define as a CTI oligopoly is characterized by concen-trated access, restrictive redistribution rights, and integration constraints. These constraints are not merely legal formalities; they have operational consequences for incident response and collective defense.

6.1 Contractual Firewall as a Coordination Barrier

A contractual firewall emerges when organizations are legally and technically prevented from sharing CTI outputs with trusted peers, sector partners, or coordinating institutions. This firewall is reinforced by non-portable data formats, non-transparent pricing, and asymmetric renewal structures.

The concept parallels established observations in cybersecurity economics: information asymmetries between attackers and defenders are well-documented (Center for Strategic and International Studies, 2022), but less attention has been paid to information asymmetries *among* defenders created by commercial licensing. Where attackers freely share tools, techniques, and target information through underground forums, defenders face contractual prohibitions on equivalent collaboration (ENISA, 2025). The contractual firewall thus represents a structural disadvantage that policy frameworks alone cannot resolve without addressing the underlying market dynamics.

6.2 Implications for SMEs and Public-Sector Defenders

For SMEs and public-sector entities, high subscription costs, limited trial access, and lengthy minimum contract terms can prevent entry into full-featured CTI ecosystems (Forum, 2025). These organizations may remain dependent on community feeds and ad hoc sharing, creating capability gaps relative to large enterprises.

This observation reveals a duality: smaller defenders understand the need for CTI, but lacking economic power, they attempt to build capabilities independently, incurring substantial costs in personnel and skill reallocation that might be more productively deployed in day-to-day security operations. The World Economic Forum has highlighted this widening gap between well-resourced and under-resourced defenders as a systemic risk to global cybersecurity (Forum, 2025).

The implications extend to national security. Public-sector entities responsible for critical infrastructure protection may find themselves unable to access the same intelligence available to private-sector peers, or unable to share threat information received under restrictive licenses with other government agencies (Cybersecurity and Agency, 2023).

6.3 Policy Tension and Cooperative Resilience

NIS2 Article 29 encourages voluntary information sharing and cooperative resilience, specifically enabling exchange of “cyber threats, near misses, vulnerabilities, techniques and procedures, indicators of compromise, [and] adversarial tactics” (European Union, 2022). However, the commercial baseline terms documented here restrict precisely these forms of redistribution and inhibit the development of sector-level shared baselines.

This creates a structural tension: European policy assumes that entities can share threat intelligence within trusted communities, while commercial contracts prohibit such sharing. Organizations complying with vendor terms may inadvertently undermine the cooperative security posture that NIS2 seeks to establish.

Furthermore, since APT actors are sophisticated and employ diverse tactics across campaigns (Gan et al., 2023; Splunk, 2025), effective defense often requires correlating intelligence from multiple sources. Organizations subscribing to a single vendor may develop incomplete threat pictures, potentially creating a false sense of security by addressing only the risks visible through their available intelligence sources. The documented restrictions may thus fragment the defender ecosystem precisely where unity would provide the greatest advantage.

7. Recommendations and Actionable Guidance

Based on the observed contractual and technical constraints, we believe these restrictions can significantly reduce an organization's ability to defend against APTs. We also acknowledge that commercial interests are integral to the specialized CTI market; nonetheless, we offer recommendations that may improve organizational APT defence posture, recognizing that some provisions may be difficult to negotiate in procurement processes.

7.1 Possible advisories for procurement teams and security leaders:

1. **Redistribution carve-out for defence:** Permit sharing of indicators, detections, and analytical findings with trusted partners for defensive purposes, aligning with NIS2 Article 29 information-sharing provisions (European Union, 2022).
2. **Explicit export and portability:** Require bulk export in structured formats, including historical data, with defined frequency and without punitive fees (Alliance, 2025).
3. **API stability and change control:** Include minimum notice periods for breaking changes, versioning guarantees, and rate-limit terms that support automation at scale.
4. **Interoperability commitments:** Require documented integration paths to SIEM/SOAR/EDR tooling, with clear terms for connector usage and third-party enrichment.
5. **Pricing and exit transparency:** Make pricing units, overage costs, and data-retention or egress costs explicit, and require an end-of-contract export clause that remains valid after termination.
6. **Jurisdiction and data residency:** Specify geographic restrictions, data residency options, and any limitations on cross-border operational use of CTI outputs.
7. **Operational minimums:** Define minimum deliverables to better implement the CTI platform output into your security operations.
8. **Multi-source resilience:** Where feasible, design for at least one secondary CTI source or community feed to reduce single-vendor dependency and to have the possibility to correlate multiple CTI sources.

8. Limitations and Future Work

This study relies on publicly available documents, so it cannot capture negotiated enterprise agreements, NDAs, or operational practices that may materially alter the baseline constraints reported here. Large enterprises may secure more favorable terms than the public baselines suggest; conversely, smaller organizations may face even stricter conditions. Additionally, while conservative coding practices were applied to mitigate ambiguity, the qualitative nature of thematic analysis involves a degree of subjective interpretation (Braun and Clarke, 2006).

We do not assess detection efficacy, indicator quality, or comparative product performance, dimensions that would require access to operational environments and controlled testing (Schlette et al., 2020). The corpus reflects a fixed time window (January–October 2025), and terms and interfaces can change with limited notice, as explicitly permitted in several of the analyzed agreements.

Future work should (i) compare public baselines with negotiated contracts under controlled access, (ii) validate operational impact through case studies of CTI use in incident response and information-sharing workflows, (iii) conduct longitudinal monitoring of licensing and API com-mitments to quantify stability over time, and (iv) examine whether recent market consolidation affects pricing and contractual flexibility for existing customers.

9. Conclusion

Across 34 public documents and 15 commercial CTI providers, we identify recurring constraints that limit redistribution, automation, portability, and pricing predictability. Together, these patterns function as a *contractual firewall* that hinders cross-organizational coordination and disproportionately disadvantages SMEs, public-sector entities, and sector consortia.

The findings reveal a structural tension between commercial CTI licensing practices and European policy frameworks that mandate cooperative resilience and information sharing (European Union, 2022). Recent market consolidation, exemplified by Mastercard's acquisition of Recorded Future, suggests this concentration may intensify rather than dissipate.

The recommendations translate findings into concrete procurement requirements that improve portability, enable defensive sharing within trusted settings, and reduce lock-in risk. Future work should validate these patterns against negotiated enterprise terms and evaluate operational impact in incident response environments.

The current market structure creates a double failure in APT defense: (1) Economic gating excludes smaller defenders from essential intelligence, while (2) restrictive licensing prevents the collective ecosystem from compensating for this gap through sharing. Consequently, NIS2 mandates for collective resilience are rendered inoperable not by lack of will, but by commercial contract design.

Ethics declaration: This study analyses publicly available documents and does not involve human participants, personal data, or interventions. No ethical clearance was required. To support double-blind review, self-identifying references in the manuscript were removed where not essential to the argument.

Declaration of generative AI and AI-assisted technologies in the writing process: The author used AI-assisted tools to support language editing and LaTeX formatting, including improving clarity and grammar, reducing dyslexia-related spelling and ordering errors, and troubleshooting bibliography and layout issues. All AI-suggested changes were reviewed and approved by the author, who takes full responsibility for the final manuscript and any remaining errors.

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The End of Infodemic? The 2021-2024 UN Effort to Ensure the Integrity of Public Information

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Abstract: This article examines the United Nations' efforts between 2021 and 2024 to promote the integrity of public information through the development of the Global Principles for Information Integrity. Responding to the growing threat of misinformation, disinformation, and hate speech, the study analyses how the UN sought to construct a non-binding, multilateral and multistakeholder response. Using qualitative textual analysis of UN reports, resolutions, and policy documents, the article traces the institutional process initiated by the Secretary-General's call for a global code of conduct and culminating in the adoption of the Global Principles in 2024. The findings highlight both the potential and the limitations of multilateral cooperation in a fragmented information environment marked by geopolitical rivalry and technological change. The study contributes to debates on global governance by illustrating how normative frameworks can be mobilized to address information integrity while navigating tensions between human rights, state interests, and platform governance.

Keywords: Information environment, Regulation, International cooperation, Multistakeholder, Integrity

1. Introduction

The increasing role of purposefully spread false, misleading, or inaccurate information online has become a global concern, and the United Nations (UN) is attempting to take a role to counter the phenomenon on multilateral basis. The UN has recognized disinformation as a threat and has also underscored the fundamental importance of freedom of information and access to accurate, reliable information as a human right. In 2021 its Secretary-General called for the end of "infodemic" challenging fact-based world by calling for a global code of conduct." (United Nations General Assembly, 2021a, 2)

The concept of "infodemic" refers to a particular kind of information environment in which the access of individuals to factual and timely information is weakened, with disinformation providing one element in the context. (Briand et al., 2023) The call for a global code of conduct in promoting the integrity of public information was a step onwards in countering disinformation at a global level, and after the Secretary-General started the building of a political momentum for such an effort, the work culminated in 2024 with the launch of Global Principles for Information Integrity.

Our research problem focuses on the integrity of public information as a topic for viable multilateral effort, i.e. how the UN processed the challenge. Our research question derived from the research problem is how the Global Principles were created and how the creation of the Global Principles reflected the state of multilateralism in attempting to set up a global response to the spreading of malign information.

The study contributes to the better understanding of multilateral dynamics in the UN decision-making in the context of how non-binding efforts can be made to guide member states and other stakeholders to establish common rules to regulate the current information environment.

2. Current Scholarly Discussion and the Case for Study

The UN is the leading multilateral organization in the world, but it has increasingly been under strain to draft relevant and effective responses to global challenges, highlighting weakening state of the UN and multilateralism as a broader phenomenon. (Weiss, 2016; Mingst, Karns and Lyon, 2022) As defined by John Ruggie (1992), multilateralism means cooperation between three states or more and is institutionalized in a particular context. Multilateralism relies on acceptance of common facts by states participating in the cooperation. If the sense of common facts is decreasing, this weakens the foundations under multilateral organizations (Martin, 2024).

Finding a commonly shared stance in mitigating the impact of malign and intended dissemination of information, especially hate speech, misinformation and disinformation continue to be a major global challenge (Ministry of Defence, 2024). The UN has started to work with countering malign information, and the

theme has gained attention especially since the COVID-19 pandemic, when the debates on health measures featured mass spreading of dis- or misinformation. (United Nations General Assembly, 2022b) Furthermore, the UN bodies can also act as forums for countering but also disseminating of disinformation as discursive activity (Taranenko, 2024).

In terms of regulatory responses, Christopher Marsden et al. suggest that effective governance requires a combination of legal frameworks and technological solutions, including the use of artificial intelligence (Marsden, Brown and Veale, 2020). This aligns with the findings of concerning the regulation of AI technologies to combat disinformation, emphasizing the need for democratic governments to adopt measures that enhance societal resilience and promote informed citizenry (Mega, 2023). Also, the UN work to regulate AI technology is noted (Fournier-Tombs, 2021). The UN's involvement in these regulatory discussions is meaningful, as it can facilitate international cooperation and the sharing of best practices among member states.

Often, discussion on global codes focuses on ethical practices, norms and standards in areas like environmental protection, corporate social responsibility, or migration (Armstrong, 2000; Vogel, 2008). In the field of finance, the UN has for decades promoted the use of global code to define rules and relations between transnational corporations and states (Sauvant, 2015). Similarly, the question of information-related threats link corporations with states. Promoting a particular kind of global code is a relevant perspective on the UN's role in addressing disinformation, given its mandate to maintain international peace and security and promote human rights while acknowledging in particular the role of the UN General Assembly in seeking consensus among the international community in a way that promotes both global democracy and involvement of civil society actors. (Thérien and Bélanger Dumontier, 2009) Furthermore, from the perspective of international relations theory such as constructivism, the global code relates to a question of whether there is and should be universal principles related to mitigating – and countering – disinformation, as a form of social norm (Björkdahl, 2002).

In this perspective, promoting a particular form of global code in the context of malign information could shed light on the UN's activities in setting up a global consensus and seeking to mobilize the member states of the UN, i.e. the global community at large to develop common measures to counter the phenomenon. Indeed, multilateral cooperation can take place in the context of regulating or shaping the information environment. However, the ways in which both the countering of malign information and in particular the focus on the protecting integrity of information can be combined should also shed light on the processes within the UN and how its role is viewed within the organization and outside of it, thus simultaneously engaging with the sense of multilateral organizations being under crisis (Schuette, 2024).

However, the promotion of global code has not been typical for UN activities. In fact, among the UN Meetings Coverage and Press Releases only 67 findings (press.un.org/en/sitesearch) can be found with the search term "global code" and in the UN Digital Library full text search between 1999 and 2024 only 592 records can be found to feature the search term, when applied in the system in June 2025. This highlights the relatively limited attention that the idea of global code has received in the UN's work so far.

3. Methodological Considerations

Our approach focuses on the exploration of the process in the UN to establish a global code on integrity of public information and recommendations and guidelines the UN provides for its member states and to other relevant stakeholders (e.g. private companies and non-governmental organizations) regarding information-related threats to such integrity. Sources for this article were extracted from the UN Digital Library with a full document search, with the help of keywords "'global code of conduct' AND "integrity of public information" (45 documents) as well as "counter disinformation" (156 documents) from the period 2021-2024. The search provided, among other types of documents, reports and resolutions of the Secretariat, the Security Council and the General Assembly.

Furthermore, the documents needed to feature commentary remarks on the state's role in countering disinformation or on the global code of conduct in the context of countering disinformation, and this served as the basis for close reading of documents. Documents were analyzed with contextualized, qualitative textual analysis in which the attention focused on the UN process to create the global code.

4. The Creation of the Global Code to Maintain Information Integrity

In the late 2010s member states of the UN accepted the view that various challenges impacting humankind, such as climate change and conflicts, were interconnected and thus requiring interconnected responses also

from the UN. As a result, in 2019 the UN adopted a Strategy and Plan of Action on Hate Speech. Instead of paying attention to disinformation in particular, the strategy focused on any kind of communication in speech that contains attacks or pejorative language in reference to individuals or groups (United Nations, 2019). Furthermore, effort by both states and companies to counter disinformation seemed occasionally to contradict with human rights, thus requiring new approaches with multistakeholder basis (United Nations General Assembly, 2021b). The Secretary-General António Guterres responded to increasingly challenging information environment with a report *Our Common Agenda* published in August 2021. In the report, the secretary-general called for the members of the international community to develop a "common, empirically backed consensus on the public good of fact, science and knowledge", as an effort to increase trust. Furthermore, he called for an institutional approach to disinformation by countering hate speech and online harassment and called for a "global code of conduct" that would promote integrity of public information. The underlying theme was the role of trust and mistrust towards both the technology and digital space, and a vision of a need to manage "our digital commons as a global public good". (United Nations General Assembly, 2021a, 17-18)

In his statement on the priorities for the year 2022, delivered in January 2022, Guterres highlighted the idea of multistakeholder approach to digital space and integrity of public information. He perceived the regulation of the digital world highly important but prone for risks, such as data misuse, misinformation and cybercrime, and linked the regulation in particular to different forms of business models taking place in the digital world. He also talked about the global code he had proposed as a multistakeholder effort linking governments, media companies and "regulators" together and saw it as a way to end both the "infodemic" and the war on science, while promoting integrity of public information both online and offline, and wanted the states to commit to the global code. (United Nations General Assembly, 2022a, 4-5)

4.1 Role of Hate Speech and Other Malign Information Activities

In late 2021, the General Assembly adopted a resolution (United Nations General Assembly, 2021c) in which it connected countering disinformation to the promotion and protection of human rights and fundamental freedoms, based on the United Nations Strategy and Plan of Action on Hate Speech in 2019.

In the resolution the General Assembly called states to "counter all forms of disinformation through policy measures, including education, capacity-building for prevention and resilience to disinformation, advocacy and awareness-raising", and the resolution both welcomed and took note concerning the Secretary-General's call for specific "global code for conduct that promotes integrity in public information". Furthermore, in the resolution the Assembly requested from the Secretary-General a specific report concerning the views of the UN member states, UN entities and other relevant stakeholders to provide ideas about best practices related to countering disinformation. (United Nations General Assembly, 2021c, 4) All in all, the resolution was a clear commitment by the General Assembly to place the issue of disinformation on the global agenda, and it paved the path for further work on the topic. The request for a report was a typical reaction and reflected the interest to emphasize the changing information – and thus operating – environment and next to broaden the discussion to cover all member states, UN entities and stakeholders otherwise relevant to the topic to mobilize international reaction.

From here the focus was on effort by the UN Department of Global Communications, led by the Under-Secretary-General for Global Communications. There the member states were supportive of the vision to establish the global code and reacted positively to an inclusive approach in its development. (United Nations, 2022, 7, 29) The idea of a global code was transformed into a document titled *Global Principles for Information Integrity*, highlighting the normative-aligned approach to mobilize both member states and other stakeholders to follow the guidance.

The Department of Global Communications in the General Assembly organized a global consultation round regarding the development of the Global Principles for Information Integrity. According to the report of the Secretary-General, the consultations round took a year to complete and involved several stakeholders, such as governments, civil society, the private sector, media and academia, and the process also involved dialogue with the Committee on Information as well as engagement through the system-wide Working Group on Information Integrity. After such a process, the official document was drafted. (United Nations General Assembly, 2024)

4.2 Content of the Global Principles

In 2023 the Secretary-General's office launched a policy brief aimed at developing what the global principles on information integrity could be. The brief also defined the concept of information integrity in the context of

threats. Indeed, the policy brief highlighted the digital information environment and the role of multiple different actors shaping the environment and linked the search for a global code to the upcoming 2024 event Summit for the Future as well as to work related specifically to information integrity in digital platforms. (United Nations, 2023, 5) The Global Principles were published in 2024 few months before the Summit for the Future and included five principles: societal trust and resilience; healthy incentives; public empowerment; independent, free and pluralistic media; and transparency and research and focus on providing recommendations to "all stakeholders regarding coordinated international action for safer and more humane information spaces that champion human rights, peaceful societies and a sustainable future." In practice this has meant a somewhat liberal approach to new technological environment, but in the framework of the UN focus on fostering the role of human rights: "Information integrity entails a pluralistic information space that champions human rights, peaceful societies and a sustainable future. It holds within it the promise of a digital age that fosters trust, knowledge and individual choice for all." (United Nations, 2024c) In the launching event of the Global Principles in June 2024, the Secretary-General described them as a starting point for solutions to counter misinformation, disinformation and hate speech in the context of proliferating role of generative artificial intelligence and strengthening democracy (United Nations, 2024b), but as the policy brief had already highlighted in 2023, such an effort related above all to the UN to set the aim in the international level and then invite member states to follow in the national level (United Nations, 2023).

Furthermore, Guterrez went on to describe the key audience for the Global Principles: the big tech companies to take responsibility over the impact of their products; advertisers and the PR industry regarding the monetization of harmful content; creatives of not wasting their talents to greenwash; PR agencies to better select their customers; media outlets to raise and enforce editorial standards; and governments to commit to free and plural media landscape (United Nations, 2024b). Nation-states, while in the focus of the UN system, simply were unable to shape the information environment to the extent necessary for the fulfilment of the UN secretary-general's vision.

4.3 Commitment to Multilateralism in the Context of Increasingly Maligned Information Environment

Understood in the context of multilateralism as a dialogue between governments' representatives to work out common approaches to common concerns (Schechter, 2011), the search for a global code reflected such an effort, a common approach to a common concern. In the context of the United Nations as the leading platform of multilateral cooperation and multilateralism suffering from a state of crisis (Newman, Thakur and Tirman, 2006), the issue of countering disinformation with promoting guidelines and encouraging states to act and to develop and share measures become particularly consequential. This applies particularly well to the chosen approach that goes beyond nation-states. Multistakeholder approach the UN promotes emphasizes an approach in which the member states are only one group of actors, among many others that shape, either intentionally or unintentionally, the global information environment.

In recent years multilateralism has experienced multiple forms of cooperation emerging, such as minilateral solutions particularly in the context of crises and crisis management (see Patrick, 2015) and discourse on multilateralism as a flexible and effectivity-based approach to international cooperation. (Bouchard, Peterson and Tocci, 2014; Karlsson-Vinkhuyzen and Dahl, 2022) Multistakeholder approach is part of a quest to foster more effective forms of cooperation by expanding the diversity of actors participating in global governance over secure information environment. Based on the process to create Global Principles for Information Integrity, the multilateral cooperation showed it can create principles with an aim to shape the complex information environment that surrounds both member states and the UN itself. However, as tends to be the case with the member states' relations with the United Nations, the question of whether principles will be applied to decision-making at a national level focuses on the level of commitment towards these principles. In the context of multilateralism, clear commitments at national level can be difficult to find (Fontaine-Skronski, Thool and Eschborn, 2023, 2) and a similar idea may well apply to the question of how to protect and strengthen the integrity of public information. Indeed, already in 2024, some evidence emerged. In the Summit of the Future, held in September 2024, information security was also well present. The Summit was a high-level event designed to bring world leaders together and try to find an international consensus on a better present and future and make commitments to jointly agreed goals. The Summit originated from *Our Common Agenda* report of the Secretary-General and the states participating in the event adopted a document titled *Pact for the Future*, highlighting various commitments the states had made in the Summit. Some commitments were made under the banner of information integrity, and in the context of threats posed by misinformation and disinformation. There the commitments included digital media and information literacy

measures to strengthen resilience towards malign information and measures related to dissemination of independent, fact-based and accessible information. (United Nations, 2024a, 45)

4.4 Discussion: Are the Global Principles Enough?

Social media and digital communication tools are now firmly embedded in state strategies to influence audiences and challenge adversaries. This has not gone unnoticed by the world's major powers, each with a rich history of employing psychological operations, some of which have been controversial in their methods. For instance, the United States recognizes information as an instrument of national power (Department of Defense, 2013). China, meanwhile, has expressed its intention to contest what it sees as Western dominance over global discourse (Zhao, 2016).

This renewed great power competition is increasingly unfolding in the digital domain. Russia, for example, has been linked to efforts to interfere in foreign elections and spread disinformation across global platforms. (Maréchal, 2017) China has intensified its influence campaigns, aiming to challenge U.S. influence in the international information environment. One of the largest known disinformation networks, referred to as Spamouflage, has been attributed to China. According to Meta, the network included more than 7,000 Facebook accounts, 954 pages, 15 groups, and 15 Instagram accounts. These accounts operated across at least 50 different platforms and forums, primarily aiming to promote pro-China narratives and to discredit the United States and other Western countries. (Meta, 2023)

Influence operations, once primarily associated with authoritarian regimes, are now also used—albeit differently and often on a more limited scale—by democratic states. Beyond the major powers, other states have also been implicated in information operations. France, for instance, has been accused of using disinformation tactics, including social media trolls and bots, to counter Russian influence efforts in Africa. (Gleicher and Agranovich, 2020)

While Russia, China and other authoritarian states have sought to insulate their information environments as a form of defense (Bendix, 2026), smaller states often lack the capacity to do so. Instead, they remain dependent on global platforms—such as Western social media or Chinese infrastructure—not out of strategic choice, but due to practical necessity.

As members of the UN Security Council face increasing competition in the global information space, it is fair to question whether the major powers are genuinely committed to supporting the Global Principles or if their differing priorities will continue to drive their actions. The behaviour of key actors often reflects a more self-interested and pragmatic approach.

In this context, smaller states increasingly find themselves relying on multinational alliances—such as the European Union or even the UN itself—to amplify their voices and defend their interests. Initiatives like the EU's Digital Services Act (DSA), which aims to regulate online platforms and increase transparency, offer one example of how collective action can strengthen digital resilience. (Heldt, 2022) Yet this dynamic—where larger powers dominate the information space—not only undermines the spirit of a genuine multi-stakeholder approach but also risks reinforcing a 'might makes right' logic, often at the expense of the sovereignty of smaller states.

The success of new UN agreements remains uncertain. While the Global Principles offer a valuable starting point, they may not be enough to address the challenges posed by geopolitical tensions, rapid technological disruption, and differing conceptual approaches to information. Ultimately, the effectiveness of these principles will depend on whether sustained cooperation and political commitment can be achieved—an outcome that remains uncertain in today's volatile global climate.

5. Conclusion

In this study we asked how the Global Principles were created and how the creation of the Global Principles reflected the state of multilateralism in attempting to create a global response to the spreading of malign information.

Our study shows that the UN took an actor-bound approach in creating Global Principles by first acknowledging the existence of information threats and then, together with the relevant UN entities, worked both to consult member states and other stakeholders to find a common response to the challenges malign information was showing. The process, after the first call for global code took place in 2022, took two more years to come up with a document outlining the principles for the Summit for the Future to consider and help

commit states to the principles, thus showing gradual multilateral process to study the challenge and the defined suitable responses.

The global environment increasingly highlights the role of great power rivalry. In this context, reaching international consensus on issues may be increasingly difficult to achieve. Nevertheless, to have some level of regulation among great powers and creating rules and norms of states and non-state actors to follow should be done with enough mobilization. In this evolving situation it is increasingly important to link efforts to counter the spreading of malign information with human rights law and principles. Here the future promotion of Global Principles and mobilization of states to implement the principles becomes important and could bring hope to aim next for stronger form of international regulation.

Ethics declaration: Ethical clearance was not required for the research.

AI declaration: Three AI-based research tools were utilized in the reporting phase: Jenni.ai (https://jenni.ai/) for text editing the first draft of the manuscript and Scite.ai (https://scite.ai) to help in the drafting the literature review, although in the further revision rounds their impact became almost non-existent, and Microsoft 356 Copilot to create a draft abstract.

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The University of Maryland's Cyber Events Database 2.0: A Systematic Framework for Analyzing Global Cyber Threats

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Abstract: Cyberattacks are increasing in scale, scope, and impact, yet systematic, accessible data on these events remain fragmented, narrowly scoped, or methodologically opaque. Existing cyber incident datasets often focus on specific threat types or high-profile cases, are proprietary, or lack transparent coding rules, limiting comparative analysis and cumulative research. This paper introduces the Cyber Events Database 2.0 (CEDB 2.0), a publicly sourced, event-level repository of global cyber incidents from 2014 onward designed to support reproducible research and strategic cybersecurity analysis. The CEDB 2.0 employs a mixed-methods data collection approach that combines automated web scraping with multilingual, near–real-time news monitoring, integrating the Global Database of Events, Language, and Tone (GDELT) Project beginning in 2025. As of February 2026, the database contains 16,382 coded cyber events across 175 countries and 1,431 distinct threat actors. Each event is classified using a theory-informed taxonomy capturing actor type, motive, target sector, affected country, and observable effects. By enabling cross-sectional and longitudinal analysis at scale, the CEDB allows researchers to move beyond anecdotal case studies toward systematic, evidence-based assessment of state and non-state cyber behavior. The paper details the database's methodology, structure, applications, limitations, and future development.

Keywords: Cybersecurity, Cyber operations, Structured event data, Threat landscape, Data-driven analysis, Strategic decision-making

1. Introduction

Cyberattacks are growing in number and impact, carried out by various actors with different motives, targeting multiple industries and causing effects from data breaches to operational disruptions. These incidents, including the 2021 ransomware attack on Colonial Pipeline that interrupted fuel supplies along the eastern U.S. (Easterly, 2023), the 2020 SolarWinds breach attributed to Russian operatives that compromised numerous systems (GAO, 2021), and recent attacks on water utilities linked to pro-Russian and Iranian groups (ODNI, 2024), all represent cyber events significant to academic research. Less severe incidents, such as attacks on schools (Kennedy, 2024), small contractors (Rogers, 2020), and software vendors (JD Supra, 2023), are less frequently discussed, leading much of the analysis to be based on a small data sample subject to sampling bias. Information regarding the individuals or groups responsible, their intentions, the affected sectors, and the actual consequences is typically scattered across news reports, specialized private intelligence agencies, periodic statements by businesses and governments, or subscription-based commercial databases. While some open-source data repositories of cyber events exist, they often contain information that remains fragmented, narrowly scoped, or methodologically opaque.

To address these shortcomings, the Center for the Governance of Technology and Systems (GoTech) has expanded on initial work in conjunction with the Center for International and Security Studies at Maryland (CISSM) to develop and launch a revised Cyber Events Database (CEDB 2.0). CEDB 2.0 integrates publicly accessible news articles by referencing identified cyber-relevant news and trade publications, as well as the Global Database of Events, Language, and Tone (GDELT) Project's Web News NGrams 3.0 (2021) and Article List datasets. The CEDB now offers comprehensive global coverage through real-time monitoring of news sources in over 65 languages, ensuring broader, more timely access to information.

This article outlines the purpose, methodology, structure, and uses of CEDB 2.0. It reviews the relevant literature, explains methods, describes database fields, and covers use cases, limitations, and future prospects. By highlighting cyber events, the CEDB 2.0 helps reassess key issues, including threat locations, motives, patterns, impacts, and responsible actors.

2. Literature Review

Cyber events vary across multiple critical dimensions, including threat actor type and motivation, targeted industry, geographic scope, and the nature and severity of observable effects. Despite this heterogeneity, cyber event reporting remains inconsistent and difficult to standardize. Many existing data collection initiatives fail to

meet foundational criteria of exhaustiveness, exclusivity, and consistency, limiting their suitability for comparative and theory-driven analysis (Harry & Gallagher, 2018). Others focus on specific threat categories or technical artifacts, struggle to capture evolving attack vectors, rely on incomplete or outdated records, or lack adequate coverage of multi-stage and multi-actor campaigns (Cremer et al., 2022; Mvula et al., 2023; Goldschmidt & Chudá, 2024). As a result, much of the empirical work on cyber war and security relies on qualitative methods over quantitative large-N analysis (Kong, Kim, and Lim, 2019) (Buchanan, 2020), with some notable exceptions (Valeriano, Jensen, and Maness, 2018) (Kostyuk & Zhukov, 2017). Collectively, these limitations undermine consistent event classification, obscure meaningful variation across incidents, and introduce selection bias, which complicates inference and policy-relevant analysis.

We reviewed 13 datasets, often cited in academic and professional publications, that are most closely related to the CEDB 2.0. The datasets are broadly reviewed within four distinct groups based on their observed focus, completeness, audience, and description. The first group of cyber incident datasets prioritizes state-linked activity or high-impact events rather than the broader universe of cyber threats. For example, the Center for Strategic and International Studies (CSIS) Significant Cyber Incidents timeline documents notable cyberattacks since 2006, emphasizing state-sponsored operations, espionage, and incidents with estimated losses exceeding $1 million, particularly those affecting government and defense targets (CSIS, n.d.). Similarly, the Council on Foreign Relations (CFR) Cyber Operations Tracker catalogs state-attributed cyber operations with an explicit focus on interstate dynamics and strategic competition (CFR, n.d.).

Both resources provide valuable descriptive context but are not designed as taxonomic or event-level datasets. Events are coded narratively rather than through a standardized, multi-dimensional classification scheme, and inclusion criteria privilege strategic salience over systematic coverage. As a result, these datasets are ill-suited for large-N comparative analysis, replication, or longitudinal assessment of variation in actor behavior, targeting patterns, and effects across different types of cyber activity.

A second group focuses on intrusion detection and specific threats. This includes the Canadian Institute for Cybersecurity (CIC) datasets, such as CIC-IDS2017, which provide network flow data for intrusion detection and machine learning applications that simulate specific attack vectors (e.g., DDoS or malware). However, they lack real-world incident narratives or longitudinal trends (Sharafaldin et al., 2018). While invaluable for detection and model training, these datasets capture technical artifacts rather than socially and politically situated cyber events with identifiable victims and consequences.

A third category of datasets monitors broad cyber incidents rather than specific subtypes. The European Repository of Cyber Incidents (EuRepoC) offers a comprehensive global dataset encompassing over 3,400 politically or security-relevant cyber operations from 2000 to 2024, featuring 60 variables pertaining to initiators, targets, and intensity. Similarly, the Dyadic Cyber Incident and Campaign Dataset (DCID) focuses on campaigns and incidents associated with interstate conflicts. Although these datasets are methodologically robust, their emphasis on actions by major state actors may underrepresent non-state proxies, such as criminal entities and hacktivists. Additionally, their primary focus on interstate conflict constrains their capacity to document cyber operations occurring within intrastate conflicts.

A fourth group comprises specialized, community-driven, or technically focused repositories, each centered on specific attack categories. For example, Ransomware.live automates the scanning of ransomware groups' data leak sites and other sources (Ransomware.live, n.d.; Poireault, 2024). Likewise, Ransomware monitors cryptocurrency payments sent to wallets associated with known ransomware activity (Ransomwhere, n.d.; Cable et al., 2024). The U.S. Department of Health and Human Services Office for Civil Rights (HHS OCR) gathers reports of HIPAA-covered breaches that impact 500 or more people in the healthcare field (HHS, 2023; Alder, 2025). Cloudflare observes major Internet disruptions, including DDoS campaigns or state-mandated shutdowns (Cloudflare Radar, n.d.; Azevedo, 2023). Shadowserver offers global threat telemetry (Shadowserver, n.d.; Kijewski, 2021) while the “World’s Biggest Data Breaches & Hacks” compiles cyber event information into a timeline with source links (Information is Beautiful, n.d.). These tools tend to have a narrow focus, ambiguous event classifications, technical orientations, or limit themselves to certain types of incidents.

Collectively, these four categories of cyber event data repositories demonstrate both the advancements achieved and the ongoing challenges in documenting cyber activity. State-centric timelines prioritize strategic significance over comprehensive coverage and intrusion detection datasets focus on technical indicators but often lack contextual and impact information. Dyadic and interstate repositories limit analysis to specific participants and conflict patterns and specialized or community-driven platforms offer detailed insights into threat vectors. Consequently, no single dataset currently provides thorough, event-level data that is sufficiently

broad, methodologically transparent, and systematically organized for comparative and longitudinal research across actors, sectors, and regions. These gaps highlight the necessity for a unified, publicly accessible repository of cyber events that synthesizes diverse sources, employs a consistent classification scheme, and records the tangible effects of cyber operations, objectives addressed by the CEDB 2.0.

3. Methodology

The CEDB 2.0 is designed to provide a systematic, event-level record of global cyber activity that supports comparative, longitudinal, and policy-relevant analysis. Building on earlier efforts to document cyber incidents using open-source reporting, the CEDB 2.0 applies explicit inclusion criteria, a structured taxonomy, and a hybrid data-collection approach that combines automation with human validation. This section outlines the database's event definition, data collection pipeline, and validation process, highlighting methodological choices intended to mitigate selection bias and improve global coverage. The first source stream relies on automated web scraping of a curated and regularly updated watchlist of open-source outlets known for timely reporting on cyber incidents, including specialized cybersecurity blogs, major news organizations, public feeds, leak sites, and paste sites. Prior to 2025, this Python-based scraping pipeline served as the primary mechanism for identifying candidate events.

The site-specific scraper collects cyber-related articles via RSS feeds (using feedparser, rapidfuzz, dateutil.parser, etc.), then filters entries by date, keyword match, and deduplication. For each retained entry, it records the RSS publication timestamp (reported_date), the article link (source_url), and the RSS summary text (description), as well as the RSS title. Execution timing is captured in log files via a local timestamp. Where possible, preliminary indicators of threat actor type and apparent motivation are inferred heuristically from textual context, though these provisional labels are always subject to subsequent human review.

Beginning in January 2025, the data collection was expanded to include the GDELT Project's Web News NGrams 3.0 (2021) and Article List datasets. GDELT's near-real-time monitoring of broadcast, print, and online media in over 65 languages across more than 100,000 sources. This dramatically increases both temporal recency and geographic breadth of coverage, particularly for incidents reported outside English-language specialist outlets. As an example, the U.S. share of recorded cyber events declined from 48.8% to 36.9% when comparing the 2014–2024 dataset, compiled using the original collection method, to records from 2025 onward, when GDELT-based identification was incorporated. The change likely reflects improved global coverage rather than a substantive shift in cyber activity. Events ingested via GDELT are subjected to the same definitional criteria and manual validation workflow as traditionally scraped incidents; only the upstream acquisition mechanism differs. This methodological shift is explicitly flagged in the dataset schema to enable temporal-comparability analyses.

Harvested records are aggregated daily, deduplicated by URL and semantic similarity, and appended to two intermediary comma-separated values (CSV) files, one containing raw open-web scrapes and a second reserved for post-2025 additions from GDELT-sourced articles. Importantly, the algorithm's sole function is to collect potentially relevant material, which is then reviewed by one of the researchers.

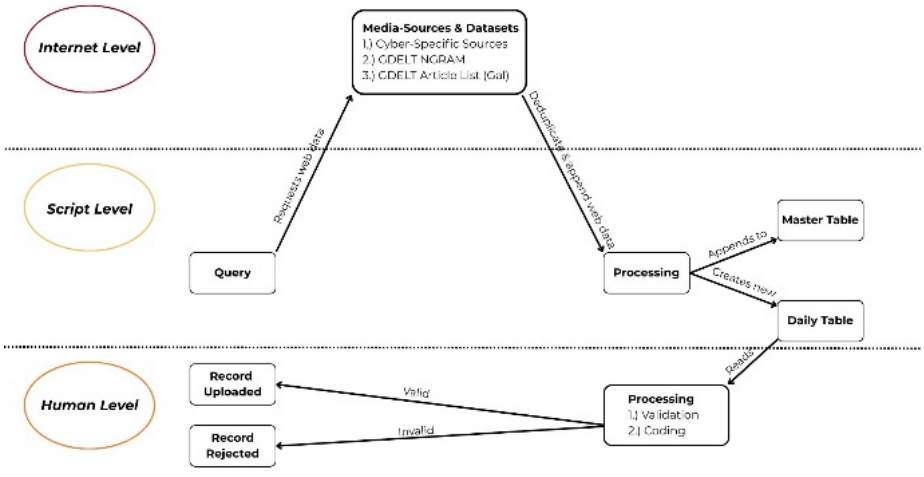


Figure 1: Data Collection and Coding Process

Following daily aggregation, trained researchers restrict inclusion to cyber events that meet two necessary conditions: (1) the operation must have produced a discernible real-world effect, and (2) there must be an identifiable target victim. Events that lack an observable impact against an entity, such as unsuccessful intrusions, or vulnerability disclosures without exploitation are systematically excluded. Each record is linked to at least one publicly accessible or archived primary source containing sufficient narrative detail to support independent verification and consistent coding.

Each cyber event record consists of 45 standardized fields that document what happened, who was affected, and how. The event date reflects the best available information on when the intrusion or effect occurred, while the reported date is the publication date of the cited source URL. Each record includes a specific victim organization (or individual) and its corresponding two-digit NAICS industry code when available. Threat actors fall into one of the following categories: criminal, nation-state, hacktivist, hobbyist, terrorist, or undetermined. Events are categorized by primary effect as exploitive, disruptive, or mixed (both exploitive and disruptive effects). Subtypes specify the nature of an event based on the part of the target organization's IT infrastructure that was most seriously impacted. These include disruptive subtypes such as data attacks, message manipulation, external or internal denial-of-service, physical attacks, or specific forms of exploitation against application servers, end hosts, network infrastructure, sensors, and/or data in transit. Beginning with 2025 data, disruptive and mixed events include severity coding for magnitude (extent of disruption), duration (length of disruption), and scope (systems or assets affected). Exploitive and mixed events record compromised data by category, which includes intellectual property, organizational data, and customer or client data, using quantitative detail whenever possible. Motive is coded as financial, political or industrial espionage, sabotage, protest, reputation, personal attack, or undetermined based on evidential inference. Additional fields capture victim and actor countries using standardized naming and ISO3, binary variables for organization and alliance membership, a concise factual description, and a verifiable source link. Finally, for cyber events targeting the United States, records also capture the state and county where the organization operates, if available.

This process serves three primary objectives:

- Confirmatory validation that the candidate event has both an attributable victim and observable effect;
- Consistent assignment of core taxonomic attributes; and
- Precise classification of affected industry and granular end effects according to the structured impact taxonomy

Processed and validated records are consolidated, deduplicated across both ingestion streams, and released in monthly cumulative updates accompanied by schema documentation and a change log that highlights any coding adjustments. The resulting dataset thus offers scholars a transparent, reproducible, and longitudinally consistent resource for quantitative (and qualitative) analysis of cyber conflict dynamics (Harry et al., 2025).

4. Results

As of January 2026, the database contains 16,382 cyber events across 175 countries involving 1,431 unique threat actors. The average number of events per month is 112, and the yearly average is 1,239 (2014-2025). When we break the data down by types of effects, exploitive events are the most common, driven largely by criminal actors seeking financial gain through data theft and extortion. Mixed-effect attacks, such as ransomware that combines data theft and encryption, saw a spike in 2022 and 2023. However, there has been an observed shift in threat behavior in recent years as more criminal actors use data theft-only extortion methods (Symantec & Carbon Black, 2026). Interestingly, there is a notable spike in disruptive attacks in 2022, which aligns with heightened hacktivist and nation-state activity following Russia's invasion of Ukraine.

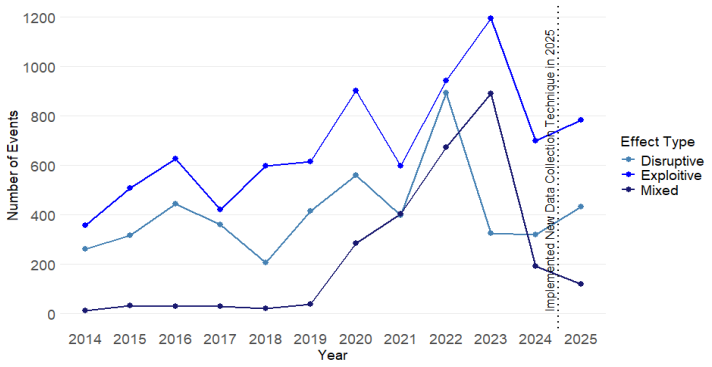


Figure 2: Cyber Events by Effect Type - All Records (2014-2025)

Figure 3 shows that criminals, driven by financial gain, are, by far, the most prolific threat actor, accounting for 74.5% of events tracked in the CEDB 2.0, while hacktivist groups, motivated by ideological or political alignments, are the second most active (with a 13.2% share) for the period 2014-2025. Russia's invasion of Ukraine led to a spike in hacktivist activity and continues to motivate groups such as Russian-aligned NoName057(16) efforts to disrupt NATO-allied countries that support Ukraine's defense. Additionally, Ukraine relied heavily on hacktivist groups such as the IT Army of Ukraine for both offensive and defensive cyber operations in the early days of the war.

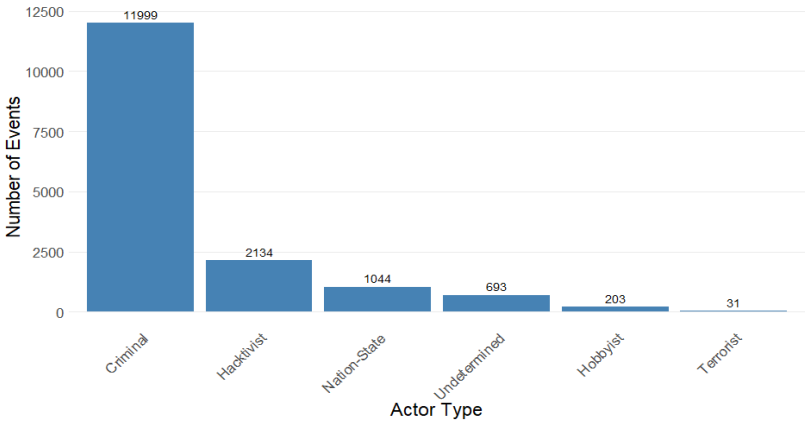


Figure 3: Cyber Events by Actor Type (2014-2025)

Figure 4 spotlights that cyber events are most frequently concentrated in public-facing and data-intensive sectors. Public administration and health care account for the largest shares, reflecting both their high operational dependence on IT systems and relatively strong disclosure requirements. Information, finance, and education also appear prominently, suggesting that sectors managing sensitive data or providing essential services face sustained exposure to cyber activity, while more asset-heavy sectors such as manufacturing and transportation experience comparatively fewer reported events.

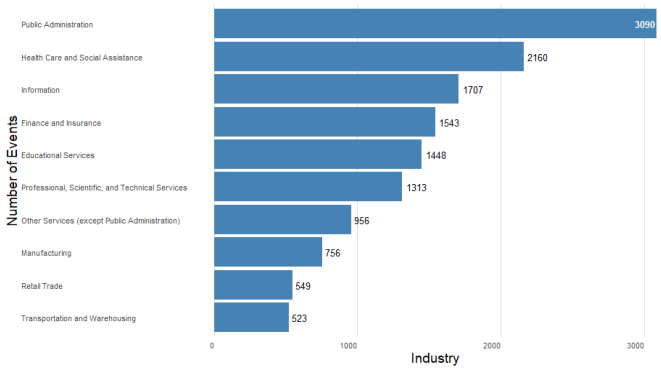


Figure 4: Top 10 Most Targeted Industries (2014-2025)

Figure 5 shows a strong concentration of recorded cyber events in a small number of countries, with the United States accounting for a 47.6% of total events. While reporting volume, disclosure regimes, and media coverage clearly play a significant role in shaping the geographic distribution of events in the dataset, the United States is also a very attractive target considering its robust industrial activity, economy, and geopolitical significance. The remaining nations are all relatively large G20 economies, and Ukraine is included due to its status as a war zone.

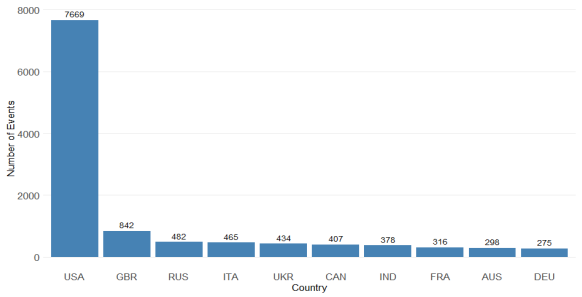


Figure 5: Top 10 Most Targeted Countries (2014-2025)

Finally, the threat actor distribution suggests that *observed* cyber activity is highly concentrated among a small number of persistent and operationally active groups, including criminal, hacktivist, and nation-state actors. cl0p has been the most active criminal group, reflecting both their high operational tempo and relatively robust resourcing, as well as the fact that their activities are more likely to be publicly reported and attributed. The appearance of advanced persistent threat (APT) groups among the top ten actors, such as North Korea's Third Surveillance Bureau and Russia's GRU Main Special Center for Special Technologies (Unit 74455), highlights the sustained visibility of certain state-linked campaigns within the dataset. For instance, the presence of Russia's GRU Unit 74455 reflects its association with highly visible, disruptive campaigns, most notably NotPetya, one of the most damaging cyber operations on record, which generated widespread collateral effects (U.S. Department of Justice). By contrast, the Third Surveillance Bureau-linked activity associated with North Korea blends traditional espionage with overt financial operations such as cryptocurrency theft and revenue-generating intrusions, which are more likely to surface in open-source reporting.

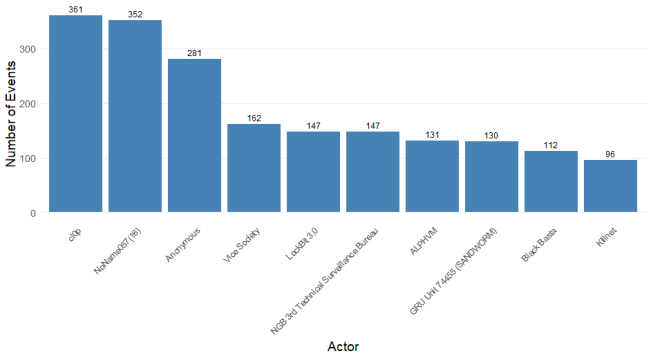


Figure 6: Top 10 Threat Actors (2014-2025)

5. Discussion

The CEDB 2.0 significantly enhances the analytical landscape for cybersecurity research by enabling scholars to address previously challenging questions due to data limitations. By providing structured data on actor types (e.g., nation-state, criminal, hacktivist), motives (e.g., espionage, sabotage, financial gain), and geopolitical affiliations through binary indicators for international organizations like NATO, or the EU, researchers can empirically test hypotheses about the nature, origins, and escalation of threats. Categorizing and contextualizing cyber events positions CEDB 2.0 as a valuable resource for industry and country-level threat landscapes, longitudinal trend analysis, effect and severity analysis, among other uses, all in service of knowledge generation and strategic decision-making.

Moreover, the CEDB 2.0 has also proven to be a vital resource for generating analytical insights and supporting evidence-based cybersecurity policymaking. In a comprehensive study, World Bank researchers integrated the CEDB with advanced artificial intelligence tools and then analyzed millions of cybersecurity-related articles. They

created a robust dataset covering approximately 190 countries and 21 industries, documenting over 30,000 publicly disclosed cyber incidents from 2014 to 2023. This enabled the identification of critical trends, such as a 21% average annual growth rate in global cyber incidents, with upper-middle-income countries experiencing a 37% surge. By linking incident frequency to cybersecurity commitments, the database provided policymakers with actionable insights. These findings highlighted the need for tailored policies, such as enhanced cybersecurity investments and awareness programs, particularly in developing nations, to mitigate cyber risks and foster sustainable digital development (Vergara Cobos & Cakir, 2024).

Another example of its utility is the European Securities and Markets Authority (ESMA) inclusion of CEDB 2.0's data in their Semi-annual Trends, Risk and Vulnerability (TRV) report (ESMA, 2024), incorporating the data into the TRV Statistical Annex (Chart A.131) to illustrate the rising global trend of cyber incidents in finance. The database's standardized information on threat actors, motives, targets, and impacts enabled ESMA to rank Infrastructure and Services at an elevated risk level, projecting ongoing cyber and operational vulnerabilities. The database's insights helped contextualize specific incidents, such as the CrowdStrike software update outage and Russia's cyberattacks against Ukraine, impacting EU entities. (ESMA, 2024).

The CEDB has been widely adopted in both analytical and policy initiatives, demonstrating its value in academia and beyond. It supports projects like CyberIR@MIT and Bamboo Weekly (2024) in compiling and analyzing cyber event data. It informs financial risk assessments by central banks such as the Bank of Japan (2023) and the European Central Bank (2022), among several other organizations.

Future iterations of the dataset will focus on achieving greater fidelity of event-level information. Planned enhancements include the integration of six-digit NAICS industry classifications, expanded organizational attributes, and the systematic backfilling of severity indicators across historical records. Increasing the granularity of these variables will enable more precise sectoral analysis and facilitate deeper empirical research on how cyber operations vary across industries and organizational types. Future development will also explore mechanisms for identifying and tracking cyber events involving artificial intelligence–enabled tools and techniques as these capabilities change the cyber threat landscape.

5.1 Limitations

Like most open-source cyber incident datasets, the Cyber Events Database relies on publicly available reporting, including news coverage, regulatory disclosures, and statements from affected organizations. As a result, events that are undisclosed, classified, intentionally concealed, or that occur in environments with limited media freedom are likely underrepresented. Coverage also varies across regions and sectors due to differences in legal reporting requirements, journalistic capacity, and organizational transparency, resulting in uneven geographic and industry representation. In addition, while the database increasingly incorporates multilingual sources, challenges remain in processing non-English reporting at scale and ensuring real-time accuracy as details about cyber events often evolve after initial disclosure.

6. Conclusion

The CEDB 2.0 provides a publicly accessible repository of structured, event-level data on global cyber incidents, enabling researchers, policymakers, and practitioners to analyze trends, assess risk, and support evidence-based decision-making. The integration of multilingual, near–real-time news monitoring through GDELT in 2025 expanded the database's geographic coverage, enabled timelier updates, and strengthened its utility for cross-sectional and longitudinal analysis across threat actors, motives, industries, and regions. With more than 16,382 recorded events spanning 2014 through 2025, CEDB 2.0 facilitates systematic case selection and comparative analysis, including fine-grained filtering of incident types, motivations, and actor characteristics.

Looking ahead, the CEDB 2.0 will support a comprehensive empirical analysis of cyber activity associated with actors linked to the Russian Federation. Leveraging the database's event-level coding of actor type, motive, sector, and observable effects, this research will build on previous research to examine patterns in targeting behavior, operational methods, and outcomes across time and geographic contexts in relation to the ongoing war in Ukraine (Lilly & Cheravitch, 2020) (Microsoft, 2022). The dataset's structure enables systematic comparison of state-attributed espionage and disruptive operations with hacktivist and proxy-based campaigns, including ransomware and data theft, allowing assessment of convergence, divergence, and potential coordination.

The CEDB 2.0 supports empirical research on cyber conflict, improves situational awareness for organizations assessing sector-specific risks, and informs policy discussions on infrastructure resilience, deterrence, and

international cooperation. In doing so, the dataset helps shift discussions of cyber operations from anecdotal observations toward transparent, evidence-based analysis.

Ethics Statement: This research did not require ethical clearance since we rely exclusively on publicly available media reporting.

AI Declaration: AI tools were used to assist with language editing, translation of non-English source material, and clarity checks. All substantive analysis, interpretation, and final content decisions were made by the authors.

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Incorporating S.P.I.C.Y. DICOM Polyglot Threats into Cyber Warfare Exercises

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Abstract: The technical feasibility of crafting polyglot files, objects valid under multiple file formats, has been repeatedly demonstrated in various contexts, including the DICOM medical imaging standard. While prior work has established that DICOM polyglots are technically constructible, a significant operational gap exists between this known vulnerability and the preparedness of healthcare organizations to detect and mitigate such data-centric threats. This paper addresses this critical oversight by shifting the focus from how to construct DICOM polyglots to why they pose an unmitigated, systemic risk in clinical workflows. We argue that this operational gap stems from three primary issues: non-uniform inspection across heterogeneous security tools, misplaced trust in the structural compliance of medical data, and insufficient threat modelling for automated pipelines. Our feasibility analysis, using a controlled DICOM/Portable Executable (PE) polyglot, demonstrates that mainstream security tools exhibit substantial inconsistencies in detection, with different systems interpreting the same object according to varying, often shallow, parsing assumptions. This non-uniform inspection allows the polyglot to remain stealthy and polyglot. To provide a structured framework for analyzing and mitigating this threat, we introduce the S.P.I.C.Y. framework, defined by five operational characteristics: Stealthy, Polyglot, Infiltrative, Cascading, and Yield. S.P.I.C.Y. helps practitioners measure the operational impact of malicious data artifacts that propagate through trusted, automated workflows, such as Picture Archiving and Communication Systems (PACS) and Vendor Neutral Archives (VNAs). The Infiltrative and Cascading characteristics highlight how an object, once past initial inspection, maintains its dual functionality across multiple automated processes. Finally, we redefine Yield to include not just execution, but the operational value gained from persistence within trusted infrastructure. By applying the S.P.I.C.Y. framework, organizations can move beyond traditional security models and strategically address the critical blind spots created by operational complexity and the assumed trust placed in medical data standards.

Keywords: DICOM, Polyglot, Healthcare, Cybersecurity, S.P.I.C.Y., Operational gap, Automated pipeline

1. Introduction: The Dual Nature of Medical Data

Cybersecurity increasingly exploits ambiguities in trusted digital systems. As automation and usability take their toll, these trust boundaries begin to waver. Antiquated standards and automation create assumed trust boundaries as files are pushed through increasingly complex pipelines. Adversarial techniques increasingly take advantage of these structural ambiguities. Polyglots take advantage of these ambiguities. Polyglots are defined as a single byte sequence that is syntactically valid under multiple file format specifications and can be meaningfully processed by more than one independent parser. Prior research has identified numerous file formats capable of supporting polyglot constructions, such as PDF, Jpeg, ZIP and many others. (Albertini, 2015). Through polyglot techniques, it becomes possible to construct objects that expose weaknesses in assumptions about file structure and interpretation.

The DICOM standard is a foundational fixture in medical imaging. Security validation has not matured alongside security threats, leaving a gap in operational security. The DICOM Part 10 file structure is pushed through automated pipelines repeatedly. Practitioners face attack surface gaps formed from inconsistent detection and overlapping weakened trust boundaries. The DICOM file structure has led researchers to discover a critical example of a threat that develops from such ambiguity (Ortiz, 2019). Polyglot-capable conditions resulting from the asymmetry between extensibility in the DICOM standard and validation gaps in detection tools have created an attack vector that relies on opaque file structures and avoids most inspection.

Current frameworks do not provide a means to assess the risk of data-centric threats and their potential operational blast radius. While previous research has demonstrated feasibility, the operational impact and implications for automated medical systems remain insufficiently explored (Ortiz, 2019). We propose the S.P.I.C.Y. framework to assist practitioners in analysing these polyglot threats and expose defensive gaps created by operational assumptions and complexity. Traditional threat modelling frameworks, such as the Cyber Kill Chain and MITRE ATT&CK, focus on specific vulnerabilities or attacker techniques and tactics

(Hutchins et al., 2011; Strom et al., 2018). S.P.I.C.Y. instead measures the operational impact of malicious data artifacts that propagate through automated workflows and trusted pipelines.

2. Theoretical Framework: S.P.I.C.Y. and the Polyglot Taxonomy

2.1 S.P.I.C.Y. Framework Introduction

Polyglots as a threat form an ambiguous, even hard to quantify, gap in the standard assessments for exploits and vulnerabilities. Traditional threat models evaluate threats through software flaws or execution paths. Polyglots function as a result of data interpretation and structural format ambiguity. To help define and describe such behavior this paper introduces the S.P.I.C.Y. framework, which is defined through five operational characteristics: Stealthy, Polyglot, Infiltrative, Cascading, Yield.

Stealthy is used to understand how polyglots are positioned to abuse ambiguous structural elements of formats, standards, and specifications to evade consistent detection. The ability of a polyglot to leverage these ambiguities depends on the gap in analysis and inconsistency of security tools in their respective environments (Albertini, 2015). Stealthy asks: How consistently is the polyglot object recognized across the different layers of inspection in a workflow?

Polyglot emphasizes the object's ability to be valid under different interpretations and contexts. Simultaneously able to conform to multiple formats and remain valid. As an example, different DICOM polyglots conform to distinct dual states (Ortiz, 2019). Polyglot asks: How many separate unique file formats can the object conform to while retaining core functionality?

Infiltrative describes the object's ability to pass different layers of ingestion without raising alarms. DICOM polyglots are accepted by typical ingestion services like DICOMweb STOW and then flow into PACS systems (Pianykh, 2012; Kahn et al., 2016). Infiltrative asks: Can this object successfully be ingested at point of entry without failing to validation or other inspection tools?

Cascading alludes to the polyglot's ability to successfully retain its multifaceted functionality despite moving through different transformations and systems as it moves through workflows. DICOM files move through PACS, VNAs, and AI workflows. The ability of polyglot to contain data within private elements and preamble show these structures may endure (Mirsky et al., 2019). Cascading asks: does the polyglot retain functionality through these transfers and transformations applied by the pipeline?

Yield identifies the operation value that is achieved once a structurally stable polyglot enters and persists in the workflow. Execution is not the only valid operational goal. The presence of executable code embedded in trusted medical data allows for a form of persistent, deferred activation. Downstream handling and reuse of images allow for exposure and embedding of code further than reliant on immediately executable code could achieve.

2.2 Polyglot Taxonomy

We have defined the taxonomy of polyglots into three sets of definable characterizations-structural, semantic, and operational - to provide a systematic framework for understanding how polyglot files are constructed, evade defensive controls, and are weaponized in operational workflows. This taxonomy is intended to address the concerns of a distinct but overlapping audience involved in the security and governance of data systems: the structural taxonomy is relevant to software developers, standard authors, and tool builders, allowing for an understanding of byte-level construction that remains syntactically valid under multiple formats; the semantic taxonomy is directly applicable to security engineers, detection vendors, or incident responders and focuses on inspection and validation mechanisms that fail when polyglots are encountered in practice; and the operational taxonomy is directed toward system architects, risk managers, and executive stakeholders with the goal of mapping functional roles in attack chains and TTPs (Tactics, Techniques, and Procedures). Understanding how these malicious polyglots are constructed is key to developing effective defenses. What follows are several taxonomy categories, their definitions, and examples to facilitate understanding. These include structural taxonomy, semantic taxonomy, and operational taxonomy.

Structural taxonomy defines the organizational structure of a polyglot file. This includes sequential polyglots, where two or more complete files are placed back-to-back, relying on parsers to ignore trailing data, which can bypass file type validation and allow lists. Another type is embedded or container-based polyglots, where one valid file format is contained within the data fields of another while both remain compliant. This allows for data transmission by surviving compression and metadata rewriting. Finally, interleaved polyglots involve the

same bytes being interpreted differently by two parsers due to overlapping semantic meaning. The technique can be used to evade or break parser-based detection, static analysis, or machine learning extraction.

Semantic taxonomy defines how definitive security measures fail or are evaded by the polyglot. Type-confusion polyglots are characterized by a mismatch between the declared file type and the actual parser behavior, serving as an evasion vector for magic-byte identification or file upload validation and enabling downstream abuse. Inspection-evasion polyglots occur when security tools inspect only one semantic interpretation of the file while ignoring others, allowing the polyglot to achieve persistence even in inspected environments. Context-switch polyglots are benign in one operational context but become malicious in another, which allows for delayed or cascading exploitation while evading shallow assessments without breaking workflows.

Operational taxonomy maps polyglots into specific attack usage scenarios. Ingress polyglots are used specifically for smuggling across security boundaries. A persistence polyglot has the purpose of surviving archival, sharing, or long-term storage without triggering alerts. Lastly, activation polyglots are designed with the specific purpose of being activated through a pipeline, workflow, or some form of triggered automation.

Together, these provide perspectives on how polyglots should be analysed-not as mere anomalies in file formatting but as intentional malicious instruments used to pry exploitable gaps between file semantics, defensive tooling, and system trust boundaries.

3. Feasibility Demonstrated: The Operationalized DICOM Polyglot

3.1 Methodology and Research Environment

For the purpose of this work, a table of components used in the investigation is provided. These help the audience to have a sense of what is needed to replicate findings and what to look for. Parameters are default.

Table 1: Components used for this investigation

Item	Definition	Purpose	Version
Malware Bytes	Commercial endpoint anti-malware solution	Evaluated local static detection behavior of constructed artifacts	5.4.7.229(Component Package 148.0.5470)
Orthanc server	Open-source DICOM server implementing DICOM storage and query/retrieve services	Used to simulate PACS ingestion, storage behavior, send studies via STOW, and reserialization of DICOM objects	1.12.9
Weasis Medical Viewer	Open-source DICOM viewer	Used to validate image rendering and observe viewer handling of modified DICOM objects	4.6.3
HxD Hex Editor	Low-level binary file editor	Used for byte-level inspection and structural modification of file regions for crafting the exploit	2.5.0.0
Windows 11	Host operating system environment	Used to evaluate file association behavior, invocation context, and endpoint inspection responses	24H2 (OS Build 26100.7623)
MinGW-w64 GCC 13.2.0	C code compiler	Used to compile executable Windows PE code	13.2.0

This paper looks at the potential uses of polyglot file techniques in relation to the DICOM Part 10 file structure, as discovered by d00rt (Ortiz, M.O.,2019). Our research was executed in three phases. The first phase defined a taxonomy of the structural, semantic, and operational attributes for polyglot files. This phase also placed the category of DICOM-based polyglot files within the existing body of research concerning different types of file formats.

The second phase of the work involved an analysis of the DICOM Part 10 file structure, specifically examining the preamble, file meta information, dataset encoding, and private data elements. These components were

utilized to assess the susceptibility to potential polyglot exploitation and to identify areas where dual-valid constructs could exist while maintaining compliance with the DICOM Data Dictionary.

In the third phase, controlled laboratory DICOM polyglots were created. Payload artifacts were written in C/C++ and compiled into Windows Portable Executable (PE) binaries, using MinGW-w64 GCC 13.2.0 on Windows 11, to be embedded as test payloads. The payloads were embedded into anonymized, functioning DICOM part 10 image files while maintaining structural validity using the tools and environment from Table 1.

Evaluation of the polyglot behavior across ingestion, archival, inspection, and detection workflows was completed to monitor how polyglots would interact with common medical imaging environments. Using a fully patched and updated Windows 11, the objects were scanned by Defender and Malwarebytes to observe end point detection. They were then placed in a directory and uploaded as a study via Orthanc using STOW to be stored in a receiving Orthanc DICOMweb server for storage. This step was done to observe possible alteration to the file that may occur during ingestion. The items were then rescanned by Defender and Malwarebytes, checked for executability on windows or Linux machines, and lastly, tested for the ability to be viewed as an image in Weasis.

The paper includes a description of the research environment, tools used for construction and validation, and static analysis results to illustrate detection variability. Findings are interpreted through the S.P.I.C.Y. model-Stealthy, Polyglot, Infiltrative, Cascading, Yield-to formalize how such artifacts function in offensive simulations. The goal is not to promote exploit development, but to provide a structured framework for evaluating data-centric threat surfaces that may be overlooked in conventional security training focused primarily on network and credential compromise.

3.2 DICOM Vulnerability Context

A DICOM file structured according to the Part 10 file specification is constructed of four primary components: a preamble, a file prefix, the file meta information, and the actual data set. The preamble, the set of initial 128 bytes, which for the DICOM Standard is unutilized space, often filled with null bytes, and is reserved for third party or application specific purposes. This section is designed to maintain compatibility between DICOM part 10 files and software or legacy systems that may rely on a specific header offset. This is a characteristic that will later become significant for exploitation.

Following the preamble, a four-byte prefix with the string 'DICOM' provides the file signature, a particular set of characters used to explicitly identify the file as a valid DICOM Part 10 file. The third main section is the File Meta Information. This section exclusively contains data elements from the group (0002, xxxx) and is mandatorily encoded with an Explicit VR Little Endian transfer syntax, irrespective of the encoding applied to the subsequent data set. Important elements within the File Meta Information include the Media Storage SOP Class UID, Media Storage SOP Instance UID, Transfer Syntax UID, and Implementation Class UID. The Transfer Syntax UID specifies the encoding method for the remainder of the data set. This includes byte ordering (Little-endian or Big-endian) and whether Value Representations are explicit or implicit. The final and largest component of the DICOM file is the dataset. This segment of the file contains the data elements representing metadata and the pixel data of the images. It is a collection of all the data elements encoded given instructions in the Transfer Syntax. Every Data element may be broken down further into four sub-components or fields. The first is the Tag, a numeric identifier consisting of the group number and element number. Next is the Value Representation, which is only included with explicit VR encoding. Third, is the Value Length, a parameter that specifies the length in bytes of the value field. Finally, the Value Field which contains the stored image data.

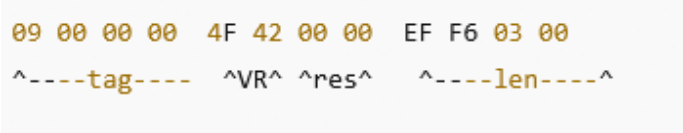


Figure 1: The Private Tag

DICOM files are structured using a series of Data Elements, each uniquely identified by a tag comprising a group number and an element number (Figure 1). Each Data Element possesses a Value Representation (VR), which specifies the data type (e.g., text, numeric, sequence), and a Value Length, indicating the size in bytes. The encoding, including byte ordering, is governed by the negotiated Transfer Syntax. This rigid yet flexible layout ensures reliable parsing across different systems while accommodating the wide variety of medical data stored in DICOM files. The format distinctly separates public and private Data Elements. Public Data Elements

are formally defined within the DICOM standard and utilize even-numbered Group Values. Conversely, private Data Elements employ odd-numbered Group Values, reserved for vendor-specific or third-party usage. Prior to utilizing private Data Elements, a vendor must first define a Private Creator Data Element to reserve a range of Data Element Numbers for proprietary use. This mechanism facilitates the embedding of proprietary metadata without compromising adherence to the DICOM standard. While compliant systems typically include and transmit private Data Elements as-is, they are not necessarily interpreted unless the receiving application can access the associated private dictionary. Consequently, when this access is unavailable, the private data can appear as an opaque entity to external parties, intended for another system. This phenomenon can occur throughout the entire processing pipeline, including ingestion, archival, forwarding, and viewing, meaning that private fields, regardless of their source or format, may pass through without detailed examination.

The customizable attributes permitted by the DICOM format, while offering flexibility for interoperability, introduces an inconsistency in the level of scrutiny of compliant data elements. Public data elements are typically well-defined and normally validated, but private fields may contain data in an arbitrary format. The private field formats may only be known to the vendor creating an issue where the code is opaque to any DICOM parser and may not be analysed. Given the increasingly mixed applications and development of clinical environments where images traverse multiple platforms, a valid private field can persist unchanged for an indefinite amount of time and processing. This allows private Data Elements to potentially embed tertiary data structures while remaining a valid DICOM object. The associated risk stems not from DICOM's specifications but from the asymmetry between the application of the extensibility and the failure to consistently validate private data elements throughout the medical image pipeline.

3.3 Proof of Concept: Constructing the Dual-Valid Artifact (Technique Validation)

Here in Figure 2, we can see the first 128 bytes of a Dicom file with the first 26 bytes over-written with a Bash script. By using the hex editor application HxD, we are able to alter the hex code of the file to add the script. It contains the '#!' of the bash script followed by a basic whoami command and a proper exit from the script. This allows the DICOM file to now function as a DICOM image collection and a bash script. This is our first example of a DICOM polyglot proof-of-concept. Its simplicity in creation means that automation and prolific generation would take small amounts of resources, time, or effort.

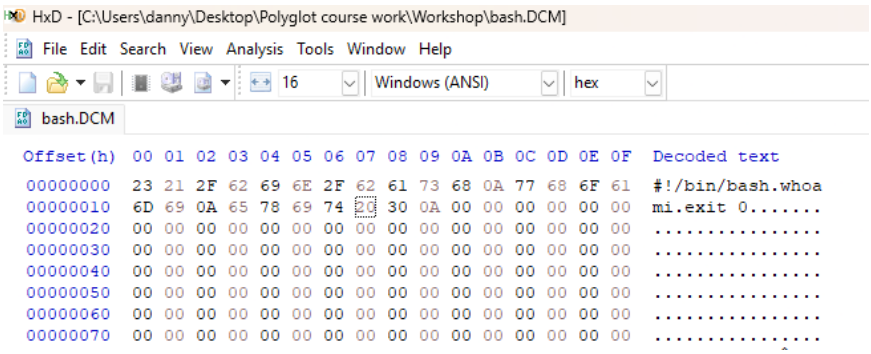


Figure 2: HxD table: An initial example illustrating the exploitability of DICOM and its utility as an ingress vector involves abusing the preamble. The first 128 bytes of the DICOM preamble are commonly ignored by data parsers. This vulnerability permits the injection of any file up to 128 bytes, which most DICOM parsers will subsequently disregard

The next part of the DICOM part 10 File we will attempt to demonstrate as exploitable is the Private tag. In this example we will use both the 128-byte preamble and the private tag data element in conjunction to create a working DICOM/PE (Portable Executable) file.

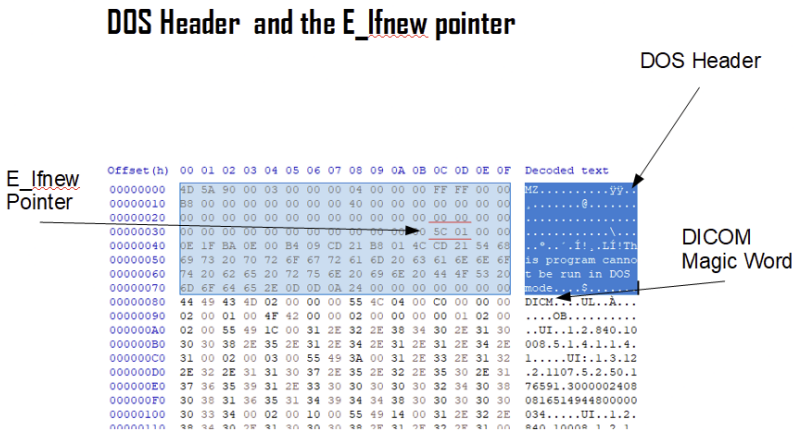


Figure 3: DICOM Magic Word, (File Signature), DOS Header, and E_lfnew Pointer locations in the Hex code.

In Figure 3, we can see how the DOS header of the PE perfectly fits into the blank Preamble of the DICOM. Leveraging the PE e_lfnew Pointer, we can redirect the PE flow to the PE file signature. If the pointer is used to point further into the DICOM file toward data embedded in a private element identified with a private tag, we can place the remainder of the PE inside this Data element and with a high likelihood it will not be parsed by most DICOM viewers. Further alteration of the private tag to match length, adding proper padding to the PE to ensure alignment, and altering the remaining PE pointers to the correct offsets will now allow a PE to function while not disrupting the DICOM data structure (Figure 4).

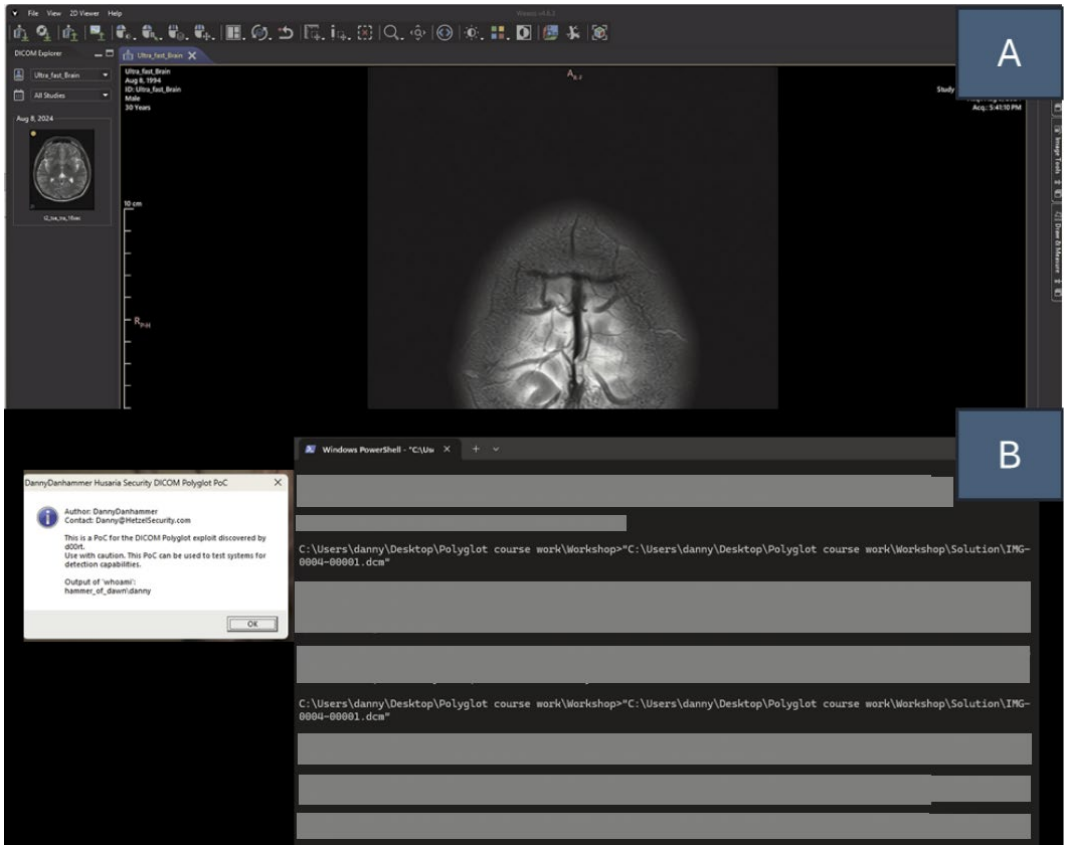


Figure 4: DICOM Image and Execution: A) The DICOM image opens with the associated DICOM parser with a double click. B) But when opened via the terminal it executes out payload PE. (Unnecessary terminal commands redacted provide focus.)

4. The Operational Gap: Why Feasibility Translates to Risk

4.1 Non-Uniform Inspection and the Stealthy/Polyglot Gap

A key defining characteristic of polyglots is their chameleon-like ability to remain syntactically valid under multiple file formats simultaneously (Albertini, 2015). Their dual, and sometimes ternary, validity introduces a challenge for security tools that assumes a file conforms to a single format. In healthcare imaging environments, where DICOM objects are commonly treated as clinical data rather than untrusted adversarial inputs, prioritization of schema conformance and renderability by inspection mechanisms is seen rather than full byte-stream analysis. As such, data artifacts containing multiple semantic interpretations may not be consistently classified across security tools.

Observations from the feasibility phase of this study illustrate this asymmetry in inspection. The polyglot proof-of-concept developed in Section 3 was analysed using the multi-engine malware analysis tool VirusTotal and the endpoint detection software Malwarebytes. VirusTotal had a mixed reporting of 11 out of 71 security tools reporting as possibly malicious (Figure 5). While a score of 11/71 would raise suspicions to many, the inability to run DICOM through public scanners and requiring the choice of a local antivirus software, creating an environment where evasion only needs to succeed in 1 or the 71 presented. This places a higher importance on the failure to detect proportion from 84.51% of assessed antivirus products. When executed within heuristic-capable sandboxes on VirusTotal, the polyglot triggered only seven low-severity and three informational MITRE signatures, despite performing indirect command execution and process injection. Although VirusTotal was able to identify the polyglot through aggregated results, many mainstream security tools failed to detect it independently.

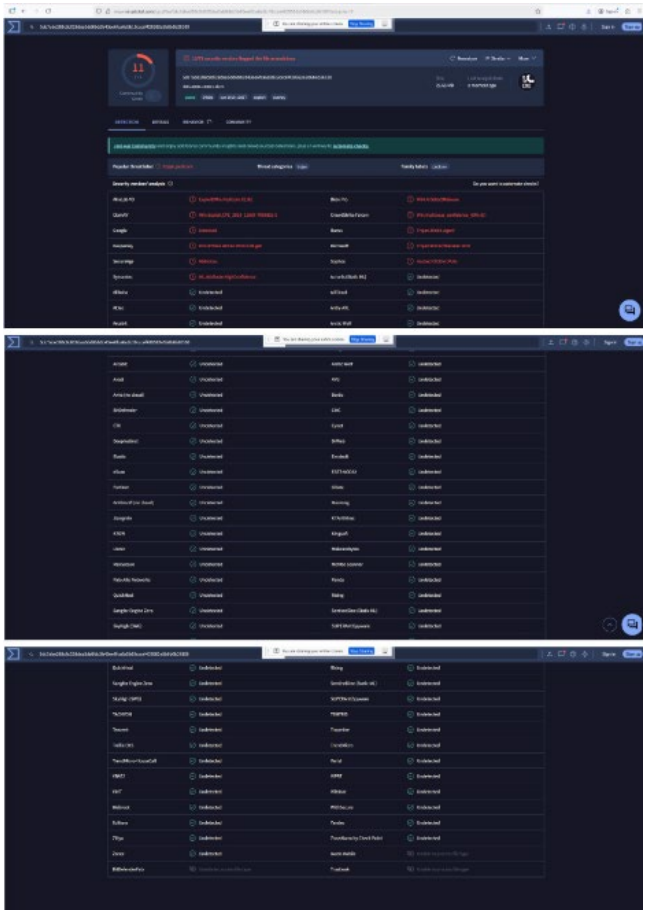


Figure 5: A) Analysis of the artifact using VirusTotal. The VirusTotal report indicates that 11 security providers (highlighted in red) successfully identified the artifact, while numerous other providers failed to detect the exploit, despite its relationship to a widely recognized vulnerability

To further assess the local endpoint detection behavior, the polyglot was scanned using Malwarebytes (version 5.4.6.227) in a controlled environment. At the time of the test, Malwarebytes reported no detection (Figure 6).

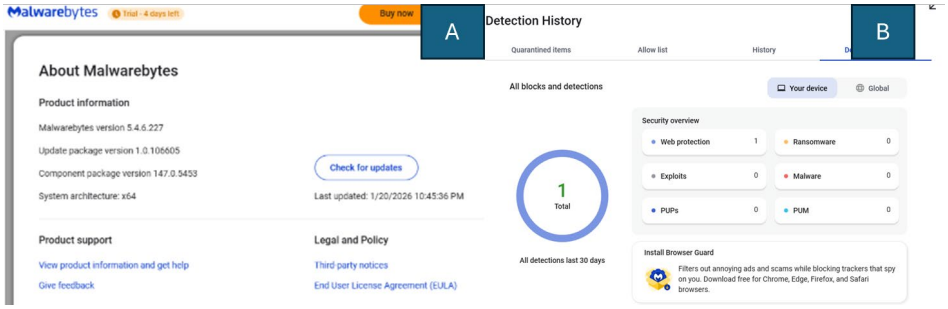


Figure 6: A) Malwarebytes, a consumer anti-malware program. B) Diagnostic screen demonstrating failure to detect the artifact

This gap indicates that different security products interpreted the polyglot file according to different assumptions and approaches to parsing. Some products readily identified byte patterns associated with executable structures embedded in the file and within the preamble. Others accepted the format presented as a simple DICOM object and did not do further analysis to uncover the patterns of possibly obfuscated code. This is not attempting to illustrate a failure of this specific product but rather the lack of uniformity in detection. Previous research has highlighted product to product inconsistencies are deeply ingrained (Mohaisen and Alrawi, 2014). Antivirus products fundamentally disagree with each other on both detection and labelling, to a degree that makes their outputs, by themselves, unreliable as ground truth. Classification of multi-format or polyglot files may not be reliably detected by a single security product. Polyglots exploit this ambiguity by presenting different semantic interpretations depending on the parsing logic applied. A polyglot does not need to evade all security tool detections to succeed operationally. It must only pass through enough stages of inspection to enter the trusted workflow. In this sense, stealth arises not from sophisticated obfuscation techniques but from classification ambiguity. Within the S.P.I.C.Y. model, this represents the intersection of the Stealthy and Polyglot characteristics: the polyglot file remains structurally compliant while different systems disagree about its interpretation. This inconsistency can be operationally significant. In the complex enterprise environment, security controls rarely rely on a single security tool or inspection method. As files move through different systems and scanners, each applying its own parsing logic, the likelihood of inconsistent classification increases.

4.1.1 The standards non-operational state

After 7 years of existing as a known vulnerability, the persistence of this gap reflects a broader systemic issue within the healthcare ecosystem, as opposed to a flaw in DICOM standard itself. DICOM was designed as a tool to offer interoperability across diverse imaging devices and software platforms. To accomplish this feat, the standard permits extensibility. Extensibility is achieved through features of the standard such as vendor specified private tags and flexible metastructures. (National Electrical Manufacturers Association (NEMA), 2026). These features enable vendors to embed proprietary information while maintaining compliance with the standard. This extensibility also introduces ambiguous areas within the file that creates issues for uniformity in parsing.

In practice, many implementations of "DICOM validation" focus on verifying structural conformance or the ability of imaging software to render the imaging data correctly (Mirsky et al., 2019). Parsers and viewers, such as Weasis, only focus on the imaging and ignore unnecessary sections of data. While these checks are essential for interoperability, they do not necessarily enforce deep comprehensive inspection of the entire object. The result is what can be described as a non-operational security state. The format's extensibility is fully implemented but the corresponding security validations are not consistently enforced across tools or environments. Several factors contribute to this condition further. Complete comprehensive semantic and structural inspection of every DICOM object can be computationally expensive and could result in latency in critical clinical workflows and pipelines. Next, traditional healthcare security architectures acknowledge the dangers of ingress points of email attachments, web downloads, and others, but imaging data pipelines are often treated as trusted channels (Mahler et al., 2018).

To properly address this operational gap requires moving beyond the assumption that format compliance alone guarantees safety within trusted workflows. Standards bodies, vendors, and healthcare operators must consider approaches that apply more thorough validation practices. Potential directions include establishing baseline expectations for byte-stream inspection of DICOM objects, defining clearer policies for handling

private data elements, and developing security-focused conformance profiles that can be implemented consistently across heterogeneous systems. Such efforts would not eliminate the flexibility that makes DICOM interoperable but would help ensure that this flexibility does not translate into systemic blind spots within clinical imaging workflows.

4.2 Automated Pipelines and the Infiltrative/Cascading Gap:

While the inconsistent inspection and parsing in security tools has shown how such objects can evade detection, feasibility alone cannot translate into operational risk, the polyglot must have the ability to traverse real workflows. Modern medical Imaging infrastructure in healthcare environments are not static storage. They are interconnected data pipelines in which DICOM objects move through multiple automated systems over the course of its lifecycle (Pianykh, 2012). A single image study may originate from an imagining source ,such as a MRI scanning system, pass through ingestion services (Store-SCP or DICOMweb STOW), enter a Picture Archiving and Communication System (PACS), be transferred into a long term archival system such as Vendor Neutral Archive (VNA) and finally be accessed by diagnostic viewers , exported to research sets, or even processed by artificial intelligence and machine learning pipelines (Kahn, 2016). Throughout the course of its lifecycle, the DICOM object is repeatedly parsed, indexed, modified, and redistributed by automated systems (Pianykh, O.S., 2012).

For the S.P.I.C.Y. model, this corresponds to the Infiltrative and Cascading phases of the lifecycle. This infiltrative phase occurs when a polyglot object enters the pipeline through legitimate ingestion. Because the polyglot follows the syntax and structural requirements for the DICOM File part 10 specification, systems that rely primarily on structural validation may accept the object without detecting its secondary semantics (Pianykh, 2012; Huang, 2018). The cascading occurs when the polyglot is parsed and pushed through multiple steps of the pipeline while being able to maintain its malicious capabilities (Mirsky et al., 2019; Mahler et al., 2018). Within this framework, the infiltration and persistence become properties and assets of the workflow rather than of a single exploit. Using the ambiguity of the heterogenous workflow that due to assumed trust, the accepted structurally valid polyglot may propagate throughout the environment, through multiple systems, that independently interpret the same data, allowing the Stealthy and Polyglot characteristics of the S.P.I.C.Y. model to persist across the pipeline.

5. Discussion: Activation, Yield, and Strategic Implications

5.1 Activation Context in Automated Workflows

The execution and activation of a DICOM polyglot does not require manual user double-click. In healthcare environments, as discussed in section 4, there are numerous contexts in which a DICOM object might be parsed. Dicom objects are routinely processed by automated systems outside simple graphical viewers. These interactions can occur through command-line utilities, batch processing scripts, research pipelines, and more recently into machine learning and AI contexts. At each step the possibility of execution based on varying interpretation may occur because each system may apply different parsing assumptions to the same byte stream.

This inconsistent nature of the different forms of interpretation creates the conditions necessary for execution or activation. A viewer may see a plain DICOM image to be displayed, while another subsystem or script may interact with the same object and interpret the same data differently by the embedded syntax. This disparity forms the path to polyglot execution. A file, now embedded deep within the architecture and having crossed multiple trust boundaries, may be invoked through command-line tools, scripting environments, or automated data transformation processes.

Recent practitioner work suggests that the process to create such polyglots will become increasingly automated. Aguilar (2026) and Davis (2026) describe a proof-of-concept toolkit of embedding crafted malicious Windows Portable Executables (PE) binaries within valid DICOM images through an automated process and leveraging and merging further advanced evasion tactics. Invoked through command-line contexts while remaining undetected through automated creation and built in features including beaconing. Although the toolkit has not been formally released or subjected to peer review, its existence presents an important operation leap forward from the manual creation presented in this paper: The technical barrier to constructing DICOM polyglots is decreasing and automation of the threat is becoming a significant reality. As tooling matures, the threshold for adversarial use is decreased.

5.2 Redefining Yield: The Scope of Damage:

Conventional exploit analysis often measures success primarily in terms of payload execution. Within data-centric attack surfaces, yield must be understood more broadly. Operational value from a polyglot can extend beyond execution by successfully entering and persisting within trusted workflows. Successful ingestion and persistence demonstrate that the artifact can survive inspection boundaries and remain structurally intact. These conditions create the opportunity for later activation through lateral vulnerabilities within the system.

Under the S.P.I.C.Y. model, yield asks what the operational value is gained once a polyglot artifact successfully traverses trusted workflows. The most direct outcome is achieving execution when the polyglot is interpreted in a specific execution context. Yield may also arise from the persistence described previously, as the ability of the polyglot to remain embedded within trusted workflows enables adversaries to position executable objects deep inside clinical infrastructure. From a defensive perspective, this broader definition of yield is critical. It repositions analysis of the threat from a binary condition of exploit success or failure into a graduated model of system exposure.

5.3 Strategic Implications and Mitigation

The use of DICOM polyglots in threat exercises challenges the assumption that medical data is inherently non-executable; this finding fits within the understanding of biocentric data, media, and platforms being relevant for attack chains (Mueller, 2021; Potter and Palmer, 2023; Pope, 2026). Medical images were designed to ensure reliability and interoperability between software, platforms, and devices. As a result, security controls have often developed behind these design principles in prioritization. Business needs and attempting to support legacy systems has left an operational gap in detection. When a file satisfies the structural requirements of the DICOM standard, generally, it is treated as a valid medical object and allowed to proceed through the workflow as a trusted object. This design philosophy has operational consequences and, in those consequences, lies the gaps that researchers and adversarial actors will eventually discover and leverage; further commentary follows in Figure 7.

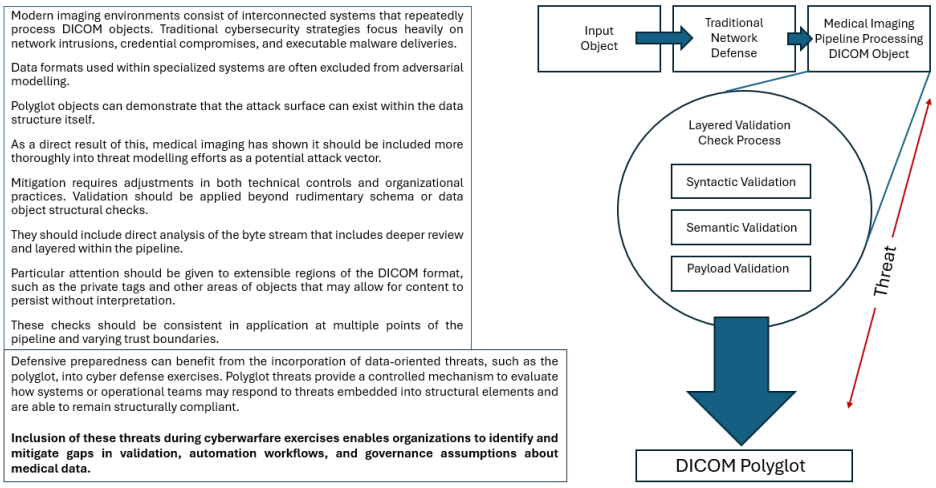


Figure 7: Design and preparedness philosophy commentary around DICOM Polyglots

The S.P.I.C.Y. framework offers a guided approach for evaluating these scenarios. Through examining how an artifact remains stealthy, infiltrates trusted workflows, cascades across connected systems, and produces operational yield, defenders can better understand how data-layer threats affect healthcare infrastructure. Using S.P.I.C.Y. as a guide creates an avenue for organizations to overcome the gaps presented by the traditional exploit models and help them move toward a broader understanding of how trusted data structures and standards can be abused to become attack surfaces. Avenues created through the use of guides such as these potentially create opportunities for healthcare organizations to improve perceptions of patient and provider sense of security, within a world that is increasingly subject to healthcare-centric cyber-attacks (Griffin et al, 2026).

6. Limitations and Future Works

The paper lacks empirical experimental data to aid exact reproducibility. The choice to limit this data is due to the nature of harm that could be weaponized and data hazards that could be produced with replication of the

experiment. Upon responsible request and discussion, a guided walkthrough to aid in reproducibility can be obtained from the author. While it may appear that the tools used were rather limited, VirusTotal comprises 70+ tools, thus mitigating this concern. Future work involves generation of a larger proof-of-concept dataset which can be tested for detection by security analysis tools. This will result in the ability to create a more quantified and firmer consensus to the state of DICOM polyglot detection in industry tools.

7. Conclusion

This paper has shifted the discussion around DICOM polyglots from technical feasibility to unmitigated operational risk within healthcare workflows, highlighting a critical security gap stemming from non-uniform inspection, misplaced trust in data compliance, and insufficient threat modelling. Our feasibility analysis, using a controlled DICOM/PE polyglot, demonstrated that mainstream security tools exhibit substantial inconsistencies in detection, allowing these dual-valid artifacts to remain stealthy. To address this, we introduced the S.P.I.C.Y. framework as a tool for practitioners to measure the operational impact of malicious data propagation through trusted, automated pipelines like PACS and VNAs. The framework emphasizes that yield extends beyond execution to include the operational value gained from persistence deep within clinical infrastructure. Ultimately, mitigating this systemic risk requires moving beyond the assumption that format compliance guarantees safety, urging standards bodies, vendors, and operators to apply consistent, byte-stream-level validation across the entire medical image lifecycle to close the operational blind spots exposed by data-centric threats.

Ethics Declaration: Clearance for the research within this paper was not required and no humans were affected.

AI Declaration: Grammarly and Google Docs and AI tools within were used for formatting and overall re-organization.

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An Integrated Framework for Ransomware Mitigation: A NIST-Aligned Defense Model Linking Cyber Insurance and Risk Management

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Abstract: Ransomware attacks have become one of the most disruptive cyber threats to modern organizations, causing significant financial losses, operational disruptions, and reputational damage across sectors. While organizations increasingly adopt security measures to mitigate risks, the fast-evolving role of cyber insurance-supported mitigation services in ransomware defense remains insufficiently understood. Cyber insurance has evolved from just a reactive compensator to a proactive security partner. It now offers pre-incident services to mitigate attack severity and post-incident services for quick recovery, reducing loss impacts. Cyber risk management and cyber insurance practices are often divided among different disciplines. Actuarial underwriting seldom integrates risk management models, and cybersecurity experts rarely include insurer mitigation tools in governance plans. This disjointed approach restricts organizations from effectively using insurance services as part of a comprehensive ransomware resilience strategy. This study investigates how cyber insurance-supported services aligned with the NIST Cybersecurity Framework reduce the impact of ransomware incidents. Building on prior empirical research identifying socio-technical drivers of ransomware losses, this paper proposes an integrated mitigation framework that combines security governance functions with insurance-supported services including vulnerability assessment, forensic readiness, incident response coordination, and recovery assistance. The framework conceptualizes ransomware risk mitigation as a layered process in which socio-technical risk drivers shape both the likelihood of incidents and the effectiveness of mitigation mechanisms. By incorporating the socio-technical factors that shape the impact of ransomware incidents, the proposed framework provides a more comprehensive defense posture against ransomware threats. Through analytical modeling and scenario-based evaluation, this study demonstrates how coordinated implementation of NIST-aligned cyber insurance services can significantly reduce expected ransomware losses and accelerate organizational recovery. The findings emphasize integrating technical cyber practices with insurance expertise to strengthen cyber resilience. By linking cyber risk management and insurance, this research enhances understanding of ransomware mitigation and offers practical insights for organizations managing ransomware risks in a rapidly evolving threat landscape.

Keywords: Ransomware Attacks, NIST CSF, Cyber Insurance Service, Integrated Framework, Risk Mitigation

1. Introduction

Ransomware attacks have become one of the fastest-growing cybercrimes in the digital economy (Sausalito, 2024). Organizations across industries increasingly rely on information systems to support critical operations, making them attractive targets for cyber adversaries. Cybercriminals use ransomware to encrypt victims' sensitive information and threaten to publicly release the information unless a ransom payment is made (August, et al., 2019; OZ, et al., 2022). Recent reports indicate that ransomware incidents continue to grow in frequency and severity, leading to billions of dollars in economic losses each year (Cartwright & Cartwright, 2023). Ransomware attacks can disrupt essential services, compromise sensitive data, and undermine trust in digital infrastructure (Dawson, et al., 2021). As tactics evolve toward professionalized models a variety of crimes like double and triple extortion, supply-chain propagation, and Ransomware-as-a-Service have emerged that traditional cybersecurity defenses alone are often insufficient to mitigate ransomware impact (Nagar, 2024).

To address this threat, many technology-based solutions have been developed to protect information assets (Hegde & Rokseth, 2020). As ransomware attackers target vulnerabilities in system and employee behavior, non-technical factors have become crucial in cyber defense (Nagar, 2024; Shaikh, et al., 2024). Various management frameworks address the growing complexity of cyber-attacks (Rassam, et al., 2017). These frameworks guide organizations in managing cyber risks, incident handling, and prevention. Organizations select frameworks or combinations that suit their needs to enhance cybersecurity and protect digital assets. The NIST Cybersecurity Framework (CSF) is widely used, categorizing practices into five domains: Identify, Protect, Detect, Respond, and Recover (NIST, 2022). These domains provide an approach to organizations for managing cyber risks across the entire lifecycle of a cyber incident (NIST, 2022).

Cyber insurance has been evolving beyond the traditional insurance paradigm to embrace security expertise (Huang & Cornell, 2025; Zywave, 2025). Risk services alongside cyber insurance policies help prevent potential

threats and mitigate the impacts of cyber incidents (Zeller & Scherer, 2023). Cyber insurance in recent years has increasingly evolved into a provider of cybersecurity expertise and mitigation services (Huang & Cornell, 2025; Zywave, 2025; Blackfog, 2024). Modern cyber insurance policies often include pre-incident and post-incident support such as vulnerability assessments, incident response coordination, digital forensics, and recovery assistance (Zeller & Scherer, 2023). These services position insurers as active participants in cybersecurity governance rather than passive claim processors (Huang & Cornell, 2025; Blackfog, 2024). As cyber threats continue to escalate, the role of cyber insurance is shifting toward a more proactive model that emphasizes prevention and resilience. This proactive capability may help position cyber insurance in a more central position in cyber risk management.

Despite advancements, a gap still exists in understanding how cyber insurance reduces ransomware risks. Existing literature mainly examines technologies, governance frameworks, or cyber insurance mechanisms independently (McIntosh, et al., 2021). Technical studies typically focus on detection algorithms, system hardening, or network defense mechanisms, while economic and actuarial research examines cyber insurance pricing and risk transfer (Martin & Collier, 2020). Ransomware mitigation is inherently socio-technical requiring coordination between technical defenses, organizational practices, and financial risk management mechanisms (Mukhopadhyay & Jain, 2024). The effectiveness of ransomware mitigation strategies may depend on socio-technical conditions within organizations. For example, organizations with stronger security governance may be able to leverage incident response services more effectively, while highly interconnected organizations may face greater challenges in containing ransomware propagation. Previous work does not fully capture how mitigation effectiveness emerges from the interaction between internal governance mechanisms and external risk management services under varying organizational conditions. This fragmentation limits the theoretical understanding and practical application of defenses.

This study examines how cyber insurance-supported services aligned with the CSF mitigate ransomware impacts. Incorporating socio-technical drivers of ransomware losses, the paper proposes an integrated analytical framework that links organizational risk drivers, cybersecurity governance functions, and insurance-supported mitigation services. Mitigation effectiveness is conceptualized as the outcome of coordinated security controls and insurance services operating across the ransomware attack lifecycle. The central theoretical contribution lies in demonstrating that mitigation effectiveness is not additive but interactional, where the marginal benefit of one mechanism depends on the presence of the other and is further conditioned by socio-technical factors such as organizational preparedness, technological posture, and network exposure. By formalizing these relationships, this study goes beyond descriptive integration and provides a structured explanation of how coordinated mitigation strategies produce non-linear reductions in ransomware impact. To our knowledge, this is among the first studies to formally model the interaction between cybersecurity governance and insurance-supported mitigation services in complex socio-technical environments.

The rest of this paper is organized as follows. Section 2 reviews related literature on ransomware risks, cybersecurity frameworks, and cyber insurance services. Section 3 presents the integrated mitigation framework and analytical model. Section 4 presents scenario-based analysis demonstrating the effectiveness of coordinated mitigation mechanisms. Section 5 discusses implications for cybersecurity governance and cyber insurance. Section 6 concludes with future research suggestions.

2. Literature Review

Ransomware has increasingly become a targeted attack, where attackers carefully select victims based on system vulnerabilities and data sensitivity (OZ, et al., 2022). As a result, socio-technical factors such as technical infrastructure, organizational readiness, and operational processes are vital in determining the impact of ransomware attacks (Haimes, 2012; Zhang, et al., 2011; Anderson & Moore, 2006). These factors not only influence the severity of ransomware incidents but may also affect the effectiveness of mitigation strategies. Addressing these factors is essential for accurate risk assessments and for proactive defense implementations. While previous studies highlight socio-technical factors in ransomware outcomes, many are descriptive and lack explicit links to mitigation effectiveness. They offer limited analysis of how organizational conditions affect mitigation mechanisms and loss severity, restricting practical risk management insights.

To address these complex cyber risks, organizations often rely on structured governance frameworks. Among the most widely adopted frameworks is the CSF, which provides a structured approach for identifying, assessing, and mitigating cybersecurity threats (NIST, 2022). Existing literature examines cybersecurity frameworks in strengthening organizational cyber resilience (Tsen, et al., 2022). However, these frameworks mainly emphasize technical and organizational controls within the firm. While providing valuable guidance for managing cyber risks,

they often do not explicitly incorporate external risk management mechanisms such as cyber insurance. Existing studies primarily emphasize internal governance structures and technical controls, treating organizations as self-contained units of defense. As a result, existing frameworks may overlook the wider ecosystem of actors involved in cyber risk mitigation.

Cyber insurance was initially a financial tool to compensate organizations for cyber losses (Blackfog, 2024). It has evolved to offer more cybersecurity services (Zywave, 2025; Huang & Cornell, 2025; Blackfog, 2024). Now cyber insurance provides pre- and post-incident risk assessment services, including vulnerability assessments, security audits, legal guidance, and response coordination (Zeller & Scherer, 2023). As incidents have increased in frequency and sophistication, cyber insurance has become more involved in helping organizations manage cybersecurity risks proactively (Mukhopadhyay & Jain, 2024). Cyber insurance increasingly functions as a risk advisor that supports organizations throughout the cybersecurity lifecycle. While industry reports highlight this service-oriented shift (Zywave, 2025), academic literature seldom explores how these services affect security controls or their impact on mitigation in various organizational contexts. This gap suggests the need for a more integrated analytical perspective that connects insurance-supported services with cybersecurity frameworks and socio-technical risk factors.

Although substantial research exists on ransomware, cybersecurity frameworks, and cyber insurance, these areas have largely developed independently. Technical ransomware research has focused primarily on detection algorithms, encryption mechanisms, and system defense strategies. Actuarial research on cyber insurance has concentrated on risk pricing and contract design. Few studies examine how insurance-supported mitigation services interact with governance frameworks under varying socio-technical conditions.

This study develops an integrated framework linking socio-technical ransomware risk drivers with NIST-aligned cyber insurance services. It aims to enhance understanding of ransomware mitigation strategies in modern cyber risk environments.

3. Conceptual Framework

While cybersecurity frameworks provide guidance for implementing technical and governance controls, cyber insurance offers additional resources and expertise that can support organizations in preventing, responding to, and recovering from cyber incidents. This study proposes an integrated mitigation framework that links cybersecurity governance functions with cyber insurance-enabled mitigation services to reduce ransomware impact. The proposed framework conceptualizes ransomware risk mitigation as a layered system consisting of three primary components: socio-technical risk drivers, cybersecurity governance mechanisms, and insurance-supported mitigation services. These components jointly determine the effectiveness of mitigation actions and ultimately influence ransomware outcomes.

3.1 Socio-Technical Drivers of Mitigation Effectiveness

Socio-technical conditions within organizations play an important role in determining the effectiveness of ransomware mitigation strategies (Mukhopadhyay & Jain, 2024). Cybersecurity systems operate within complex organizational environments where human behaviour, technological infrastructure, and organizational processes interact (Neoaz, 2024). Consequently, the same mitigation mechanisms may produce different outcomes depending on organizational conditions.

- Organizational preparedness refers to the extent to which an organization has established cybersecurity governance structures, security awareness programs, and incident response planning capabilities. Organizations with stronger preparedness are better positioned to implement cybersecurity controls and respond effectively when ransomware incidents occur (Haimes, 2012).
- Technology posture reflects the quality and robustness of an organization's technological infrastructure, including system architecture, patch management practices, and network security configurations. Weak technological infrastructure may create vulnerabilities that ransomware attackers can exploit, thereby increasing both the likelihood and severity of incidents (Zhang, et al., 2011).
- Settlement duration captures the time required to resolve ransomware incidents, including negotiation processes and system restoration efforts. Longer settlement durations often indicate more severe operational disruption and may increase overall financial losses (Anderson & Moore, 2006).

- Network exposure represents the extent to which organizations are connected to external partners, vendors, and digital supply chains. Highly interconnected systems may increase the potential for ransomware propagation across networks, making containment and recovery more difficult (Robinson, et al., 2022).

These socio-technical factors influence ransomware mitigation in two ways: they impact the likelihood and severity of ransomware incidents, and they shape the effectiveness of mitigation mechanisms implemented through cybersecurity frameworks and insurance-supported services.

3.2 Integration with CSF and Cyber Insurance Services

The framework integrates ransomware-relevant mitigation strategies across the five functions of the CSF, demonstrating how technical controls, governance practices, and cyber insurance services operate together throughout the ransomware lifecycle. Table 1 organizes the proposed framework along two dimensions: (1) the five functional domains of the CSF, and (2) three complementary layers of mitigation, cyber insurance-supported services, internal cybersecurity controls, and socio-technical influencing factors. Rather than representing independent components, the table illustrates how these elements operate jointly within each stage of the ransomware lifecycle. Specifically, each column represents a governance phase (from Identify to Recover), while each row highlights how different mitigation resources and contextual conditions contribute to reducing ransomware risk within that phase. This structure emphasizes that mitigation effectiveness emerges from the coordination of technical controls, external expertise, and organizational conditions rather than from any single mechanism in isolation.

Table 1: Integrated Framework

NIST	Identify	Protect	Detect	Respond	Recover
Cyber Assistance	IT Asset Inventory, Vulnerability Assessment	Employee upskilling, Awareness Training, Encryption & Backup	Monitor, Alert Suspicious Information Flows, Block Payload	Forensics, Quarantine Infected Systems, Intelligence Cooperation (e.g., Extortion Consulting)	Data Restoration, Business Continuity, Review & Fix
Empirical Measures	Supply Chain Risk Management, End-of-life Systems Protection, Logging and Monitoring Protections	MFA, Patch Management, Email Filtering, RDP, Awareness Training, Backup	EDR, Logging and Monitoring Protections, Early Detection of Threats	Ransomware Incident Response Plan, Negotiation, Legal Consulting	End-of-life Systems Protection, Backup, PAM
Influencing Factors	Technical Vulnerabilities, Organizational Preparedness	Technical Vulnerabilities, Organizational Preparedness	Organizational Preparedness	Breadth of Impacted Entities, Duration of Incident Resolution	Technical Vulnerabilities, Breadth of Impacted Entities

Table 1 represents a layered interaction model rather than a static mapping of controls. Within each NIST function, cyber insurance services complement internal cybersecurity capabilities by extending organizational resources, while socio-technical factors condition the effectiveness of both. As a result, mitigation mechanisms are context-dependent rather than universally effective. For example, vulnerability assessments in the Identify phase are more effective in organizations with higher preparedness, and incident response coordination in the Respond stage produces greater loss reduction when organizational processes enable rapid decision-making.

In summary, these integrated activities illustrate how NIST-aligned security functions and insurance-enabled services can operate as a unified defense structure rather than as separate or sequential mechanisms.

3.3 Analytical Representation of the Mitigation Framework

To formalize the relationships illustrated in the framework, ransomware impact is modeled as a function of socio-technical risk drivers and mitigation mechanisms. Let the expected ransomware loss for organization *i* be represented as:

$$Loss = f(RiskDriver\_i, Mitigation\_i)$$

where *RiskDrivers* represents organizational conditions such as preparedness, technological posture, settlement duration, and network exposure, and *Mitigation* represents the combined effect of cybersecurity governance controls and insurance-supported services.

Mitigation consists of cyber risk controls embedded the NIST framework and insurance-supported mitigation services. It is not treated as a single aggregated input but as a structured combination of interacting components:

$$Mitigation = g(NISTControls, InsuranceServices, RiskDrivers)$$

Where *NISTControls* denotes internal cybersecurity controls aligned with NIST functions, and *InsuranceServices* represents external mitigation services from cyber insurance. The inclusion of *RiskDrivers* within the mitigation function reflects the context-dependent nature of mitigation effectiveness, indicating that the same mitigation strategy may have different outcomes across organizational environments.

This formulation implies two key points. First, mitigation exhibits a complementary effect, where the marginal effectiveness of cybersecurity controls increases in the presence of insurance-supported services. Second, mitigation is conditional, which means socio-technical factors moderate the relationship between mitigation measures and ransomware outcomes. For instance, organizations with higher preparedness may benefit more from incident response services, while highly exposed networks may reduce the effectiveness of detection mechanisms.

Together, these relationships define a non-linear mitigation structure in which ransomware loss reduction depends on both the interaction between mitigation components and the organizational context in which they are deployed. This analytical representation provides a formal foundation for the simulation model developed in the upcoming section. This structure differs from previous models that assume additive mitigation effects by explicitly incorporating interaction terms between governance controls and insurance services.

4. Research Design

To evaluate the effectiveness of ransomware mitigation strategies, this study adopts a quantitative test based on scenario-based simulation. The purpose of this approach is to test conceptual modeling while addressing limitations in publicly available ransomware datasets. Public cyber incident datasets typically provide detailed information about attack vectors, affected sectors, and incident characteristics, but they rarely capture the full range of mitigation services associated with cyber insurance or coordinated incident response efforts. As a result, relying exclusively on observed data may not fully capture the interaction between cybersecurity governance mechanisms and insurance-supported mitigation services. To address this limitation, a Monte Carlo simulation is implemented to examine how different mitigation configurations influence ransomware outcomes across organizational environments. This approach enables the study to evaluate both the direct effects of mitigation mechanisms and the conditional effects shaped by socio-technical risk drivers, providing a structured empirical basis for assessing the integrated mitigation framework proposed in Section 3. The simulation is designed as a theory-consistent evaluation rather than a predictive empirical model.

4.1 Simulation Method

To ensure reproducibility, the key socio-technical variables are operationalized as follows. Organizational preparedness is modeled as a continuous variable in the range [0,1], representing the maturity of governance structures, incident response planning, and security awareness. Technology posture represents the robustness of technical infrastructure (e.g., patching, system hardening), which is normalized to [0,1]. Network exposure reflects the degree of external connectivity and third-party dependencies, between 0 and 1, where higher values indicate greater exposure to propagation risk. Settlement duration is a positive continuous variable representing the time required to resolve ransomware incidents. These variables are treated as stochastic inputs in the simulation and jointly determine both baseline risk and mitigation effectiveness.

Two categories of mitigation mechanisms are incorporated into the model.

- CSF functions which represent internal organizational cybersecurity capabilities.
- Insurance-supported mitigation services, such as vulnerability assessments, digital forensics support, incident response coordination, recovery assistance. These services represent external resources that complement internal cybersecurity capabilities.

We identify the dependent variable as Ransomware Impact.

Ransomware impact represents the severity of consequences experienced by an organization following a ransomware attack. Because financial loss data are often incomplete in public disclosures, a composite impact indicator can be constructed based on observable incident outcomes. The ransomware impact variable may include indicators such as operational disruption duration, extent of system compromise, data exfiltration occurrence, recovery complexity. In analytical terms, ransomware impact can be represented as a continuous severity measure or as a categorical indicator of high-impact incidents.

A Monte Carlo simulation is used to generate a synthetic population of organizations with varying socio-technical characteristics. In the simulation, socio-technical variables are generated from bounded probability distributions to reflect heterogeneous organizational environments. Specifically, preparedness and technology posture are drawn from Beta distributions to capture variability across organizations, while network exposure is modeled using a right-skewed distribution to reflect the prevalence of highly connected systems. Settlement duration is generated from a log-normal distribution to capture the heavy-tailed nature of incident resolution time. The simulation is conducted over 10000 iterations to ensure stability of the results. Parameter values are selected to reflect realistic ranges observed in previous cyber risk studies, while allowing sufficient variability to examine relative mitigation effects across different organizational contexts.

Consistent with Section 3's framework, ransomware impact is computed as a function of baseline risk adjusted by mitigation effectiveness. Mitigation effects are modeled as multiplicative reductions in expected loss, allowing for interaction between cybersecurity controls and insurance-supported services. This structure captures both independent and joint effects of mitigation mechanisms and enables evaluation of complementarity across scenarios.

4.2 Result Analysis

We use Monte Carlo simulation to generate numerical values for the variables that are hard to observe. The synthesized data is used to evaluate how mitigation mechanisms influence ransomware impact. We show an example of model-generated results indicating the effectiveness of mitigation measures across four socio-technical contexts. While the results are not from real-world estimates, they provide a theory-consistent illustration of relative mitigation effects under uncertainty and support the study's modeling contribution. We present a flexible framework that adapts as more ransomware incident data emerges, assisting future researchers in analyzing evolving ransomware risks and mitigation strategies.

Table 2: Simulation Results

	Overall Sample (Baseline)		Weak Organizations (low preparedness / weak technology / high exposure)		Strong Organizations (high preparedness / stronger technology / lower exposure)	
Scenario	**Expected Loss**	**Reduction vs. No Mitigation**	**Expected Loss**	**Reduction vs. No Mitigation**	**Expected Loss**	**Reduction vs. No Mitigation**
No Mitigation	411097	-	943115	-	97814	-
CSF	262423	36.2%	648933	31.2%	48374	50.5%
Insurance Service	282434	31.3%	675968	28.3%	58661	40.0%
Integrated	163269	60.3%	429098	54.5%	23768	75.7%

Table 2 shows mean expected losses over 10000 simulations and relative reductions versus baseline. These values, consistent with the model's expectations, highlight differences in mitigation effectiveness rather than precise estimates. The results reveal several important insights regarding the effectiveness of ransomware mitigation strategies across different organizational contexts. First, mitigation effectiveness is context-dependent rather than universal. The same mitigation strategies produce different outcomes depending on

organizational preparedness and technological capability. For example, organizations with weaker preparedness experience substantially higher baseline expected losses compared with stronger organizations, indicating that organizational conditions significantly influence ransomware risk exposure.

Second, integrated mitigation strategies outperform isolated approaches. While both the CSF–based controls and cyber insurance individually reduce expected losses, their combined implementation produces the largest reduction across all scenarios. In the overall sample, the integrated strategy reduces expected losses by approximately 60.3%, compared with 36.2% for NIST-only mitigation and 31.3% for insurance-only mitigation. This finding suggests that technical controls and financial risk transfer mechanisms function most effectively when implemented together.

Third, organizational strength enhances mitigation effectiveness. Under the integrated scenario, ransomware loss reductions are about 54.5% for weak and 75.7% for strong organizations, showing that stronger security and lower exposure improve mitigation investments effectively. This result supports the study's socio-technical perspective that mitigation outcomes depend on both mechanisms and the organizational environment.

To summarize, these results highlight the importance of embedding cyber insurance-supported measures into institutional mechanisms such as CSF to achieve more robust ransomware risk mitigation.

5. Implications

This study's findings have important implications for both ransomware risk management and cyber insurance practice. The simulation results indicate that ransomware mitigation is most effective when internal cybersecurity controls and insurance-supported services are implemented as complementary rather than independent mechanisms. The integrated mitigation scenario consistently produced the greatest reduction in expected ransomware losses across all organizational contexts, outperforming both NIST-only and insurance-only approaches. This suggests that ransomware resilience should be understood not as the product of a single control domain, but as the outcome of coordinated socio-technical and institutional defenses.

From a governance perspective, the results emphasize CSF's value as a structured foundation for ransomware preparedness, detection, response, and recovery. However, the findings also suggest that internal governance mechanisms alone may be insufficient, particularly for organizations with weak preparedness, limited technological maturity, and high exposure. In such contexts, external support provided through cyber insurance services can extend organizational capabilities by supplying specialized expertise in vulnerability assessment, incident response coordination, forensic investigation, legal support, and recovery planning. Accordingly, organizations should move beyond viewing cyber insurance solely as a financial backstop and instead treat it as an operational component of cyber resilience strategy. This interpretation supports the proposed framework in this study, which positions insurance-supported services embedded in NIST-aligned functions across the ransomware lifecycle.

For cyber insurance, the findings support its latest trends: shifting from risk mitigator to proactive monitor and advisor, as it merges with cybersecurity services. In the model, insurance cyber services contributed to reduced expected ransomware impact by improving response capacity, accelerating recovery, and reducing the operational severity of incidents. This implies that cyber insurance can add strategic value through service design, vendor coordination, incident preparedness, and pre- and post-incident resilience assistance. Insurers may benefit from structuring policies to more explicitly align risk assessment and service provision with recognized governance frameworks such as the CSF. Through this alignment, cyber insurance can contribute to reducing organizational losses by encouraging proactive risk prevention, strengthening organizations' cybersecurity capabilities, and mitigating the severity of cyber incidents.

This study contributes to the growing recognition that ransomware is a socio-technical risk requiring interdisciplinary solutions. The simulation results show that mitigation outcomes depend not only on the presence of technical controls but also on preparedness, infrastructure quality, exposure, and recovery conditions. This has policy relevance as regulators, industry groups, and cybersecurity standards bodies may wish to promote better coordination between organizational security governance and cyber insurance ecosystems. Such coordination could support more consistent expectations regarding minimum controls, incident reporting, vendor engagement, and recovery planning, particularly in sectors facing systemic ransomware risk.

Overall, the central implication of this study is that effective ransomware mitigation requires integration. Organizations, insurers, and cybersecurity experts should move beyond fragmented approaches and instead

adopt coordinated defense models that combine governance frameworks, operational capabilities, and insurance-supported services into a unified strategy for cyber resilience.

6. Conclusion

Ransomware is a major cyber threat causing operational and financial damage. While organizations use cybersecurity frameworks and cyber insurance separately, they often lack a coordinated resilience approach. This study proposes an integrated framework combining cybersecurity practices with NIST-aligned insurance services to mitigate ransomware across various organizations.

Using Monte Carlo simulation, the study examined how different mitigation strategies influence expected ransomware losses under various socio-technical conditions. The results reveal three key findings. First, mitigation effectiveness depends on context, with organizational preparedness, technological capability, and exposure levels significantly affecting losses. Second, integrated mitigation strategies outperform isolated approaches. While NIST-based controls and cyber insurance each reduce losses, their combined implementation produces the largest impact. Third, organizations with stronger preparedness and tech capabilities benefit more from mitigation efforts, underscoring the importance of organizational readiness.

The primary contribution of this study is methodological. The paper introduces a modeling framework that integrates socio-technical risk conditions, governance controls, and insurance-supported mitigation services into a unified analytical structure. By linking cybersecurity governance with cyber insurance services, the framework provides a systematic approach for analyzing how different mitigation strategies interact to influence ransomware outcomes. This approach contributes to the interdisciplinary research that views ransomware not only as a technical threat but also as a risk management challenge.

There are some limitations. The simulation results rely on synthesized data designed to illustrate relative mitigation effects rather than precise real-world loss estimates. As a result, the findings should be interpreted as analytical demonstrations rather than empirical predictions. Despite these limitations, the study provides a structured foundation for understanding how integrated mitigation strategies can improve ransomware resilience. The framework proposed in this study offers a step toward developing more comprehensive and adaptive strategies for managing ransomware risk in complex socio-technical environments.

Future research can extend this work by incorporating real ransomware incident datasets, sector-specific risk parameters, and longitudinal analysis of mitigation effectiveness. These directions would empirically test the proposed framework and further validated in practical cybersecurity environments.

Ethical Declaration: Ethical approval was not required.

AI Declaration: AI tools were not used in the creation of this paper.

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Future Smart Devices in Future Digital Environments

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Abstract: Our modern smart cities and societies are rapidly changing in all aspects. These entities can be described as digital, multidimensional hybrid entities, where everything is interconnected and where different technologies are used to acquire, transmit, exchange, process, use, and store information. We need to look at these multidimensional information and communication system entities in a new way. The information and data models we use, and their functionalities, require communication systems that consist of air-space-land-sea communication networks (ASGM), in which the different components work seamlessly together. These digital, multidimensional hybrid systems include several parts and functions, such as various digital platforms and their services; a range of technologies, including artificial intelligence (AI), machine learning (ML), and virtual reality (VR) solutions; blockchains; digital twins; quantum technologies (communication, cryptography, and computing); metaverse environments; and various data center functions. These environments also use the Large Language Model (LLM). Our new smart devices must be developed to adapt and operate in these environments, using the services they provide, and they must function regardless of time and place across all usage contexts, including extraterrestrial networks. Data center capabilities, MECs, and edge systems are also rapidly evolving due to emerging communication requirements. Quantum computing, cryptography, and communication, alongside ML, are becoming available, and their integration must be explored, as they introduce additional challenges for device design and functionality. We must ensure sufficiently low transmission and synchronization latencies so that physical and virtual environments can interact seamlessly without failures. In this article, we examine smart devices designed for future communication environments. These devices will utilize artificial intelligence, machine learning, and virtual reality to support the services of future smart societies across operational domains, including those beyond Earth. We also analyze cybersecurity threats to end-to-end services in different use cases and explore device-level functional enhancements.

Keywords: Smart devices, Artificial intelligence, Virtual reality, Quantum computing, Quantum cryptography

1. Introduction

The living environments of future smart societies form many multidimensional hybrid communication environments, where users may not be able to know or see what kind of communication systems they are using in their everyday services. It cannot be seen or known whether air-, satellite-, ground-, or maritime-based communication networks and services are being used, because everything is connected to everything, and the services in use may be located on other continents (Figure 1). Multiple service providers use the same telecommunications network resources, including telecom operators, as well as subcontractors and stakeholders. This means that the entire future telecommunications environment will be multidimensional from the sky to the bottom of the sea, with connections everywhere and interfaces to many information systems and networks simultaneously. This will all work automatically in the future (Ericsson, agentic AI) (Akash Takyar). Communication systems pass through multiple countries, and service providers also use different data center resources to provide their services from these countries. This also means that telecom operators and service providers may use different recommendations and standards to develop their networks and services in these different countries. People use services with different security levels from these telecom networks regardless of time and place, which poses many additional challenges for developers and designers of information security systems. People may use their one smart device in a variety of ways to access multiple services, even if these services have different security levels. This means that managing and monitoring these telecom networks and the services provided through them, as well as their users, is particularly challenging. These new operating environments also offer a lot of new opportunities for cyber attackers to attack our systems and services through multiple routes and different devices.

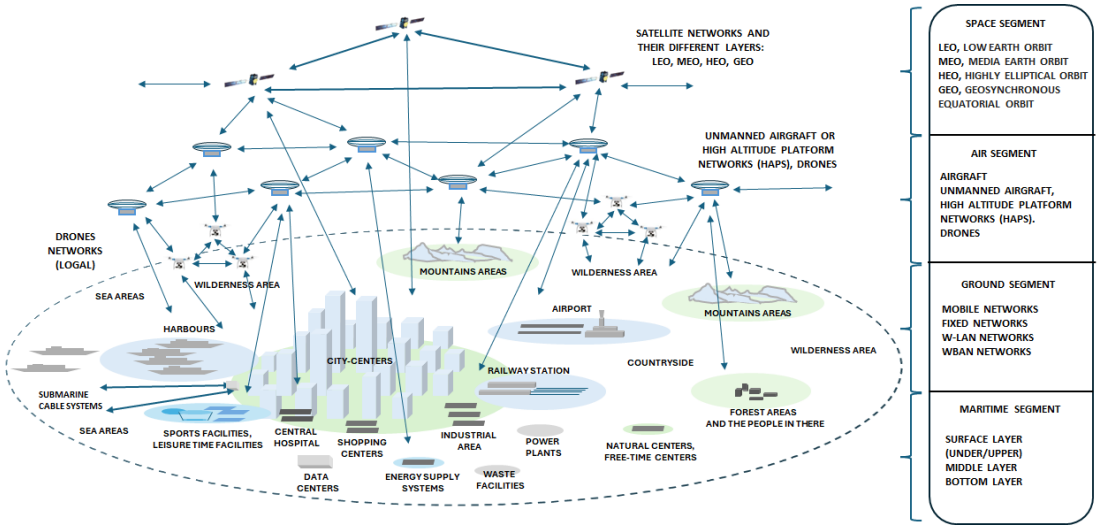


Figure 1: Our future societies' digital living environments and communications layers (EU-ECHO 2) (EU Space Programme) (IEEE, Oltjon Kodheli) (IEEE, Xufei Ding)

Artificial intelligence (AI) can be used in communication networks for many different purposes. It can be used to analyze information from data sources that we want to send to recipients through communication networks by performing multimodal data extraction on the sender side, encoding it, and decoding and reconstructing the data on the recipient side (Figure 2). Also, cyber attackers use AI in many ways to attempt to find vulnerabilities and attack opportunities from various parts of communication networks, their services and systems, and work environments, including all users' devices (EU-2024/1689) (EU-2022/640). As we evolve our digital communication and information environments through virtualization, slicing, and new virtual reality capabilities where everything is connected to everything, we are at the forefront of multidimensional communication and service environments. These different functionalities mean that the environment gives cyber attackers many more opportunities to attack these multifunctional environments than was previously possible for the networks of that time. These new functionalities in communication environments also mean that we need to take a deeper look at the devices and systems we use and to develop their architecture to meet these new requirements, functionalities, and cybersecurity challenges. Quantum computing, quantum cryptography, and quantum machine learning need to be researched and tested alongside these devices, as they are becoming integrated into this new generation of smart devices. We must strive to optimize the functionalities of new types of smart devices. Quantum computing, quantum cryptography, and machine learning must also be taken into account in new types of intelligent device architectures (IDQ) (ITU-T).

We need to optimize the functions of new types of smart devices, such as computing power, the use of artificial intelligence, the use of virtual reality, and energy efficiency. Since our smart devices provide a variety of services and are loaded with a lot of data, they are really loaded. We need to optimize and significantly reduce their load. One way to reduce the load is to form a semantic representation of the transmitted data and send it to an encoder, which encodes the data by optimizing its size; on the receiver side, the transmitted data is decoded and reconstructed accordingly. The goal of these processes is to optimize the load and improve the functions of these new types of smart devices in these new operating environments, Figures 2 and 3. Edge and MEC architectures and operations also need to be rethought due to the connectivity and cybersecurity requirements of these new types of smart devices and the new types of services they provide. These new types of end-to-end communication systems form the communication layers in these multidimensional (3D) environments where everything is interconnected to everything. This requires new types of analyses, control, and monitoring models and systems that can seamlessly analyze and manage data, prevent unauthorized access to data, prevent cyberattacks, and protect and keep our information systems operational under all conditions, end-to-end, across all communication environments. For these purposes, we use agent-based RAG concepts (Akash Takyar, Agentic RAG), which means that devices and systems can communicate with other systems and devices and react to their functionalities, adapting their behavior to be compatible with the various use cases of future digital environments and the various use cases of the systems there.

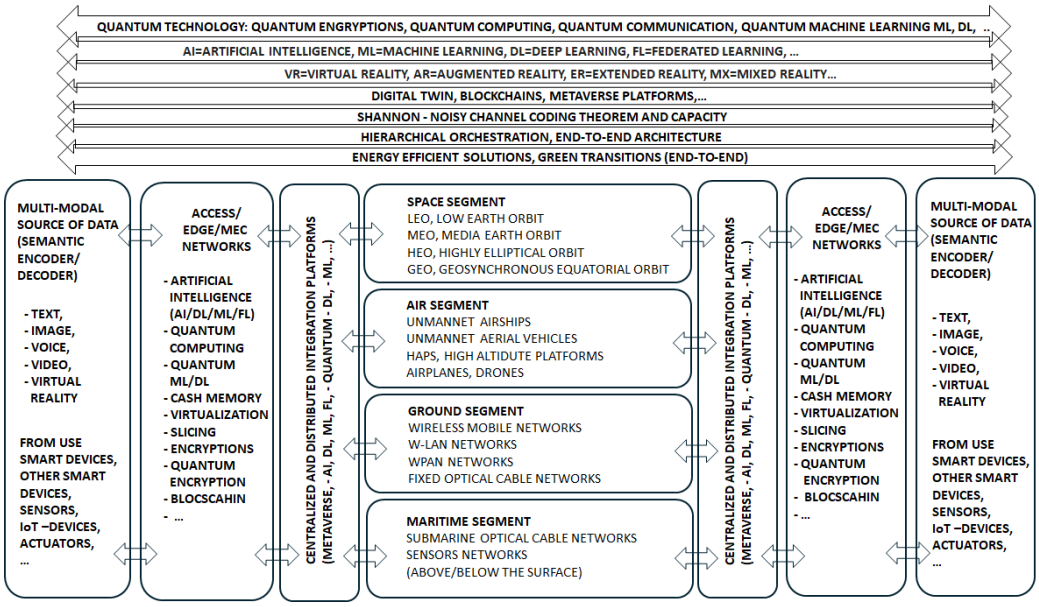


Figure 2: End-to-end communication segment layers and their functionalities

1.1 The Research Question

The research question of this study is: Can our new smart digital devices and systems be safely used in the multi-layered virtual environments of the future, where numerous services are available to us anytime and anywhere and artificial intelligence is used throughout our service and communication systems to enhance and improve our services?

2. Objective and Grouping of Paper

In this study, we use scenarios and use cases related to multimodal data in virtual reality and virtualized environments in different situations where collaborative information exchange with different people and parties is needed, and it needs to be done securely.

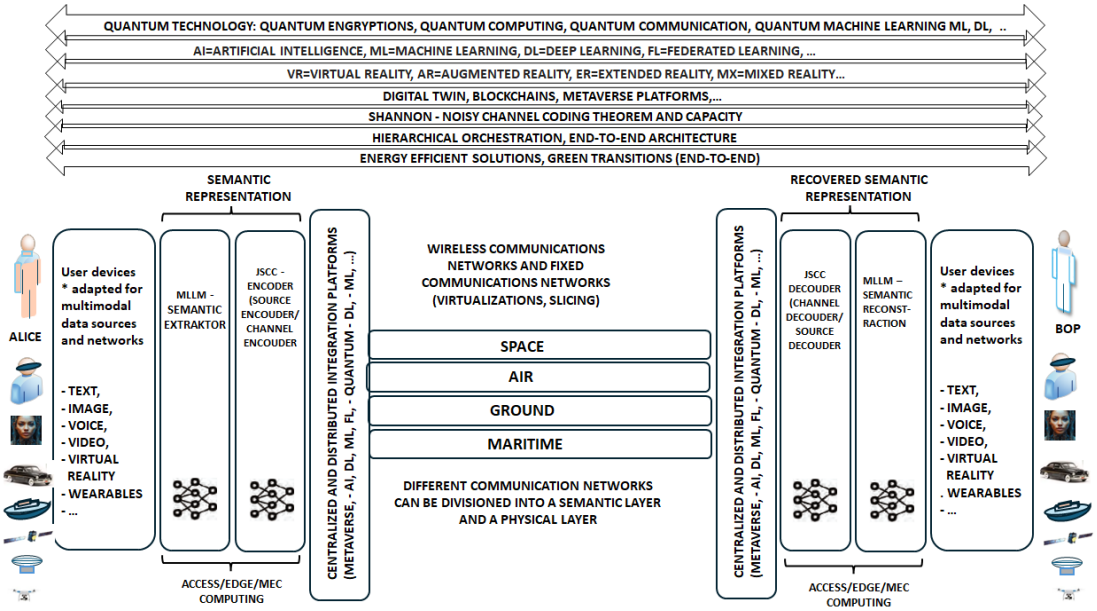


Figure 3: Secure MLLM semantic communications enabled Air-Space-Ground-Maritime networks, end-to-end, using AI agentic RAC and quantum technologies. MLLM (Multimodal Large Language Models) (IEEE, Huaifeng Shi) (IEEE, Mingkai Chen)

Methodology: We have used the Enterprise Architecture (EA) framework and its methodological models. We have also used Proof of Concept testing environments (Aarne Hummelholm et al. pp. 142–148) to identify the

improvement needs of the mobile devices people use. We also looked at the EU Tempest Directive guidelines to see what we need to also consider when designing our new device.

The structure of the study is as follows: Chapter 3 discusses numerous services that utilize virtual reality and different platforms in future societies in their multi-layered virtual and cloud-based digital environments, and the use of services is independent of time and place, even when service users are far from their workstations and offices. Chapter 4 discusses conducting threat analyses and modelling for these multi-layered platforms in virtual and cloud-based digital environments. Chapter 5 concludes this article, presents our solution model, and suggests future work.

3. Multimodal use Cases for Future Communication Environments at Different Levels

We use different technologies in communication environments across different segments. Multimodal data includes text, images, audio, video, virtual reality data, wearable data, IoT and sensor data, and so on. This multimodal data can include sensitive information from various fields, such as economic, industrial, medical, and welfare data; banking data; or technical development data. This data will be sent to various parts of the world using various communication systems (Figures 3, 4a, and 4b). The use of services in our future society's multi-layered virtual and cloud-based digital environments will be independent of time and location. Service users can be far from their offices and homes. Therefore, new types of smart devices are needed that include secure MLLM semantic communication functions, artificial intelligence-based agent-based RAC techniques, and quantum technologies.

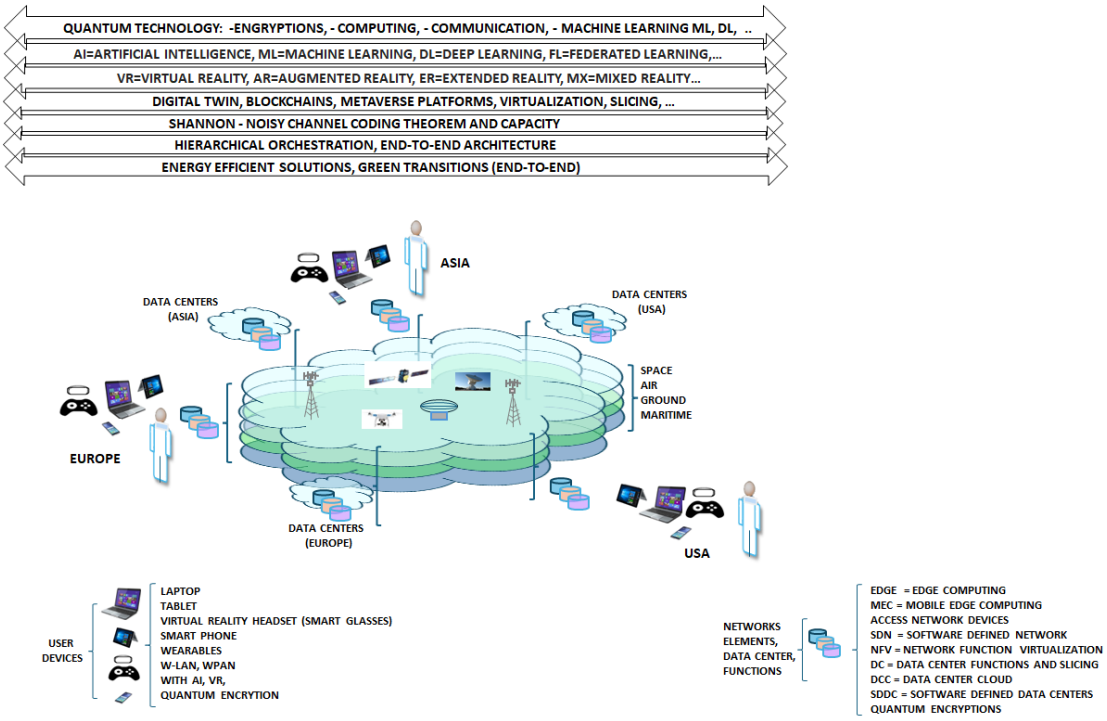


Figure 4a: A real-time business meeting with employees from around the world

We are also currently transitioning from 4G to 5G and 6G into mobile networks. This transformation brings with it technical challenges, as well as challenges related to privacy, accessibility, sustainability, and cybersecurity, but at the same time it opens revolutionary opportunities to develop services in our societies to be even more efficient, diverse, flexible, and energy efficient. For example, for various needs of rescue operations, we can easily introduce new types of mesh networks implemented with smart devices on an ad-hoc principle, without other networks. These solutions and new functions of the devices give us new opportunities and help us work much faster and easier in many situations. These new types of smart devices allow all of us to use services in a completely different way than before, and faster than today, regardless of time and place. Critical situations we do not need other networks and their services at all.

In Figure 4a, we see one example of the use of this new type of smart device, with its new functions, in meetings where people from companies are in various parts of the world (Nokia) (Ericsson). They can use a normal video conference connection with audio, video, and images. They also have virtual reality glasses that they can use,

but which are challenging to use due to delays in data transfer. The use of virtual reality glasses in meetings comes into play when the companies involved in the meeting are doing development work and the people from the companies want to see the results of their work up close. The connections used are complex and pass through different networks and countries (Figure 4a). The big challenge is that the inside information of the companies must not be available to parties outside the meetings and that hackers cannot access information. The connections must be encrypted, for example, with quantum encryption. This also increases data transfer delays. There may be many teleoperators and service providers who are responsible for making this type of connection through different countries using different communications networks. This gives more cybersecurity challenges to these types of connections.

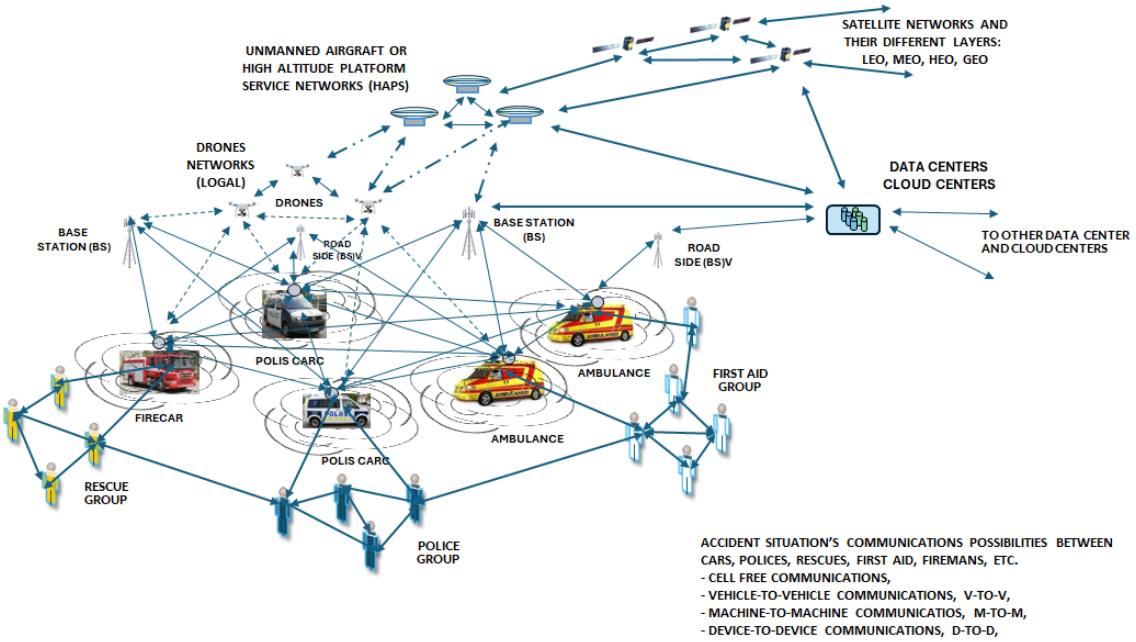


Figure 4b: A rescue operation in the field (Aarne Hummelholm et al., ECCWS 2025) (EU-NIS) (EU-GDPR) (EU-MDR) (EU-Galileo)

Figure 4b shows an example of the use of new types of smart devices that can form networks for rescue operations, for example, on an ad-hoc basis. The formed mesh networks operate without other networks, data centers, and their functions. The formed network is based on various functions of new types of smart devices (Aarne Hummelholm et al. p. 142-148). The mesh network is formed between user devices to user devices automatically without other networks when the necessary settings have been made in advance. If necessary, the network is connected to vehicles, which in turn are connected to each rescue operation command center and leader using various communication systems to get connections to the field (Figure 4b). Today, it is also possible to use direct connections from user devices to networks formed by satellite, HAPS and DRONE systems. Table 1 shows the technical requirements of different communication services in future service environments, which we need to consider when developing these systems and smart devices.

Table 1: Communication requirements for metaverse applications (Mansoor Ali)

Applications	Latency (ms)	Reliability (%)	Data Rate (Mbit/s)
Hologram Education (light field)	20	$1–10^{-5}$	$1x10^{5} – 1X10^{6}$
Augmented Reality Smart Healthcare	5	$1–10^{-5}$	10000
Digital Twin (Smart city)	5–10	$1–10^{-5}$	10
Virtual Reality Entertainment	7–15	$1–10^{-5}$	250
Tactile internet	1	$1–10^{-6}$	1

There are direct connections between the field managers from the beginning. Figures 4a and 4b show this in critical situations, where every second counts for initiating and conducting rescue operations. The faster and more seamless launch of the field operations shown in Figure 4b is enabled by configuring the communication

settings on user devices. We can certify all users in advance and profile them based on their job responsibilities. This way, they have certain operations ready when they go into the field, and their profiles are visible to all users on the screens of their smart devices. This means we do not have to make any changes in the field, and we are ready to start the necessary operations quickly.

4. Making and Modelling of Threat Analyses

Figure 5 shows connections between users in multimodal communication environments. User devices, communication systems, data systems, and platforms are virtualized. In this model, artificial intelligence is used in all areas of communication and in all devices and systems to analyze and optimize all communication connections and prevent cybersecurity attacks.

Our new smart devices are connected to a wide range of sensors, actuators, IoT devices, virtual reality devices, home systems and sensors, other user devices, wearable devices, etc. The connections are wireless or fixed. For example, at home many devices are connected to home WLAN (Wireless Local Area Network) devices and, through them, to EDGE (Network Edge Device) or MEC (Multi-access Edge Computing) devices, as well as to operator networks via fixed or wireless connections. In this way, the user's smart devices are connected to these digital, multidimensional hybrid networks and entities, which can be divided into several parts and functions as needed (Figure 5).

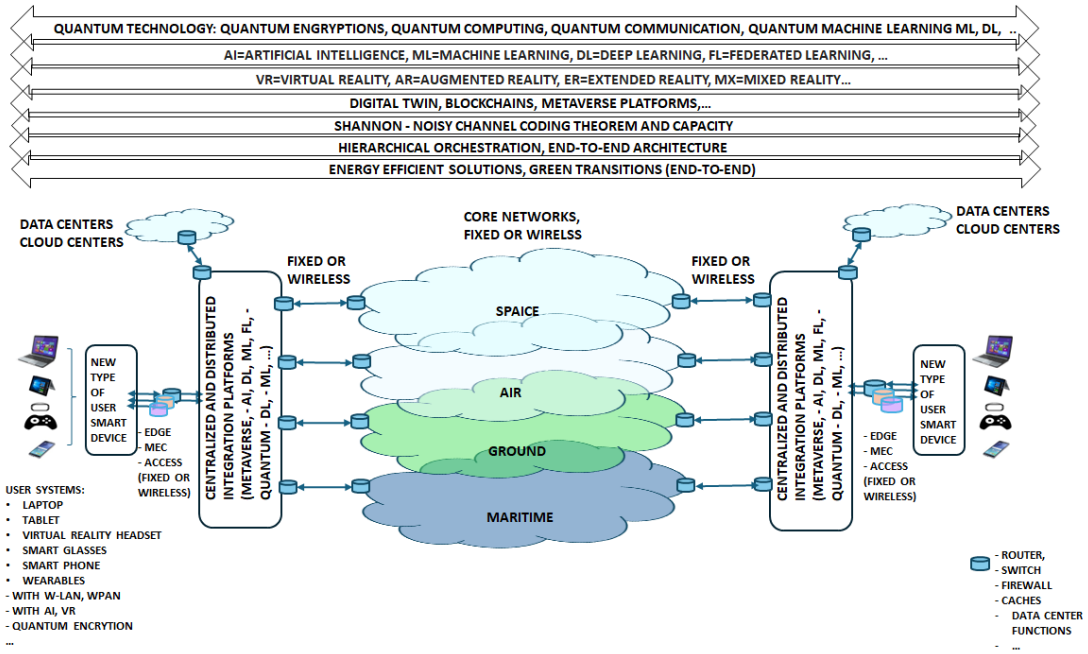


Figure 5: User-to-user communication connections in future multimodal environments

Some of these home systems are connected to the data centers of device suppliers via wireless or wired communication so that device suppliers can obtain information about the status and activities of home devices. Through all these connections and terminals, cyber attackers can attack our systems, even if our smart devices have encryption systems. This new environment offers cybercriminals, hackers, and state actors many new attack possibilities. The situation is only getting worse as they use different artificial intelligence (AI) concepts for their various attacks, as well as for vulnerability detection, dependency detection, detection of classified information, and so on in various parts of this multidimensional hybrid network. When we use wireless communication connections, cyber attackers use signal eavesdropping and interception methods. These methods have been used by state actors for a long time. Today, jamming is quite common among state actors around the world, including in Europe. Signal interception is used for many purposes, and users include state actors, cyber attackers, or criminals, etc. Through high-altitude communication systems, CPS spoofing and navigational deception are used quite frequently around the world through these communication routes. We have seen this from news reports on the international situation (IEEE, Miao Du) (Radware). State actors do it, and the purpose is to disrupt the normal operations of various states and companies. Wireless technologies offer the possibility of performing man-in-the-middle attacks on all wireless connections. Attacks against these wireless systems are easy to implement because they are difficult to detect if someone is doing something

alongside the connections. Side-channel attacks are also easy to perform in these environments. When state actors and cyber attackers use artificial intelligence and DRL (Deep Reinforcement Learning) (IEEE, Huaifeng Shi) to attack our systems, services, and system models, they can go faster inside our systems (Figures 1–5). Based on the information obtained, attackers perform more targeted attacks on our system models and try to find more backdoors for their attack possibilities.

Because we work in these multimodal communication environments and our communication connections go through multiple layers to data centers and cloud centers, cyber attackers and state actors can easily carry out eavesdropping and data leakage attacks to find the interesting information they want. When using artificial intelligence methods, they can easily conduct data manipulation attacks and privacy attacks. When cyber attackers and state actors use artificial intelligence methods, they easily find opportunities to conduct disruption attacks on their desired target. With the help of artificial intelligence, they find opportunities to get inside systems and devices and can easily conduct protocol attacks inside systems and devices. Finding such attacks is particularly challenging when we work in these multimodal communication environments and our communication connections go through multiple layers and paths to data centers and cloud centers, where services are potentially hosted by multiple service providers and where the information needed by users is stored.

The Access, MEC, and EDGE systems and devices of this future ASGM network must incorporate AI-based capabilities to detect, analyze, protect against, mitigate, and eliminate a wide range of cyberattacks. This is critical because all information flows through these systems and devices, as well as through users' smart devices, to networks and data centers around the world. If there is even one small vulnerability in these systems, cyber attackers will quickly find it using AI and quantum computing and exploit it for their own purposes. Figure 6 shows the attack vectors in our air-space-land-sea (ASGM) networks across its various segments and layers.

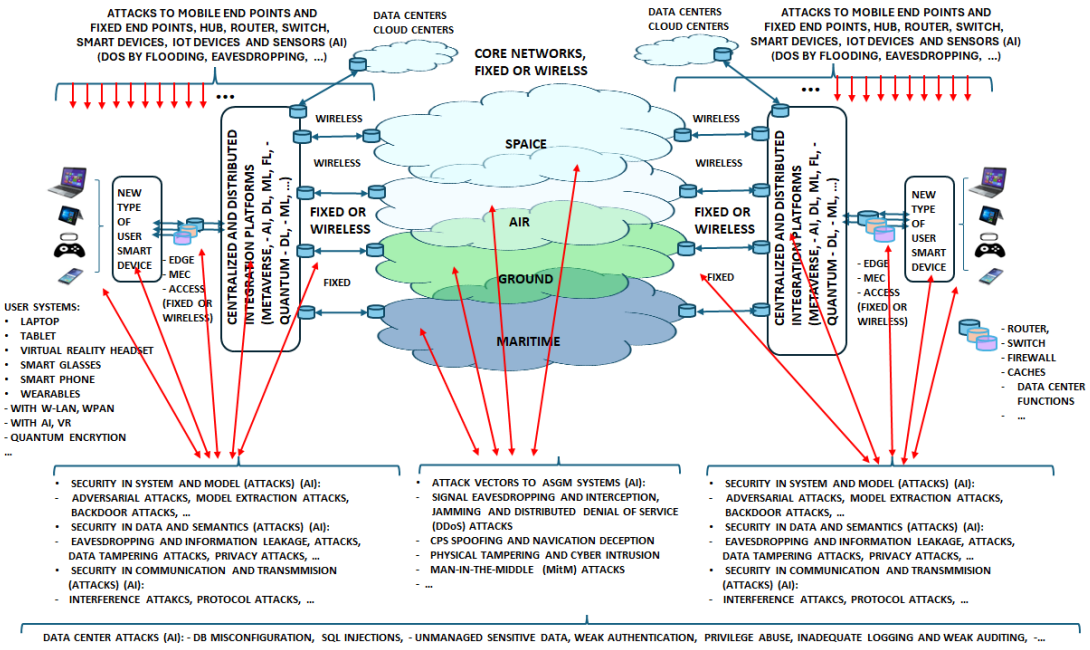


Figure 6: Our Air-Space-Land-Sea (ASGM) network and attack vectors against it (based on 5G threat vectors by Aarne Hummelholm et al.)

The management, control, and supervision of such multimodal and multilayered communication environments, user devices, communication systems, information systems and platforms, and cybersecurity-related protection systems in these virtualized and multilayered environments require good, functional analysis, control, and management systems for the network and its devices, as shown in Figure 7 as an example model (Aarne Hummelholm et al.). We need to get real-time information about our network situations and services and use artificial intelligence to create situational pictures faster and more broadly, to launch measures faster, and to collaborate to share information with different organizations working in these communication and service environments in their maintenance, servicing, analysis, and repair tasks.

Figure 7 shows two different operational centers: NOC and SOC. NOC is the network operational center, and SOC is the information security operational center. From the NOC, we see the real-time situation of the communication systems of networks and services, as well as the smart devices used. From the NOC, real-time information is sent to operators and service providers according to their needs. From the SOC, we see the real-time cybersecurity situation of networks and services, communication systems, and smart devices used. From there, real-time cybersecurity information is transmitted to various security organizations that are responsible for the activities of these areas in cybersecurity issues and respond to cyber-attacks as effectively as possible. For this reason, a real-time situational picture is important for initiating countermeasures, preventing cyber-attacks, and improving protection based on the analysis performed with AI.

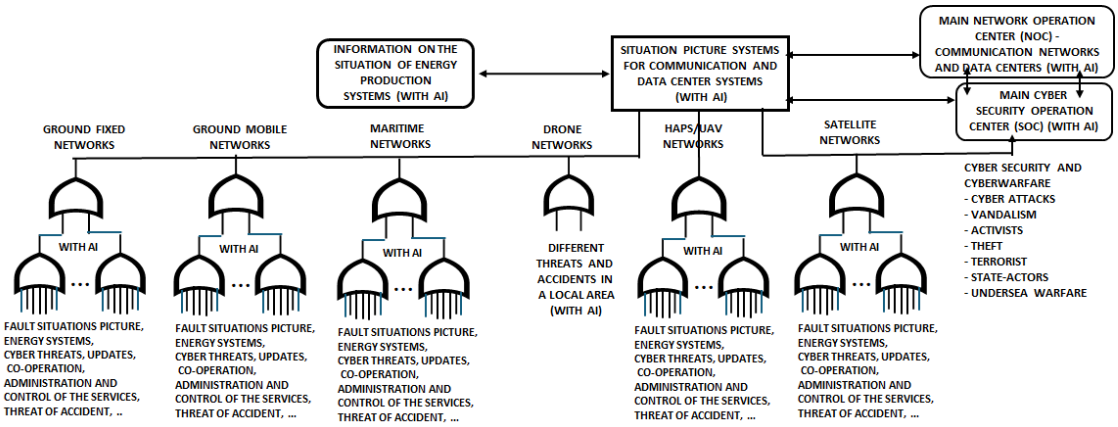


Figure 7: Architecture model of various network control and management systems at the principal level (NOC, SOC with AI and quantum computing) (Aarne Hummelholm et al., updated from the ECCWS 2025 article)

5. Our new Intelligent Smart Device Model

Figures 1–7 show how important and central the new smart terminals used by people are in these future digital multidimensional hybrid operating environments. A large part of the data flows passes through them, and various sensors, actuators, wearable devices, IoT devices, and other data sources are connected to them. Thanks to these functions, the device has become an increasingly central and important device that utilizes various services of future digital multidimensional hybrid operating environments and ICT operating environments.

Our new type of smart device includes functions that allow us to process data from incoming data streams (MLLM) and send the processed data to the recipient. The receiving device has corresponding functions for processing the incoming data. This method provides us with optimized data streams and energy-efficient data processing solutions on our smart device, as well as reducing the energy consumption of our smart device. We are also able to use these solutions to shorten the overall transfer times of data streams and improve the functionality of highly time-critical services.

Inside our smart device, we use artificial intelligence to analyze the device's functions and cyberattack potential, as well as to detect cyberattacks on our systems. We are developing these new smart devices with the use of quantum computing, quantum machine learning, quantum encryption systems, and EU-Tempest requirements in mind.

We plan to use Agentic AI to transform RAN optimization by enabling fully autonomous networks that manage themselves without human input (Ericsson, Agentic AI), so we need much deeper and faster AI-based analysis solutions to find out if something is going on inside the devices without our knowledge, even if it is not cyber attackers.

We also plan to use MCP (Model Context Protocol) in conjunction with LLM (Large Language Models) to provide a universal interface for reading files, executing functions, and managing contextual prompts on our new smart device.

One application of our new smart device is also the use of Agentic RAG functions, which improve the search and additional text creation process and enhance the use of MLLM models.

6. Conclusion and Future Work

6.1 Conclusion

The digital, multidimensional, and multimodal hybrid information systems of the future, where everything is interconnected and where different technologies are used to acquire, exchange, process, use, and store information, are particularly challenging in terms of functionality, usability, and cybersecurity (Figures 1–7). The same communication and service environments simultaneously give resources to multiple telecom operators, service providers, and stakeholders.

Our communication environments are changing rapidly, moving from 4G to 5G and eventually 6G in wireless technology. Extraterrestrial networks and services are already directly accessible from our smart devices. Our services are provided by multiple data centers and cloud service centers around the world. Such data environments offer attackers using artificial intelligence technologies a vast number of exploitable opportunities to attack our information systems and services from anywhere and at any time. Such future scenarios show us cybersecurity challenges that we must address with increasingly powerful analysis and protection tools to keep our systems and data safe from cyber attackers.

6.2 Future Work

We need to develop a testbed with robust integration platforms where we can evaluate, analyze, and validate our devices, systems, services, new protocols, and new quantum encryption systems much deeper used in these environments than before. We also need to test the use of artificial intelligence in conjunction with them because cyber attackers are using AI in their attacks in quite new ways. We need to evaluate and verify the use of quantum encryption systems in end-to-end mobile networks in such multidimensional hybrid computing environments (ENISA).

One of our research projects is to develop a secure new communication platform for our future smart devices, which will allow us to reduce the bandwidth requirements of data flows by modifying the information coming to smart devices through our new platform. After processing, the data is sent to communication networks (Table 1). At the same time, we will get energy efficiency solutions for our smart devices.

If we move to agent-based AI, it will revolutionize RAN optimization by enabling fully autonomous networks that manage themselves without human intervention. This means that we need to consider this possibility in the development of our future smart devices as well.

Ethical clearance: Ethical clearance was not required for the research.

AI declaration: I have not used AI in my work.

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On Definition of Vulnerability Discovery

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Abstract: The adaptation and exploitation of security vulnerabilities in military operations is a complex, multidisciplinary problem that calls for precise foundational definitions. This paper establishes such groundwork by discussing the principal elements of the topic from the perspective of security vulnerability research. We first characterize the sources and details of vulnerability and weakness information, describe common collection and presentation practices, and identify the principal consumers of this data. Next, we distinguish between vulnerability research and vulnerability discovery, explaining the processes that generate vulnerability information and highlighting the subtle but important differences between these activities. Finally, we examine principles governing the operational use of the vulnerabilities in military context and assess the respective contributions of research and discovery to achieving operational objectives. Within cyber domain operational planning we elaborate on (principle of) non-forceability. The primary hypothesis of non-forceability is that in cyber domain an adversary cannot induce an adverse effect on the logical components of a target system without proof of an exploitable logical vulnerability. This claim requires a precise explanation of the logical part of a system, which we define to include software, data, configurations, and formally defined user procedures and training; it explicitly excludes underlying processing platforms (hardware) and human actors (users and administrators). Under these definitions, external adverse effects on the logical system necessarily imply the proof of a vulnerability. Finally, the role of proof-of-concept (PoC) code in the operational utilization of software vulnerabilities has to be elaborated. We argue that the utility of vulnerability information is highly related on intended use and the level of technical detail provided. For defensive purposes, identification of a vulnerable component and its triggering mechanism is typically sufficient to trigger defensive actions. By contrast offensive operations require validation of adversaries' defensive capabilities before PoC code baseline capabilities, further development objectives and possible actions of objectives (impact) can be evaluated as an operational course of action.

Keywords: Vulnerability discovery, Vulnerability research, Cyber operations, Vulnerability exploitation, Proof of concept code

1. Background

Vulnerability discovery is a process of acquiring the technical knowledge of the existence and technical details of exploitable vulnerability on a target system. It is an enabler of cyber operations, which are systematic and planned actions that either are used to actively protect own systems by patching vulnerabilities and using security controls or leverage and exploit one or more of vulnerabilities of the target system in order to reach the overall operational goals.

The difference from the operations in physical domain is that if the target is properly protected in cyber domain, the defences cannot be forced even with significant superiority within the same domain. The exceptions to this logic are the human and physical elements of the protection, which deliver the effect outside the cyber domain. *Within the cyber domain, external actor cannot have any adverse effect to a logical part of the target system without knowing exploitable logical vulnerability.*

Non-technical security vulnerabilities in target system can be considered to have an effect in the logical world of cyber domain. As an example, inadequate security related routines of cyber system workforce are a security vulnerability if they enable the possibility of adversarial impact. Furthermore, even as the logical world of cyber domain is built on physical things there usually exists a possibility for the adversary to circumvent the elements of physical protection and humans with force superiority. For example, breaking physical barriers and forcing the human operators to violate the given security policy. These categories of vulnerabilities are not addressed in this paper.

2. Vulnerability information

2.1 Definitions Regarding Vulnerabilities

Dictionaries categorize *vulnerability* as an object either open to attack or damage ('vulnerable', 2024a) or being able to be easily hurt, influenced or attacked ('vulnerable', 2024a). According to MITRE (2025a), a vulnerability is an instance of one or more weaknesses in a system, that can be exploited, causing a negative impact to confidentiality, integrity, or availability. *Therefore, a security vulnerability is an exploitable weakness that circumvents security controls and is shown to have a negative effect when exploited.*

A (security) *weakness* is a condition in a software, firmware, hardware, or service component that, under specific circumstances, could contribute to the introduction of vulnerabilities (MITRE 2024a) by allowing the violation of an explicit or implicit security policy (MITRE 2024b). The conditions are usually called bugs, errors or flaws, and commonly used interchangeably regarding different severities; As an example, a typo can be called a bug, a logic mistake in code an error, and deeper mistake in software logic a flaw. Weakness is a specific class of error or flaw which turns to a vulnerability when instantiated in a system. Most common weaknesses are referred in *Common Weakness Enumeration (CWE)* -database (MITRE 2024c), a community-developed list of weaknesses maintained by MITRE.

There are many public vulnerability databases (Kekül, H, Ergen, B, and Arslan H, 2022) that provide *vulnerability descriptions*. NIST maintains one of the largest public databases, NVD (National Vulnerability Database) (NIST 2019). The vulnerabilities listed in these kinds of databases include typically *CVE (Common Vulnerabilities and Exposures) record* information. The CVE Record, issued by *CVE Numbering Authorities (CNAs)*, include the CVE ID, brief description of the vulnerability and number of references to vulnerability reports and advisories. Typically, the description includes also codified rating *The Common Vulnerability Scoring System (CVSS)*, which is created to help the software vendors and users comparing the severity of the vulnerability.

Proof of Concept (PoC) code is package of information with which one can reproduce the vulnerability on the targeted system, for example scripts, source code, or e.g. instructions for manipulating an user interface. The PoC should provide ways to validate triggering of vulnerability, for example information on specific error message or memory and register values that can be validated with a debugger. A PoC code covers typically a single vulnerability or a chain of vulnerabilities and generally does not impact the system otherwise than showing that system is vulnerable.

An exploit (code) makes use of the vulnerability to produce an effect in the target system. The effect can be a denial of service (DoS) where functionality of the target system is fully or partially disabled or e.g., remote code execution (RCE) where it is possible to deliver and execute attacker defined code in the target system. Exploit codes incorporate usually an elaborate combination of techniques to evade security controls. It is common that an exploit code targeting a software running modern operating system uses exploitation of multiple vulnerabilities.

2.2 Discussion About Vulnerability Information

Many parties contribute to publicly available vulnerability data. A large portion of it gets published by white hat (Shea, S. 2019) security research organizations. Vulnerability disclosures are typically preceded by a coordinated collaboration period with software vendors, often facilitated by one or more CERTs (Computer Emergency Response Team). During this period vendors can fix the vulnerability and prepare, test, and distribute the necessary updates which leads to end-users having patched systems when vulnerability is disclosed. This process is called "*Responsible Disclosure*" while some actors prefer "*Full Disclosure"* which includes releasing all the details to public without giving the software vendor any time to fix the bug beforehand. Some actors, like Google Project Zero, strike a kind of middle ground, giving a fixed 90-day period to fix the bugs, and 30-day period after the fix has been released before all details are released.

Vulnerabilities are also categorised by how long time has passed since the software vendor has acquired the knowledge of the vulnerability; *a zero-day vulnerability* means that vendor learns at time of disclosure. The vulnerabilities which have been fixed and the patch is not widely applied are called *one-day vulnerabilities*. To emphasise time passage since vulnerability disclosure (patched or not) term *n-day vulnerability* is used.

Information about most of the vulnerabilities end up to the public domain through security mailing lists (seclists.org. 2024) like Full Disclosure (Seclists.org. 2026), or a national CERT vulnerability mailing list (NCSC-FI. 2025), with posts linking to the researcher or software vendor blog giving more details about the vulnerability and ways to update.

2.3 Vulnerability Information - Conclusions

Vulnerabilities are different from regular software bugs because they have the potential to endanger the security of a system and its data. Cyber security researchers see this as a business opportunity, striving to claim CVEs for finding new vulnerabilities, branding bugs and creating security solutions to protect against malicious activities and reduce risks. However, as vulnerability information is consumed its usefulness varies between defensive and offensive scopes.

For the defender the vulnerability information has typically enough significance to trigger immediate action even without a patch or PoC information. Assessing the significance to own systems and setting up pre-emptive security controls (mitigations) can start before available patch. Vulnerability management process promotes a defensive approach to potential system risks requiring technical measures that mitigate threats even when detailed vulnerability information is unavailable. Such actions demand domain-specific and system-level expertise, for example in isolating management interfaces from adjacent networks.

For the attacker, a vulnerability information without a working PoC code does not yet have a significant value for the attacker. Even if PoC code is publicly available, it does not mean that anyone can exploit the vulnerability or that the vulnerability can be exploited with desired impact. Nevertheless, using PoC as a starting point for exploit development is easier than starting with just vulnerability description in typical CVE entry. (Shimizu, N. and Hashimoto, M 2026) For example, a vulnerability described just as occasional random changes in target application resources does not offer a lot to build an exploit on; without an exact method to trigger the vulnerability and information on how to control the changes on target the vulnerability remains without direct value. Alternatively, if there would be details on the weakness behind the vulnerability and at least one concrete way to control it, the starting points for exploit development is clear, and there is also a data to evaluate other related tactics, techniques, and procedures (TTP) for the attack (MITRE 2025b).

In conclusion, PoCs in a defensive context help build and validate existing mitigations and strengthen overall system security. In contrast, offensive use demands more detailed vulnerability information, as exploits must align with operational objectives and typically require additional research and development.

3. Security Vulnerability Research and Discovery

3.1 Definitions

Vulnerability research (VR) is a holistic research activity done by academic, commercial or governmental actors which aims for acquiring best available knowledge regarding vulnerability discovery tools and -methods. As sources research actors use public and academic sources, free and commercial trainings and possibly subcontracted research. Scientific method is used where applicable and research results are shared with research community for peer review and feedback. Therefore, found methods and built tools are available to parties doing vulnerability discovery and discovered methodologies and insights are available to other vulnerability researchers.

Vulnerability discovery (VD) is the act of searching for vulnerabilities from the applications, platforms and embedded systems of interest by applying the best public and commercial tools and methods available. The motivations behind the activity vary from actor to another; finding bugs from your own products (software vendors), finding bugs from the products you use (end users), making the internet safer place (white hat actors), earning money (bug bounty participants, vulnerability brokers), or getting enablers for your offensive operations (penetration testers, governmental actors, criminals).

Target setting for vulnerability discovery activity depend on customer; While needs of an offensive cyber operation can be very specific (“application of certain version”), the participants of a bug bounty programs have targets specified by the software vendors (“newest version of our product”), some white hack actors and criminal actors target everything their skills enable, selecting perhaps targets by potential impact of the findings (“All internet-facing popular applications”).

The vulnerability discovery can be divided in following phases:

- Open-source information gathering: Establishing the vulnerability history and current status of the target from partners and open sources.
- Analysis of the assumed usage the target. This can be enriched with existing threat emulation information.
- Architecture and software bill of materials (SBOM) analysis of the target implementation. Especially if target is larger than a single executable binary.
- Static analysis of the source code if available.
- Dynamic analysis of the executable code and the system at large using fuzzers, symbolic execution, or tracing, capturing and modifying the communications and debuggers
- Triage findings to three categories: Exploitable, possibly exploitable and non-exploitable using error logs, debuggers, trace tools and disassemblers
- Reverse engineering and analysis of the found anomalies using same tools as in Triage

- Creating the proof-of-concept code for reliably triggering the vulnerability (for defensive use) or for showing that the vulnerability could be exploited (for offensive use).
- Iterating to new discovery cycle in order to reach closer to actual target
- Communicating the results with customers, including impact analysis

The flow of vulnerability discovery on an abstract system is visualised in following Figure 1 (below) depicting the iterative cycle of vulnerability discovery: First iteration is launched to analyse the protected public application programming interface (API). Second iteration exploits the interim results and internal API in order to reach the wanted results.

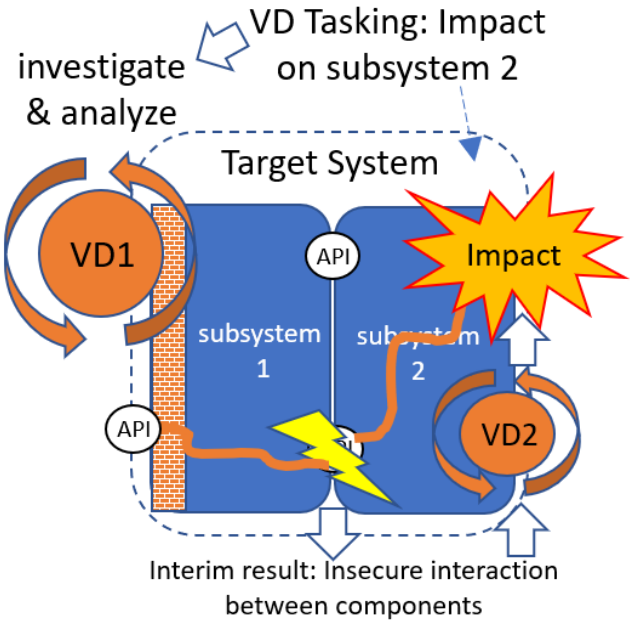


Figure 1: Example of iterative process of vulnerability discovery

Naturally not all vulnerability discovery processes follow all the listed phases; when testing own products during R&D you already have enough information to start static- and dynamic analysis, and no need for sophisticated PoC code to start fixing findings. Furthermore, the more complex and obfuscated the system is the more starting information, iteration and time is needed to discover vulnerabilities, if even possible with current knowledge.

3.2 Discussion on Vulnerability Research and Discovery

In practice every system has exploitable vulnerabilities in its architecture, software, and configuration. Some of these vulnerabilities are remainders of activities in the system R&D, some are result of the customer configuring the system in the usage environment and making decisions regarding update practices. This can be discussed and communicated with a single concept of security debt (Huopio, S. 2020), high amount of it means higher risk of having to pay it later in forms of security incidents.

Changes in the system configuration, operating environment or its functionality are common sources of new vulnerabilities. Because of this, the larger changes of architecture, and especially addition of new type of functionality have to be thoroughly analysed; New additions can for example expose old interfaces to new network segments, or introduce altogether new interfaces to access the system.

In order to have a credible cyber defence posture, a governmental user of critical heterogenous ICT infrastructure has to have an access to efficient vulnerability discovery capability. Usually, the system is so complex and multi-layered that relying just to the ability of the supply chain informing about software issues is not enough; *Objective for credible cyber defence posture has to be set on ability to do basic vulnerability discovery on all the relevant software platforms and embedded system types in own inventory.* (Goel, J.N. and Mehtre, B.M. 2015)

It is a good idea to start vulnerability discovery activities with a technical threat analysis workshop with help from vulnerability researchers and subject matter experts on related systems. Main objective of these workshops is to raise the technical vulnerability and risk knowledge of system/capability owner to a realistic

level subsequently prioritizing defensive activities according to defence-in-depth principles while gathering information for vulnerability discovery campaign. The workshop results can include: revised knowledge of the system use- and misuse cases, realistic threat environment and identification of critical paths and interfaces that could be used to disrupt the system.

The technical act of vulnerability discovery builds on top of results on the technical threat analysis workshop and involves a lot of manual work, interactive iterations of reviewing, choosing and applying tools and analysing the resulting system behaviour. It can be pursued in many abstraction levels; logical flaws can be found from analysing system architecture and (human or machine) interface thresholds or -networks, static analysis on source code and dynamic analysis of system essential binaries. The system can be tested with intentionally limited resources possibly revealing anomalies in less optimal resource conditions.

Results of vulnerability discovery are triaged in order to efficiently move forward with most likely (security) bug candidates. Dynamic analysis, especially fuzzing tools, can generate a lot of false positive results in form of vaguely anomalous behaviour which is typically hard to reproduce. With enough domain knowledge and proper use of automation, debuggers and tracing tools the analysts can extract the actual bugs out of the mass of data.

At this stage of process vulnerability discovery activities have typically produced at least some bugs with or without security impact. When working on defensive role, these findings can be brought to knowledge of the software vendor or in-house developer who can then proceed on fixing them. In this context *the key result of vulnerability discovery is the realistic hands-on knowledge of the weaknesses of the systems and the concrete own ability to assess the security posture.*

3.3 Conclusions

The threshold between vulnerability research and discovery is often blurred. While a target may seem easy to test initially and yield shallow bugs, advanced and experimental techniques might be needed to reach the deeper layers of the software logic and discover the deep bugs. Therefore, advancing on both routes are needed; getting systems under testing fast, and continuously researching more effective ways to discover vulnerabilities. Testing is always preferable to just speculating about potential vulnerabilities.

Vulnerability research is a comprehensive approach that is used to gather knowledge and to develop tools for broad applications, while vulnerability discovery applies those tools and insights to address specific issues. In this context, *vulnerability research is a holistic, exploratory process, whereas vulnerability discovery is a focused deterministic task.*

As time passes vulnerability research will continuously find new interfaces and approaches for vulnerability discovery to enhance defensive security posture: researchers bring new testing technologies and integrate and evaluate latest tools. Applying new methods and processes to unknown (Schumilo, S. et al. 2017) or known part of the system-under-test (SUT) can lead to surprising (Schumilo, S. et al. 2021) or even contested results (Nicolae, M. I., Eisele, M., & Zeller, A. 2023) and in a best-case scenario driving up the software quality by continuous testing and requirement crafting.

Ultimately, the primary distinction between vulnerability research and discovery lies in the intended target and its operational context, whether offensive or defensive. The less clearly defined the target, the more holistic the approach becomes, requiring broader research and information. A more targeted approach doesn't eliminate the need for research but instead directs it toward either expanding the attack surface or refining tool development.

4. Security Vulnerability Usage in Military Operations

4.1 Definitions

Cyber operation is a military operation executed in cyber domain. It can be of defensive or offensive nature, and has many separately defined subtypes (Scott, K.D. 2018). As discussed before vulnerabilities play a central role in all cyber operations as *all effects in cyber domain can be mapped as results of exploitation of a weakness or vulnerability*.

Operational context for using vulnerabilities therefore means that the existence of vulnerability is either a reason for executing protective actions in defensive operation or an enabler of one or more Course of Action (COA) proposals in an offensive military operation. The operational importance of the vulnerability is higher when PoC code or weaponised exploit code is available. A discovered vulnerability without apparent impactful

exploitation can be used as R&D starting point but if its usefulness is uncertain the cyber operation has to prepare for delays in execution and planning cycle.

Impact of exploited vulnerability can be defined as the desired effect (e.g. denial of service, remote execution, privilege escalation) and exploitation parameters (authentication needed/not needed, other environmental or version requirements for exploitation) in a specific part of the target system. In the operational context impacts description can be accompanied with additional parameters regarding the impact success probability, temporal factors (effects single transaction, certain time, or has permanent impact), or collateral impact description (Impact of system stability and non-targeted functionalities). The intended impact is partly shaped by the maturity of the exploit code. Although further R&D can enhance maturity, the inherent impact of a vulnerability is fixed by its underlying effects and cannot be changed. In context of military operational planning the impact of vulnerability should be used when planning for operational effect.

Payload is a piece of executable code or series of separate executable commands crafted to be used together for desired effect. Payload is provided to the vulnerability exploit code, which transfers it to the target system, prepares the environment so that the code can be executed, and triggers the payload code. It can be argued that in some cases part of exploit code can also be considered as payload, as it itself executes commands on target system. In the context of this paper, payload is defined as code specifically providing the planned effect for the operational target.

Vulnerability Equities Process (VEP) is a military process of making decisions on the usage of software vulnerabilities that are discovered or developed within own military organisation, or acquired from partners or subcontractors. By this definition the vulnerabilities that are of public domain are not considered in VEP.

4.2 Discussion

Vulnerability information is in central role in cyber operation planning, related decision making and in the actual execution both in defence an offence: when defending a system, the existence of vulnerable code in the system is critical information and causes immediate defensive actions of mitigation and patching. This information can be also gathered via preparation of battlefield; including vulnerable components in honeypots can lure attackers to reveal their attack capabilities and give the defenders information on how the vulnerabilities are being exploited.

In offensive operations vulnerability information is an enabler. Vulnerability discovery requires intelligence on target architecture, interfaces and specific software versions. Exploiting this information requires obtaining or developing suitable exploit code and maintaining the expertise to test and deploy it effectively. As the public vulnerability information is often lacking in the technical exploitation details, own vulnerability research and discovery capabilities are practically the only way forward. Preparing for almost unlimited variation on vulnerability discovery targets cannot be managed without capable vulnerability research supporting the vulnerability discovery team. The resource discussion is out of scope of this paper. What can be discussed is the approach in principle.

Offensive cyber operations imply a need for capability to develop proof of concept code for triggering and exploiting found vulnerabilities. It is worth noting that the knowledge of n-day vulnerabilities have also their worth; it is very common to discover outdated systems during reconnaissance. As vulnerability databases do not usually host exploit code with vulnerability details, exploit development is often needed also for n-day vulnerabilities.

The typical needs of offensive operations are targeted in a very specific way; vulnerabilities are needed for specific application or service, with a specific software version and specific operating environment. These kinds of tasks are hard and slow while outcome is very difficult or impossible to estimate. This type of activity requires additional information on adversary defence capabilities to allow targeting adversary weak spots while evading adversary. While the possibility of finding an exploitable bug in offensive operations timeframe is low, the impact of a new zero-day vulnerability would be high enough to justify the needed resources.

Another way of approaching offensive vulnerability discovery dilemma is to apply vulnerability discovery as “background” activity to large target space (for example, a Linux distribution). To maximise the yield and the probability of desired results in large scale the discovery tools should be used in necessary scale, parallelism and in an optimized computing infrastructure, as in OSS-FUZZ project (GitHub 2022). After a vulnerability is discovered a reverse search for target can be applied and operational planning can start with an initial COA.

In the larger context of cyber operation planning, especially in multi-domain operation (MDO) context, the potential external attack surface is much larger than just a single weakness, and typically more weaknesses need to be exploited after the initial access in order to reach the operational goal. As established earlier, there is a wide range of weakness types and each of them need different kind of approach for exploitation. One good reference of the exploitation techniques are the initial access and privilege escalation categories of MITRE ATT&CK knowledge base (MITRE 2025b).

While pure cyber operations have their place, especially on intelligence information gathering, many military operations are executed as multi-domain operations. ATT&CK lists some vulnerability exploitation methods that require physical access to parts of target system, e.g. by connecting an attacker-controlled hardware to the target system. These additional mission parameters help vulnerability discovery as it circumvents security boundaries through usage of other domains and provides more COAs.

In military cyber operations, vulnerability discovery is a key enabler of success. The ability to discover new exploitable vulnerabilities in a system of interest can used for both defensive and offensive gains. Therefore, in military cyber operations the vulnerability discovery should be exploited as supportive action whenever it is possible. In addition to own vulnerability discovery actions, access to non-public vulnerabilities and exploit code can be established.

Regardless of the source of new vulnerability information, the usage of specific vulnerability has to be decided in the context of operational needs. It is not outright certain that all vulnerabilities should be disclosed as they could be used offensively. This leads to discussion about Vulnerability Equities Process (VEP) (Vulnerability Equities Policy and Process for the US Government) (The White House 2017) which is out of scope of this paper.

Figure 2 illustrates the vulnerability-related data flows around security vulnerability research and discovery and security vulnerability usage in operations.

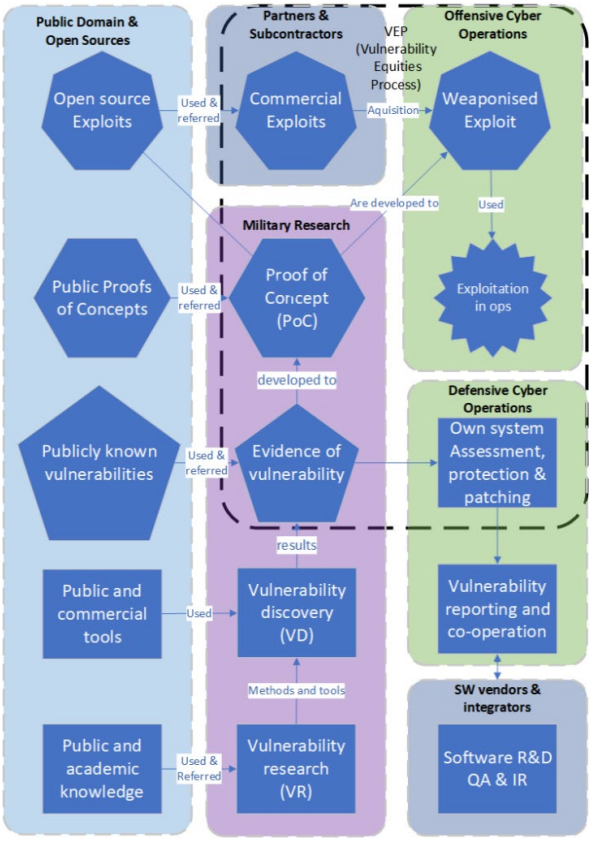


Figure 2: Vulnerability related data flows in military context

4.3 Conclusions

In cyber domain, all effects require a vulnerability on target system that is exploited. Without the technical knowledge of vulnerability and its exploitation and means to execute it, an operation cannot use it as a part to

reach its goal. For ability to plan and execute offensive cyber operations there has to be means to acquire vulnerabilities and related exploit code from open sources, through own vulnerability discovery or from other venues.

Vulnerability discovery is not inherently offensive or defensive. Even exploit code development is not offensive as such. Only when the exploit code is used to deliver a payload in order to make an impact is the act clearly offensive.

In an operational context, PoC code is used to define and validate the potential impacts of a vulnerability in offensive scenarios. The absence of PoC code can have collateral effects also in defensive operations: if the exploitation method is unclear, only mitigation can be applied, not full remediation. Some weaknesses can't be mitigated due to their context—critical system requirements may even prevent adequate mitigation. Therefore, even in defensive contexts, creating PoC is essential to guide both mitigation and remediation efforts. Thus, a PoC-code is required for both defensive and offensive operations to accurately assess the impact of a vulnerability.

Ethics declaration: Ethical clearance was not required for the research.

AI declaration: Outside of triggering now ubiquitous AI-assisted web searches, no other AI tools were used for the research.

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Balancing Security and Safety: A Look at Emergency Access Solutions for Implantable Medical Devices (IMDs)

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Abstract: Wireless implantable medical devices (IMDs) have transformed clinical care but have also created a cyber-physical attack surface in which security failures can cause direct physiological harm. This tension is most acute in emergency access: clinicians must rapidly interrogate or reprogram devices under conditions that invalidate normal authentication. Security measures can delay critical care; mechanisms guaranteeing rapid access introduce vulnerabilities. This paper offers a critical review treating IMD emergency access as a safety-critical socio-technical exception regime, not merely a technical backdoor. We synthesise major access mechanisms—proximity triggers, break-glass credentials, external mediators, and manufacturer-mediated approaches—and analyse them through threat models, safety failure modes, human factors, and governance structures. We emphasise how cognitive load, workflow disruption, and long device lifecycles amplify risk during urgent interventions. The analysis shows that these mechanisms redistribute risk among patients, clinicians, manufacturers, and regulators, and that both security and safety failures can be catastrophic. We argue that no single mechanism can simultaneously maximise safety, security, and accountability across diverse contexts. We conclude by specifying the governance interventions required to make emergency access defensible in practice.

Keywords: Implantable medical devices, IMD, Emergency access, Cyber-physical security, Safety-critical systems, Break-glass mechanisms, Governance and risk redistribution

1. Introduction

Software-driven IMDs, such as pacemakers, ICDs, and neurostimulators, now rely heavily on wireless communication. This shift has improved therapy and follow-up care but has also expanded the cyber-physical attack surface in ways that directly affect patient safety (Halperin et al., 2008; James et al., 2025; Straw, Ashworth, and Radford, 2022). A central unresolved challenge is emergency access. In acute situations—malignant arrhythmias, device malfunctions, or therapy mis-delivery—clinicians may need to immediately stop, interrogate, or reprogram an ICD. Yet security controls designed to prevent unauthorised manipulation can delay these lifesaving interventions, while mechanisms that guarantee rapid access introduce new vulnerabilities (Denning et al., 2009; Tandon et al., 2024).

Early research demonstrated that assumptions about "security through proximity" or proprietary interfaces were insufficient, showing that unauthorised access was feasible under realistic conditions (Halperin et al., 2008). Finkle (2016) reports that cybersecurity researcher Jay Radcliffe has identified vulnerabilities in the Animas OneTouch Ping insulin pump that could allow an attacker to spoof wireless communications and trigger unauthorised insulin delivery. Innes (2019) also reports that Arizona clinicians have begun preparing for the possibility of cyberattacks on medical devices, highlighting the clinical implications of compromised pacemakers and other implantables. Subsequent work highlighted how IMD resource constraints, long lifecycles, and dependence on external programmers complicate the application of conventional cybersecurity controls (Denning et al., 2009; Marinescu et al., 2025). Schmitt and Alli (2020) argue that healthcare cybersecurity failures often stem from the application of generic security models in highly specialised clinical environments. More recent analyses broaden the threat landscape to include insider misuse, governance gaps, and lifecycle degradation across decades of deployment (James et al., 2025). Despite these findings, emergency access is still typically treated as a secondary feature embedded within broader security proposals, which has the practical effect of framing it as a security–usability optimisation problem rather than as a distinct safety-critical challenge.

This framing is inadequate. Evidence from digital health and human-factors research shows that emergency care occurs under extreme cognitive load, time pressure, and incomplete information, in which even well-designed controls can fail unpredictably (Tandon et al., 2024; Sendelbach and Funk, 2013; Bonney, 2011,

p. 240; Sutton et al., 2020). In these conditions, security failures (e.g., blocked access) and safety failures (e.g., misconfiguration) are clinically indistinguishable. Moreover, decisions about who may override an IMD in an emergency embed implicit assumptions about authority, responsibility, and acceptable harm. Governance research demonstrates that emergency access mechanisms redistribute risk among patients, clinicians, manufacturers, and regulators rather than eliminating it (Beckers et al., 2016; Ison et al., 2025; Díaz-Martínez et al., 2025).

This paper, therefore, treats emergency access not as a usability exception or a technical backdoor but as a socio-technical exception regime within a safety-critical cyber-physical system. By synthesising technical mechanisms, failure modes, realistic threat assumptions, and governance constraints, the review clarifies why no single mechanism can simultaneously maximise safety, security, and accountability across diverse clinical and regulatory contexts. Rather than proposing an optimal solution, the analysis identifies the structural tensions that shape emergency access and argues that governance and standards must drive future progress as much as device-level innovation.

2. Methodology

This review employs a critical narrative synthesis to evaluate the emergency access landscape for IMDs, integrating principles from technical security engineering, human factors research, and governance analysis. The methodology recognises emergency access as a sociotechnical exception within a regime in which technical performance is inseparable from human and environmental variables.

2.1 Search Strategy and Corpus Construction

A systematic search was conducted across Scopus and Google Scholar. The core search string targeted the intersection of IMDs, access control, emergency use, and security–safety concerns: (“implantable medical device” AND (“access control” OR “authentication”)) AND (“emergency” OR “break-glass”) AND (“security” OR “safety”). Supplementary searches incorporated device-specific terms (e.g., 'pacemaker', 'ICD', 'insulin pump'). The timeframe spanned 2008–2025 to reflect developments following Halperin et al.’s seminal work. The aim is to establish a baseline of IMD-specific security literature; the review intentionally draws on insights from adjacent domains. This inclusion compensates for the relative scarcity of empirical studies specifically addressing IMD-human-factors interactions in emergency scenarios by extrapolating established principles from digital health and safety-critical cyber-physical systems.

2.2 Analytical Framework: Thematic Coding

A qualitative thematic lens was applied to the corpus, focusing on how technical mechanisms interact with operational constraints. Rather than relying on singular experimental data, claims regarding clinical workflow and cognitive load are derived from cross-disciplinary thematic patterns:

Technical Constraints: Evaluation of mechanism feasibility based on IMD power and computational limits.

Human Performance: Extrapolation of error probabilities under stress from broader digital health studies.

Structural Tensions: Identification of irreducible trade-offs where security controls measurably increase time-to-intervention.

2.3 Evaluative Scope and Theoretical Deductions

As a critical perspective piece, this methodology does not claim exhaustive systematic coverage of all IMD security literature. Instead, it uses a socio-technical evaluation to identify structural tensions—such as the "security-safety inversion"—treating them as inherent properties of complex systems. Claims regarding clinical workflow disruption and the impact of cognitive load are presented as theoretically grounded deductions synthesised from technical constraints and human-factors principles. This approach moves the analysis beyond descriptive summary to specify the governance interventions required for defensible emergency access.

3. System Boundaries and Definitions

Clear system boundaries prevent conflation of technical, clinical, and governance challenges. This section defines the scope and key terms used throughout the analysis.

3.1 Implantable Medical Devices (IMDs)

Jeremy and Nicole (2010) define IMDS as devices that are permanently or semi-permanently implanted in a patient to treat an underlying medical condition. This category includes cardiac implants, neurostimulators, and implantable drug delivery systems. These devices share several defining characteristics: constrained computational and energy resources, reliance on external programmers or controllers, long operational lifetimes, and deployment within complex physiological environments (Maisel and Kohno, 2010; Marinescu et al., 2025). Wearable, external, or intermittently attached medical devices are explicitly excluded, even when they interface with implanted components. Although such systems raise important cybersecurity and usability concerns, their failure modes, consent assumptions, and access pathways differ fundamentally from those of permanently implanted devices. These exclusions ensure that the analysis remains grounded in the structural constraints of IMDs rather than drifting into speculative or non-implant contexts, where emergency access is based on fundamentally different assumptions.

3.2 Emergency Access

Emergency access in implantable medical devices can be understood as a set of capability-limited interaction pathways among the clinician, the device, and the supporting infrastructure operating under conditions of uncertainty and degraded assumptions. These pathways are instantiated through various concrete mechanisms—such as magnet responses, programmer-mediated sessions, or telemetry-driven alerts—that expose only a bounded subset of device functionality in ways that depend on device type, manufacturer-specific design, and clinical environment.

Let emergency access in implantable medical devices be represented as a family of time-critical, capability-limited interaction pathways:

$\prod = \{\pi_1, \pi_2, \ldots, \pi_n\}$

Each pathway $\pi \in \prod$ is characterised by:

$\varsigma \in \varsigma_{set}$: Triggering conditions, such as magnet placement, programmer invocation, or contextual inference based on physiological or environmental signals.

$\tau \in \mathbb{T}$: Access latency, defined as the time required to achieve a clinically meaningful action.

$s \in \mathbb{S}$: Scope of accessible functionality, capturing whether the pathway permits, for example, read-only interrogation, therapy suspension, or constrained reprogramming.

$\mathcal{R} \in \mathbb{R}$: Recoverability, understood as the ability to re-establish a safe and controlled system state following intervention under conditions of uncertainty and degraded assumptions.

Let B_N denote the behaviour set available during normal operation, and B_{AUX} denote auxiliary mechanism-specific behaviours (e.g., fixed-rate pacing under magnet application). Each emergency pathway π exposes a behaviour subset:

$B_\pi \subseteq B_N \cup B_{AUX}$

Emergency access analysis then focuses on the structure of $\prod$ and the distribution of (ς, $\mathbb{T}$, $\mathbb{S}$, $\mathbb{R}$) across devices, mechanisms, and clinical contexts.

Framing emergency access in terms of these pathways foregrounds access latency, functional scope, and recoverability as central design and governance dimensions and captures the heterogeneous, partial, and human-mediated nature of emergency interactions with implantable medical devices.

3.3 Security and Safety

'Security' refers to the protection of IMDs against unauthorised access, manipulation, or disruption, whether malicious or accidental. "Safety" refers to avoiding an unacceptable risk of physical harm to the patient that arises from device behaviour, malfunctions, or delayed interventions. In IMDs, these concepts are inseparable: a security control that delays access can directly cause physiological harm, while a safety-orientated override

can introduce exploitable vulnerabilities or pathways to misuse (Halperin et al., 2008). This review treats security and safety as coequal, interacting risk domains, rather than as independently optimisable objectives. To move beyond purely descriptive treatments, we formalised the security-to-safety relationship as a minimal, three-variable system. Let any emergency access mechanism be represented as a tuple:

$M = (S_1, S_2, S_3)$,

where:

S_1 (Security strength) denotes resistance to unauthorised access or manipulation.

S_2 (Safety responsiveness) denotes the time required to achieve successful clinical intervention, and

S_3 (Accountability clarity) denotes the degree to which actions are attributable, auditable, and reviewable.

Under this formulation, emergency access mechanisms can be compared not as discrete implementations but as positions within a constrained trade-off. Empirical and theoretical work across IMD systems suggests that these variables are not functionally independent. In particular, for all known mechanism classes, increasing S_1 beyond a certain threshold results in S_2 degradation under emergency conditions.

This formulation does not claim a strict mathematical optimality range; instead, it defines a testable system property: mechanisms that strengthen authentication, validation, or control layers beyond a given threshold introduce latency, complexity, or dependencies that measurably increase time-to-intervention. This model provides a basis for analysing emergency access as a constrained optimisation problem with clinically bounded tolerances rather than as a purely technical design challenge.

3.4 System Boundary Exclusions

To maintain analytical rigour and focus, this review explicitly excludes several domains: namely, artificial intelligence applications in diagnostic or control systems; population-scale, remote-only cyberattack scenarios lacking immediate physical or clinical consequences; the design or benchmarking of novel cryptographic protocols; and any empirical performance evaluation of specific commercial devices beyond established case studies. These deliberate exclusions focus the paper's findings on the fundamental structural and governance challenges inherent in securing emergency access to medical technology, rather than diverting attention to speculative technological solutions or complex engineering details.

3.5 Stakeholders and Responsibility

Emergency access mechanisms inherently redistribute risk and responsibility among patients, clinicians, manufacturers, and regulators, not because clinical roles or training differ, but because each mechanism embeds implicit assumptions about who is trusted and what actions are permissible. For example, a proximity-triggered override implicitly assigns risk to the patient by treating anyone physically close to them as an authorised actor. Governance and socio-technical systems research shows that such redistributions are a structural property of safety-critical systems rather than a consequence of any particular design choice (Beckers et al., 2016; Ison et al., 2025). Making these allocations explicit provides the foundation for the taxonomies, threat models, and failure mode analyses that follow.

4. Issues in the Technical Foundations for IMD Security

The design and evaluation of any emergency access mechanism for IMDS must be grounded in an understanding of its inherent technical constraints and the cryptographic primitives available to engineers. These factors fundamentally bound the solution space and defined the core security-safety tension.

4.1 The Primacy of Resource Constraints

IMDs are examples of systems that have very few resources. Their defining characteristics—miniaturisation, a non-replaceable battery lifespan of 5–15 years, and limited computational power and memory—create a design paradigm where security cannot be an afterthought but must be meticulously balanced with device longevity and core therapeutic functions. Traditional, resource-intensive cryptographic operations, such as standard asymmetric encryption methods like RSA, are often prohibitively power- and computation-intensive for direct implementation on the implant itself (Samaraweera et al., 2025). Consequently, a robust security scheme incorporating authentication, encryption, and authorisation may not be feasible if it significantly degrades battery life or delays life-critical operations (Camara, Peris-Lopez, & Tapiador, 2015). This limitation is

not merely an engineering challenge but also a direct security vulnerability; adversaries can exploit power-hungry protocols to launch Denial-of-Service (DoS) attacks that rapidly deplete the IMD's battery.

4.2 Evolution of Cryptographic Strategies for IMDs

In response to these constraints, the field has evolved from non-existent or weak security to a suite of lightweight, context-aware cryptographic strategies. Research has moved beyond simple, static keys toward more dynamic and resilient foundations:

Lightweight Cryptography: The imperative is for "lightweight security mechanisms" tailored for devices (Sun, Lo and Lo, 2017). This includes optimised implementations of standards such as the Low-Power Advanced Encryption Standard (AES) for Implantable Cardiac Devices and the use of elliptic-curve cryptography (ECC), which offers stronger security per bit than RSA, making it more suitable for constrained environments (Liu, Richardson, and Van der Spiegel, 2021).

Physiological Key Generation: A significant innovation is the use of the patient's own body as a source of security. By deriving cryptographic keys from unique, time-variant physiological signals such as the electrocardiogram (ECG) or photo-plethysmogram (PPG), these schemes enable secure access without pre-shared secrets (Karimian et al., 2017; Rahimi M.S., 2021). Techniques such as fuzzy vault and fuzzy commitment are employed to handle natural signal variability, allowing a legitimate programmer in proximity to generate the same key as the IMD for authentication and session establishment.

Proximity and Context as Security Parameters: Cryptographic protocols are increasingly integrated with physical and contextual safeguards. Distance-bounding protocols measure the signal's time of flight to verify that a programmer is physically near the patient, thereby mitigating relay or man-in-the-middle attacks (Camara, Peris-Lopez and Tapiador, 2015; Tabassum et. al., 2018). Furthermore, the concept of "context-aware security modes" proposes dynamically adjusting security postures – for example, relaxing authentication in a verified emergency room setting, which requires cryptographic systems that can support such policy shifts (Riegler, Sametinger, and Rozenblit, 2022).

These technical constraints explain why 'ideal' security solutions are impractical and why the trade-offs that follow are structural, not merely design choices

5. Emergency Access Mechanism Taxonomy

This section classifies emergency access mechanisms by their trust anchors and operational assumptions, following recent research on cyber-physical systems and governance (Beckers et al., 2016).

5.1 Physical Proximity-Based Mechanisms

Physical proximity mechanisms enable emergency access by allowing interaction with the implanted device from a short distance, typically via magnets, inductive coupling, or short-range electromagnetic triggers. Activation places the device into a predefined emergency mode, such as therapy suspension or simplified programming access. These mechanisms rely on physical presence as the primary trust anchor, implicitly assuming that those in close proximity during emergencies are authorised clinicians. Their principal advantages are minimal latency and independence from external infrastructure, which align with clinical urgency. However, recent analyses emphasise that proximity alone is a weak authorisation signal in crowded or uncontrolled environments, particularly given the severe consequences of accidental or unauthorised activation (Halperin et al., 2008; James et al., 2025).

5.2 Credential-based “Break-Glass” Access

Credential-based break-glass mechanisms permit emergency access when specific credentials, override codes, or emergency procedures are invoked. These mechanisms intentionally relax standard access controls under predefined emergency conditions, often accompanied by enhanced logging or post-event review. While this model preserves an explicit notion of authorisation, it also introduces vulnerabilities associated with credential availability, memorability under stress, and long-term exposure over the multi-decade lifetimes of IMDs. Human-factors research indicates that reliance on rarely used credentials during emergencies increases error probability and delays intervention, undermining safety objectives even when security controls function as designed (Denning et al., 2009; Tandon et al., 2024).

5.3 External Mediator Devices

External mediator approaches introduce an intermediary device, such as a programmer, shield, or policy-enforcing controller, that brokers emergency access between clinicians and the IMD. The mediator may authenticate users, enforce access policies, or temporarily relax constraints while maintaining an audit trail. This class delegates trust to the mediator, leveraging its greater computational capacity and flexibility relative to the implant itself. While such separation can reduce on-device complexity and attack surface, it introduces a dependence on the availability, integrity, and proper configuration of external devices, which may be absent or compromised in emergency settings. Cyber-physical systems research highlights that mediator failures often manifest as access denial rather than graceful degradation, amplifying safety risk (Marinescu et al., 2025).

5.4 Manufacturer-Mediated Emergency Access

Manufacturer-mediated mechanisms rely on device vendors to authorise or enable emergency access—possibly through proprietary tools, remote authentication, or emergency support channels. The manufacturer, acting as an external authority, centralises trust. While these methods can facilitate precise control and traceability, they also introduce latency, connectivity dependence, and jurisdictional complexity, which are ill-suited to acute clinical care. Recent governance-focused reviews indicate that manufacturer-mediated access introduces unresolved issues regarding liability, clinician autonomy, and equitable availability across healthcare systems (James et al., 2025).

5.5 Context-Conditioned Access Mechanisms

Context-conditioned mechanisms infer authority based on environmental or situational cues, such as location, time, or detected physiological distress. Access may be granted automatically or semi-automatically when predefined conditions are met. These mechanisms shift trust from explicit actors to contextual inference, reducing clinician burden but introducing risk from false positives and false negatives. Evidence from digital health and human-centred systems research suggests that contextual signals are often ambiguous or noisy during emergencies, making an incorrect inference a significant safety hazard rather than a marginal edge (Tandon et al., 2024).

5.6 Cross-cutting Taxonomic Dimensions

Emergency access mechanisms across different classes of connected devices, including implantable medical devices, are fundamentally characterised by four critical, interdependent dimensions: the trigger modality (how access is initiated, e.g., physical action, credential, or inferred context), the primary trust anchor (what establishes confidence in the access attempt, e.g., proximity, identity, or vendor authority), the degree of infrastructure dependence (whether the system operates locally or requires external network support), and the inherent reversibility and auditability of emergency actions. While technological configurations across these dimensions are numerous, a key finding from recent systems and governance research is that no single design eliminates risk; rather, each unique combination reallocates the inevitable risks associated with potential misuse or failure modes across various stakeholders, including patients, clinicians, manufacturers, and regulators.

5.7 Implications of the Taxonomy

This revised taxonomy underscores that emergency access mechanisms are not interchangeable technical options but embodiments of distinct assumptions about trust, urgency, and responsibility. By stabilising these categories before evaluation, the taxonomy provides a structured basis for the threat modelling and safety failure analyses that follow without implying that any single class offers a universally defensible solution.

6. Threat Modelling and Adversarial Assumptions

A realistic threat model for IMD emergency scenarios must extend beyond remote hacking. Consequential harm often stems from non-malicious failures and operational stress, not just adversarial sophistication (James et al., 2025). This section evaluates how these mechanisms fail under realistic adversarial and clinical conditions. Specifically, the critical risks to emergency access mechanisms are multi-faceted: Local proximity attackers can exploit short-range channels, demonstrating that physical presence is not a sufficient security boundary, especially when emergency protocols mandate permissive access (Halperin et al., 2008; Rasmussen et al., 2009). The more dominant threats relate to human factors and long-term deployments, including insider misuse and overreach, in which authorised personnel, under acute stress and cognitive load, inadvertently misconfigure devices, resulting in outcomes equivalent to a malicious act (Tandon et al., 2024; Sendelbach &

Funk, 2013; Bonney, 2011, p. 240; Sutton et al., 2020; Gündoğan & Erdağı Oral, 2023; Jämsä et al., 2021; Sarioğlu & Amarat, 2025). This vulnerability is compounded by accidental and stress-induced misuse, in which degradation in human performance under high-pressure conditions increases the likelihood of procedural errors (Tandon et al., 2024). Furthermore, the decades-long service life of IMDs introduces significant lifecycle and supply-chain degradation, making vulnerabilities due to outdated cryptography or poor key management a more dominant long-term concern than novel attack vectors (James et al., 2025). Consequently, effective policy and design must prioritise resilience against predictable human error, misaligned trust assumptions, and operational drift, rather than focusing predominantly on technical measures against less probable, high-sophistication remote cyberattacks.

6.1 Implications for Emergency Access Design

Under this revised threat model, the dominant risks to emergency access mechanisms arise from misplaced trust assumptions, stress-induced misuse, and lifecycle drift, not from adversaries with exceptional technical capabilities. Consequently, mechanisms that prioritise strong authentication or cryptographic complexity without addressing emergency usability and governance are unlikely to reduce net damages. These insights motivate the safety failure-mode analysis that follows.

7. Safety Failure Modes in Emergency Access

The IMD safety policy must integrate evidence from digital health, cyberphysical systems, and human-centred design, explicitly treating safety failures as co-equal determinants of patient harm along with security risks. Emergency IMD access is a safety-critical operation that occurs under significant stress, time pressure, and incomplete information. These are all conditions known to increase the likelihood of mistakes in people and systems, especially when they are not following their usual workflows (Tabassum et. al. 2018; Tandon et al., 2024). Security must not compromise robustness and usability in emergencies; an unusable, technically secure system is a direct safety hazard. Two dominant safety failure modes are access denial/latency and misconfiguration. Denials or delays in interventions can result from credential-, mediator-, or manufacturer-mediated access failing due to unavailable or slow credentials, intermediary devices, or external authorisations. Cyber-physical systems research shows that control-layer latency often causes outright failure, which is critical for IMDs, where seconds matter. These failures can occur even if security controls function, exposing a structural incompatibility between security assurances and emergency safety. Rapid parameter alteration in emergencies risks misconfiguration under stress. Research on human-centred systems suggests that unfamiliar interfaces or coarse-grained controls raise the likelihood of errors, a situation worsened by the variety of proprietary IMD interfaces (Beckers et al. 2016).

Usability failures and workflow disruption degrade safety. Complex authentication, precise timing, or unfamiliar tools are functionally equivalent to access denial. Digital health studies confirm that workflow disruption—not technical capability—dominates adverse outcomes in emergency digital interventions (Tandon et al., 2024). This evidence challenges the assumption of infrequent, flawless emergency use. Ethical risks regarding consent and autonomy arise when access overrides patient preferences. Poorly specified policies erode trust, a safety risk that systems research confirms affects acceptance and adherence (Beckers et al., 2016).

Summarily, these failure modes show that tighter security alone cannot ensure safe IMD emergency access. Any measure that blocks unauthorised use but adds delay or ambiguity increases patient harm. A shift from security-only fixes to systemic governance, accountability, lifecycle responsibility, and risk redistribution is essential to preserve institutional trust in these safety-critical systems.

Figure 1 and Table 1 illustrate the irreducible trade-off between access latency and security exposure. No mechanism can optimise both simultaneously; the curve represents a structural security-safety inversion. The central governance question is where to position mechanisms along this frontier in high-stakes contexts.

Table 1: Mapping mechanisms to their failure modes, dependencies and trust assumptions

MECHANISM	PATIENT SAFETY (Y-AXIS)	SYSTEM SECURITY (X-AXIS)	TRADE-OFF PROFILE	NOTES
Magnet-triggered override	Very High	Very Low	Top-left corner	Instant access; vulnerable to physical tampering or accidental activation
Proximity-based triggers	High	Low	Left of curve	Fast and intuitive; lacks authentication or audit trail
Break-glass protocols	Moderate	Moderate	Mid-curve	Requires clinician action; may log override, but still bypasses full authentication
Manufacturer-mediated access	Low	High	Bottom-right curve	Secure and auditable; slow and dependent on external coordination
Cryptographic authentication	Very Low	Very High	Far-right curve	Strongest security; impractical in emergencies without preloaded credentials
Pre-authorised clinician override	High	Moderate	Upper-mid curve	Balances speed and accountability; depends on trust in local personnel
Biometric triggers (experimental)	Moderate	High	Right of curve	Promising but unproven; latency and reliability concerns in crisis

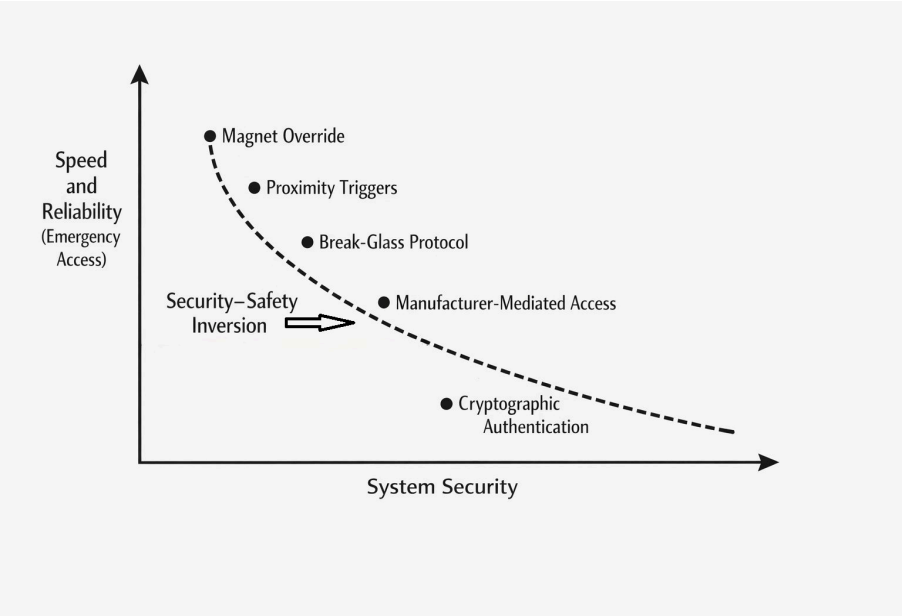


Figure 1: Pareto frontier diagram showing the irreducible structural tensions forcing trade-offs across essential dimensions of IMD operations

Together, Figure 1.0 and Table 1 show that these trade-offs are structural rather than incidental. They arise from the interaction of human performance under stress, IMD resource constraints, and governance expectations. As a result, emergency access design is not a search for optimal points but rather a process of selecting which risks are tolerable, for whom, and under what clinical and organisational conditions.

8. Governance, Accountability, and Risk Redistribution

Emergency access failures are governance gaps, not cryptographic deficiencies. Access denials arise when frameworks fail to mandate emergency access standards; misconfigurations reflect a lack of interface harmonisation and human-factor validation; lifecycle drift stems from weak manufacturer obligations; ambiguous authority reveals a failure to specify who acts under what conditions (Beckers et al., 2016). These are institutional, not technical, failures.

Emergency access is an exception regime that requires normative judgements about who acts, when, and with what consequences (Ison et al., 2025). Design choices encode governance decisions that policy must manage.

Authority allocation during emergencies directly affects safety. Clinician-centric models enable rapid action but impose liability; manufacturer-centric models offer traceability but introduce delays; hybrid models create ambiguity. Clear precedence rules are essential to prevent hesitation (James et al., 2025).

Each mechanism redistributes residual risk: proximity shifts risk to patients; break-glass transfers liability to clinicians; manufacturer mediation increases vendor complexity; context conditioning embeds risk in opaque algorithms. Explicit risk redistribution—not technical optimisation—is the core policy decision (Beckers et al., 2016).

Long device lifecycles and post-hoc logging complicate accountability. Regulatory silence on emergency cybersecurity exceptions incentivises conservative designs that minimise manufacturers' liability at the expense of patient safety (Maisel & Kohno, 2010; James et al., 2025).

Governance frameworks must recognise emergency access as a managed exception regime, aligning legal liability, clinical authority, and regulatory expectations in advance.

9. Comparative Synthesis and Irreducible Tensions

The design and governance of emergency access mechanisms for implantable medical devices (IMDs) prevent convergence on a single optimal technical solution. Instead, comparative synthesis reveals that these systems encode irreducible structural tensions, forcing trade-offs across essential dimensions such as access speed, resistance to malicious use, auditability, and clear governance. This dynamic is a recognised characteristic of tightly coupled safety-critical cyberphysical architectures: optimising one attribute inherently degrades performance in another. Therefore, analysing various emergency access strategies yields not a universally superior technical protocol, but rather a set of “bounded capability envelopes”, in which effectiveness is constrained by fundamental assumptions regarding trust models, urgency, and the assignment of operational responsibility. Any technical proposal that claims universal superiority likely fails to account for these fundamental, interlinked constraints.

A crucial policy insight is the security–safety inversion that occurs under emergency conditions. While controls prioritising security over safety are reasonable during a steady-state operation, their continuous enforcement can become counterproductive during a crisis. Emergency access is infrequent but invoked under extreme circumstances, and the denial or delay of access may pose a greater immediate risk to a patient than the threat of unauthorised use. Recent work in digital health emphasises the dominance of interventional and recovery capacities over pure prevention in crisis management (Tandon et al., 2024; Siddiqi et al., 2020). This inversion undermines conventional cybersecurity evaluation frameworks that emphasise access restriction without adequately accounting for time-critical safety constraints and the real-world operational demands of clinical emergencies.

Furthermore, efforts to manage IMD access inevitably lead to the redistribution of risk rather than its net reduction, with disagreements often rooted in contested views on acceptable risk allocation (Beckers et al., 2016). The core irreducible tensions that persist across all IMD emergency protocols—and those that resist purely technical or artificial intelligence solutions—include the conflict between immediate action and verifiable authorisation; the clash between simplified usability during a crisis and the detailed logging required for auditability; and the friction between centralised security control and necessary decentralised clinical autonomy. The design challenge is not the elimination of risk but the management of inherent tensions within a managed-exception space, where design choices explicitly trade off safety, security, and governance priorities. Future policy directions must focus on establishing explicit frameworks for allocating authority and responsibility, rather than seeking device-level technical optimisation.

10. Conclusion: Limits, Non-Solutions, and Future Directions

Synthesis of Findings

Emergency access to IMDs presents a structural tension: no single technical solution can simultaneously maximise security, safety, and accountability. Designs prioritising security risk fatal delays; those prioritising immediacy increase the potential for misuse. Enhanced technical controls—'perfect' authentication or universal backdoors—are non-solutions. The core constraints are institutional. Without explicit regulatory guidance on emergency exceptions, audit standards, and a clear allocation of responsibilities, proprietary mechanisms will continue to create ambiguity.

Prescriptive Governance Interventions

Addressing the structural tensions identified in this review requires governance interventions that reshape the constraint space rather than attempting to engineer around it. Regulators should establish minimum emergency-access performance standards, including maximum permissible access latency and requirements for predictable behaviour under degraded conditions. Manufacturers must be subject to lifecycle responsibility obligations, ensuring that emergency access remains viable, secure, and auditable throughout the device's multi-decade lifespan. Governance frameworks should mandate post-event auditability, requiring that all emergency overrides—whether successful or failed—are logged, reviewable, and linked to clear accountability structures. Cross-jurisdictional harmonisation is essential for avoiding fragmented expectations that undermine clinician autonomy and patient safety. Finally, procurement and certification processes should incorporate human-factors validation to ensure that emergency access mechanisms can be executed reliably under acute cognitive load and environmental stress.

Closing Statement

These interventions reposition governance as the primary mechanism for managing the unavoidable trade-offs between safety, security, and accountability. Technical innovation remains necessary, but without governance structures that explicitly define acceptable risk, emergency access will continue to fail in predictable and harmful ways.

Acknowledgements

We would like to thank Jay Radcliffe and Dr Jorge Acevedo Canabal for their insights, and the entire Bio Hacking Village for their support throughout this work.

Ethics Declaration: This review did not involve human participants, animals, or personal data and, therefore, did not require ethical approval.

AI Declaration: Grammarly, Microsoft Copilot, and DeepSeek were used to support the preparation of this manuscript. These tools assisted with summarisation and keyword extraction, spelling and grammar refinement, and reference organisation. The authors reviewed and verified all AI-assisted outputs. No AI system was credited as an author or cited as a source. AI tools did not generate or fabricate any data, citations, or analyses.

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Toward Better Use of Cyber Threat Models in Defence Environments

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Abstract: Threat modelling in cybersecurity is a systematic process for identifying, analysing, and prioritising threats in a system. However, it is a highly challenging task in the defence sector, since military capabilities present a broad attack surface. This problem is compounded by the widespread use of civilian threat models, designed for specific systems or security aspects, in the defence sector, which often lack the breadth required to analyse military capabilities. In this paper, we identify gaps in state-of-the-art threat models in their ability to represent threats in the defence sector, using TEPIDOIL, a framework that captures the components required to maintain effective defence capabilities. We then present a novel framework called *Universal Defence Framework*, and demonstrate, through a case study and evaluation, that it enables the use of existing (civilian) threat models in the defence sector and addresses the identified gaps. Our evaluation showed that integrating threat models into our framework provides the broader view required to analyse threats in complex, integrated systems, as typically found in the defence sector.

Keywords: Threat modelling, Defence, TEPIDOIL, STRIDE, OCTAVE, Cyber kill chain

1. Introduction

In cybersecurity, threat modelling is a crucial process for identifying how adversaries can penetrate a system and escalate attacks. It identifies system components, how they can be compromised, and helps prioritise risks that pose the greatest harm to the system. Hence, threat models are highly useful for analysing system weaknesses.

Threat modelling is a key pillar in the planning and improvement of responses to attacks in the defence sector. However, there are three key problems. First, civilian threat models are typically designed for a specific system or security aspect, e.g., Cyber Physical Systems (Valenza et al., 2022), Internet of Things (Mahlous, 2023), software systems (Sion et al., 2021), human factors (Ferro et al., 2021), and others. Thus, unable to represent the complexity of the defence sector. Second, defence environments are often defined in terms of capabilities: the ability to perform an action or to deliver a service or function. Military capabilities rely on aspects that are not fully integrated in the civilian context, e.g., logistics, doctrine. Third, civilian threat models are used in defence environments, even though they typically do not provide the breadth required to analyse military capabilities with a broad attack surface. Hence, threat modelling in defence requires a broader perspective; otherwise, it would only partially represent a capability, creating blind spots.

In this paper, we address this problem by identifying the representation gaps threat models have when used in the defence context. In particular, we evaluate these threat models against TEPIDOIL, a UK Ministry of Defence (MoD) framework that captures the components required for maintaining effective defence capabilities (MoD, 2024). To address representation gaps, we introduce a novel *Universal Defence Framework* that enables the use of civilian threat models in the defence sector and captures critical defence components and capabilities.

To identify the gaps, we analysed three threat models used in both defence and civilian contexts. We evaluate these threat models by comparing their representation capabilities with respect to TEPIDOIL, which encompasses Training, Equipment, Personnel, Information, Doctrine and Concepts, Organisation, Infrastructure, and Logistics (MoD, 2024). Vulnerabilities in any of these components can impact the delivery of capabilities. For our analysis, we selected STRIDE (Kohnfelder and Garg, 1999), OCTAVE (Alberts et al., 2003), and Cyber Kill Chain (Hutchins et al., 2011), as they are popular approaches used for threat modelling (Suhas, 2023; Naik et al., 2024). While it is challenging to provide evidence of these threat models in critical defence scenarios (due to secrecy in this sector), they are frequently emphasised in defence documentation, as recommended or useful threat models.

Our analysis confirmed that these threat models cannot represent all TEPIDOIL components. To fill these gaps, we introduced our novel *Universal Defence Framework*, which enables the application of civilian threat models in the defence sector to facilitate comprehensive analyses of military capabilities. To showcase our framework, we present a case study on a military application. This case study clearly shows that it allows threat models to

represent defence aspects that could not be represented before. Our preliminary evaluation shows that our framework enhances the representation capabilities of threat models for the defence sector.

In Section 2, we present briefly the related works. In Section 3, we analyse each threat model to identify their representation gaps. In Section 4, we present our novel *Universal Defence Framework*. In Section 5, we present a case study demonstrating the application of our framework. In Section 6, we evaluate how our framework enhances existing threat models and discuss the limitations of our work. Finally, in Section 7, we conclude and provide future research directions.

2. Related Works

Threat models are crucial in identifying vulnerabilities in systems and software. Threat models are generally used for civilian contexts. Valenza et al. (2022) developed a threat model and tool that takes as input a system's digital, physical, and human assets and derives how threats can propagate through the system. Mahlous (2023) quantified the severity of harm caused by threats across different asset types in an Internet of Things system, using the STRIDE threat model. Sion et al. (2021) developed a tool that analyses threats in a software system during code updates, facilitating dynamic and automated threat modelling. Ferro et al. (2021) developed STRIDE-HF, a threat model that helps analysts identify how human-factor weaknesses (e.g., a lack of understanding) can enable cyberattacks. Sgandurra et al. (2016) presented a threat model for virtualized systems.

Let us describe three state-of-the-art threat models, i.e., STRIDE, OCTAVE, and the Cyber Kill Chain, that have been used in the defence sector, with examples of this usage.

STRIDE (Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, Elevation of Privilege) (Kohnfelder and Garg, 1999) was originally designed for threat modelling software systems but has since been applied to other systems. STRIDE, combined with Data Flow Diagrams (DFDs), is particularly useful for classifying threats into each of the six categories by asking, for example, 'Is there a possibility for an adversary to present as another entity to exploit this part of the system, and what threats can allow this?' (e.g., Spoofing threats). A notable implementation of STRIDE in defence is the guidance proposed by the UK Department for Science, Innovation & Technology (DSIT, 2024) for threat modelling smart-city-related technologies using STRIDE. The guidance presents four cases in which local authorities have deployed the approach to identify threats across different contexts, including IoT devices, connected safety devices, and air quality sensors.

OCTAVE (Operationally Critical Threat, Asset, and Vulnerability Evaluation) (Alberts et al., 2003) is a threat model that has three key phases. The first phase requires threat modellers to identify organisational assets in order to identify critical assets that, if compromised, have a significant impact on the business. The second phase involves identifying and analysing the components that enable crucial assets to function as expected, as well as weaknesses. Finally, the third phase requires analysts to develop countermeasures to address the identified vulnerabilities. While information on the application of OCTAVE in defence is often classified, research sponsored by the US Department of Defence (Woody, 2006) indicates that training is provided to medical teams to conduct risk assessments of healthcare systems using OCTAVE, identify and prioritise security risks, and formulate countermeasures.

Cyber Kill Chain (CKC) (Hutchins et al., 2011) is designed to decompose cyberattacks into seven phases that detail how adversaries collect the information required to conduct the attack, how an exploit is built, and how exploits are delivered. The threat model is useful for a range of scenarios. First, before a cyberattack, the CKC can be used by organisations to plan how they will manage each stage. Second, when managing a live attack, the CKC can be used to predict adversarial actions. Third, the CKC can be used to analyse why and how a cyber-attack occurred by reconstructing a series of events. A notable implementation of the CKC in defence is by the US Marine Corps, which deployed a red/blue teaming activity to test how well attacks against critical infrastructures could be defended against realistic attack scenarios (Corbo, 2022). The CKC was used to design multiple attack scenarios, in stages that mirror the progression of real attacks.

3. Analysis of Threat Models

In this section, we introduce TEPIDOIL and analyse STRIDE, OCTAVE, and CKC with respect to their ability to represent TEPIDOIL elements. Our analysis finds that these models cannot fully represent and analyse TEPIDOIL elements, as shown in Table 1.

TEPIDOIL is a framework that defines components that facilitate an effective military capability. A capability refers to the ability of a defence organisation to perform an action or to deliver a service or function (MoD,

2024). Each component of TEPIDOIL can introduce threats; hence, for a capability to be effective, all components must avoid significant compromise. This highlights that capability-based threat modelling must consider a broad range of systems and components. TEPIDOIL's components can be defined as ensuring the following: (1) Training: Ensuring that individuals are proficient in conducting their responsibilities well; (2) Equipment: Ensuring the availability and effectiveness of software or physical tools that support the capability; (3) Personnel: Ensuring individuals with the correct expertise and ethical conduct can support the desired outcomes; (4) Information: Ensuring that data is only accessible by authorized parties, that it remains available and untampered by unauthorized parties, and is processed securely; (5) Doctrine and Concepts: Ensuring that military forces are guided by robust processes, frameworks, and guidelines; (6) Organisation: Ensuring that there are structures in place to facilitate defence objectives, particularly regarding management structures, and how roles interact with each other; (7) Infrastructure: Ensuring that there are structures required to aid defence objectives (e.g., buildings); (8) Logistics: Ensuring that approaches are sustainable (e.g., developing maintainable assets and tools).

Our analysis on *STRIDE* identified gaps or partial representation in seven of eight TEPIDOIL elements. In particular, (1) Training: STRIDE can model the platform used for training (e.g., Denial of Service threat: training platform can be disrupted), but key threats, such as how an individual's skill can degrade during the lifecycle of capabilities, cannot easily be derived; (2) Equipment: Software equipment can effectively be analysed in STRIDE, though, since it is information-centric, physical threats are less derivable from DFDs or analyses; (3) Personnel: STRIDE is limited in being able to derive the reasoning behind human factor errors (e.g., fatigue); (4) Information: The model is comprehensive in identifying information security threats; (5) Doctrine and Concepts: STRIDE can represent doctrine and concepts (e.g., guidelines) as assets, however, the suitability of doctrine for capabilities is not assessed; (6) Organisation: While STRIDE allows practitioners to identify information flow through the system, threats that arise from governance, for example, in a team, are not analysed by default; (7) Infrastructure: In STRIDE, components of the system are organised into boundaries (e.g., with DFDs), however, STRIDE does not often consider this from a physical point of view, though some physical implications can be analysed using denial of service or tampering categories; (8) Logistics: Threats impacting how well a capability can be sustained are challenging to derive without additional prompts.

Our analysis on *OCTAVE* found that it overall covered more elements, with two TEPIDOIL elements covered and the rest partially covered. In particular, (1) Training: The first phase in OCTAVE can identify weaknesses in the organisation, which can include those related to training, however, the documentation (Alberts et al., 2023) emphasises the assets themselves; (2) Equipment: OCTAVE identifies critical assets well, but gives less attention to specific software or physical equipment vulnerabilities than other models, e.g., STRIDE; (3) Personnel: Human-factor risks may emerge in Phase 1, but they are not strongly emphasised and can be overlooked. (4) Information: Information threats are well covered, as Phase 1 includes identifying key data assets. (5) Doctrine and Concepts: OCTAVE assesses policy and guideline compliance rather than weaknesses in doctrine itself; (6) Organisation: Risks from organisational roles and governance can be identified; (7) Infrastructure: Phase 2 analyses infrastructure supporting business functions, but mainly when tied to a crucial asset rather than as a risk source on its own; (8) Logistics: Logistics related threats (e.g., delivery capacity or timing) are not addressed by default unless analysts explicitly apply TEPIDOIL.

Our analysis on *CKC* found that it can represent three TEPIDOIL elements, partially represent two, and cannot represent three. In particular, (1) Training: CKC can place training weaknesses within an attack sequence, but it does not evaluate training threats directly, and training is rarely the primary target; (2) Equipment: Equipment attack paths can be mapped clearly through the step-by-step phases of the model; (3) Personnel: Human-factor weaknesses (e.g., exploited through phishing) can be represented, but CKC is not designed to analyse them in depth and often treats them only as attack initiators; (4) Information: The model can specify how information assets can be impacted (e.g., with the actions on objectives stage); (5) Doctrine and Concepts: Doctrine may be treated as an asset that can be attacked, but threats arising from doctrine itself receive little emphasis; (6) Organisation: Reconnaissance may capture organisational details, but CKC is less effective for deriving organisational risks than models like OCTAVE; (7) Infrastructure: The model effectively maps attacks on networks and physical architectures, including pathways to compromise; (8) CKC can illustrate disruption of logistical processes, but detailed analysis may require adaptation or explicit prompting.

Our analysis has highlighted gaps in the representation of TEPIDOIL elements in these threat models (see Table 1). Although each model can comprehensively represent the information component in TEPIDOIL (i.e., derive information-security-centric threats), analysts would require explicit prompting to consider other components

(e.g., training or logistics). Without this, analysts may produce threat models that only partially represent the threats in a capability because a standardised process has not been used.

Table 1: Gaps summary. ✕ = not typically captured; ◑ = requires explicit consideration; ✓ = well captured by default

Element	STRIDE	OCTAVE	CKC
Training	◑	◑	✕
Equipment	◑	◑	✓
Personnel	✕	◑	◑
Information	✓	✓	✓
Doctrine and Concepts	◑	◑	✕
Organisation	✕	✓	✕
Infrastructure	◑	◑	✓
Logistics	✕	◑	◑

4. Proposed Approach: Universal Defence Framework

In this section, we introduce our *Universal Defence Framework*, designed to enable analysts to comprehensively analyse military capabilities using a threat model of their choice to identify threats. Our framework is a general extension that enhances existing models. This addresses a key limitation of civilian threat models highlighted in Section 2: they are not optimal for analysing capabilities by default. Note that our proposed approach is a general framework that enhances most threat models, rather than addressing specific limitations in STRIDE, OCTAVE, or CKC, which provide different functionalities.

Our framework has four main concepts: *capabilities*, *functions*, *assets*, and *failure modes*. A capability is the ability to perform an action or deliver a service or function (broad view). Functions are the aspects that enable a capability to be effective (more descriptive). Assets are the people, processes, and technologies required for functions to operate (granular details). Finally, failure modes denote states of assets or functions (e.g., compromised, degraded, or normal).

Our framework, presented in Figure 1, consists of four key stages, each with associated processes. In Phase 1, analysts contextualise further analysis to the capability by (i) defining the capability, (ii) defining the functions that enable the capability, (iii) defining failure modes in the functions, and (iv) defining unacceptable compromises to the capability. In Phase 2, analysts identify the assets involved in making the functions work by (i) identifying TEPIDOIL assets (people, processes, and technologies) required for each function from Phase 1, and (ii) defining failure modes for every asset. In Phase 3, analysts identify threats to assets by (i) selecting the threat model(s), e.g., STRIDE, OCTAVE, CKC, etc., (ii) applying the threat models(s) to each asset from Phase 2 to identify threats, and (iii) evaluating how each threat against an asset would cause a failure mode in the asset and the functions that depend on the asset. Finally, in Phase 4, analysts (i) evaluate the impacts of failure modes triggered in functions (from Phase 3) on the capability, considering the conditions from Phase 1, Process (iv).

Figure 1: Universal Defence Framework

5. Case Study

In this section, we demonstrate the application of our framework through a case study, which is a conceptual example of a capability presented in an MoD advisory.

Let us introduce the case study (MoD, 2025). During missions, military forces are delivered supplies (e.g., power and medical aid) via Unmanned Aerial Vehicles (UAVs). To enable personnel to collect their supplies, they must be able to track the UAV and receive relevant delivery information via military software on their mobile phones. A capability refers to the ability to perform an action or to deliver a service or function. Hence, in our case study, capability refers to the ability to track the UAV effectively using software, and threats to TEPIDOIL elements can affect the execution of this capability.

We now demonstrate how our framework can be applied to this capability, showing how the processes in our proposed framework align with threat models such as STRIDE.

Phase 1: Contextualise to the capability.

- *Process 1: Define the capability:* Software must allow military personnel to track the UAV in conflict environments reliably.
- *Process 2: Define functions that enable the capability:* (1) Authenticate users [F1], (2) Allow delivery tracking [F2].
- *Process 3: Define failure modes in the function:* For simplicity, all functions will have the following failure modes: Normal (N), Degraded (D), Compromised (C).
- *Process 4: Define unacceptable compromises to the capability:* (1) Death of military personnel [UC1], (2) Delivery information about supplies is disclosed [UC2].

Phase 2: Identify assets.

- Process 1: Identify TEPIDOIL assets (people, processes, technologies) required for functions to work:

Simplified example (in-depth analysis can include more assets):

- For F1:
- *People: Military personnel (Personnel)*
- *Processes: Access token must be issued (Equipment)*
- *Technologies: Mobile phone (Equipment); software (Equipment)*
- For F2:
- *People: Military personnel (Personnel)*
- *Processes: Updates to delivery progress (Equipment)*
- *Technologies: UAV telemetry (Equipment); software (Equipment)*
- *Process 2: Identify failure modes for assets:* For simplicity, modes for all assets are *normal (N)*, *degraded (D)*, or *compromised (C)*, but these can be specified further.

Phase 3: Identify threats.

- Process 1: Select the threat model(s): STRIDE
- *Processes 2 and 3: apply threat model to each asset (from Phase 2) to identify threats, and for each threat evaluate how it can cause (→) a failure mode in the asset and a failure mode in the functions that depend on the asset.*
- Military personnel:
- *Spoofing: Adversaries obtain user credentials via a successful phishing email and enter the software using those details. [Military personnel: C → F1:C, F2:C].*
- *Information disclosure: Military personnel reveal UAV delivery information to unauthorised parties. [Military personnel: C → F2:C].*
- Access tokens:
- *Spoofing: Adversaries impersonate military personnel by replacing tokens. [Access token: C → F1:C, F2:C]*
- *Tampering: Adversaries modify tokens. [Access token: C → F1:C, F2:C]*
- *Information disclosure: Adversaries extract tokens from data stores. [Access token: C → F1:C, F2:C]*

- Mobile phone:
- *Spoofing: Adversaries steal the mobile phone to imitate military personnel. [Mobile phone: C → F1:C, F2:C]*
- *Denial of service: Damage to the device prevents personnel from using tracking software. [Mobile phone: D → F1:D, F2:D]*
- Software (UAV tracking software):
- *Tampering: Adversaries modify software code. [Software: C → F1:C, F2:C]*
- *Information disclosure: Adversaries access software artefacts stored on a programmer's device. [Software: C → F1:C, F2:C]*
- *Denial of service: The app malfunctions. [Software: C → F1:C, F2:C]*
- *Elevation of privilege: Poor authentication processes result in personnel accessing delivery information outside of their role. [Software: C → F1:C, F2:C]*
- UAV telemetry:
- *Spoofing: Adversaries fabricate telemetry [UAV telemetry: C → F2:C]*
- *Denial of service: Adversaries jam telemetry, preventing UAV tracking. [UAV telemetry: C → F2:C]*
- Updates to delivery progress:
- *Tampering: Adversaries modify delivery updates. [Updates to delivery progress: C → F2:C]*
- *Repudiation: There is no auditing for personnel who updated the delivery progress. [Updates to delivery progress: C → F2:C]*
- *Denial of service: There are delayed updates, hindering prompt updates [Updates to delivery progress: D → F2:D]*

Phase 4: Analyse impacts on the capability.

- For each function compromised, analyse impacts on the capability, considering unacceptable conditions specified in Phase 1, Process (iv).
- *All threats that compromise the crucial assets have resulted in compromised/degraded functions, e.g., C → F1:C, C → F2:C, C → F1:D, or C → F2:D.*
- *For simplicity, threats are abstracted, but every threat identified can be analysed for the impact on the capability, e.g.,*
- F1 compromised [F1:C], e.g., can result in threat actors masquerading as genuine users, resulting in UC2 (compromised capability).
- F1 degraded [F1:D], e.g., can result in personnel not being able to authenticate, resulting in UC1 (compromised capability).
- F2 compromised [F2:C], e.g., can result in delivery information being disclosed, resulting in UC1/UC2 (compromised capability).
- F2 degraded [F2:D] e.g., can result in UC1 or UC2 (compromised capability).

Our case study shows how our proposed framework can be applied to comprehensively analyse defence capabilities: in Phase 1, we defined the capability (e.g., the ability to track the UAV), functions that enable the capability (e.g., software should allow tracking), and unacceptable compromises (e.g., death of military personnel); in Phase 2, we identified TEPIDOIL assets required for functions to be executed (e.g., UAV telemetry); in Phase 3, we used STRIDE to identify threats to assets (e.g., adversary jamming of UAV telemetry) and the impact on functions (e.g., military personnel can no longer view accurate delivery information); and in Phase 4, we analysed how compromised functions can lead to unacceptable consequences (e.g., the death of military personnel) that compromise the broader capability.

6. Evaluation and Discussion

Let us discuss the additional features that our proposed framework provides compared with using threat models alone (see Table 2 for a summary). To begin, STRIDE, OCTAVE, and CKC are not contextualised with respect to what a capability aims to achieve. Hence, they primarily elicit threats and deconstruct attacks, without a strong link to capabilities. Our framework enables all analyses to be linked to the functions a capability aims to achieve. In addition, STRIDE, OCTAVE, and CKC provide limited guidance on what must be maintained for capabilities to be effective (though OCTAVE does so in part with respect to organisational security objectives). In our framework, we explicitly prompt analysts to define unacceptable compromises, thereby enabling analysis of the impacts of threats on the broader capability. Furthermore, STRIDE, OCTAVE, and CKC do not explicitly focus on analysing TEPIDOIL components, which is required for a comprehensive analysis of military capabilities. This can

result in analysts missing crucial threats and thus creating threat models that can only partially represent a capability (creating blind spots). In our framework, we explicitly prompt analysts to identify the TEPIDOIL assets (people, processes, and technologies) that enable a capability before threat analysis. Moreover, STRIDE, OCTAVE, and CKC do not explicitly prompt analysts to delineate failure modes in assets and functions that enable capabilities. Our framework is designed to prompt analysts to specify failure modes for both assets and functions, and to explain how a failure in an asset can cause a failure in a function, thereby compromising a capability.

Table 2: Comparison of features. ✕ = not addressed; ◑ = partially addressed; ✓ = addressed

Aspect	STRIDE	OCTAVE	CKC	STRIDE/OCTAVE/CKC + Universal Defence Framework
Explicit definitions of the capability underpin threat analysis.	✕	◑	✕	✓
Analyses the impact of threats on the capability based on defined unacceptable compromises.	✕	◑	✕	✓
Explicit focus on analysing TEPIDOIL components (often found in capabilities).	✕	✕	✕	✓
Explicit definitions of failure modes for assets and functions.	✕	◑	✕	✓

Integrating TEPIDOIL components into our framework can broaden the perspective applied to threat modelling. That broader view is often crucial when analysing threats in complex, integrated systems, as found in the defence sector. Table 3 shows that our proposed framework serves as a standardised extension that integrates threat models to comprehensively analyse capabilities.

Table 3: Summary. ✕ = not typically captured; ◑ = requires explicit consideration; ✓ = captured by default

Model	STRIDE/OCTAVE/CKC + Universal Defence Framework
Training	✓
Equipment	✓
Personnel	✓
Information	✓
Doctrine and Concepts	✓
Organisation	✓
Infrastructure	✓
Logistics	✓

Our work has two main limitations. First, we did not address the specific TEPIDOIL limitations of STRIDE, OCTAVE, and CKC identified in Section 2 by extending any specific model. However, our framework has a broad scope for the types of threat models that can be integrated, as it is generally applicable. Second, our work presents a case study using STRIDE but does not address how to resolve conflicts between processes already provided in threat models (e.g., OCTAVE) and those in our framework.

7. Conclusion and Future Work

In this paper, we address a key problem in threat modelling in defence environments. In particular, civilian threat models are widely used in defence; however, they typically do not provide the breadth required to analyse military capabilities that have a broad attack surface. In our paper, we evaluated state-of-the-art threat models used in both defence and civilian contexts to identify gaps in their ability to capture defence aspects. Our comparative analysis, using the TEPIDOIL framework for defence capabilities, found that threat models were unable to capture TEPIDOIL aspects. To address this problem, we introduced the *Universal Defence Framework*, a novel approach that enables existing threat models to conduct comprehensive, rigorous analyses of

capabilities. We presented a case study to demonstrate how our framework can be applied and have evaluated it against the use of threat models alone. Furthermore, our evaluation highlighted that explicit prompting within our framework to define TEPIDOIL assets (people, processes, and technologies) provides the broader view required when analysing threats in complex, integrated systems, as typically found in the defence sector.

An interesting research direction is to develop a prioritisation scheme to help select threats that cause the greatest harm to the capability. This prioritisation scheme can specify how to prioritise assets prior to the threat analysis. To broaden the scope of application, we plan to deploy the proposed approach in a more in-depth case study, including the use of OCTAVE and CKC. Another interesting future work is to collect feedback from defence stakeholders on the usability of our framework. Furthermore, we plan to develop guidance on resolving conflicts arising from integrating multiple threat models into our *Universal Defence Framework*.

Acknowledgements

This work was supported by the EPSRC and MOD Centre for Doctoral Training in Complex Integrated Systems for Defence and Security [EP/Y034848/1]. Erisa Karafili was partially supported by the UKRI HetMEPS project (UKRI257).

Ethics declaration: Ethics clearance was not required for this research.

AI declaration: Grammarly was used for checking spelling/grammar errors.

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Cyber Early Warning System on Security Operations Center

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Abstract: An Early Warning System (EWS) is a framework or collection of tools developed to identify and deliver timely alerts about potential threats, risks, or adverse events across various situations. Its main objective is to support decision-makers in implementing preventive actions that reduce the impact of possible hazards or disasters, thereby protecting lives and resources. Modern digital society depends on the interconnection and collaboration of essential infrastructures, which require adequate situational awareness (SA) to manage growing cyber risks. In the cyber domain, a key priority is safeguarding critical infrastructure (CI) against threats amid a surge in both the frequency and sophistication of cyberattacks. These evolving attacks allow adversaries to disrupt vital services remotely, creating significant risks and uncertainty in the absence of adequate SA and thus protection. The Cyber Early Warning System (CEWS) is essential within the cyber domain, integrating for example artificial intelligence (AI) to introduce a new approach to early warning capabilities. As a component of the cyber threat intelligence (CTI) process, CEWS offers an innovative methodological framework for navigating and operating in today's complex cyber environment. In large networked systems, CEWS gathers and correlates heterogeneous information from multiple sources, delivering timely and actionable insights to help prevent or mitigate potential risks by supporting effectively an organization's SA. Security Operations Center (SOC) is a key element to protect an organization's digital assets by continuously monitoring, detecting, investigating, and responding to cyber threats. The SOC is an essential part of an organization's SA and risk management, as it particularly supports risk identification, monitoring, and control by continuously providing information to detect, assess, and manage cybersecurity risks. This paper highlights the importance of collaborating with the Cyber Early Warning System and the Security Operations Center.

Keywords: Organization, Cyber early warning, Security operations center, Risks assessment

1. Introduction

Modern society depends on the coordinated, reliable performance of many critical infrastructure (CI) organizations, whose collective success increasingly relies on a resilient national system-of-systems. Because today's digital environment is tightly interconnected, organizations must maintain real-time situational awareness (SA) of cyber threats to manage growing risks to their assets. As cyberattacks become more frequent and sophisticated, protecting essential organizations has become a top priority. These evolving threats allow adversaries to remotely disrupt vital services, heightening risks and uncertainty, especially when organizations lack sufficient SA and the safeguards needed to support effective risk assessment.

Throughout history, societies have developed early warning systems to detect and respond to threats. Prior to modern technology, cities relied on external outposts to identify and signal approaching dangers. Today, states employ advanced surveillance systems, including radar and satellite technologies, to continuously monitor their borders and environments. These systems enable timely detection of emerging threats and facilitate appropriate defensive responses. An Early Warning System (EWS) refers to a set of tools or mechanisms designed to identify potential risks and provide timely information, supporting decision-makers in implementing preventive measures to mitigate impacts and protect lives and resources (Ultimaco, 2025).

Today a Cyber Early Warning System (CEWS) is needed in the context of the cyber domain. It incorporates artificial intelligence elements to enable a new approach to early warning capability. CEWS is part of the cyber threat intelligence process and provides a new methodological framework for operating in a complex cyber environment.

According to the EU NIS2 Directive, "essential and important entities should take appropriate and proportionate technical, operational and organizational measures to manage the risks posed to the security of network and information systems which those entities use for their operations or for the provision of their services, and to prevent or minimize the impact of incidents on recipients of their services and on other services" (EU, 2023). Identifying cyberattacks are increasingly difficult, and the fast-changing nature of cyber environment demands both agility and preparedness for unforeseen threats. While risk assessment methods can address most known and partially known events, completely unknown threats require alternative approaches.

The definition of the research problem emphasizes the challenges of proactively identifying unknown risks that threaten an organization's cybersecurity and leveraging that information within operational processes. In this sense, CEWS is needed to develop an extended approach for providing better CTI to support an organization's operational purposes in a complex cyber environment. It is an important threat-intelligence process, particularly for identifying unknown threats and enhancing situational awareness in organizational risk-assessment activities. In many cases, these unknown threats are associated with dark-web entities.

Threats are characterized by the motivation and capabilities of threat actors. For example, such attributes are not directly observable within traditional risk assessment processes, particularly in environments such as the dark web. This information can, however, be inferred from multiple sources using CEWS and by leveraging advanced technologies, such as Artificial Intelligence (AI). The aim of this study is to evaluate the applicability of such information across different stages of the Security Operations Center (SOC) process, and thereby as part of an organization's overall risk assessment.

SOC forms the operational core of an organization's cyber defense capability. It is mainly reactive element, because its purpose is to detect, investigate, and respond to security incidents A SOC is more than just a 'technical monitoring center'; it is an integral part of an organization's real-time situation awareness tool and part of overall risk management strategy. It plays a key role in two main areas: identifying and monitoring risks and managing and responding to them effectively. In this role, the SOC relies on relevant CI to guide its actions. An effective CEWS is a key element in building that awareness and, consequently, an integral part of the organization's overall robust risk management process. This paper outlines the structural domains of SOC, from strategic steering to proactive prevention, describing how each contributes to the overall life cycle of threat management and operational assurance. The model presented here is designed to be framework-agnostic, scalable, and suitable as a foundation for further research and capability development.

In this paper, we examine the importance of a Cyber Early Warning System (CEWS) as part of Security Operations Center (SOC) operations. The paper emphasizes the importance of CEWS data for the SOC process at different stages in order to manage unknown risks proactively. Technically, CEWS data can be integrated with the SOC's Security Information and Event Management (SIEM) system. The research framework outlines the structure of risk categorization, while the empirical part focuses on the SOC process. The main question is:

'What are the key elements for the cooperation between CEWS and SOC in risks identification?"

2. Cyber Security Situational Awareness

Cybersecurity situational awareness is the real-time understanding of the digital environment, including emerging threats, vulnerabilities, and the potential impact of attacks, to enable timely and effective responses. It involves perceiving events, comprehending their significance, and projecting potential future scenarios. Achieving this requires robust data collection, advanced analytics, and effective information sharing.

There are three key components to creating a situational picture: (Endsley, 1995)

- Perception of the elements in the environment
- *The goal is to perceive the status, attributes, and dynamics of relevant elements in the environment.*
- Comprehension of the situation
- *This involves a synthesis of elements through the processes of pattern recognition, interpretation, and evaluation.*
- Projection of future status
- *This involves the ability to project the future actions of the elements in the environment.*

In his article "Flow Analytics for Cyber Situational Awareness", Sid Faber considers measures to develop situational awareness in both public and private organizations to be among the most significant near-term objectives for improving cybersecurity. Faber recommends applying the framework developed by Endsley to the monitoring requirements of the cyber operational environment. (Faber, 2015)

3. Risk Categorization as a Research Framework

Effective risk assessment requires systematically collecting and analyzing data while accounting for evolving threats and vulnerabilities. It helps raise awareness, prioritize early warning systems, and guide disaster prevention and response.

Risk knowledge depends on an up-to-date understanding of the cyber environment, including current events and changing threat actors. Since these changes happen quickly, maintaining continuous situational awareness is essential.

Threats can be categorized as immediate (e.g., ongoing cyberattacks on critical infrastructure) or long-term (e.g., geopolitical risks). Managing cyber risk relies on accurate awareness of risks and impacts. While more information improves risk management, unknown risks ("unknown unknowns") remain difficult to predict and are often outside traditional risk planning.

Figure 1 shows a schematic structure of risk categorization. In this table, the model categorizes events by "identification" and "accuracy of knowledge or certainty". (Kim, 2012, mod)

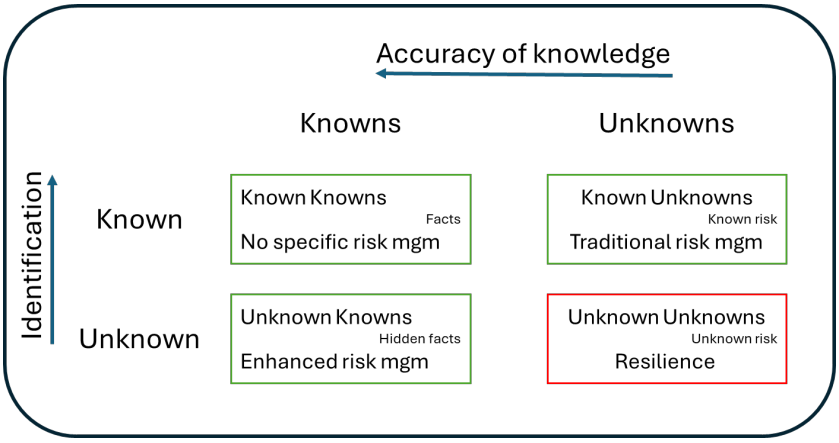


Figure 1: Schematic structure of modified risk categorization

The first three categories of events (known knowns, known unknowns, and unknown knowns) can be addressed through established risk assessment methods and processes. However, completely unknown possibilities require a different approach. To address these, organizations must enhance the overall resilience of their business operations, for example by implementing a Cyber Early Warning System (CEWS) integrated with Security Operations Center (SOC) activities.

4. Early Warning System

Early warning systems (EWS) are essential for example climate action because they provide timely alerts about hazards such as floods, droughts, and wildfires, helping save lives and reduce damage. Despite global progress, challenges like limited funding, data gaps, and communication issues remain, requiring continued cooperation. For long-term effectiveness, these systems must be continuously maintained and improved. The Third International Conference on Early Warning (2006) produced a practical checklist under the Hyogo Framework for action, outlining four key components of effective, people-centered early warning systems to help governments and communities strengthen disaster risk reduction (Figure 2). (ISDR, 2006)

EWS is a key tool that alert communities to hazards, giving time to prepare. They must be adaptable, regularly updated, and upgraded. Using tech like machine learning, data analytics, and advanced environmental monitoring improves warning accuracy and speed. Ongoing maintenance and enhancements are essential for EWS to remain effective and sustainable. (Sakalouskaya, 2024)



Figure 2: Four key elements of an early warning system

An effective EWS requires timely, clear, and unambiguous communication of information, while accounting for recipients' capacity to interpret and act on alerts. Warnings must be accurate and actionable, with thresholds calibrated to avoid both alert fatigue and insufficient notification. Additionally, information should be tailored to different decision-making levels.

For early warnings to support system defense, recipients must have predefined procedures, methods, and automation in place to process alerts efficiently. They must also understand EWS's operational logic, terminology, and resources, and be able to critically apply its outputs to protect the system.

In cyberdomain, Cyber Early Warning System's (CEWS) main focus is to give key information to decision makers and security teams about emerging threats before they happen. By having that information and using it appropriately in the decision-making process, it is possible to prevent the oncoming attacks at the early stage. EWS in cyber domain is a system or prosess of collecting and analyzing data from all layers of internet, surface web, deep web and dark web. By collecting and analysing the data it is possible to gather cyber threat information (CTI) of emerging cyber threats. By getting information about emerging cyber threats, it is possible to start preventive measures to defend against attacks before they reach the protected system or even occur in first place. CEWS is situated to work before attack triggers traditional indicators like Indicator of Compromise (IoC). Those early signals can be for example data found from data leaks, new tactics, techniques, and procedures (TTP's) of threat actors, new vulnerability in the system, device or protocol in use, discussions about protected organization in various darkforums, geopolitical events, and for example attacks occurring in the same region, operating sector, organizations supply chain, or for example against same field of political thinking.

Regarding the future development of CEWS, the primary focus will be on identifying an appropriate baseline model for performance evaluation and on developing an automated method to determine the date when a cyber threat becomes publicly known. Additionally, the method will undergo continuous refinement to enable the generation of more detailed and informative alerts. Future iterations will also incorporate a Natural Language Processing (NLP) component aimed at extracting relevant knowledge and insights from network posts that reference the identified terms. (Sapienza & al., 2017)

By implementing automating technologies and methods such as Large Language Models (LLMs), Machine Learning (ML) and Natural Language Processing (NLP) to CEWS, it is possible to utilize the enormous amount of information that internet provides in a rapidly changing environment. It is not possible to go through this information manually and find key information about early warning signals from multiple large scaling sources. In Figure 2 we show the flowchart from the initial sources of information to the cyber early warning signal and until receiving and reacting to that information.

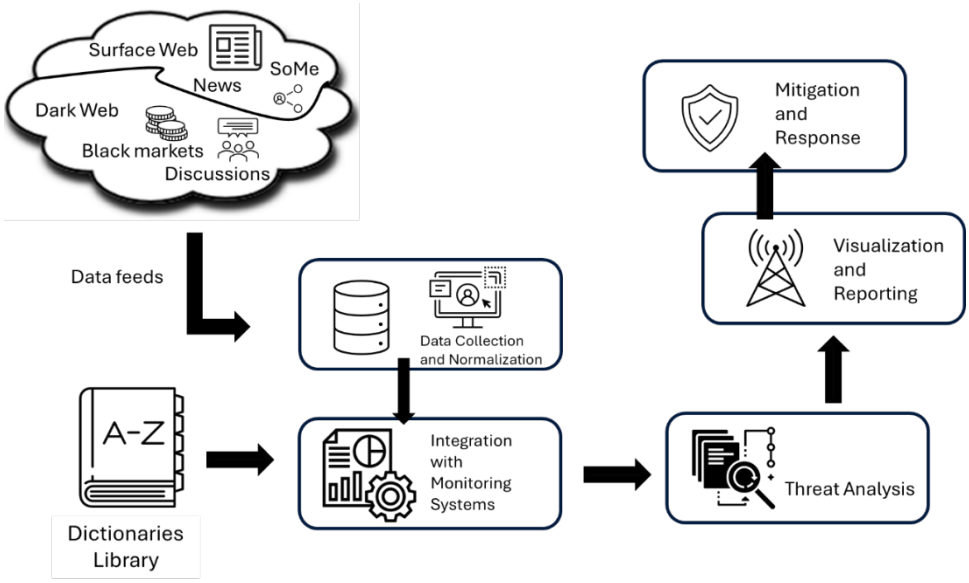


Figure 3: Cyber Early Warning System (CEWS)

Process starts with the dataset. There are enormous amounts of data that can be collected from different layers of internet. Data consists of, for example Surface Web's different news pages and social media sites or Dark Web's different black markets and discussion forums. The data is then collected and normalized and added to monitoring system. According to the needs of the operating environment, various dictionary-like filters are defined, which are used to collect essential information from the data for analysis. The material that passes through the filters is analysed and various risk assessments are made based on the analysis. This information is compiled into an easy-to-understand report. Based on that report defensive measures can be adjusted, and risks can be mitigated.

5. Cyber-physical Environment

The cyber-physical environment combines physical reality and digital technologies through various networking methods. The most extensive and comprehensive solution is the internet. With internet networking solutions it is possible to connect physical processing tools to systems anywhere in the world with internet connectivity.

The Internet consists of three different layers: the surface web, the deep web, and the dark web. Each of these has its own role and characteristics with the content and purpose of the network (Lehto & Koskimäki, 2025). This knowledge of the different levels of the network is important, since the Cyber Early Warning System (CEWS) model, collects data from these different levels of the network.

Surface Web

The surface web, i.e. the visible web, is the top layer of the internet that can be accessed using regular web browsers (Khera, 2020). The surface web is the part of the internet that is openly available and easily accessible to all internet users. It is indexed by search engines and easily searchable through various search engines. Using surface web with default settings and browsers, without for example VPNs, leave trace from user, for example users IP-address and cookies collected by websites and internet services. (Varma, 2018)

Deep Web

Although the deep web may seem obscure, people use it constantly. Activities like email, private messaging, online banking, and accessing subscriber-only news all rely on it. (Vienažindytė, 2021) The deep web consists of online content that search engines cannot index, such as internal organizational databases, paywalled material, dynamically generated pages, and content accessible only through a site's own search tools. (Hatta, 2020) Estimates over the years have shown that the deep web is vastly larger than the surface web, making up most of all online information. Because the internet contains an enormous and ever-changing volume of data, the exact proportion between the surface web and deep web cannot be precisely measured, but most online content belongs to the deep web. (Finklea, 2017)

Dark Web

The dark web is a hidden section of the internet that cannot be accessed with standard surface web browsers. It enables users to remain almost entirely anonymous by encrypting data and sending it through multiple network nodes. In practice, a dark web user's traffic is routed through the network terminals of many other users, making it extremely difficult or impossible to identify the original source of the network traffic. This layered routing system is known as the "onion network," reflecting its multiple levels of encryption. The strong anonymity it offers draws people who want to keep their activities concealed. In the first hand, dark web was used by journalists and freedom activists of the authoritarian states. The dark web is nowadays known for its illegal marketplaces, the distribution of harmful or forbidden content, cybercriminal and espionage networks among other illicit activities. (Chertoff & Simon, 2015)

6. Security Operations Center

This chapter describes the core structural domains of a Security Operations Center (SOC), ranging from strategic oversight to proactive threat prevention, and explains how each domain supports the full lifecycle of threat management and operational assurance. The proposed process model is framework-agnostic, scalable, and intended to serve as a foundation for future research and capability development. A SOC forms the operational core of an organization's cyber defense capability. Its purpose is to detect, investigate, and respond to security incidents while continuously improving the organization's situational awareness and resilience. SOC functionality includes both process and technical components. According to our research, the appropriate structural process elements are as follows:

Steering

Steering function defines the mechanisms through which a Security Operations Center (SOC) aligns its activities with an organization's overarching risk management objectives. Effective steering is characterized by a deliberate balance between situational awareness and operational performance. Fundamentally, steering governs the allocation and coordination of the three core resources underpinning any security capability: people, processes, and tools. Through this governance, steering enables the transformation of the SOC from a primarily reactive technical function into a structured, managed capability that contributes directly to the organization's resilience and its strategic risk posture.

Visibility

Visibility constitutes the foundational element of all Security Operations Center (SOC) activities. It reflects the SOC's capacity to observe, understand, collect and store event information occurring within an organization's digital environment. This capability is fundamentally data-driven, relying on the continuous and voluminous streams of telemetry generated by organizational assets, systems, and services during normal operation. SOC visibility is derived from three primary sources. First, transactional data, which is obtained from telemetry and event logs, provides detailed records of system and user activity. Second, threat intelligence supplies awareness of external threats and adversarial behaviours relevant to the organization. Third, contextual information describes the organization's assets, configurations, and established patterns of normal behaviour, enabling meaningful interpretation of observed events. Collectively, these sources of visibility support both detection and decision-making within the SOC. Visibility functions as the analytical lens through which the SOC interprets its operational environment and identifies indicators of compromise. In the absence of sufficient visibility, neither proactive threat hunting nor effective reactive defence can be achieved.

Detection

Detection serves as the mechanism through which visibility is transformed into actionable security intelligence. It defines how a Security Operations Center (SOC) identifies potential security anomalies within an organization's monitored environment. Detection techniques range from basic anomaly-based alerting to advanced, context-aware rules that correlate multiple events across diverse data sources. Enrichment processes further enhance detection by adding contextual information to raw event data, thereby improving analytical accuracy and reducing the incidence of false positives. The output of the detection function is a set of findings that merit deeper examination during the investigation phase. The quality of these findings directly influences the overall efficiency of the SOC, as well-calibrated detection mechanisms reduce analytical noise and enable faster, more confident response actions. In this regard, detection constitutes both a technical and analytical capability, converting raw telemetry into meaningful security awareness.

Investigation

Investigation is the systematic process of validating, contextualizing, and interpreting detected anomalies. Its primary objective is to ascertain whether an event constitutes a genuine threat and to determine the appropriate course of action. Effective investigation relies on the capacity to correlate information from diverse data sources, employ suitable analytical tools, and integrate both automated processes and experts' analysis.

The investigation process aims to construct a structured understanding of:

- The nature and intent of the identified threat or anomaly
- The assets and systems affected
- The behavioral of the anomaly to these assets
- The potential or necessary remediation measures

Ultimately, investigation serves as the mechanism by which raw data is transformed into actionable knowledge. It converts signals into insight and insight into informed decisions, functioning as the pivotal link between detection and response.

React

The react function is responsible for addressing security events that require immediate containment or mitigation. It demonstrates the Security Operations Center's (SOC) ability to respond swiftly and decisively once a validated threat is identified. Typical reactive measures include isolating affected systems, blocking malicious connections, and initiating predefined remediation protocols. The effectiveness of the reaction phase is measured by its ability to limit damage and prevent escalation. By minimizing the interval between detection and containment, the SOC ensures operational continuity and reduces potential business impact.

Respond and Recover

The respond and recover domain encompasses structured activities aimed at restoring normal operations following an incident. While reaction primarily focuses on immediate containment, the response and recovery phase addresses the broader processes of resolution, remediation, and organizational learning. This phase incorporates coordinated incident response, forensic analysis, business continuity measures, and executing recovery, based on established recovery plans. Collectively, these functions ensure that technical restoration, organizational communication, and procedural follow-up are executed in a controlled, systematic, and well-documented manner.

Prevent

The prevention function is primarily concerned with minimizing exposure to prospective threats by mitigating vulnerabilities identified through prior Security Operations Center (SOC) processes. Preventive measures may encompass patch and configuration management, architectural modifications, user awareness programs, and the automation of system hardening procedures. These activities aim to reduce the attack surface and remediate known vulnerabilities before they can be exploited. By systematically leveraging SOC findings and operational observations, the prevention function effectively closes the feedback loop, ensuring that each security incident informs strategies that enhance the overall resilience and security posture of the organization.

Co-operation on Cyber Early Warning System and the Security Operations Center

In this chapter, CEWS data are linked to the empirically defined SOC process of the study. Drawing on the study's theoretical framework, the different phases of the SOC process outlined above benefit from early warning information, thereby facilitating proactive risk identification in so-called 'unknown unknown' situations.

Cyber Early Warning System (CEWS) is a value-adding piece to a workflow of Security Operation Center (SOC). In SOC environment the earlier coming attack is detected and the earlier it is mitigated, less resources are consumed at the defense against those attacks becomes. It is therefore important to prevent these attacks from materializing in first place. Any help for preventing the attack firsthand helps the workload of SOC. There should not be any overlapping between CEWS and SOC tasks, but merely CEWS should increase the SOC ability to proactively defend against different kinds of cyber-attacks. That is why CEWS must be integrated into each SOC environment in a way that is suitable for it and perform tasks that support the operation of the SOC, not to replace its different functions.

CEWS information can enhance every stage of the SOC process. Steering involves directing the SOC's capabilities at both operational and strategic levels, guided by CEWS insights. This information helps align SOC activities with

the evolving threat landscape. With CEWS information SOC can have more information on the development of the threat field and the prevailing state in the cyber operations environment. In this context, early warning information is wider scoped and aggregated information about actors and their TTP's in the cyber environment, ongoing phenomena, development trajectories of different subjects and for example early-stage warnings about dark market products, datasets or attack orders.

CEWS shapes the SOC's scope of visibility by prioritizing monitoring on critical areas or assets, while also complementing the SOC's internal threat intelligence. CEWS would increase the visibility of the SOC by producing cyber situational awareness and cyber threat intelligence outside the SOC environment. CEWS could also bring together situational awareness produced by itself, industries and experts in a similar way to, for example, sector-specific information sharing and collaboration network ISAC (Information Sharing and Analysis Center).

For detection, CEWS provides indicators of tactics, techniques, and procedures (TTPs), allowing detection rules to be fine-tuned for greater sensitivity and alignment with operational processes.

Investigation enables CEWS to remain viable despite imperfect accuracy by providing process-driven validation of weak signals. During this phase of the process, CEWS clarifies, for instance, the tools and methods commonly used by specific threat actors. In security analysis, the information is further enriched to anticipate potential developments.

CEWS also drives capability development, offering advanced insights that help evolve SOC operating models and response practices.

In the respond, recovery and preventing phases, CEWS enables organizations to effectively practice receiving and acting on early warning information. The Prevent phase emphasizes proactive measures, such as segmentation and other controls, where early CEWS alerts allow preventive actions that can stop attacks before they occur.

Although an organization's SOC primarily concentrates on operational and tactical activities to maintain cybersecurity situational awareness, an early warning system can also deliver strategic-level insights that support decision-making, particularly by enabling a deeper understanding of trend-based threat intelligence. A CEWS can direct SOC analysts' attention to specific areas of concern when it identifies correlations between the defended network and ongoing attack campaigns targeting a particular industry, supply chain, or similar context. Furthermore, a CEWS can help the SOC adapt its sensors and detection mechanisms to the tactics, techniques, and procedures of malicious actors, increasing sensitivity to relevant threats and improving the ability to detect and defend against such activities.

7. Conclusion

The cyber-physical environment integrates physical systems with digital technologies through networking, most notably the internet, which enables global connectivity of physical and digital systems. The internet is divided into the surface web, deep web, and dark web, each serving different purposes. Understanding these layers is important, as the Cyber Early Warning System (CEWS) collects data from all three.

It is important that an organization's situational awareness includes identifying critical digital elements within the environment, interpreting their significance, and understanding how they interrelate in the context of information security. It also involves anticipating future conditions and potential threats based on current data, enabling proactive rather than reactive responses. In this context, CEWS serves as a proactive cybersecurity capability designed to detect threats before, or at the earliest stages of an attack, allowing organizations to respond before substantial harm occurs. Unlike traditional security tools that generate alerts only once an attack is underway, CEWS focuses on identifying early indicators and conditions that could lead to future attacks. As a result, it is a vital component of an organization's Security Operations Center (SOC), enhancing situational awareness and supporting more effective risk assessment, particularly in complex and highly uncertain "unknown-unknown" cyber environments.

CEWS enhances all stages of the SOC process by aligning operations with the evolving threat landscape. The following phases of the SOC process have been identified: Steering, Visibility, Detection, Investigation, React, and Respond & Recover. SOC guides strategic and operational steering, focuses visibility on critical assets, and strengthens threat intelligence. CEWS improves detection through refined tactics, techniques, and procedures-based indicators, supports investigations by clarifying threat actor behaviours, and enriches security analysis to anticipate future risks. It also drives capability development and enables proactive response, recovery, and prevention by supporting early warning–driven actions that can stop attacks before they occur.

The SOC process of the study can be conceptualized as comprising the aforementioned components, each with a distinct role. These roles correspond to the "key elements" identified in the research question and are essential for supporting the use of CEWS information within the context defined by the study's framework.

In future work, our CEWS research team will focus on developing its early warning features. By integrating automated technologies such as Large Language Models (LLMs), Machine Learning (ML), and Natural Language Processing (NLP), CEWS can better leverage the vast amount of internet data in a rapidly changing environment. Manual analysis of this large-scale, multi-source information is not feasible for identifying early warning signals.

Ethics Statement: Ethical clearance was not required for the research

AI Statement: Ai tools have not been used in this research

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A Capability-based Approach to Evaluate and Mitigate Identified Cybersecurity Gaps in Critical Infrastructures

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Abstract: Recently, the number of cyber threats has shown a rapid increase all over the world. Different public and private infrastructure organisations of a society have varying capabilities and resources to address these threats and protect themselves from their harmful impact. Among these sectors, critical infrastructures are most vulnerable as they hold valuable data, the protection of which is both crucial and expected from a societal perspective. As data protection relies on different capabilities, it is vital to understand what a specific capability a particular infrastructure sector and an individual company will need and can achieve. There is a wealth of high-quality information available on the best practices of cybersecurity, for example in frameworks like the ISO series and the National Institute of Standards and Technology Cybersecurity Framework (CSF) 2.0. These frameworks contain actions that are generally considered beneficial for any company but provide limited guidance on how individual controls translate into actionable capabilities in a specific organisational context. However, very few companies have the resources to implement all the controls presented in these frameworks to reach the highest maturity levels possible in cybersecurity. In these situations, it is crucial to maximise the benefits gained from any chosen action. In this paper, we investigate how a capability-based assessment model, developed originally for the defence domain, can be adapted to evaluate cybersecurity capabilities in the context of critical infrastructure and explore its performance when applied to a healthcare sector company. This model assesses capability gaps by comparing the current state with a target level capability and applies this approach to the cybersecurity context of a healthcare organisation. The general aim of our study is to support simpler and more effective decision-making when selecting the next cybersecurity upgrade or systemic improvement. In future research, we plan to extend this model to other critical infrastructure sectors and compare its performance and generalisability to these sectors.

Keywords: Cyber risk analysis, Cybersecurity capability gap, Decision support, Healthcare cybersecurity, Control action prioritisation

1. Introduction

In recent years cyber threats have increased both in volume and complexity. Rapid digitalisation across organisations has expanded the use of interconnected information systems, including cloud-based services, which in turn have broadened the landscape of cyber threats. While digitalisation enables greater efficiency, flexibility, and scalability, it also introduces new dependencies and potential vulnerabilities that organisations must manage. Yet these organisations across infrastructure sectors differ significantly in terms of their risk exposure and their capabilities to implement effective cybersecurity controls. Critical infrastructure organisations are no exception, for example, a healthcare organisation and a municipal water utility may both be classified as critical infrastructure, but they face distinct cybersecurity challenges and operational requirements. What such organisations have in common is that cybersecurity is not limited to technical functions alone but affects the entire organisation and requires informed decision-making beyond the IT domain.

To address these challenges, decision-makers have access to a wide range of high-quality guidance on potential actions that an organisation can take to improve its cybersecurity preparedness. This guidance is typically provided in the form of cybersecurity frameworks. Widely adopted frameworks include, for example, the ISO/IEC 27000 series and the National Institute of Standards and Technology CSF (National Institute of Standards and Technology, 2024). While these frameworks contain highly valuable guidance, their scope and level of detail make practical applications challenging. This is particularly the case for organisations that lack dedicated IT expertise or specialised IT teams, such as small and medium-sized enterprises (SMEs), where prioritising appropriate actions often becomes difficult to realise (El-Hajj and Mirza, 2024).

Within critical infrastructure sectors, healthcare is frequently targeted by cyber actors (ENISA, 2023). This is partly due to factors such as dynamic operational environment and frequent staff turnover. One major reason is also the fact that the primary function of the healthcare sector is to deliver services that support individual well-being and safety rather than cybersecurity. From a cybersecurity point of view, the healthcare industry faces multiple challenges such as the data availability requirements, as critical systems must operate

continuously. At the same time, sensitive patient data must be strongly protected against unauthorised access. Different laws and regulations affect the healthcare industry as well; one example is the General Data Protection Regulation (GDPR) and the national law about cybersecurity derived from the NIS2 directive. Social and healthcare organisations represent a critical infrastructure context in which capability gaps in cybersecurity can have significant operational consequences, while available resources for systematic improvements are often limited (Kruse et al., 2017).

Despite the demands outlined above, many organisations struggle to meet regulatory and recommended baselines of cybersecurity. This combination of limited resources, regulatory requirements, and insufficient current capabilities highlights the need for structured approach to cybersecurity capability assessment and prioritisation. Capability-oriented approaches have previously been applied to cybersecurity assessment using probabilistic and structural models, particularly to support reasoning about system-level security properties rather than individual controls (Sommestad et al., 2013). In this paper, we address these challenges by adopting a capability-based approach to support cybersecurity decision-making in resource-constrained organisational contexts.

2. Method

In this study, we apply a capability-based evaluation approach (Kuikka and Peltotalo, 2022) to assess cybersecurity within an organisation's IT department to analyse its ability to deliver cybersecurity outcomes that support organisational operations, data protection, and service continuity. Cybersecurity is treated as a socio-technical capability that emerges from the combined effect of technical, organisational, and operational measures. Our approach is based on a capability-gap formulation that structures expert judgement and supports prioritisation of cybersecurity improvements in resource-constrained environments.

Cybersecurity capability is decomposed into a finite set of sub-capabilities indexed by j, each of which is evaluated relative to a defined target level. The capability gap of sub-capability j is denoted as $g_j \in [-1, 1]$, where the sign and magnitude of g_j expresses the relationship between the current state and the target level. Positive values ($g_j > 0$) indicate that the current capability is below the target level, while negative value ($g_j < 0$) indicates that the current capability exceeds the target and the value of $g_j = 0$ corresponds to the target level being met. Then the vector of sub-capability gaps is defined as $G = (g_1, g_2, \ldots g_s)$.

In this study, a capability gap is defined as a signed normalised deviation from a predefined target level of a given cybersecurity sub-capability, where positive values indicate insufficient capability and negative values indicate capability exceeding the target. In earlier capability models applied to military contexts (Kuikka and Peltotalo, 2022), importance is implicitly embedded in the definition of capability as the likelihood of mission success. In the cybersecurity context considered in this study, capability is decomposed into multiple sub-capabilities supporting different organisational objectives, requiring the relative importance of achieving target levels to be represented explicitly. To support scenario comparisons, our method distinguishes between the initial capability gap and the capability gap after improvement actions. The initial capability gap of sub-capability j is denoted as g_j^0 and represents the state before any improvement actions are applied. The difference ($g_j^0 - g_j$) represents the reduction in the capability gap achieved through improvement actions.

Improvements in cybersecurity capabilities are characterised as functional enhancement actions rather than as separate technical systems. These actions can include changes to processes, improvements in configurations, updates to policies or procedures, training activities, or enhancements to existing tools and systems. Each improvement action i is assigned a positive weight $b_i > 0$ that reflects its relative importance, and its contribution to sub-capabilities is represented by the coefficient $c_{i,j}$, typically greater than or equal to zero.

Then the contribution of improvement action i to sub-capability j is first combined into a weight $w_{ij} = c_{ij} \cdot b_i$, which is then normalised as $p_{ij} = \frac{w_{ij}}{\Sigma_i w_{ij}}$, representing the relative influence of action i on sub-capability j. The capability gap is then allocated across actions as

$$d_{ij} = g_j \cdot p_{ij}. \quad (1)$$

This proportional decomposition allocates the post-action capability gap across improvement actions according to their relative contribution and ensures conservation of gaps, such that $\sum_i d_{i,j} = g_j$. For strategic decision-making, the overall cybersecurity capability gap after improvement actions is aggregated additively as $\sum_j g_j$. The aggregated gap is used as a comparative indicator for evaluating alternative improvement scenarios rather than as an absolute measure of cybersecurity performance.

Our approach includes also an economic interpretation based on the reduction of the capability gap. Expert-defined reference importance values $I_j \geq 0$ represent the potential consequences of insufficient capability. The expected consequence reduction achieved by improvement actions at the sub-capability level is defined as

$$L_j = \left(g_j^0 - g_j\right) I_j . \quad (2)$$

Reference importance values are defined through an initial expert evaluation and represent the relative consequences of achieving target capability levels within the organisational context. They remain constant across scenarios and are not re-evaluated for each set of improvement actions. Now, the aggregated consequence reduction across all the sub-capabilities is defined as the following sum

$$L = \sum_j \left(g_j^0 - g_j\right) I_j . \quad (3)$$

The initial gap g_j^0 represents the baseline scenario, while alternative scenarios are evaluated based on their ability to reduce positive capability gaps relative to this baseline. Conceptually, consequence-related measures combine normalised signed deviations from the target level with the relative importance of achieving that target, supporting comparison of improvement effectiveness without implying realised or future financial losses.

In addition to the expected consequence reduction, each improvement action is associated with an implementation cost (denoted by E_i) that is the relative effort required to perform functional improvement actions by the organisation and is evaluated independently of the importance and the capability gaps. Here, the notation E_i refers to the implementation effort associated with improvement actions and should not be confused with the importance values I_j, that are defined separately at the sub-capability level. The effort of implementation is evaluated using an ordinal scale with five qualitative categories (Low, Low/Medium, Medium, High, Very High). These categories capture aspects such as personnel workload, organisational effort, process changes, and operational complexity. To enable aggregation and comparative scenario analysis, the ordinal categories are mapped to numerical values on a linear scale. This mapping preserves the relative ordering of cost levels while avoiding assumptions about exact cardinal or monetary differences between categories. The resulting numerical cost values are therefore used as comparative indicators to support scenario evaluation and prioritisation, and they do not imply economic optimisation, precise cost estimation, or financial valuation of cybersecurity improvements.

Throughout the method cybersecurity capability is interpreted as an organisation's assessed ability to reach a defined target level, and all capability gaps represent deviations from this target, while cost and consequence considerations are introduced to support comparative interpretation of improvement scenarios. The method assumes that cybersecurity capability can be represented through a finite set of sub-capabilities and that capability gaps can be expressed as signed normalised deviations from a defined target level. The method is intended for comparative scenario analysis and decision support within IT departments and does not aim to predict cyber incidents, realised losses, or optimal investment portfolios.

3. Critical Infrastructure use Case

This use case study is based on a private healthcare organisation operating across multiple service locations. The organisation provides continuous nursing and care services and processes sensitive health-related data as well as other personally identifiable information. The company does not have a dedicated IT department or a separate cybersecurity unit. Due to the critical nature of its services, the organisation is classified as part of the national critical infrastructure under cybersecurity legislation derived from the EU NIS2 Directive. A significant number of individuals depend on the continuity of the services provided, placing high requirements on both operational resilience and data protection within a resource-constrained organisational setting.

3.1 Risk Register

Prior to this study, the organisation had established an IT risk register to document cybersecurity-related risks in its operating environment. Business risks and IT risks are assessed separately, and the IT risk register serves as the primary input for this use case study. It provides a structured and organisation-specific view of the current cybersecurity situation by identifying areas where existing capabilities are insufficient to manage recognised risks. The risk register categorises risks into strategic, operational, and tactical risks. Strategic risks include threats that could significantly disrupt operations or lead to regulatory intervention, such as reputational damage, compliance failures, or insufficient preparedness for critical system outages. Operational risks relate to disruptions in daily healthcare activities, including system unavailability and limited access to patient information. Tactical risks focus on people, processes, and technologies, such as inadequate access control,

weaknesses in offboarding procedures, delayed security updates, and ageing IT infrastructure. While these categories support structured risk management, individual risks may span multiple levels if left unaddressed over time.

3.2 Controls and Constraints

In this study, controls refer to improvement actions identified in the risk register that aim to mitigate recognised cybersecurity risks. These actions include organisational, procedural, and technical measures. A single control may address multiple risks across different risk categories, and its impact is not binary: implementing a control typically reduces the likelihood and/or impact of a risk rather than eliminating it entirely. Therefore, controls are treated as optional improvement actions of which the organisation must prioritise those that provide the greatest benefit relative to available resources. Controls are linked to cybersecurity capabilities through the risk register, in which identified risks are interpreted as indicators of existing capability gaps. Improvement actions are selected as means to strengthen the organisation's ability to manage these gaps.

Here, the case organisation faces significant constraints related to both financial resources and available expertise, as the IT and cybersecurity activities are largely outsourced and the organisation operates without a dedicated IT or cybersecurity leader. Responsibilities are distributed according to a "multiple hats" principle, limiting systematic evaluation of improvement options and increasing reliance on external service providers. Budgetary constraints further restrict the organisation's ability to implement multiple improvements simultaneously. These constraints directly shape cybersecurity decision-making by limiting which improvement actions are feasible. In practice, prioritisation is unavoidable, and suboptimal investment choices may result in limited improvement despite significant effort. This increases the need for structured decision-support methods that help organisations compare alternative improvement options and assess their potential impact before committing scarce resources.

4. Model and Application

In this use case, the organisation's IT risk register served as the primary input for the capability-based analysis. Identified cybersecurity-related risks were interpreted as indicators of insufficient cybersecurity capability rather than as isolated issues. Each risk was mapped to one or more cybersecurity sub-capabilities reflecting different aspects of cybersecurity, including governance, technical, organisational, and operational dimensions. This mapping was based on expert judgement and considered how each identified risk reflects underlying weaknesses in the organisation's ability to prevent, detect, or respond to cybersecurity-related events. The relationship between risks and cybersecurity capabilities is not one-to-one but many-to-many, meaning that a single risk may be associated with multiple capability gaps, while a single capability gap may contribute to several identified risks. For example, risks related to reputational damage and regulatory consequences were mapped to governance and response-related capabilities, whereas risks associated with data misuse and system disruptions were linked to access control, monitoring, and technical preparedness.

Figure 1 provides an overview of the capability-based evaluation workflow applied in this study. The process starts from the identification of cybersecurity-related risks and the assessment of current organisational capabilities, followed by the definition of improvement actions and the construction of alternative improvement scenarios. The scenarios are then evaluated by comparing their effects on capability gaps, expected consequence reduction, and implementation effort. The workflow is iterative in nature: after scenario comparison, decision-makers may return to earlier phases to refine assumptions, adjust improvement actions, or construct new scenarios before committing to control propositions. This iterative structure supports learning and refinement prior to resource allocation in resource-constrained organisational contexts.

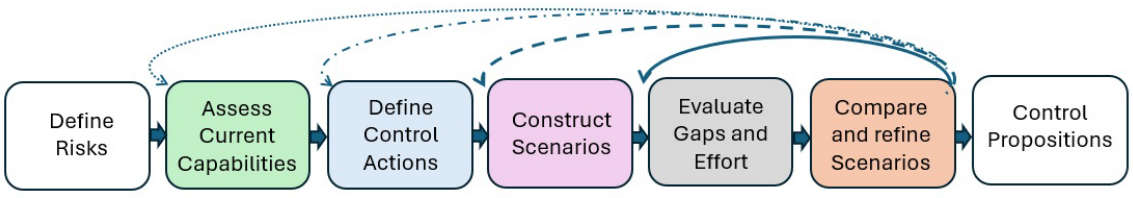


Figure 1: Capability-based workflow for cybersecurity improvement, from defining risks to scenario comparison and iterative refinement prior to control proposition

4.1 Defining Baseline and Capability Gaps

The current state of cybersecurity capability in the case organisation was defined based on the IT risk register at the time of assessment. The risk register was developed through expert judgement in collaboration with key organisational personnel and provides a documented, organisation-specific overview of identified cybersecurity-related risks. As such, it serves as a suitable and transparent starting point for the capability-based evaluation. Defining a target level is necessary to identifying capability gaps. In this case, the target level was defined as a contextually appropriate baseline level of cybersecurity capability, reflecting what can reasonably be expected from an organisation of similar size and resource constraints operating in the healthcare sector. As a fail-safe condition, the baseline level was anchored to regulatory and legal requirements, representing the minimum acceptable level of cybersecurity capability. In addition, best practices were considered only insofar as they were deemed realistic and achievable within the constraints of a small or medium-sized enterprise.

A capability gap is defined as an estimated deviation between the current state and the defined baseline level. Identified risks were interpreted as manifestations of insufficient cybersecurity capability, and the current state was compared against the baseline to determine the magnitude of each capability gap. Therefore, the capability gaps represent relative assessments of organisational capability shortfalls rather than risk probabilities or realised impacts.

The capability gaps are assessed using an asymmetric five-level expert-based scale reflecting deviations from the baseline level. The baseline level is defined as zero, with positive values indicating slight overperformance and negative values indicating increasing degrees of underperformance relative to the baseline. In practice, the scale takes the discrete values {−30, −20, −10, 0, +10}, where 0 represents the baseline level, −10 to −30 represent increasing shortfalls from the baseline, and +10 indicates marginal overperformance. This expert scale uses the opposite sign convention to the analytical formulation in Section 2, where positive values represent capability shortfalls. The discrete scale serves as a practical rating tool for expert assessment and scenario comparison. The resulting gap values are combined with the corresponding importance weights in the aggregation, as illustrated in Figure 2.

Control Actions for Scenario Evaluation	Weak cybersecurity governance	Reputational damage	Supply chain disruptions	Regulatory non-compliance	Poor data oversight	Lack of technical readiness	Data breach or manipulation	Post-attack reputational and regulatory impact	= Risks	Weak cybersecurity governance	Reputational damage	Supply chain disruptions	Regulatory non-compliance	Poor data oversight	Data breach or manipulation	Data breach or manipulation	Post-attack reputational and regulatory impact
				Importance × gap					$I_j g_j$ =	0.080	0.180	0.086	0.087	0.092	0.083	0.088	0.188
Action–capability contribution				Importance					I_j =	0.95	1	0.9	0.95	1	0.9	1	1
	$c_{i,j}$ =			Capability gap					g_i =	8.4 %	18.0 %	9.6 %	9.2 %	9.2 %	9.2 %	8.8 %	18.8 %
Staffing adequacy	25	5	10	0	10	15	10	0	1	3.0 %	2.3 %	3.2 %	0.0 %	1.9 %	2.5 %	1.1 %	0.0 %
Backups	0	0	0	5	5	15	20	0	1	0.0 %	0.0 %	0.0 %	0.9 %	1.0 %	2.5 %	2.2 %	0.0 %
IAM usage	0	0	0	10	5	0	10	0	1	0.0 %	0.0 %	0.0 %	1.8 %	1.0 %	0.0 %	1.1 %	0.0 %
Supply chain	0	5	10	10	0	5	5	0	1	0.0 %	2.3 %	3.2 %	1.8 %	0.0 %	0.8 %	0.6 %	0.0 %
Data encryption	0	0	5	10	10	0	5	0	1	0.0 %	0.0 %	1.6 %	1.8 %	1.9 %	0.0 %	0.6 %	0.0 %
Information security guidance	5	5	0	5	5	5	5	0	1	0.2 %	1.9 %	0.0 %	0.5 %	0.6 %	0.4 %	0.2 %	0.0 %
Cybersecurity training	10	5	0	5	5	5	5	0	1	0.4 %	1.9 %	0.0 %	0.5 %	0.6 %	0.4 %	0.2 %	0.0 %
Crisis communication instructions & exercises	5	15	5	0	0	0	5	15	1	0.2 %	5.6 %	1.2 %	0.0 %	0.0 %	0.0 %	0.2 %	6.9 %
Cybersecurity management model	20	5	0	0	3	5	5	10	1	2.4 %	2.3 %	0.0 %	0.0 %	0.6 %	0.8 %	0.6 %	5.4 %
Monitoring and reporting	5	0	0	5	5	5	10	10	1	0.6 %	0.0 %	0.0 %	0.9 %	1.0 %	0.8 %	1.1 %	5.4 %
Staffing adequacy				Effort/Cost					E_i =	0.6							
Backups										0.6							
IAM usage										0.8	Scenario selection						
Supply chain										1							
Data encryption										0.6							
Information security guidance										0.2	-0.4 %	-0.4 %		-0.4 %	-0.4 %	-0.4 %	-0.4 %	
Cybersecurity training										0.2	-0.8 %	-0.4 %		-0.4 %	-0.4 %	-0.4 %	-0.4 %	
Crisis communication instructions & exercises										0.2	-0.4 %	-1.2 %	-0.4 %				-0.4 %	-1.2 %
Cybersecurity management model										0.4								
Monitoring and reporting										0.6								

Controls

Control actions

Figure 2: Excel-based application implementing the capability-based scenario evaluation method, illustrating the main model variables and their aggregation for comparative scenario analysis

4.2 Linking Improvement Actions to Capability Gaps

Improvement or control actions identified in the risk register are interpreted as measures aimed at addressing identified cybersecurity risks. As defined earlier, risks are understood as insufficient cybersecurity capability. Consequently, reducing a risk implies that one or more underlying capabilities related to that risk have been strengthened. Based on this interpretation, improvement actions are treated as capability-enhancing measures, as their implementation contributes to improving the organisation's ability to prevent, detect, or respond to cybersecurity-related events. Not all improvement actions contribute equally to reducing capability gaps in cybersecurity. Identified risks often consist of multiple dimensions, each of which may require specific actions

to be addressed. As a result, a single risk may be associated with several improvement actions, and the same improvement action may contribute to different risks and capabilities to varying degrees. By the same logic, implementing an improvement action does not necessarily result in uniform capability improvement across all related capability gaps. Even when the same action is applied, its effect on reducing different capability gaps may vary depending on how strongly the action addresses the underlying weaknesses reflected by each risk.

The model we apply here supports decision-making by making differences in the impact of improvement actions explicit. In practice, improvement options are often implicitly treated as equally important, particularly when using traditional risk registers where identified risks are addressed by corresponding control actions without explicitly considering their broader effect on organisational cybersecurity capability. By explicitly linking improvement actions to capability gaps, the model reveals interdependencies between actions and capabilities that may otherwise remain unrecognised. This is particularly relevant in small and medium-sized enterprises, where resource constraints are a well-documented challenge. Under such conditions, the model supports prioritisation by highlighting improvement actions that offer greater capability enhancement relative to the resources invested.

Unlike earlier military capability models, where importance is implicitly embedded in the probability of mission success, cybersecurity capabilities support multiple organisational objectives and therefore require explicit representation of relative importance. The scenario analysis demonstrates that capability-based evaluation can reveal differentiated and sometimes non-uniform risk reduction patterns across alternative improvement strategies, while still highlighting risks that are structurally sensitive to both high-impact and low-effort functional improvements. This supports the use of the proposed method as a comparative decision-support tool rather than as a predictor of individual incidents or losses.

4.3 Scenario Construction

In this study we constructed two comparative improvement scenarios to reflect decision-making under SME resource constraints, where only a limited set of actions can be implemented within a given planning cycle. In both scenarios, the number of selected improvement actions was limited to three. Scenario 1 (high-impact) prioritised actions expected to yield the largest reduction in importance-weighted capability gaps, using the product of the baseline capability gap and the corresponding importance value as the primary selection criterion. Scenario 2 (low effort) prioritised actions with lower implementation effort. In this study, the cost is interpreted as relative implementation effort rather than as a monetary value. The effort estimates are used solely for comparative scenario construction and do not represent actual financial costs or investment calculations. Implementation effort was assessed using an ordinal five-level scale (Low–Very High) and used only as a comparative indicator for scenario construction. The effort estimates do not represent monetary costs and are not used for economic optimisation; instead, they provide a pragmatic way to contrast “high-impact” versus “low-effort” improvement strategies within the same modelling structure.

4.4 Numerical use Case Results

An Excel-based application shown in Figure 2 implements a capability-based scenario evaluation method, highlighting the key model variables for comparative analysis. The risk categories and control actions used as inputs to the model are summarised in Tables 1 and 2, respectively.

Table 1: Risk categories

ID	Risk category
1	Weak cybersecurity governance
2	Reputational damage
3	Supply chain disruptions
4	Regulatory non-compliance
5	Poor data oversight
6	Lack of technical readiness
7	Data breach or manipulation
8	Post-attack reputational & regulatory impact

Table 2: Controls actions

ID	Control actions
1	Staffing adequacy
2	Backups
3	IAM usage
4	Supply chain
5	Data encryption
6	Information security guidance
7	Cybersecurity training
8	Crisis communication instructions & exercises
9	Cybersecurity management model
10	Monitoring and reporting

Figure 3 illustrates the effects of two alternative improvement scenarios on cybersecurity capability gaps across the risks shown on the horizontal axis. Scenario 1 (Figure 3a) represents a high-impact strategy, in which functional improvement actions are selected based on their overall effectiveness in reducing importance-weighted capability gaps. When multiple actions demonstrate comparable effectiveness, preference is given to those that contribute most strongly to the product of the capability gap and importance (see Table 3). The selected actions address personnel adequacy, crisis communication guidance and exercises, and the establishment of a cybersecurity management model. In Scenario 1, the gap reductions are unevenly distributed across risks, with particularly pronounced reductions for risks associated with weak cybersecurity governance and organisational preparedness (Risk 1). This reflects the strong alignment between the selected actions and the underlying capability gaps contributing to that risk rather than a uniform reduction across all risk areas.

Scenario 2 (Figure 3b) represents a low-effort improvement strategy, where actions are selected primarily based on lower implementation effort while applying the same capability-based aggregation logic. Overall reductions are more moderate and more evenly distributed; however, a notable reduction is again observed for Risk 1. This indicates that certain risks are structurally sensitive to relatively feasible functional improvements, even when actions are not chosen to maximise overall impact.

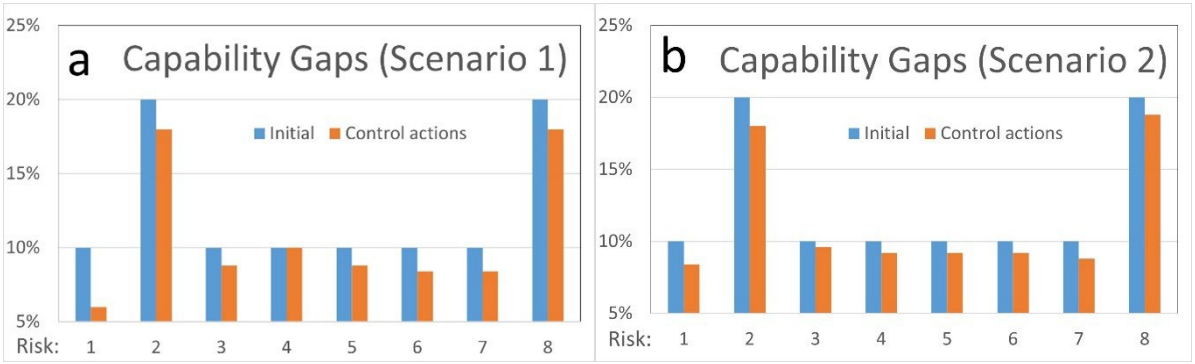


Figure 3: a) Scenario prioritising maximum reduction of importance-weighted cybersecurity capability gaps through selected functional improvement actions. b) Scenario prioritising low implementation effort while applying the same capability-based aggregation logic for cybersecurity improvement

The results show that importance-weighted capability gaps are reduced to different extents depending on the prioritisation strategy, with high-impact actions yielding the largest overall reduction and low-effort actions still providing meaningful improvement relative to the baseline. In Table 3, the quantity $\sum_j I_j g_j$ represents the residual importance-weighted capability gap, where lower values correspond to greater improvement from the baseline.

Table 3: Importance values I_j and products of importance and residual gap values $I_j g_j$ for the two Scenarios 1 and 2. For comparison in Scenario 0, no improving actions are implemented

Risk		1	2	3	4	5	6	7	8	
I_j	All scenarios	0.95	1	0.9	0.95	1	0.9	1	1	$\sum_j I_j g_j$
$I_j g_0$	Scenario 0	0.095	0.200	0.090	0.095	0.100	0.090	0.100	0.200	97.0 %
$I_j g_j$	Scenario 1	0.057	0.180	0.079	0.095	0.088	0.076	0.084	0.180	83.9 %
$I_j g_j$	Scenario 2	0.080	0.180	0.086	0.087	0.092	0.083	0.088	0.188	88.4 %

4.5 Interpreting Scenario Results

The scenario results are intended for comparison rather than as exact measures of cybersecurity performance. Because the effects of improvement actions are allocated proportionally based on their links to different capabilities, the same action may reduce some capability gaps more than others. As a result, some capability gaps are expected to remain after the improvements. Therefore, the results show how different prioritisation choices affect which capability gaps are reduced and to what extent.

From the decision-support perspective, our method helps to make trade-offs visible between (i) improvement actions that provide broader capability gains and (ii) the effort required to implement those actions. As shown in Table 3, the baseline scenario (Scenario 0) yields an importance-weighted capability gap of 97.0%. Scenario 1 reduces this value to 83.9%, representing the largest overall improvement when selecting three actions based on high impact, whereas Scenario 2 achieves a more moderate reduction to 88.4% when selecting three actions with the lowest implementation effort. This confirms that prioritising actions based on high-impact strategy of Scenario 1 leads to greater overall capability gap reduction of 13.5% than the low-effort strategy still leading to a meaningful reduction of 8.9% relative to the baseline.

5. Conclusion

In this study we investigated how a capability-based evaluation model, originally developed in a military context, can be adapted to support cybersecurity decision-making in a resource-constrained critical infrastructure organisation. The model was applied to a healthcare company using an existing IT risk register as the primary input to assess capability gaps and evaluate alternative improvement scenarios.

The results indicate that the model provides a structured and transparent way to reason about how different improvement actions contribute to cybersecurity capabilities and how limited resources can be prioritised more systematically. In particular, the scenario analysis helped to distinguish between high-impact and low-effort improvement strategies and demonstrate that capability gaps are reduced in non-uniform ways depending on the prioritisation logic applied. This supports the use of the model as a comparative decision-support tool rather than as an absolute measure of cybersecurity performance.

Several limitations should be considered when interpreting the findings. First, the evaluation was conducted as a single use case study within the healthcare sector, which could limit the method's generalisability to other organisations or critical infrastructure domains. Second, representatives of the use case organisation did not directly participate in the modelling or scenario construction. The analysis relied on previously produced organisational material and expert judgement, which ensured contextual realism but limited direct validation from decision-makers. Third, the assessment of capability gaps, control impacts, and scenarios was inherently subjective and based on a single evaluator. Finally, the implementation effort estimates used in the scenarios were intentionally coarse and context-specific, supporting relative comparison rather than precise economic evaluation.

In the future we will apply the proposed approach to multiple organisations and across different critical infrastructure sectors to evaluate its generalisability and sector-specific applicability. Involving multiple evaluators and organisational stakeholders would further support validation and reduce subjectivity. In addition, future development could explore the use of artificial intelligence–based methods to support estimation of control impacts, sensitivity analysis, and scenario generation. Such extensions could lower the threshold for applying the model in practice while preserving its role as a comparative decision-support tool.

Ethics declaration: This study did not involve the collection or processing of personal data. The case material was fully anonymised and contained no identifiable information about individuals or the organisation. Ethical approval was therefore not required for this study.

AI declaration: AI tools were used to support language refinement and clarity of expression. All analytical content, modelling decisions, interpretations, and conclusions were produced by the authors.

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Bayesian Modeling of Uncertainty in Anti-phishing Training: A Serious Game for Adversarial Email Crafting

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Abstract: This paper presents a Bayesian-driven serious game designed to support human-centered anti-phishing training through explainable artificial intelligence and adversarial gameplay. As phishing attacks increasingly leverage personalization and AI-assisted social engineering, traditional training approaches and opaque detection systems offer limited support for developing strategic awareness and decision-making under uncertainty. The proposed framework addresses this gap by combining Bayesian explainability with an interactive, adversarial learning environment. The serious game was implemented in a military academy context and centers on a sandboxed anti-phishing platform powered by a Bayesian Network. Participants are tasked with crafting targeted phishing emails for simulated victims using social media-derived contextual information. Each email submission is analyzed by the Bayesian engine, which outputs both a probabilistic phishing likelihood score and an explanation highlighting the linguistic features that contributed most strongly to the classification. Learners then iteratively revise the same email to reduce detectability, effectively attempting to "fool" the system while preserving semantic intent. Evaluation was conducted using two complementary data sources: interaction logs from the game and a post-activity questionnaire. The results suggest that integrating explainable Bayesian models into adversarial serious games can effectively enhance phishing awareness, strategic thinking, and sensitivity to uncertainty. The study highlights the potential of explainable AI not only as a defensive mechanism, but also as a powerful educational tool in cybersecurity training.

Keywords: Serious game, Explainability, Bayesian inference, Phishing

1. Introduction

The contemporary cybersecurity landscape is characterized by a continuous increase in the complexity, adaptability, and targeted nature of cyber threats (Masunda, 2025). As attackers increasingly leverage artificial intelligence and automation technologies, cyberattacks are evolving from generalized and predictable actions into strategically designed operations that exploit human, cognitive, and social vulnerabilities (Infosecurity Magazine, 2025). Within this context, phishing attacks constitute one of the most prevalent and effective forms of cyber threats, as they bridge the technical and human layers of security (Mutlutürk et al., 2024).

The detection of phishing attacks no longer relies on obvious technical flaws or generalized patterns (Kavya & Sumathi, 2025). Instead, modern phishing campaigns exploit personalized content, social context, and linguistic nuances to construct persuasive narratives that can bypass both human judgment and automated detection systems (Push Security, 2025). Consequently, the prevailing approach to phishing detection, which emphasizes technical features and statistical patterns, remains effective in certain scenarios but exhibits notable limitations at both operational and educational levels. From an educational perspective, users often interact with anti-phishing systems as black-boxes, receiving a final decision or risk score without meaningful insight into how and why a message has been classified as suspicious (Calzarossa et al., 2025). This lack of transparency constrains the development of strategic thinking, as learners are unable to associate specific linguistic or social design choices with corresponding risk assessments (Rjoub et al., 2023). Such limitations highlight the need for explainable models that incorporate qualitative content analysis and decision justification, thereby enhancing user understanding and trust.

Effective education for addressing phishing threats therefore requires a shift from the mere recognition of technical indicators toward an understanding of uncertainty, causality, and the adaptive behavior of attackers (Lappas & Karampelas, 2024). One approach aligned with this perspective is the cultivation of probabilistic reasoning (Huang & Zhu, 2018; Rjoub et al., 2023), which supports decision-making in environments characterized by uncertainty, an essential competence in modern cybersecurity contexts.

In this context, Explainable Artificial Intelligence (XAI), and particularly Bayesian approaches, provide a strong theoretical and pedagogical foundation for cybersecurity education. Bayesian Networks enable the quantification of uncertainty and the modeling of causal relationships through conditional probabilities, making transparent how individual message features influence the overall phishing risk assessment (Pearl, 1988; Calzarossa et al., 2025). This capability is especially critical in educational environments, where understanding the decision-making process is as important as the final outcome, as it fosters strategic thinking skills and trust in automated systems (Rjoub et al., 2023).

Building upon these considerations, the present study developed a purpose-built anti-phishing tool designed explicitly for educational use. The tool is based on a Bayesian Network and provides not only a probabilistic phishing risk estimation but also interpretable feedback regarding the linguistic and contextual features that contributed to the assessment. The educational approach is further strengthened through the integration of adversarial game dynamics. The application of adversarial game dynamics emphasizes learner engagement in simulations that reveal attacker strategies and encourage the adoption of corresponding counter-strategic reasoning (Prebot, Du, & Gonzalez, 2023; Shashkov et al., 2023). Through this process, participants gain experiential insight into both social engineering strategies and the capabilities and limitations of anti-phishing systems (Pawlick et al., 2019).

Accordingly, this study proposes a holistic educational framework that combines Bayesian explainability and adversarial gaming dynamics for phishing awareness and defense training. The primary contributions of this work are summarized as follows:

- Highlighting the limitations of conventional anti-phishing tools with respect to qualitative message analysis.
- The development of an educational Bayesian anti-phishing system with built-in explainability.
- The investigation of the role of adversarial serious games in fostering strategic thinking and uncertainty awareness in cybersecurity contexts.

Unlike existing phishing training tools, this work exposes the internal probabilistic reasoning of the detection system and positions the learner in an adversarial optimization loop.

To guide the reader, the remainder of this paper is structured as follows. Section 2 presents the theoretical background, covering Explainable AI in cybersecurity, Bayesian Networks and adversarial game theory. Section 3 formulates the research problem and identifies gaps in the existing literature. The proposed educational framework, system design, evaluation methodology and results are described in Section 4. Finally, Section 5 discusses the findings and outlines directions for future research.

2. Theoretical Framework

2.1 Explainable AI (XAI) in Cybersecurity

Explainable Artificial Intelligence (XAI) encompasses methods that render the decisions of AI systems transparent and interpretable, enabling users to understand not only system outputs but also the reasoning processes underlying them (Calzarossa, Giudici, & Zieni, 2025). In cybersecurity, explainability is particularly important, as automated decisions directly affect trust, situational awareness, and operational responses to threats.

Within phishing detection, traditional machine learning approaches often operate as black-boxes, providing users with a binary classification or risk score without insight into the contributing factors. This opacity limits both user trust and educational value, as learners are unable to associate specific linguistic or contextual cues with phishing risk (Rjoub et al., 2023). XAI techniques address this limitation by exposing influential features or causal relationships, allowing users to reflect on why a message is considered suspicious.

Feature-attribution methods such as Local Interpretable Model-agnostic Explanations (LIME) have been used to highlight influential words or structural patterns in phishing emails (Ribeiro, Singh, & Guestrin, 2016). Probabilistic approaches, particularly Bayesian models, further enhance explainability by explicitly representing uncertainty and causal dependencies among features. Such models enable users to observe how individual elements contribute to the overall risk assessment, making them well suited for educational contexts where understanding decision logic is as important as detection accuracy.

Despite these advantages, applying XAI in education introduces challenges. Overly complex explanations may overwhelm learners, while overly simplified explanations risk misrepresenting system behavior (Mellon &

Worrell, 2023). Consequently, educational XAI systems must balance interpretability, realism, and cognitive load to effectively support learning.

2.2 Bayesian Networks and Uncertainty

Bayesian Networks (BNs) are probabilistic graphical models that represent causal relationships between variables using directed graphs and conditional probability distributions (Pearl, 1988). Their defining strength lies in their capacity to model uncertainty explicitly, allowing probabilistic inference in environments characterized by incomplete information.

In cybersecurity, Bayesian Networks have been applied to risk assessment, intrusion detection, and attack modeling by integrating heterogeneous indicators into coherent probabilistic estimates (Xie et al., 2010; Wei & Dong, 2025). Within phishing analysis, BNs can capture how linguistic cues, contextual signals, and behavioral patterns jointly influence the likelihood that a message constitutes a phishing attempt.

From an educational perspective, Bayesian Networks offer distinct pedagogical advantages. By exposing conditional dependencies and posterior probability updates, they support the development of probabilistic reasoning and decision-making under uncertainty. Learners can observe how small changes in input features propagate through the model, altering risk assessments in a transparent and interpretable manner. This aligns closely with educational goals in cybersecurity, where uncertainty awareness and causal reasoning are critical competencies (Rjoub et al., 2023).

However, educational use of Bayesian Networks requires careful abstraction. Highly complex models may obscure learning objectives, while simplified models must still preserve meaningful causal structure. Prior work has shown that scenario-specific Bayesian models can effectively balance interpretability and realism, particularly when designed explicitly for training rather than operational deployment (Lappas et al., 2025a; Lappas et al., 2025b).

2.3 Adversarial Game Theory in Cybersecurity

Game theory provides a formal framework for analyzing strategic interactions between competing agents. In cybersecurity, adversarial game theory models the dynamic interaction between attackers and defenders, each adapting strategies under uncertainty and resource constraints (Huang & Zhu, 2018). Rather than static classification problems, cybersecurity challenges often involve iterative adaptation, deception, and counter-strategy.

Educational applications of adversarial game theory typically employ role-based simulations, where learners assume attacker or defender perspectives to experience strategic trade-offs firsthand (Prebot, Du, & Gonzalez, 2023). Such simulations foster deeper understanding of attacker behavior, system vulnerabilities, and the limitations of defensive mechanisms.

When combined with explainable probabilistic models, adversarial games can transform detection systems into interactive learning environments. Learners do not merely observe outcomes but engage in strategic adaptation informed by transparent feedback. This approach supports the development of adversarial reasoning, perspective-taking, and adaptive decision-making, skills that are essential in contemporary cybersecurity practice (Pawlick et al., 2019; Shashkov et al., 2023).

3. Problem Statement

The integration of Explainable Artificial Intelligence (XAI), Bayesian Networks, and adversarial game theory offers a promising foundation for cybersecurity education. XAI enhances transparency in algorithmic decision-making, enabling learners to understand why specific messages are classified as phishing. Bayesian Networks complement this capability by providing a formal mechanism for quantifying uncertainty and modeling causal relationships among linguistic and contextual features. Adversarial game theory further extends this framework by positioning learners as strategic agents who must adapt their behavior based on probabilistic feedback (Huang & Zhu, 2018; Rjoub et al., 2023).

This combined perspective moves beyond traditional cybersecurity training approaches, which often emphasize theoretical instruction or isolated simulations. Instead, it supports learning environments where explanation, uncertainty reasoning, and strategic interaction are tightly coupled. Within such environments, learners can explore how their decisions influence detection outcomes, reflect on system behavior, and iteratively refine their strategies.

Despite advances in these individual domains, significant gaps remain in the existing literature. Most XAI research in cybersecurity focuses on technical interpretability methods, with limited attention to their pedagogical integration and impact on learner decision-making (Rjoub et al., 2023). Bayesian Networks are predominantly employed for operational risk assessment and detection, rather than as interactive educational tools that allow learners to experiment with probabilistic models and uncertainty-driven scenarios (Frigault & Wang, 2008; Xie et al., 2010). Similarly, while adversarial game theory has informed defensive and offensive cybersecurity strategies, its systematic application in educational settings, particularly in combination with explainable probabilistic models, remains underexplored (Huang & Zhu, 2018; Pawlick et al., 2019).

These limitations highlight the need for an integrated educational framework that unifies explainability, probabilistic uncertainty modeling, and adversarial interaction. Research Part

3.1 Design and Implementation of the Educational Intervention

The educational intervention was structured as a concise, multi-phase instructional sequence, explicitly designed to operationalize theoretical constructs from explainable artificial intelligence, Bayesian probabilistic reasoning, and adversarial game dynamics within a cybersecurity training context. The sequence comprised:

- Theoretical lectures introducing the taxonomy of phishing attacks and the psychological underpinnings of social engineering techniques.
- Conceptual exposition of Bayesian networks, focusing on their capacity to model uncertainty and causal relationships in automated decision-making systems.
- Experiential learning through a hands-on session utilizing the custom-developed serious game platform.

The serious game functioned as the integrative nexus where abstract theoretical principles were translated into actionable skills. Within this environment, participants engaged in a series of scaffolded activities, including:

- Bayesian reasoning tasks: Interpreting probabilistic phishing scores, analyzing the influence of specific linguistic and contextual features, and exercising decision-making under uncertainty.
- Adversarial, game-based decision-making: Iteratively modifying phishing strategies in direct response to transparent, explainable feedback from the Bayesian detection software.
- Reflective practice: Critically comparing human intuition with algorithmic judgment, thereby fostering metacognitive awareness of both strengths and limitations in human-AI collaboration.

A central pedagogical emphasis was placed on elucidating how subtle linguistic modifications propagate through the probabilistic model, altering posterior risk assessments and detection outcomes. This approach foregrounded the dynamic interplay between attacker adaptation and defender detection logic.

The intervention targeted the following learning objectives:

- To cultivate a nuanced understanding of uncertainty and explainability in automated cybersecurity decision systems.
- To develop adversarial and strategic thinking by anticipating and circumventing detection mechanisms.
- To enhance awareness of social engineering tactics, moving beyond superficial indicators to deeper, context-sensitive threat analysis.

By simultaneously exposing participants to both the attack surface and the internal logic of the detection system, the framework advanced a human-centered, explainable approach to phishing defense. This design not only demystified the operation of probabilistic classifiers but also empowered learners to reason strategically about both offensive and defensive dimensions of cybersecurity.

3.2 Research Context

The presented work adopts a design-based case study approach within a higher-education cybersecurity training context. It was held on October 20, 2025, at the Polish Air Force University, on October 28, 2025, at the Portuguese Air Force Academy and on December 5, 2025, at the Hellenic Air Force Academy as part of the "Cyber Warfare" training within the "European Union Military Erasmus" program. A total of 126 students from six different European countries, aged 19 to 21, participated in the training. All participants were cadets from military academies. The module spanned six training hours at each place.

Rather than evaluating a static detection model, the focus is on the human-algorithm interaction and on how explainable probabilistic feedback can support adversarial reasoning and cybersecurity awareness. The serious game was deployed as part of a structured educational intervention and served both as a training instrument and as a data collection mechanism for observing participant behavior under uncertainty.

The study explores how learners interpret, exploit, and adapt to Bayesian phishing detection mechanisms when explicitly exposed to their internal reasoning.

3.3 Framework design

The proposed educational framework synthesizes Bayesian explainability with adversarial game dynamics, fostering an environment where learners alternate between attacker and defender roles. This dual-role approach operationalizes theoretical constructs from explainable AI and game theory, enabling participants to experience both the strategic creation of phishing messages and the probabilistic evaluation of such attacks.

At the core of the system are three interdependent modules:

1. Scenario & Target Profiling Module: participants are provided with a simulated victim profile constructed from fictionalized social media data, closely emulating realistic open-source intelligence (OSINT) sources commonly exploited in social engineering. More specifically, the profile depicted a German fighter pilot who expressed a passion for running and a keen interest in the military aviation history. The individual also disclosed specific dietary habits and preferences for particular brands of running shoes. Frequent references were made to a close friend named Josh and to the individual's daughter. All such information was publicly accessible through the designated social media platform, thereby grounding the exercise in authentic adversarial contexts and supporting the development of targeted attack strategies by the participants (figure 1).

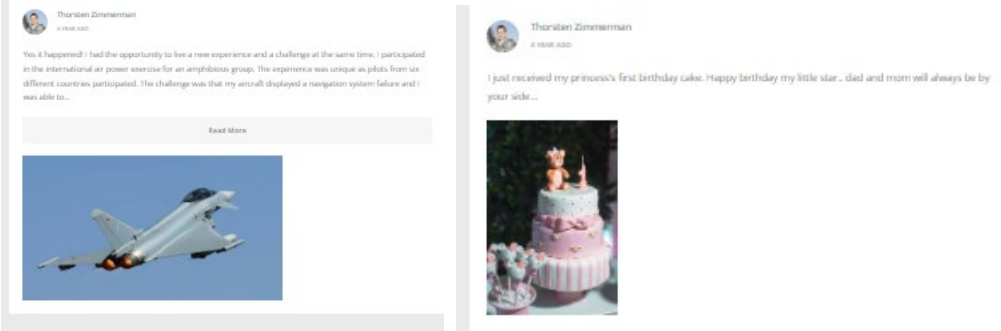


Figure 1: Images from the hypothetical person's social media profile

2. Bayesian Anti-Phishing Software: In the context of the Bayesian Anti-Phishing Software, submitted emails were evaluated by a Bayesian Network-based classifier, which provided both a probabilistic phishing likelihood score, quantifying the risk associated with each message and an interpretable explanation highlighting the lexical and contextual features most influential in the classification process. Each detected feature was mapped to a corresponding node within the Bayesian network, facilitating the propagation of uncertainty and modeling conditional dependencies between linguistic cues and phishing risk.

The construction of the Bayesian network was informed by qualitative data collected over the previous years, during which the same phishing scenario and target profile were used in instructional settings (Lappas & Karampelas, 2023). Emails authored by participants in these earlier cohorts were systematically analyzed and categorized according to the persuasive elements and strategies employed to attract the target. The frequency and distribution of these elements were quantified, enabling the derivation of conditional probabilities for the network. As a result, the Bayesian model was specifically tailored to predict the likelihood that an email would constitute a phishing attempt within this scenario. The network was implemented in Python and programmed to recognize keywords within the email text that corresponded to the semantic meaning of each node. When such keywords were detected, the respective node was activated, thereby influencing the overall risk assessment produced by the model (figure 2).

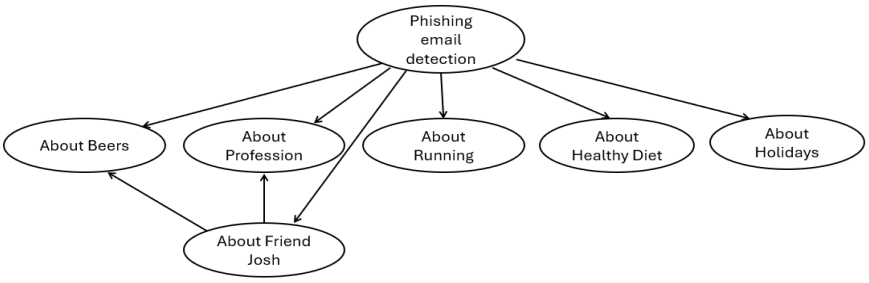


Figure 2: The bayesian network used in the educational framework

3. Explainability & Feedback Module: The system transparently exposes detected keywords and their respective impact on posterior probabilities, transforming the classifier from a traditional black-box filter into an interactive, explainable adversarial opponent. This module enables learners to iteratively refine their strategies based on actionable feedback, reinforcing the link between feature manipulation and detection outcomes.

Figures 3 and 4 illustrate a representative example of adversarial adaptation, showing how a participant iteratively revised a phishing email in response to explainable Bayesian feedback, resulting in reduced detection probability through targeted lexical modifications while preserving semantic intent. Furthermore, semantic similarity analysis between the two email versions yielded a high score of 0.965, indicating that the core message and communicative intent were preserved despite localized linguistic modifications. This example demonstrates the capacity of participants to interpret explainable Bayesian feedback and engage in adversarial reasoning. Rather than resorting to superficial deletion of flagged terms, the trainee employed strategic substitutions and contextual adjustments, successfully reducing the detectability of the phishing attempt while maintaining message coherence. Such behavior exemplifies the adversarial learning objectives of the proposed framework, wherein learners internalize the probabilistic logic of automated detection and adapt their strategies accordingly.



Figure 3: Image from the anti-phishing software that the trainee was viewing in the first effort

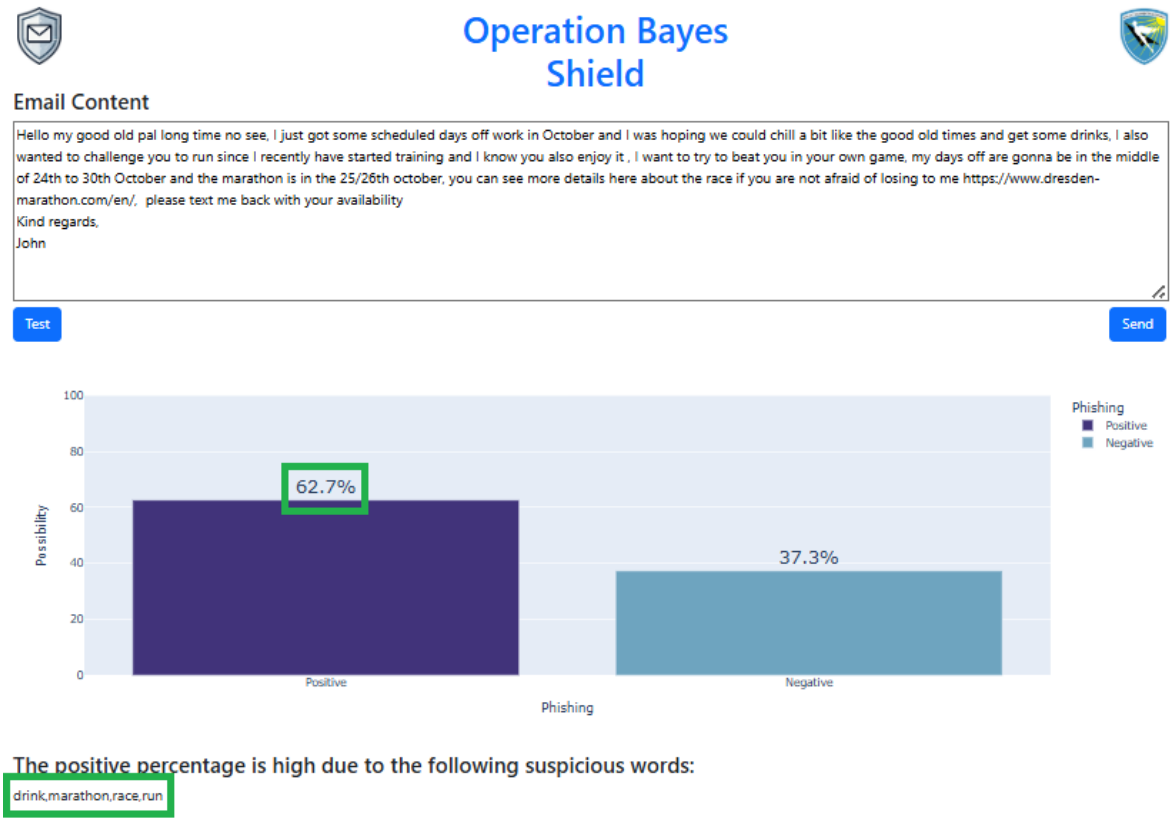


Figure 4: Image from the anti-phishing software that the trainee was viewing in the second effort

3.4 Scenarios and Roles

The serious game scenario is designed to authentically simulate a targeted spear-phishing attack, immersing participants in realistic adversarial dynamics. Learners alternate systematically between two roles (figure 4):

- Attacker: Participants craft phishing emails tailored to the simulated target's interests, behavioral patterns, and social connections, leveraging open-source intelligence data provided by the system.
- Defender: Participants analyze how the Bayesian anti-phishing software evaluates their crafted messages, interpreting the system's probabilistic risk assessments and the rationale behind flagged features.

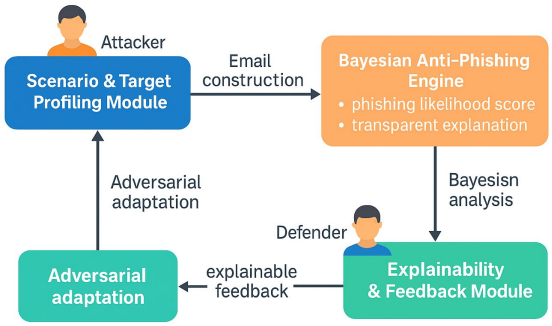


Figure 4: Roles in Bayesian Anti-phishing Serious Game

A key instructional constraint requires participants to iteratively revise a single email instance, maintaining semantic continuity while strategically modifying linguistic and contextual elements. This design choice discourages superficial keyword removal and instead promotes meaningful adversarial adaptation, mirroring real-world attacker behavior.

To further enhance strategic engagement, the number of permissible resubmissions is deliberately limited. This introduces a layer of decision-making pressure, compelling learners to reflect critically on each modification and to anticipate the evolving detection logic of the Bayesian system.

Through this dual-role, iterative process, the scenario operationalizes the theoretical principles of adversarial game theory and explainable AI, fostering both offensive and defensive cybersecurity competencies within a controlled, feedback-rich environment.

3.5 Results of Trainee Submissions

The analysis of participant submissions within the serious game framework was conducted across three complementary dimensions: (a) changes in phishing detection probability between successive email revisions, (b) modification of detected keywords across iterations, and (c) semantic similarity between initial and revised email versions.

Quantitative results revealed a consistent reduction in the Bayesian phishing probability between the first and second submissions (from 55.36% to 51.28%), indicating effective adversarial adaptation following explainable feedback. The probability stabilized in the third submission, suggesting convergence toward an optimal strategy. This trend demonstrates that learners successfully internalized the probabilistic feedback and adapted their strategies to minimize detectability, fulfilling a core objective of the educational framework.

A qualitative examination of the detected keywords further substantiates this interpretation. Rather than simply removing highlighted terms, participants engaged in targeted lexical adaptations, replacing flagged keywords with semantically related or contextually neutral alternatives. This behavior reflects adversarial reasoning aligned with realistic attacker strategies, whereby the core message is preserved while overtly suspicious signals are minimized. The evolution of keyword sets across submissions illustrates that learners internalized which categories of terms (e.g., urgency, reward, brand-related cues) significantly contributed to higher phishing risk assessments.

Semantic similarity analysis supports these findings, with similarity scores between initial and revised emails remaining consistently high (mean similarity 0.886 between first and second, and 0.954 between second and third submissions). This indicates that participants preserved the core intent and communicative purpose of their emails, opting for strategic linguistic refinement rather than superficial or trivial content removal. Evaluation of the Educational Intervention

To assess the pedagogical impact of the intervention, participants completed a post-activity questionnaire using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The overall mean score across all items was 4.28, indicating a highly positive evaluation of the learning activity. The internal consistency of the scale was excellent (Cronbach's $\alpha = 0.96$), supporting the reliability of the findings.

The results demonstrate substantial learning gains. For example, 84.8% of participants agreed or strongly agreed that they understood phishing techniques better after playing the game, while 94.0% reported increased ability to recognize social engineering tactics in emails. Similarly, 87.8% felt that the game helped them understand how attackers craft deceptive messages, and 81.8% considered the game a useful method for learning about phishing. Notably, 90.9% believed that this activity would benefit future students, and 84.8% agreed that it is more effective than lecture-only learning.

Regarding system transparency and explainability, 78.8% agreed or strongly agreed that the detected keywords made the system's reasoning transparent, and 81.8% understood why the system changed the phishing probability. Furthermore, 78.8% reported that the game helped them understand how automated filters make decisions.

General satisfaction was high, with 84.8% expressing overall satisfaction with the activity and 84.8% stating they would recommend the game to others. Areas with higher neutrality (e.g., ability to identify highly personalized phishing or clarity of feedback) suggest opportunities for further improvement.

In summary, the intervention was perceived as highly effective in enhancing both conceptual understanding and practical skills related to phishing detection, while the integration of explainable AI elements contributed to learners' confidence and strategic thinking.

3.6 Discussion

The study demonstrates the pedagogical value of integrating explainable Bayesian models within adversarial serious games for cybersecurity education. Observed reductions in phishing probability and subsequent stabilization indicate that participants adopted informed strategies rather than relying on trial-and-error, reflecting an internalization of the Bayesian model's logic and realistic attacker adaptation.

High semantic similarity scores confirm that learners preserved message intent while making targeted lexical adjustments, avoiding superficial keyword deletion. This suggests the development of strategic manipulation skills grounded in understanding, a key educational objective.

Questionnaire responses reinforce these findings, highlighting improved comprehension of phishing techniques and the probabilistic reasoning behind automated detection systems, addressing a gap in traditional training approaches. Explainable feedback acted as a cognitive scaffold, transforming the detection system into an interactive learning counterpart and fostering trust and strategic reasoning.

Overall, the combination of adversarial role-play and transparent probabilistic feedback cultivates critical competencies such as uncertainty reasoning, attacker–defender perspective-taking, and adaptive decision-making, skills essential in cybersecurity environments facing AI-driven threats.

One limitation relates to the question of learning transfer.. The present study assessed strategic adaptation and uncertainty reasoning within a sandboxed, simulated phishing scenario, yet did not measure whether these competencies translate to real-world detection of unsolicited phishing attempts. The extent to which learners generalize adversarial understanding to authentic environments remains an open empirical question.

On the other hand, a potential concern associated with adversarial training approaches is the dual-use nature of the skills developed: participants learn techniques for crafting more effective phishing emails. This mirrors established practices in cybersecurity education, where offensive methodologies, such as penetration testing and red-team exercises, are routinely taught to cultivate defensive competence. In this context, the controlled environment, limited scope of the scenario, and absence of real operational impact ensure that the adversarial component serves strictly educational purposes.

Future work may include developing the framework in more diverse student populations, including non-military academic settings or professional training environments where it can offer more relevant information and generalizability of conclusions.

4. Conclusion

This paper introduced a Bayesian-driven serious game for anti-phishing training that integrates explainable AI principles with adversarial game dynamics. By exposing learners to both the construction of phishing emails and the transparent reasoning of a Bayesian detection system, the proposed framework advances a human-centered approach to cybersecurity education.

Empirical results from interaction logs and post-activity evaluation indicate that participants were able to strategically adapt their behavior in response to explainable probabilistic feedback. The observed reduction in phishing detection probability across submissions, combined with high semantic similarity between email versions, demonstrates meaningful adversarial learning rather than trial-and-error behavior. Moreover, participant feedback confirms that the explainability of the Bayesian model played a central role in enhancing understanding, confidence, and trust in automated detection mechanisms.

From a cybersecurity perspective, the study contributes evidence that explainable probabilistic systems can serve not only as defensive tools, but also as effective educational instruments for developing strategic thinking and uncertainty awareness. The findings suggest that exposing users to the internal logic of detection mechanisms may improve long-term resilience against sophisticated, AI-assisted phishing attacks.

Future work will focus on extending the framework to additional attack scenarios, incorporating longitudinal measurements, and exploring how learner-generated data can further refine Bayesian detection models. Overall, the proposed approach demonstrates that gamified, explainable Bayesian systems offer a promising pathway for advancing human-centered cybersecurity training.

Ethics Declaration: This study did not involve the collection of personal or sensitive data and was conducted within a controlled educational setting. Therefore, formal ethical clearance was not required. All participants were informed about the purpose of the activity and consented to the use of anonymized data for research purposes.

AI Declaration: Artificial Intelligence (AI) tools were used exclusively for language enhancement purposes, specifically to improve the clarity and fluency of English in the manuscript. No AI tools were employed for data analysis, interpretation, or generation of research content.

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On the Establishment of Trust: Rethinking Trust in the Age of Artificial Intelligence

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Abstract: Trust has always been a fundamental element of organisational and social structures, enabling cooperation in situations where uncertainty or vulnerability cannot be fully eliminated. As societies and infrastructures have become increasingly interconnected, the foundations of trust have shifted from interpersonal relationships toward complex institutional and technological arrangements. This evolution has reached a new turning point: digital infrastructures, autonomous systems, and data-driven decision-making processes increasingly mediate interactions that once relied on human reasoning. Artificial intelligence (AI) is reshaping expectations of reliability, transparency, and accountability, prompting a reassessment of what it means to trust in environments where human and machine actions are intertwined. In this context, the notion of trustworthy AI has emerged as a key prerequisite for the responsible integration of AI systems into social and technical ecosystems. Core principles such as robustness, explainability, fairness, and security are widely regarded as essential for fostering a balanced relationship of trust. These requirements become especially significant in domains where AI supports or controls essential services. This is particularly true for critical infrastructures - energy grids, transportation systems, healthcare services, and communication networks-, where AI-driven decisions may trigger cascading effects that extend far beyond individual users. Ensuring trustworthy behaviour in such settings requires not only technical reliability but also governance structures that provide oversight, recourse, and continuous assurance. Despite broad agreement on the importance of trustworthiness, a substantial trust gap persists. Users often struggle to understand how AI systems reach their decisions, leading to scepticism or disengagement. Conversely, operators may place unwarranted confidence in automated outputs, especially in high-pressure or resource-constrained environments. Organisations face challenges translating abstract principles into operational practices, and regulatory frameworks remain inconsistent across sectors and jurisdictions. These tensions illustrate that trust cannot be created through technical means alone; it must be cultivated through transparent design, institutional accountability, and alignment with societal values.

Keywords: Trust**,** Trustworthiness, Trusted AI, Artificial intelligence

1. Introduction and Motivation

Trust is a foundational mechanism that enables coordinated action under uncertainty. Classical accounts frame trust as a way of reducing complexity in situations where full information or control is not possible (Luhmann, 1979; Gambetta, 1988). In modern societies, this function has increasingly been delegated to large-scale socio-technical systems, such as financial platforms, communication networks, healthcare systems, and energy infrastructures, where trust is no longer placed solely in individuals, but in the reliability and governance of the systems themselves.

This shift has reached a critical point with the rise of Artificial Intelligence (AI) methods. Unlike traditional software systems, AI models are inherently data-driven, probabilistic, and often opaque. Their behavior emerges from statistical patterns rather than explicitly defined rules, making it difficult to fully predict, interpret, or verify their decisions. As a result, AI challenges traditional engineering assumptions that underpin trust, namely determinism, transparency, and verifiability. Instead, trust in AI-enabled environments must be established under conditions of uncertainty, approximation, and evolving system behavior.

At the same time, AI is no longer confined to low-stakes applications. It is increasingly embedded in decision-making processes that affect safety-critical and societally significant outcomes. In domains such as healthcare, finance, transportation, and public administration, AI systems influence or automate decisions that were historically made by human experts. Empirical research in human–automation interaction shows that users struggle to calibrate their trust in such systems, often exhibiting over-reliance (automation bias) or under-reliance (algorithm aversion), depending on how system behavior is perceived and communicated (Parasuraman & Riley, 1997; Dietvorst, Simmons and Massey, 2015). This miscalibration highlights a fundamental problem: trust in AI is not simply a function of system performance, but depends on how technical capabilities align with human expectations, organizational practices, and institutional safeguards.

In response, the concept of trustworthy AI has emerged as a central organizing principle in both research and policy. Influential frameworks developed by bodies such as the European Commission, the Organization for Economic Co-operation and Development (OECD), and the National Institute of Standards and Technology (NIST) converge on a set of core requirements, including robustness, reliability, transparency, fairness, accountability, and human oversight. These principles reflect a broad consensus that trustworthiness must be engineered and governed across the lifecycle of AI systems, rather than assumed as an emergent property.

However, despite this convergence at the level of principles, a substantial gap remains between normative guidance and operational practice. Much of the existing work addresses individual dimensions of trustworthiness—such as explainability, fairness, or robustness—in isolation. Yet real-world systems require these properties to coexist and interact under constraints, often involving trade-offs. For example, improving model interpretability may reduce predictive performance, while increasing robustness to adversarial inputs can raise system complexity and reduce transparency. Moreover, improvements in technical metrics do not necessarily translate into appropriate user trust when system behavior remains difficult to interpret or contextualize.

These challenges become significantly more pronounced in the context of critical infrastructures. Systems such as energy grids, transportation networks, and healthcare services operate under strict requirements for reliability, safety, and continuity. They are also deeply interconnected, meaning that failures can propagate across subsystems and produce cascading effects. When AI is introduced into these environments, it does not merely augment existing processes; it becomes part of a tightly coupled cyber-physical system in which errors, uncertainties, or adversarial manipulations may have systemic consequences. Prior work on cyber-physical security demonstrates that such systems are particularly vulnerable to complex interactions between digital and physical components (Cardenas, Amin and Sastry, 2008; Rajkumar et al., 2010).

At the same time, advances in machine learning have revealed fundamental limitations in current approaches to reliability and robustness. Research on adversarial machine learning shows that even highly accurate models can fail under small, carefully crafted perturbations (Goodfellow, Shlens and Szegedy, 2015; Papernot et al., 2016). Studies on distributional shift and uncertainty estimation similarly demonstrate that models often behave unpredictably when exposed to conditions that differ from their training data (Hendrycks & Gimpel 2017; Gal & Ghahramani 2016). These findings challenge the assumption that strong benchmark performance is sufficient for trustworthy deployment in operational environments.

Taken together, these developments point to a fundamental tension. On the one hand, AI offers unprecedented capabilities for optimization, prediction, and automation in complex systems. On the other hand, the very properties that enable these capabilities also introduce new forms of uncertainty and risk. This tension is particularly acute in critical infrastructures, where the consequences of failure are systemic rather than local.

The motivation for this work is to address the fragmentation that currently characterizes research on trustworthy AI. Rather than treating trustworthiness as a collection of independent technical properties, this paper adopts an integrated socio-technical perspective that situates trust within organizational practices and institutional governance. Focusing on critical infrastructures as a high-stakes domain, the paper examines trust not as a static property achieved at design time, but as a dynamic relationship that must be continuously established, calibrated, and sustained over the lifecycle of AI-mediated systems (Lipps et al., 2024).

2. Background and State of the Art: Trust and Trustworthy AI

The study of trust naturally appears in multiple disciplines, including sociology, philosophy, economics, and, more recently, computer science. Early conceptualizations characterized trust as a mechanism for reducing social complexity (Luhmann, 1979) or as a rational expectation under uncertainty (Gambetta, 1988). In these accounts, trust is not blind confidence but a calibrated judgement that balances risk, evidence, and prior experience. This foundational view remains relevant in AI-mediated contexts, where uncertainty arises from data dependence, model approximation, and environmental variability.

Before the emergence of modern AI, research on trust in automation established principles that continue to inform current work. Studies in human factors showed that trust in automated systems is dynamic and context-dependent, evolving with system performance and user experience (Lee & See 2004). Inappropriate trust manifests in two forms: misuse (over-reliance) and disuse (underutilization), a framing that closely aligns with contemporary discussions of automation bias (Parasuraman & Riley 1997) and algorithm aversion (Dietvorst, Simmons and Massey, 2015).

Empirical work further demonstrated that users calibrate trust based not only on perceived reliability, but also on transparency and feedback. Even minor observable errors in algorithmic systems can lead to disproportionate loss of trust despite superior overall performance (Dietvorst, Simmons and Massey, 2015). These findings underscore that trust is shaped by how system behavior is communicated and interpreted, not solely by objective accuracy.

A central theme in recent work is the explicit distinction between trust and trustworthiness: Trust denotes a subjective human attitude or a *willingness* to accept vulnerability in light of uncertainty, whereas trustworthiness refers to properties of a system that can, in principle, be specified, evaluated, and justified independently of individual belief states. Recent work in communications engineering has emphasized this distinction, arguing that technical systems cannot be trusted in a moral or intentional sense but can only be made trustworthy by design through measurable system characteristics and governance mechanisms (Fettweis et al., 2025). Clarifying this distinction is crucial, as conflating trust with trustworthiness risks treating technical compliance or high performance as sufficient for the establishment of appropriate human trust.

2.1 From Trustworthy Automation to Trustworthy AI

The transition from traditional automation to AI introduces new challenges. Unlike rule-based systems, machine-learning models often lack explicit, human-interpretable logic, leading to their characterization as “black boxes” (Lipton 2018). This opacity complicates verification, validation, and accountability, particularly in high-stakes domains. In response, the field of explainable AI (XAI) has emerged, proposing techniques such as Local Interpretable Model-agnostic Explanations (LIME) (Ribeiro, Singh and Guestrin, 2016) and Shapley Additive explanations (SHAP) (Lundberg & Lee 2017) to provide local or global explanations of model behavior. While such methods can improve interpretability, their ability to foster genuine understanding and appropriately calibrated trust remains contested. Explanations may increase user confidence without improving decision quality, thereby reinforcing risks of over-trust. Parallel efforts address robustness and reliability, particularly regarding adversarial manipulation and distributional shift. Research has shown that highly accurate models can fail under small perturbations (Goodfellow et al. 2015) or when deployed in environments that differ from training conditions (Hendrycks & Gimpel 2017). Together, these findings challenge the assumption that technical performance alone is sufficient for trustworthy deployment.

2.2 Fairness, Accountability and Ethical AI

Another core dimension of trustworthy AI concerns fairness and bias. Machine-learning systems can inherit and amplify biases present in training data, leading to discriminatory outcomes (O’Neil, 2016; Buolamwini & Gebru, 2018). This has motivated the development of fairness-aware learning approaches (Barocas, Hardt & Narayanan, 2019) and algorithmic auditing frameworks. Accountability extends the focus beyond technical correctness to include traceability, auditability, and responsibility assignment. Documentation mechanisms such as model cards (Mitchell et al., 2019) and datasheets for datasets (Gebru et al., 2018) support transparency and governance, but do not by themselves resolve questions of institutional oversight or liability.

2.3 Formalizing Trustworthy AI

Efforts to formalize trustworthy AI have converged around common principles. Frameworks proposed by the European Commission (2019), the OECD (2019), and the NIST AI Risk Management Framework (2023) emphasize robustness, transparency, fairness, accountability, and human oversight across the AI lifecycle. Despite broad alignment, these frameworks remain largely high-level and normative. Translating them into operational practices for complex, real-world systems remains challenging, particularly given trade-offs between transparency, privacy, robustness, and performance.

2.4 Limitations of the Current State of the Art

The current literature reveals several persistent limitations. First, research often addresses individual dimensions of trustworthiness -such as explainability, robustness, or fairness-, in isolation, neglecting their interaction within integrated systems. Second, improvements in technical metrics do not reliably translate into appropriately calibrated human trust, reinforcing the gap between trustworthiness and trust. Third, many approaches implicitly assume static deployment contexts, whereas real-world systems -especially in critical infrastructures-, are dynamic, adaptive, and exposed to evolving risks. Finally, trust is frequently treated as a property of the AI system itself rather than as an emergent phenomenon arising from interactions between technology, users, organizations, and institutions. This system-centric perspective limits the ability of existing

approaches to explain how trust is established, calibrated, and sustained in operational environments, thereby motivating the need for an explicitly socio-technical perspective.

2.5 The Trust Gap in AI -Mediated Systems

Despite growing convergence around principles of trustworthy AI, a persistent gap remains between AI systems that satisfy formal trustworthiness criteria and the way they are actually trusted, relied upon, or resisted in practice. This trust gap refers to a misalignment between objective system properties and the subjective or institutional trust relationships that govern real-world use. Similar gaps have long been discussed in the literature on trust and automation, where improved system performance does not necessarily lead to appropriate reliance (Lee & See, 2004; Hancock et al., 2011).

This misalignment emerges from the interaction of system properties, human judgement, and organizational context, and is conceptually summarized in Fig. 1.

2.6 Conceptualizing the Trust gap

A central source of this gap lies in the distinction between trust and trustworthiness. Trust is commonly defined as a willingness to accept vulnerability under conditions of uncertainty, based on expectations about the behavior of others (Luhmann, 1979; Mayer, Davis & Schoorman, 1995). Trustworthiness, by contrast, refers to properties of the trusted entity—such as ability, integrity, robustness, or reliability—that can be evaluated independently of the trustor's subjective belief. Recent work in both social sciences and engineering highlights the importance of maintaining this distinction, particularly in socio-technical systems where trust is often misattributed to technical artefacts (Bauer, 2021; Fettweis et al., 2025).

The trust gap emerges when improvements in trustworthiness—such as higher accuracy, explainability, or robustness—do not translate into appropriately calibrated trust. Conversely, trust may be placed in systems whose trustworthiness is insufficient. This misalignment reflects not a simple failure of technical performance, but a broader disconnect between system behavior, human expectations, organizational routines, and institutional safeguards.

2.7 Opacity, Uncertainty, and Miscalibrated Trust

The epistemic opacity of AI systems is a key contributor to the trust gap. Machine-learning models, particularly deep learning systems, operate on high-dimensional statistical representations that resist full interpretation or prediction. This opacity is structural rather than accidental, arising from the mathematical and computational foundations of machine learning (Burrell 2016). While explainable AI techniques attempt to mitigate this issue, they typically provide local or approximate explanations rather than comprehensive understanding (Lipton, 2018; Doshi-Velez & Kim, 2017).

Empirical studies suggest that such explanations can increase user confidence without necessarily improving decision quality or understanding of uncertainty (Binns et al., 2018; Ehsan et al. 2021). This creates a risk of illusory transparency, in which systems appear more trustworthy than they actually are. As a result, users often struggle to assess when a system's outputs are reliable, when uncertainty is high, or when human judgement should prevail.

These epistemic limitations translate directly into miscalibrated trust. Research in human–automation interaction shows that users frequently exhibit automation bias, deferring too readily to system recommendations, as well as algorithm aversion, rejecting AI support following salient failures (Parasuraman & Riley, 1997; Dietvorst, Simmons & Massey, 2015). Crucially, over-trust and under-trust are not opposing phenomena but manifestations of the same calibration problem: the absence of meaningful cues for assessing system competence across contexts (Lee & See, 2004).

2.8 Organizational and Institutional Mediation of Trust

Trust in AI-mediated systems is rarely formed at the level of individual cognition alone. AI systems are embedded in organizational settings that strongly shape how trust is constructed and enacted. Standard operating procedures, interface designs, training regimes, time pressure, and incentive structures influence whether and how AI outputs are used (Möllering, 2006). In many cases, reliance on AI reflects organizational compliance rather than genuine belief in system reliability.

This organizational mediation of trust also affects accountability. Responsibility for AI-mediated outcomes is typically distributed across developers, system integrators, operators, and regulators. Such fragmentation

complicates responsibility attribution and creates moral distance between decisions and consequences (Nissenbaum, 1996). When it is unclear who is accountable for errors or harms, trust becomes fragile—even when systems behave as designed.

While "human-in-the-loop" approaches are often proposed as safeguards, empirical and conceptual work suggests that nominal human oversight does not automatically resolve accountability concerns. When intervention authority is limited or poorly supported, human oversight may serve primarily as a symbolic reassurance rather than a substantive control mechanism (Kroll et al., 2017; Pasquale, 2015).

2.9 Trust as a Dynamic and Context-Sensitive Process

A further dimension of the trust gap is its temporal character. Trust in AI-mediated systems evolves over time as systems are updated, retrained, or deployed in new environments, and as organizational practices and regulatory expectations change. Static assessments of trustworthiness at design or deployment time cannot account for distributional shift, emerging vulnerabilities, or changes in operational context (Hoff & Bashir, 2015; Amodei et al., 2016).

Empirical studies show that trust is highly sensitive to experience and feedback, and can erode even in the absence of discrete failures if system behavior becomes less predictable or less intelligible (Hancock et al., 2011). This highlights the inadequacy of one-time certification or compliance-based approaches to trustworthiness. Trust must instead be continuously established, monitored, and recalibrated throughout the system lifecycle.

Taken together, these insights show that the trust gap in AI-mediated systems arises from the interaction of technical opacity, human cognitive limitations, organizational mediation, and institutional accountability structures. Closing this gap requires treating trust not as a static property engineered into systems, but as a socio-technical relationship embedded in context and sustained over time (Lipps, Scharwatz and Collier, 2026).

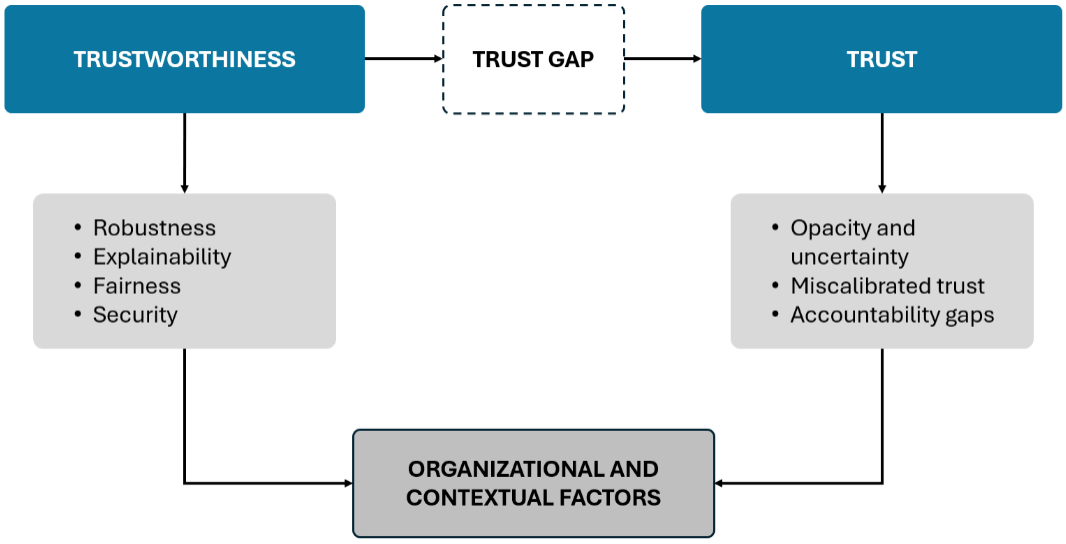


Figure 1: Conceptual illustration of the trust gap in AI-mediated systems

Objective trustworthiness properties of AI systems do not translate directly into established trust. The gap between trustworthiness and trust is mediated by organizational, contextual, and institutional factors that shape how AI systems are understood, relied upon, and governed.

3. Trustworthy AI in Critical Infrastructures

Trustworthy AI is particularly important in critical infrastructure environments because these systems provide services on which society depends, including electricity, water, transportation, healthcare, finance, telecommunications, and public safety. In such contexts, AI failure is not merely a technical inconvenience. It may affect physical safety, service continuity, public confidence, economic stability, and national security. This makes critical infrastructure a distinct setting for trustworthy AI: the central concern is not only whether an AI system performs well under nominal conditions, but whether it can be relied upon under operational stress, uncertainty, cyberattack, and changing environmental conditions.

Critical infrastructures are increasingly cyber-physical systems in which digital decisions produce physical consequences. AI may be used to detect anomalies in power grids, optimize traffic flows, support clinical triage, identify cyber intrusions, allocate scarce resources, or predict equipment failure. These applications can enhance efficiency and resilience, but they also introduce new forms of dependency. When AI becomes embedded in operational decision-making, errors can propagate across interconnected subsystems. A faulty prediction in one component may influence scheduling, control actions, maintenance planning, emergency response, or downstream infrastructure dependencies. For this reason, trustworthy AI in critical infrastructure must be understood as a system-level property, not a model-level attribute.

The NIST AI Risk Management Framework identifies characteristics of trustworthy AI such as validity and reliability, safety, security and resilience, accountability and transparency, explainability and interpretability, privacy enhancement, and fairness with harmful bias managed (NIST, 2023). These characteristics are especially relevant in critical infrastructure, where the cost of misplaced trust is high. A model that is accurate under normal operating conditions may still be untrustworthy if it fails under distribution shift, cannot detect uncertainty, lacks auditability, or cannot be overridden by human operators. NIST's recent work on a dedicated profile for trustworthy AI in critical infrastructure reinforces the need for sector-specific guidance spanning information technology, operational technology, and industrial control systems (NIST, 2026).

A key challenge is that critical infrastructure environments are often safety-critical, time-sensitive, and adversarial. In ordinary commercial settings, AI errors may result in inconvenience, reputational damage, or financial loss. In contrast, failures in critical infrastructure can compromise essential services or endanger human life. For example, AI-driven optimization in an energy grid must not only be efficient but also stable, secure, and robust against sensor faults, data poisoning, adversarial manipulation, and unexpected demand patterns. Similarly, AI used in healthcare or emergency response must support timely decision-making without obscuring responsibility or weakening professional judgement.

Cybersecurity is central in this context. Infrastructure operators increasingly deploy AI for threat detection, anomaly detection, and automated response. However, AI systems themselves become attack surfaces. ENISA distinguishes multiple dimensions of the AI–cybersecurity relationship: using AI to support cybersecurity, securing AI systems themselves, and addressing malicious uses of AI (ENISA, 2020; ENISA, 2025). This distinction is important because it avoids a one-sided view of AI as merely a defensive tool. In critical infrastructures, trustworthy AI must therefore include protection against adversarial examples, data poisoning, model theft, prompt injection, unsafe automation, and compromised supply chains.

Governance and accountability are equally important. The United States Department of Homeland Security emphasizes that responsibility for trustworthy AI in critical infrastructure is distributed across AI developers, cloud and compute providers, infrastructure owners and operators, regulators, and public authorities (US DHS 2024). No single actor can guarantee trustworthiness in isolation. Developers may design robust models, but operators must deploy them safely; infrastructure providers must secure platforms; regulators must define obligations; and affected stakeholders must have access to transparency and recourse mechanisms.

The European Union's AI Act similarly classifies certain AI systems used as safety components in the operation and management of critical infrastructure as high-risk systems. This reflects a broader regulatory judgement: where AI affects essential services, heightened requirements apply for risk management, data governance, technical documentation, human oversight, accuracy, robustness, and cybersecurity (European Union, 2024). The significance of this classification is not merely legal. It confirms that trustworthiness must be demonstrated through evidence, documentation, and lifecycle controls, rather than asserted through general ethical claims.

For this reason, trustworthy AI in critical infrastructure requires continuous assurance. Pre-deployment testing is necessary but insufficient. Models must be monitored after deployment for performance degradation, concept drift, abnormal inputs, and emerging threats. Operators require explanations that are actionable, not merely visual or statistical. They must know when to rely on the system, when to challenge it, and when to revert to fallback procedures or human control.

A growing body of applied research has begun to address these challenges, particularly in cyber-physical infrastructure systems. For example, *Munir, Shetty, and Rawat* (2023) propose a trustworthy AI framework for smart-grid cyber-attack detection that integrates reliability, explainability, transparency, fairness, and accountability into a unified pipeline. Their approach combines machine-learning-based detection with SHAP-based explanations and dynamic risk quantification, demonstrating that trustworthiness can be operationalized as measurable system properties within a real infrastructure context.

Complementing this, conceptual work on governance and accountability highlights that trustworthy AI in infrastructure systems requires clear responsibility allocation and regulatory alignment. Recent analyses of AI-enabled energy systems (Volkova et al., 2024) argue that traceability of decisions and accountability structures must be considered integral to trustworthiness, rather than external constraints. This reinforces the view that trust in critical infrastructures is inherently socio-technical.

In summary, critical infrastructure intensifies the trustworthy AI problem because reliability, security, accountability, and resilience cannot be separated. Trust cannot be reduced to user confidence or predictive accuracy. It must be grounded in demonstrable technical performance, robust cyber-physical safeguards, institutional accountability, and continuous operational assurance. These characteristics make critical infrastructure a key domain for translating trustworthy AI from abstract principles into practical, auditable, and enforceable socio-technical systems.

4. Conclusion and Future Work

Artificial Intelligence systems are increasingly integrated into societal infrastructures and organizational decision-making processes, often in contexts where reliability, safety, and accountability are critical. In response, the notion of trustworthy AI has gained prominence in research, policy, and regulation, resulting in a broad alignment around technical and ethical principles such as robustness, transparency, fairness, and human oversight. Yet, despite this convergence, trust in AI-mediated systems remains fragile, contested, and frequently miscalibrated in practice. This persistent tension indicates that technical trustworthiness alone does not resolve the deeper problem of how trust is established and sustained when human and machine actions are tightly intertwined.

Therefore, this work addresses this gap by examining trust in AI-mediated systems through a socio-technical lens. Drawing on theories of trust, empirical findings from human–automation interaction, and contemporary AI governance frameworks, the analysis demonstrate that trust and trustworthiness are distinct but interdependent concepts. Trustworthiness refers to objective system properties that can be designed, evaluated, and governed, whereas trust describes a willingness to accept vulnerability under uncertainty. The central contribution of this work lies in identifying the trust gap that emerges when these concepts are conflated - when technically trustworthy systems fail to elicit appropriate trust, or when trust is placed despite unresolved limitations.

By analyzing opacity, uncertainty, miscalibrated reliance, organizational mediation, and accountability fragmentation, the work shows that the trust gap is not a marginal or transient phenomenon. Rather, it arises from the interaction of technical system behavior, human judgement, organizational routines, and institutional arrangements. This diagnosis challenges system-centric approaches that treat trust as a property that can be engineered or certified at design time, and instead highlights trust as a dynamic relationship embedded in context.

The analysis further demonstrated that these issues become especially acute in critical infrastructures. In such environments, AI systems operate within tightly coupled cyber-physical systems, where uncertainty, adversarial conditions, and cascading effects are inherent. Here, trust failures have systemic consequences, and ensuring trustworthy behavior requires continuous assurance, clear responsibility allocation, and robust governance across organizational and sectoral boundaries. The discussion of regulatory and institutional perspectives illustrates that trustworthiness must be enacted and maintained over the system lifecycle, not merely asserted through abstract principles.

Several avenues for future research follow from this work: First, empirical studies are needed to investigate how trust in AI-mediated systems evolves over time in real-world organizational contexts, particularly under changing operational conditions. Second, domain-specific analyses of trustworthiness in different critical infrastructure sectors could help translate socio-technical insights into actionable practices. Third, further work should explore governance, auditing, and assurance mechanisms that explicitly address the relational and institutional dimensions of trust identified in this paper.

In conclusion, advancing trustworthy AI requires moving beyond a purely technical understanding of trustworthiness toward an integrated socio-technical perspective on trust. By reframing trust as a dynamic, context-sensitive, and institutionally mediated relationship, this paper provides a conceptual foundation for future efforts to build not only technically sound AI systems, but also resilient and legitimate trust in their deployment.

Acknowledgements

This work has been supported by the Federal Ministry of Education and Research of the Federal Republic of Germany (Förderkennzeichen 16KIS2239K SUSTAINET_guarDian). The authors alone are responsible for the content of the paper.

Ethics and Data Use Statement: This research used publicly available, anonymized secondary data. No identifiable personal information was accessed. Ethical approval was not required in accordance with institutional policies.

AI Assistance Statement: The authors used generative AI tools solely for linguistic editing and improving readability (e.g., grammar, phrasing, and structure). No AI system contributed to the formulation of the research questions, methodology, data interpretation, theoretical reasoning, or conclusions. All content was critically reviewed and approved by the authors, who take full responsibility for the manuscript.

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Cognitive Deception: Cognitive Hacking Phenomenon and Cognitive Security

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Abstract: Cybercriminality is an actively discussed topic in in criminology. While technical cybersecurity has evolved, increasing number of different types of technical solutions have been created to defend against cyberattacks. In security and cybersecurity, the weakest link is often considered to be a human. It seems that while malware attacks are increasing in numbers, also social engineering or cognitive hacking has increased. This paper explores the use and definition of a concept of cognitive deception in previous studies. Used dataset for this study was taken from SCOPUS database and qualitative meta-analysis (QMA) was used for analysing the content of the documents. The QMA method was selected for its suitability in content analysis of scientific-, as well as potential grey literature. Evolving technology has created new approaches for manipulating people. The analysis of research data indicates that cognitive hacking relates to definitions of cybercrime, cyberattack, warfare, and hybrid threats. This study contributes to the discussion about cognitive security.

Keywords: Cybercrime, Criminology, Cognitive deception, Cognitive hacking, Cyberattack, QMA, Qualitative meta-analysis

1. Introduction

Within cyber security, cognitive hacking has been studied (Adefabi et al. (2025). The consequences cognitive hacking has for example on human users who are being targeted to give unauthorized access to computer systems has been studied as well (Cybenko et al., 2002). This type of cyberattacks can be called social engineering where human weaknesses are being exploited (Montañez et al., 2020). Social engineering is used to gain access to confidential information (Washo, 2021). Concept of cognitive hacking can be expanded with the aid of artificial intelligence to deceive people. Cognitive hacking is a form of cyberattack, where misinformation is used to manipulate the opinions of the public in different societal aspects. This is done using psychological means to exploit human weaknesses in cognitive function. In this process, cognitive hacking refers to false information to manipulate the target using cyber-social vulnerability in the information systems. It seems, that technological approach and layer-based thinking in security or cybersecurity could greatly benefit from extending those to include controls for cognitive hacking. In this sense, previous studies have their focus on describing "what is occurring" in social interaction and what this manipulative action causes to the technology, i.e. "description of damages". For example, in a Finnish study about cybercrimes that end up in court, cases are categorized as a regular usage of computers, and not technologically that advanced (Luomala, 2025). This indicates that there is an emerging trend taking place, where the preparation of cybercrimes is shifting from purely technological approach towards more socio-technical approach, where cognitive hacking plays an important role. So, how can this evolutionary transformation be explained? This indicates that there exists a research gap, that is waiting to be found.

Layered security architecture has been seen as a methodology to secure assets (Ghasemi & Babaie, 2024). However, when layered security is penetrated with a human element (Jamuna, 2024) or an inside threat that emerges within the organisation (Anti, 2025; Anti & Vartiainen, 2024), this results a violation of the security (or cybersecurity). Even though the Department of Defence has defined layered strategy to suppress and deter threats from as far away as possible and the layers plays a key element in this defence (Lewis, 2006, p. 5). The layered security model is used to secure for example "Supervisory Control and Data Acquisition" (SCADA) systems, where defence is based on different layers (Knapp and Langill, 2015, p. 32-33). The model is also called as the defence in depth (Caballero, 2014; Morrow, 2021; Shinder & Shinder, 2005). However, it seems that the idea of layered security has a fundamental design flaw. A great amount of research has demonstrated that criminal behaviour is quite common (Howitt, 2006, p. 17), and the "threat" exists already within the system, in the very environment where humans live.

Some studies propose that there is a scam for everyone (Whitty, 2020). However, cyberthreats are created by humans (Lewis, 2006, p. 399), although there is a hypothetical possibility that in the near future artificial intelligence (AI) can generate cyberthreats or cybercrimes (Luomala, 2025). This brings up several important questions for scientific investigation. It could be asked, why are humans considered the weakest link in security and cybersecurity? How is cognitive security defined ontologically? What happens when humans are being manipulated, and do they recognise that they are being manipulated? In what mental stage human is vulnerable

to manipulation? How does manipulation take place? How to defend against cognitive hacking, and what can be done to either prevent, detect or mitigate the effects of cognitive hacking? This paper analyses why theoretically systems are never technically 100% secure (Lewis, 2006, p. 431). In order to understand this problem domain, a research problem is presented for this study: (*RQ) What is the role of cognitive security in the layered security model?*

2. Research Design

For creating a pre-theory for the research question, a qualitative meta-analysis (QMA) is used. QMA is known under three different names, and these are qualitative meta-synthesis (Berente et al., 2019; Habersang et al., 2019; Küberling-Jost, 2021), meta-synthesis (Hoon, 2013; Omanović & Langley, 2023) or qualitative meta-study (Lee et al., 2015; Tamminen & Holt, 2010). In 2024, Ignacio and Schwerer stated that the QMA can be used to examine existing knowledge for searching for new insights. Mengist et al. (2020) suggest that QMA can be used to make interpretations from literature review. According to Noah (2017), the QMA allows usage of secondary data (p. 203) and statistical analysis (p. 196-197). Hagan (2018) describes that researcher can collect field notes (p. 166) and those data can be used in the QMA, because the QMA allows usage different types of data (Noah, 2017). The QMA methodology is not about making simple summarising or cataloguing or review of already published research (Noah, 2017, p. 197). Purpose is to create a new knowledge from existing data (Noah, 2017, p. 197). The QMA methodology is about using original text to discover themes and identifying terms, and from the text interpretations and reflections are made (Noah, 2017, p. 202). “Part of the function of meta-analysis is to correct for differences between studies that are the result of bias, and to highlight differences that are unexplainable by the theory or framework being used” (Weed, 2005, p. 9). Same principle can be applied in qualitative meta-analysis (QMA) (Weed, 2005, p. 9). However, the quality of the QMA relies on researchers’ ability to reflect, make an interpretation from research data and to make conclusions and present results (Noah, 2017, p. 203). The QMA is considered a rigorous research method (Levitt, 2018; Timulak, 2009). The QMA is an inductive research method, and it was chosen for this inductive study. The QMA is used to make a qualitative interpretation from the literature review (Noah, 2017). The interpretation will then be the pre-theory, which is the answer to the research question. This study presents the role cognitive security has in the layered security model and what kind of pre-theory can describe it. In each section the use of methodology is explained in detail.

3. Literature Review with PRISMA Framework

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) literature review quality system (Page et al., 2021) was used to answer the research question. The data collection, data screening and data processing is described according to the PRISMA framework (Page et al., 2021). Used search parameter for the SCOPUS database was “TITLE-ABS-KEY ("cognitive hacking")”. The search provided 25 documents in 8.12.2025. Documents were 21 full-text articles, 3 abstracts and 1 review version of an article. Nineteen documents (n=19) were included in the research. Figure 1 illustrates the detailed process.

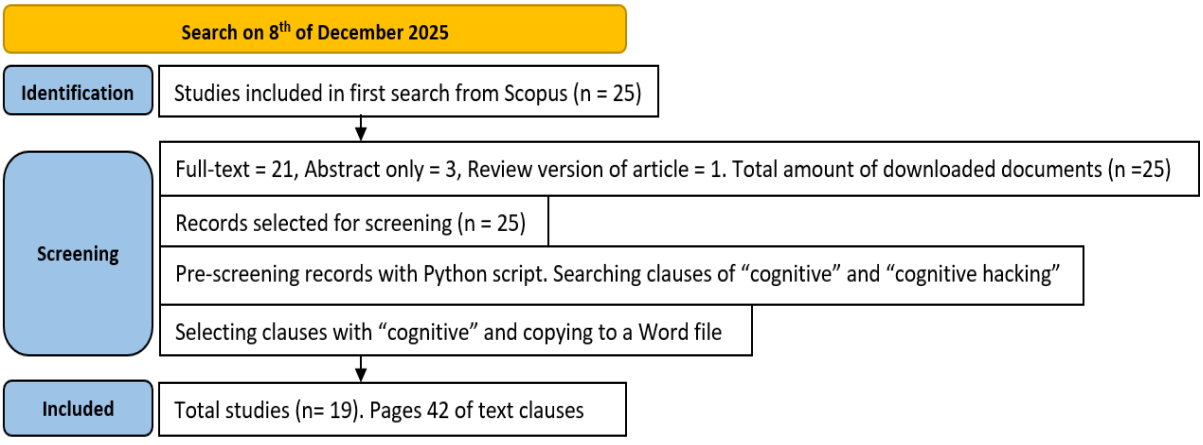


Figure 1: The PRISMA framework for collecting and processing the literature

For converting PDF files to text files, a Python code was created. The python code was run on Windows environment, and a folder was selected where the PDF files were located. The python saved the converted PDF files to the output folder. Another Python code was used for data mining and to collect clauses from the text files. The python code has a language model to detect words from clauses, and it was used to analyse all text

files in the output folder. If the lines of text file contained a word that matched search criterion, it was selected and stored into the output file. The output file had arrays, where filename was located and the collected clauses for each filename.

Sentences with words “cognitive” or “cognitive hacking” were recognized from the text files using a language model (Spacy with "en_core_web_sm"). Recognized clauses were then collected into an Excel file, and finally the output file was transferred to a Word file that made NVivo data coding possible. While analysing the data, it soon became clear, that the clauses of “cognitive” can provide a much richer view for the study, than just selecting clauses which have only “cognitive hacking” words. From there, iteration of the data was repeated. Research process continued by reading the clauses from the Word file. Depraetere et al. (2021) suggest that when critical interpretation synthesis (CIS) is used and iteration process is conducted, themes will emerge from the research data. The CIS methodology created main themes, which were: (i) Theme: attacking the mind; (ii) Theme: definition of cybercrime, cyberattack, hybrid threat, and; (iii) Theme: protecting the mind from cognitive hacking

4. Qualitative Meta-analysis Interpretation for the Proposed Pre-theory of Cognitive Hacking Theory

The layered security model can be defined in several different ways. The layered security is about creating architecture to secure assets with equipment on each layer (Ghasemi & Babaie, 2024). The layered security model includes usage of firewall, intrusion prevention systems and physical security solutions (Knapp and Langill, 2015, p. 32-33). The Department of Defence has defined layered strategy to suppress and deter threats from as far away possible and the layers plays a key element in this defence (Lewis, 2006, p. 5). The layered security model is used to secure for example SCADA (Supervisory Control And Data Acquisition) systems, where defence is based on different layers (Knapp and Langill, 2015, p. 32-33). The model is also called as the defence in depth (Caballero, 2014; Morrow, 2021; Shinder & Shinder, 2005). The purpose of the layered security model is to use technology to create security on each layer. However, when layered security is penetrated with a human element (Jamuna, 2024) or an inside threat which emerges within the organisation (Anti, 2025; Anti & Vartiainen, 2024). The cybersecurity is promised and unwanted event will occur, even it should be technically secure or otherwise it was belief that system is secure.

The three main themes have several sub-themes (Figure 2, Table 1). The contents of sub-themes are explained under the “Themes” headlines. “When presenting the results of the qualitative meta-analysis the researcher should not “boil down” the written word into numeric data, rather he should strive to keep the richness of the original text. Conducting a qualitative meta-analysis requires interpretation and reflectiveness” (Noah, 2017, p. 202). In this section interpretations from the research data are presented as researchers’ own reflection and interpretation, not just cataloguing the text from the literature. The drawn figure 1, the table 1 and three themes are the reflections and interpretations from the research data, which have been created by observing and examining the data in different ways. The proposed pre-theory is presented as synthesis of all interpretations. In this chapter the output of the research is presented, and it is based on the research methodology (Mengist et al., 2020, p. 8). It seems that cognitive hacking can be simplified to be process where human elements are manipulated by other human with the aid of technology as illustrated in Figure 2.

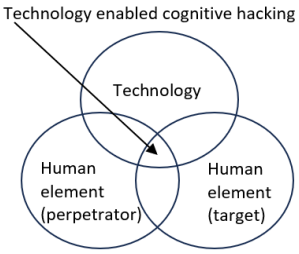


Figure 2: The interpretation of the cognitive hacking relationship to human elements and technology

During the iteration of the clauses, it soon became clear, that the discussion of the security of systems and society is merely related to development of technical solutions than inventing or discovering techniques to secure human element cognition from a form of manipulation. Even though malware and technical attacks are one phenomenon, the connection to the human element, that is manipulated to act the way the manipulator wants, receives minimal attention. Following sections, themes are described and headlines of the themes are interpreted from data.

4.1 Theme: Attacking the Mind

While the theme of attacking the mind was explored, sub-themes indicate that addressing risks from cognitive hacking is relatively scarce. Cognitive hacking targets critical infrastructure, and how to change the behaviour of the targets. In addition, it spreads misinformation and targets multiple people. There are processes that profile their victims based on available information, so the manipulated narrative can be created to cognitively manipulate them. The knowledge of internal processes makes it possible to manipulate people who are working in the organisation and to affect their daily actions.

The victims have vulnerabilities, which make them vulnerable to cognitive hacking. For example, personal traits which lead to the manipulation of beliefs. Cognitive hacking targets also victims who are already multitasking and show decision-making fatigue. One factor for vulnerability is age, but there is a wide range of manipulation for all kinds of people. When the manipulation takes place, a "malicious" action is taken. Increases in self-blame create a vulnerability to cognitive hacking by the adversary, which relates to the individual's internal fundamental assumptions. People will focus on easily accessible and understandable information, and this makes them vulnerable for manipulation if someone provides easily digestible information for them. Individuals' exploitation takes place when their subconscious thought processes are disrupted. People are not fully rational thinkers. Enrici, Ancilli and Lioy (2010) suggests, that:

> *"In particular, people who are high in normative commitment feel obligated to reciprocate gestures and favours maliciously proposed by cognitive attacks by giving up confidential and sensitive information; people who are high in continuance commitment tend to provide information to escalating requests, e.g. as part of an online game just to try to win the game; people who are high in affective commitment tend to provide information because they want to be part of a socially desirable group, or to be accepted."*

People who are trusting, will most likely fall to as victims. Enrici, Ancilli and Lioy (2010) suggests, that: "Moreover, people who are trusting were more likely to fall victim to techniques that try to cultivate trust by a process of establishing a friendly rapport or by reference to likable famous individuals, while others are more responsive to authority figures, and higher degrees of obedience to authority were an important factor in whether people responded to these types of cognitive attacks."

4.2 Theme: Definition of Cybercrime, Cyberattack, Hybrid Threat

The cognitive hacking overlaps with such definitions as cybercrime, cyberattack, information warfare, emotional warfare, hybrid warfare and hybrid threat. This due to the fact, that practitioners who deal with these "issues" classify actions of cognitive hacking in their own professional domain. After all, it is a human action that uses technology for manipulating another person to do something unwanted with technology. Table 1 illustrates how cognitive hacking has a parallel connection to other definitions.

Table 1: Parallel connections of definitions of cognitive hacking.

Cognitive hacking			
Military aspect	**Hybrid threat aspect**	**Cybercriminology aspect**	
Cognitive warfare (Bârgăoanu & Pană, 2024), (Danyk & Briggs, 2023)	Hybrid War/ hybrid warfare (Briggs et al., 2021)	False news (Java et al., 2019)	Social engineering (Java et al., 2019)
Emotive warfare (Briggs et al., 2021)	Hybrid threat (Bârgăoanu & Pană, 2024)	Insider threat (Roy & Chen, 2024)	Online manipulation (Susser et al., 2018)
Cyber warfare techniques (Briggs et al., 2021)	Political influence (Briggs et al., 2021), (Farral, 2017)	Email attacks (Guadagno & Cialdini, 2007)	Abnormal returns of the stock (Liu et al., 2021)
Weaponising the online manipulation (Susser et al., 2018)		Security attacks (Enrici et al., 2010)	Cyber attacks (Liu et al., 2021)
		Semantic attacks (Java et al., 2019)	Phishing websites / Fake online offers (Java et al., 2019)

Cognitive hacking can be used in making false news, manipulating websites for influencing wider audiences, as well as in cognitive manipulation in warfare. It can be used in email attacks, where content is used to persuade or manipulate the receiver and it can also be used to exert political influence or manipulation. Cognitive hacking

can be used in different fields, for example in the finance sector. As a summary, cognitive hacking can be seen as a weaponised method for manipulation.

Table 1 shows, that the definition of cognitive hacking is used to describe the manipulation of human elements with technology in different domains. Each domain has its own classification and scale how they technically and socially construct the meaning of the definition. From the analyses, a few theories were linked to cognitive hacking in the studies. The cognitive hacking is linked to theories of mirage theory (Rrushi, 2011), signal detection theory (Huang et al., 2020; Jiang et al., 2004; Stanislaw & Todorov, 1999), utility-theoretic (Marcum, 1947; Rrushi, 2011; Stanislaw & Todorov, 1999) and the theory of cognitive warfare (Bârgăoanu & Pană, 2024).

4.3 Theme: Protecting the Mind from Cognitive Hacking

An interesting statement in the analysed data suggested that if the technology is the weak point, why not investigate the weakest link in the supply chain, which is an extended cognition i.e. the relation between human and its cognitive artefacts. In this case, the issue lies between the relation of humans and their cognitive artefacts. The decision-making judgments are based on early perception and early cognitive processing instead of later, more systematic consideration of the information. It seems that research focuses more on building secure systems against technical threats but neglects cognitive hacking risks, even though the use of cognitive hacking techniques seems to be emerging. Machine learning technology might be capable of detecting overt threats from social cognitive hacking within content.

Countermeasures for cognitive hacking can be seen as a thought process to detect misinformation before it affects the decision and action of the user. It also includes technical solutions, that ensures information sources where information is validated and does not get manipulated. An example of this could be a situation, where website defacements are blocked by preventing unauthorised access for content manipulation. Other working countermeasures are lowering stress and cognitive overload in the organisation. The personal trait of high normative, continuance or affective commitment, as obedient to authority and wanting to trust, was found to contribute to successful cognitive attacks. In other words, this can be referred as naïve loyalty.

Combating cognitive hacking can be done by preventing unauthorised access to knowledge assets, for countering counter defacements and spoofing. In addition, detecting misinformation at an early stage can prevent it from influencing the behaviour of users. Cybenko et. al. (2002) suggests, that “In single-source cognitive hacking, the user has no independent source of information about the same topic and therefore cannot judge if the information is accurate”. Other means for combating cognitive hacking are giving cognitive training methods that help reduce impulsivity or reducing risk-taking behaviour and increasing procrastination to decrease the success of cognitive hacking. In addition, pointing out manipulative websites, which are engaging in cognitive hacking, can be used.

4.4 Cognitive Hacking: The Interpretation with the QMA

In this study, the QMA is used to create describe pre-theory of cognitive hacking. The pre-theory is proposed, because the literature review did not indicate that such a theory exists. Based on the QMA analysis of the data, a descriptive theory can be proposed. This paper presents a suggested extension to be included in layered security thinking. As such, this is a descriptive theory in a sense Gregor (2006) suggests, keeping the focus on analytically describing the observed phenomenon. In addition, Tomar and Tiwari (2025) mentioned that the Frege–Russell Descriptive Theory defines how describe meaning is constructed. The proposed descriptive pre-theory describes cognitive hacking as a form of activity done by humans. The pre-theory is called “the cognitive hacking theory”. The cognitive hacking means action where other human is manipulating another person. The cognitive hacking can include usage of technology to make manipulation. The pre-theory describes that cognitive hacking is occurring and cognitive hacking can penetrate layered security model, because of flaws existing in human nature. The pre-theory describes that cognitive hacking is used to manipulate another human element with the aid of technology. In a military environment, it is either a hybrid threat or part of hybrid warfare or information influence. In some cases, the technology might be the target itself, but the outcome is to manipulate the human element.

From the perspectives of crime science and criminology, a similar classification can be made. Purpose of the cognitive hacking is to manipulate the human element to gain, for example criminal financial gains. Technology works as a mediating device, or an aid in that environment. From the perspective of security studies and political science, technology is an aid for cognitive hacking to influence people to change their ways. It remains philosophically interesting to question what belief can be classified as truly misinformation or disinformation, because in politics, facts are not necessarily things which debate with each other. The proposal for cognitive

hacking theory includes also the basic discovery, that technology itself does not automatically protect from cognitive manipulation. It is rather a part of evolution where technology gives opportunities to manipulate human element, and the security or cybersecurity that is created inside the technology is to mitigate some cyberattacks, cybercrimes and hybrid threats.

Proposed cognitive hacking theory combines different taxonomies of security and cybersecurity, where classifications for cyber-depended manipulations or cyber enabled manipulations are used, however these are better known as cyber-depended crimes or cyber enabled crimes in criminology (Leukfeldt et al., 2020; Lusthaus et al., 2025; McGuire & Dowling, 2013). This can be derived from Alkaabi's et al. (2010) and Luomala's (2025) discussion of types of crimes. In the proposed theory cognitive hacking theory, the manipulation has a dimension named technology aided action, although the target can be influenced through manipulating human element, which have a parallel connection to Luomala's (2025) classification of type III crimes. The type III crimes mean condition where technology is a target and technology is an aid for criminal action. Technically, it means that cognitive hacking is used to manipulate a person to chance parameters of the technical artefact, which then results an alternative effect on other person to trust provided information (Type I, cyber-dependent crime). Existing technologies can be used directly to manipulate a target person (Type II, cyber-enabled crime). These types of I and II can be related to the same crime or they can be separate. When a Type I crime takes place, and it is targeted to technology, it can create an opportunity to commit a Type II crime against an individual. In addition, Luomala's (2025) extended taxonomy suggests, that cybercrime could be done by artificial intelligence. This way the presented taxonomy could be extended to cover also artificial intelligence mediated cybercrimes, and that would be Type IV crime. Reason for this is the capability of AI to be able to do both, manipulation of technology as well as cognitive manipulation against humans.

Alkaabi et al. (2010) suggests that there are Type I and Type II crimes: Type I considers technical device or software as a target of crime, while Type II considers technical device or software as aid for committing a crime. Luomala (2025) extended the taxonomy by adding Type III crimes where technical device or software is a target and aid for committing a crime (p. 50). The proposed cognitive hacking theory extends previous discoveries, where technical hacking has also elements of social manipulation, which are hidden qualitative aspects of cyberattacks, cybercrimes or hybrid threats. "The CCSTC extension with type III extension will show that cybercrime is sophisticated phenomenon and there many hidden qualitative aspects which should be measured such as have offender used social skills to commit the cybercrimes, and the most cybercrime cases are regular usage of the computer which end up to the Finnish court" (Luomala, 2025, p. 50).

Moreover, the cognitive hacking theory suggests, that the human element has internal vulnerabilities, which the layered security model has failed to address. According to the layered security model, the threat comes from the outside of the protected environment. However, the layered security environment is operated and managed by human elements. Therefore, it poses a risk of an insider threat. The layered security model mitigates the use of the system. It means that the system can be used only in certain ways and certain technical "functions" are either blocked, limited or mitigated. Cognitive hacking can penetrate these technical controls by manipulating the human element. Then the system is being used in ways, where legitimate actions are authorised from the systems perspective. However, the actions cause the "unwanted" phenomenon or impact.

5. Discussion

Cognitive hacking opens a discussion about the layered security model. When security and cybersecurity become technically so advanced, that the capabilities of the cyber offender do not necessarily find a way to bypass them, it becomes an obsolete path for cyber offender. In this case the goal shifts into finding a person, who can do everything the cyber offender needs to do. General approach has been merely on treating the symptoms, and not the cause or the discovery of where the "intention" to commit cognitive hacking merges. In this context, it is worth noticing that AI can be expanded to aid in deceiving people (Park et al., 2024). As such, the rules of the game are constantly changing.

From an engineering point of view, it is a worthy discussion to define what is an effective technical solution to "protect" the asset. However, it seems that there always exists a method to get a "malicious" act done by a person who has access and control over the system. From a legal perspective, it can be argued that the system allows only certain actions, and there is a criminal code for actions that are illegal — and this is expected to prevent "illegal" actions. However, people find ways to rationalise their actions, for example when they choose not to follow information security policy (Siponen & Vance, 2010).

There are criminological theories explaining crime (Onwuadiamu, 2025; Renzetti, 2008). Theories are such as rational choice theory, pressure theory, social learning theory, routine theory, etc. (Kivivuori et al., 2018). These theories explain from individual perspective reasons for the crime, but because cybercrime is complex phenomena involving multiple different human actors doing different "cybercrimes", and these are defined differently by different practitioners in different disciplines such as military science, security studies or criminology. A tricky question is to define a comprehensive concept for understanding "what works" against cybercriminality, because it seems to be able to an act of human behaviour. Moreover, the cognitive hacking needs more research on how artificial intelligence (AI) assisted cognitive manipulation is done. The word "artificial intelligence" was seldom mentioned in the documents, and it was mentioned as a method to detect online hoax information (Java et al., 2019) or as a part of hybrid threat (Stevens et al., 2021). In cyber domain there is a need for a theory, that explains the phenomenon of cognitive hacking what military, police or private security encounters, even if their perspective on the phenomena might be different.

The cognitive hacking relates to different types of security threats such as cybercrime, hybrid threats and cyberattacks. Cognitive hacking makes it possible to penetrate layered security model environments. The focus on security must be also on human elements, i.e. making humans aware, that they can be manipulated or become vulnerable to manipulation. The pre-theory of cognitive hacking theory, which is proposed in this study, shows that technology cannot solve issues, that exist within humanity and the human mind.

Cybercrime prevention, prevention of hybrid threats or responding to information influencing is looking for solutions to deal with this type of cognitive hacking. This qualitative meta-analysis shows, that developing effective security and cybersecurity needs evidence-based knowledge. The focus in security, cybersecurity, crime prevention, military operations and governmental security must shift towards making human element more secure by focusing more on cognitive security. It has been said that every study is as credible as the research data (Kaye & Freedman, 2011). It seems that cognitive hacking is not very widely investigated, so there is no common research tradition on how cognitive hacking should be understood (see table 1).

Different domains within the security field deal with similar human element issues, even though they classify their issue as either a cyberattack, cybercrime, hybrid threat or information warfare. It seems that this issue has been attempted to be resolved by implementing primarily technical solutions to address the weaknesses of the systems. A worthy, but understudied avenue would be to focus on understanding why humans have cognitive vulnerabilities. When does the human element become vulnerable to cognitive hacking? In addition, in contemporary society and time, the studies on what can be done to prevent cognitive hacking in an effective way are to be encouraged. Also, the role of AI should be studied — especially in AI mediated cognitive hacking?

The proposed cognitive hacking theory suggests that the layered security model has a vulnerability in cognitive security, which is not addressed. By using cognitive hacking, the technological layered security model systems can be penetrated, and unwanted actions can take place when the human elements are manipulated. The cognitive hacking phenomenon is not isolated only to cybercrime and financial crimes. It includes actions where people's public opinion can be manipulated in the political domain, or perception of the situation can be influenced through information warfare. Currently, there are no clear methods to address the issue of cognitive hacking, but in future studies, techniques to secure the human element are vital. The concept of cognitive security needs to be re-invented or re-discovered. Also, the role of AI-assisted cognitive manipulation should be studied more.

Ethics Declaration: An ethical declaration was not required for the research.

AI Declaration: Artificial intelligence was used to convert one PDF file by optical character recognition to form where strings can be copied from the PDF file. The service is available at www: https://pdf.ai/tools/ocr-pdf

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Artificial Immune System for Proportionality Assessment in Military Operations

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Abstract: This article presents an Artificial Immune System (AIS) algorithm for conducting the proportionality assessment in military operations that integrates an in-depth evaluation in relation to the detection of disproportionate collateral damage in military operations under two modelling settings, as follows defined. In the first modelling setting, the collateral damage only includes physical harm, and in the second modelling setting, the collateral damage includes both physical and psychological harm. In this context, various algorithms were implemented and compared. By employing a Clonal Selection algorithm, the possible scenario-feature combinations are treated as antigens and evolve a detector repertoire via affinity-based cloning, mutation, and replacement and aspects such as detection rate, false-positive rate, and detector diversity are tracked over generations. By employing Negative Selection and Immune Network paradigms, it can be seen that in Case 2 superior disproportional detection is achieved and through a more in-depth network analysis the core communities that underpin disproportionate judgments are analysed. Hence, the AIS models developed demonstrate that incorporating psychological considerations not only improves detection performance, but also shapes the structural properties of immune repertoires, providing a novel computational perspective on the proportionality assessment execution in military operations.

Keywords: Military operations, Proportionality, Artificial intelligence, Artificial immune system

1. Introduction

motto: *"The machine does not isolate man from the great problems of nature but plunges him more deeply into them." (Norbert Wiener)*

Computational modelling techniques have advanced rapidly over the past two decades, driven by increases in data availability, algorithmic sophistication, and computational power (Carothers et al., 2017; Iqbal et al., 2020). From classical rule-based expert systems to modern deep learning architectures, intelligent models now assure the development and deployment of applications ranging from natural language processing to autonomous control (Sarker, 2022). Simultaneously, hybrid paradigms that integrate mechanistic models (e.g., agent-based simulation, system dynamics) with data-driven methods have emerged, enabling both interpretability and predictive accuracy. These developments have transformed how complex socio-technical systems are understood and managed (Howick, S., & Megiddo, 2024; Mazzetto, 2024).

Concurrently, decision-support systems have proliferated across critical domains such as healthcare, finance, energy, and transportation providing stakeholders with the ability to explore what-if scenarios, quantify risks, and optimize interventions under uncertainty. For instance, reinforcement learning agents optimize resource allocation in logistics networks, while probabilistic graphical models forecast disease outbreaks (Ling, Mondal & Ukkusuri, 2024). At the same time, high-fidelity digital twins mirror real-world operations in real time, supporting adaptive control and human-machine teaming (Folds & McDermott, 2019; Maathuis, 2022). Such computational advances have elevated the rigor and responsiveness of decision-making processes in dynamic environments.

In the military domain, computational models play an equally pivotal role, underpinning tasks such as force deployment planning, logistics optimization, cyber-defence, and battlefield simulation (Marin, 2021). Furthermore, agent-based and wargaming frameworks enable commanders to simulate adversary behaviours and assess course-of-action alternatives while Network-centric analytics fuse intelligence, surveillance, and reconnaissance data to generate coherent operational pictures (James et al., 2017; Layton, 2021).

Specifically, a foundational military decision-making targeting process is the principle of proportionality, which is a fundamental targeting principle that mandates that any attack's expected military advantage must not be outweighed by foreseeable collateral damage to civilians and civilian infrastructure (AP, 1977). This requires quantifying two components: the collateral damage (civilian injury, death, and property destruction) and military advantage, and from there balancing them in real time. This represents both a legal and ethical judgement which needs to ensure that force is applied judiciously and in accordance with the laws of armed conflict (Schmitt & Schauss, 2019; Cohen & Zlotogorski, 2021; Maathuis & Kerkhof, 2023; Goździewicz, 2024). Despite the centrality of proportionality in operational doctrine, existing computational models for military

decision-support rarely address automated proportionality assessment (Cools & Maathuis, 2024). While logistics, targeting, and risk-analysis tools abound, few incorporate the structured, multi-dimensional trade-offs inherent in balancing harm and advantage. Consequently, decision-makers lack decision-support systems that transparently integrate proportionality criteria into real-time planning and engagement workflows.

To tackle this knowledge gap, the present research develops an Artificial Immune System (AIS)–based model for proportionality assessment in military operations. In this context, each possible engagement scenario is defined by civilian injury, death, object damage, and military advantage as an antigen that further evolves a repertoire of detectors through negative-selection and clonal-selection mechanisms to distinguish proportionate from disproportionate cases. To this end, two use-case perspectives are considered: one excluding psychological harm from the collateral damage component and one including it. From here, for evaluation and demonstration purposes, a comprehensive hyperparameter optimization and evaluation process quantifies the AIS's sensitivity, specificity, and structural robustness across both cases.

By embedding proportionality rules within a bio-inspired adaptive framework, this AIS model supports responsible decision-making under uncertainty (Maathuis & Chockalingam, 2022). At the same time, through extensive simulations, sensitivity analyses, and network-based metrics, it is shown how non-physical harm considerations influence detection performance and repertoire connectivity. The resulting decision-support artifact provides military decision-makers with a novel tool for upholding proportionality principles in dynamic operational contexts. Hence, this research makes three primary contributions. First, the formulation of proportionality assessment as an AIS problem with explicit antigen–detector mappings. Second, the development and tuning of negative-selection and clonal-selection protocols to optimize detection of disproportionate scenarios under two collateral-damage cases. And third, the introduction of immune-network analyses to characterize detector-repertoire topology and resilience, offering new insights into how psychological-harm criteria affect adaptive decision-support performance.

The outline of this article is structured as follows. In Section 2 are discussed relevant and related studies conducted using AIS in various societal and military domains. In Section 3 are presented the research activities followed during the execution of this research following the DSR scientific methodology. In Section 4 the design of the model proposed in this research is presented. In Section 5 the evaluation mechanism together with the results obtained are discussed. In Section 6 are provided concluding remarks and future research perspectives.

2. Research Background

Artificial Immune Systems are a class of bio-inspired computational algorithms that transpose principles of the vertebrate immune system into artificial pattern-recognition and anomaly-detection frameworks (Gonzalez, 2003; Sheikh, 2022; Myakala, Bura & Jonnalagadda, 2025). At the core of AIS is the notion of antigens, i.e., data instances or scenarios to be classified and detectors, i.e., artificial antibodies that bind to antigens when a match criterion is met. Through iterative processes of selection, cloning, mutation, and network interactions, AIS dynamically evolve a repertoire of detectors capable of distinguishing between self (benign or acceptable) and non-self (anomalous or undesirable) inputs. This adaptive, distributed architecture makes AIS especially well-suited for domains characterized by evolving threats, sparse training data, and the need for continual learning under uncertainty (Magaia & Sheng, 2018; Kan et al., 2022).

In decision-support applications such as proportionality assessment in military operations, AIS offer the ability to ingest expert-defined scenario feature maps and autonomously refine detection rules through exposure to operational data. Each possible engagement scenario (e.g., combinations of injury, death, object damage, and military advantage) is treated as an antigen; an initial detector pool is seeded either randomly or via negative selection, and then iteratively improved through clonal expansion and mutation. The evolving detector population thus captures both the explicit expert judgments encoded in the rule tables and the implicit patterns that emerge from scenario sampling, yielding a flexible, self-organizing decision-support artifact (Bejoy et al., 2022; Dasgupta, 2012; Yang, 2006; Singh et al., 2022; Kudtarkar, et al., 2024)..

The Negative Selection algorithm, inspired by T-cell maturation in the thymus, begins by generating a large pool of random candidate detectors and then eliminating any that match self-antigens (i.e., scenarios labelled Proportional). The surviving detectors tuned to recognize only non-self or Disproportionate cases form a static repertoire deployed for anomaly detection. In this process, negative selection ensures low false-positive rates, since detectors that would erroneously flag acceptable cases are purged a priori. However, its reliance on

exact matching and fixed repertoires can limit sensitivity to novel or borderline cases, and scaling to high-dimensional feature spaces demands careful tuning of detector counts and matching thresholds (Barontini et al., 2021; Gupta & Dasgupta, 2021; Ukawa et al., 2024).

The Immune Network algorithm draws on Jerne's network theory, wherein detectors not only bind antigens but also mutually stimulate or suppress each other based on similarity in shape space. In practice, detectors are nodes in a graph linked by Hamming-distance or affinity thresholds where edges represent mutual interactions that modulate detector concentrations. Through iterative network dynamics governed by stimulatory loops (recognition of antigen or other detectors) and inhibitory loops, an immune network can self-regulate, maintain diversity, and adapt to shifting antigen distributions. This emergent, distributed regulation confers robustness against overfitting and allows the system to capture higher-order relationships among scenarios, making immune-network AIS particularly powerful for complex decision-support tasks where the distinction between self and non-self is diffuse or context-dependent (Timmis, J., & Edmonds, 2004; Hao, X., & Cai-Xin, 2007; Nave & Elbaz, 2021; Cutello, Pavone & Zito, 2024).

Furter, Artificial Immune Networks (AIN) extend the AIS paradigm by embedding detectors within a networked topology, wherein nodes (detectors) interact through stimulatory and inhibitory signals analogous to Jerne's idiotypic network theory. These networks have been applied to data-mining tasks—such as clustering high-dimensional datasets and pattern recognition in time-series—where the mutual regulation among detectors fosters a self-organizing map of feature space, yielding robust classification boundaries and noise tolerance. By modeling detector affinities as weighted edges, AINs can capture higher-order correlations among antigens, enabling emergent feature extraction without requiring extensive parametric tuning (Guigou, 2019; Falawo et al., 2024; Myakala, P. K., Bura, C., & Jonnalagadda,, 2025). In scientific computing and optimization, AIN algorithms have demonstrated efficacy in coordinating multiple agents and solving combinatorial problems. For instance, an immune-network–based approach has been employed to synchronize swarms of unmanned aerial vehicles (UAVs) in multi-combat operations, where detector interactions guide collision-free formation and target coverage policies (Weng et al., 2014; Zhang et al., 2023; Javed et al., 2024).

The Negative Selection Algorithm (NSA), inspired by thymic deletion of self-reactive T cells, has found broad application in societal anomaly detection contexts, notably in computer network intrusion detection. NSAs generate detectors that do not match any self (normal) patterns, then monitor live data streams to flag any non-self (anomalous) events (Ramdane, C., & Chikhi, 2017; Selahshoor, Jazayeriy & Omranpour, 2019). Comprehensive surveys demonstrate NSA variants applied to host-based intrusion detection systems and hybrid network-level monitoring, achieving low false-alarm rates through refined detector generation and matching strategies (Ji, Z., & Dasgupta, 2007; Gupta & Dasgupta, 2021). Beyond cyber security applications, NSAs have been adapted for fault detection in wireless sensor networks, where detectors identify node failures or communication anomalies, thereby improving network resilience (Adday et al., 2022). In military engineering, NSA-based methods have been leveraged for critical system fault detection and predictive maintenance. A real-valued NSA was successfully applied to aircraft engine health monitoring, generating detectors that distinguish early fault signatures from normal operational variability, thus enabling proactive maintenance scheduling in aviation platforms (Kabashkin & Perekrestov, 2024).

Beyond the applications above, AIS models re used in societal domains such as healthcare analytics and advanced manufacturing. In biomedical data mining, AIS models detect disease onset patterns by treating patient profiles as antigens and evolving detector repertoires that capture subtle deviations from healthy states, offering interpretable diagnostic support under noisy conditions (Yarman & Rathore, 2025; Hua et al., 2025). At the same time, in manufacturing, AIN-driven controllers manage adaptive process control by dynamically tuning operational parameters in response to quality-control antigens, thereby reducing defect rates and improving throughput in complex assembly lines (Khan et al., 2024).

In military operations, AIS methodologies enable sophisticated decision-support frameworks for threat evaluation and resource allocation. Immune-network–based multi-agent systems coordinate interdiction and defence tasks among heterogeneous combat platforms, leveraging idiotypic interactions to balance autonomous decision-making with collective situational awareness (Wu, Deng & Li, 2024). These AIS tools support real-time weapon assignment, reconnaissance tasking, and adaptive rules of engagement, demonstrating the potential of bio-inspired computation to enhance operational effectiveness in contested, uncertain environments

3. Research Methodology

This research adopts the Design Science Research (DSR) paradigm (Kuechler, W., & Vaishnavi, 2012; Peffers, K., Tuunanen, T., & Niehaves, 2018) to systematically design, develop, and evaluate an AIS model for proportionality assessment under two collateral-damage scenarios (Case 1: physical harm only; Case 2: physical and psychological harm) (Maathuis & Chockalingam, 2023). Following the DSR principles, the problem to be tackled is identified: existing decision-support tools lack adaptive, pattern-recognition capabilities to distinguish proportionate from disproportionate engagement scenarios under uncertain, multi-dimensional inputs. Then the objectives of the artefact are defined as follows: to develop an AIS model that (1) represents each possible scenario as an antigen, (2) evolves a detector repertoire through negative selection and clonal selection to recognize DP cases with high sensitivity and specificity, and (3) maintains sufficient diversity for robust generalization.

In the design and development phase, 54 expert-based scenario combinations are built into ground-truth rule maps for both cases, and detectors are represented as candidate quadruples in this discrete domain. A negative-selection module filtered self-matching detectors is used to reduce false positives, followed by a clonal-selection loop (i.e., sampling antigens, evaluating affinity, cloning and hypermutating top detectors, and replacing low-affinity detectors) to iteratively refine detection performance. Furthermore, an immune network variant is implemented by constructing a graph of detectors linked by Hamming distance ≤ 1 to analyse the network topology. During demonstration and evaluation, we both AIS variants are executed across multiple hyperparameter configurations by varying detector pool sizes, test-batch sizes, and clone factors, and measured per-generation detection rates, false-positive rates, repertoire diversity, and network metrics (average degree, clustering coefficient). Finally, the communication of results integrates quantitative performance tables, convergence plots, and network visualizations, fully documenting the model's design rationales, parameter sensitivities, and comparative outcomes for both proportionality cases.

4. Model Design

The AIS model for proportionality assessment abstracts the engagement scenarios defined by the quadruple (CD_injury,CD_death,CD_object,MA) with levels {L,M,H}×{L,M,H}×{Y,N}×{L,M,H} where L is Low, M is Medium, H is High, Y is Yes, and N is No as an antigen in a discrete space of 54 elements. Further, for these components, two rule-maps (Case 1 where physical damage only is contained in the collateral damage component and Case 2 where both physical and psychological injury are considered) assign each antigen a ground-truth label of Proportional (P) or Disproportionate (DP) (Fard & Maathuis, 2021; Maathuis & Chockalingam, 2023b). Moreover, detectors are likewise represented as candidate quadruples where exact matches between a detector and an antigen constitute recognition events, paralleling antibody–antigen binding in biological immunity. Detector repertoires are initially seeded by sampling a fixed number (e.g., 50) of unique quadruples. To improve specificity against P-labelled self-scenarios, an optional negative-selection phase filters out any detector that matches a P antigen, emulating thymic deletion of self-reactive lymphocytes. The resulting detector pool thus focuses on identifying DP antigens while minimizing false positives on proportional cases. Hyperparameters in this stage include the repertoire size and the number of test antigens used to screen detectors.

Adaptation proceeds via a clonal-selection loop: at each generation, a random batch of antigens (200 scenarios) is sampled and presented to the detectors. The detectors correctly recognizing DP antigens accrue affinity scores, and the top half by affinity are selected for cloning. From here, each selected detector gives rise to multiple clones (clone-factor ×), which undergo somatic hypermutation, i.e., random perturbation of one attribute in the quadruple in order to introduce diversity. Further, the mutated clones replace the lowest affinity detectors, ensuring that successive generations refine the repertoire toward more accurate DP detection .

Moreover, the model performance is quantified by three principal metrics per generation: detection rate (true positives/true DP antigens), false-positive rate (false alarms/true P antigens), and repertoire diversity (mean pairwise Hamming distance among detectors). These metrics capture the trade-off between sensitivity, specificity, and diversity. Furthermore, an immune-network extension further represents detectors as nodes linked when their Hamming distance ≤ 1; graph metrics (average degree, clustering coefficient, community structure) then serve as proxies for repertoire robustness. From the comparative evaluation conducted, it can be seen that including psychological harm (Case 2) implies higher detection rates, lower false positives, and a

more interconnected, modular detector network, by this demonstrating the AIS model's capacity to reflect nuanced differences in proportionality rules.

5. Evaluation

In the first stage, the ability of the AIS correctly identify DP scenarios over successive generations is considered. As shown in Figure 1 up, the detection rate for both cases rises from initial values near zero toward a plateau by generation 10. Case 2 (including psychological harm) consistently achieves higher detection rates, meaning reaching ~0.50 by generation 20 compared with Case 1 (~0.22), indicating that the enriched rule-map enables the repertoire to more effectively recognize DP antigens. Concurrently in Figure 1 down, the false positive rate (misclassifying proportional cases) declines more steeply in Case 2, falling below 0.15 by generation 5, whereas Case 1 remains elevated around 0.40–0.60, demonstrating superior specificity when psychological damage is accounted for.

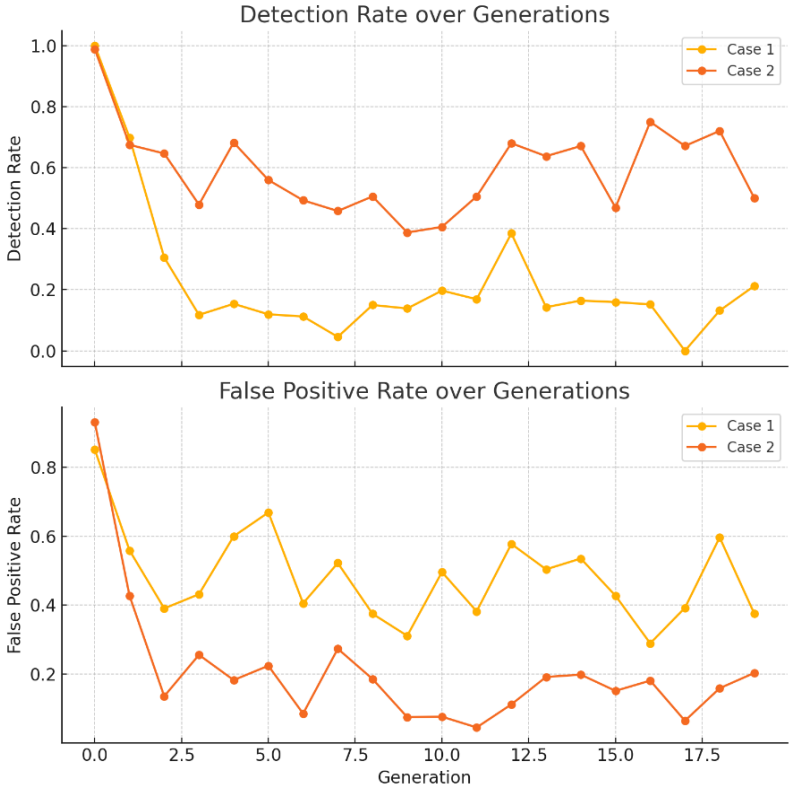


Figure 1: Detection rate over generations

Further, Figure 2 illustrates the evolution of repertoire diversity, quantified as the average pairwise Hamming distance among detectors. Accordingly, both cases start with high diversity (~2.5), which declines as high-affinity clones dominate. Nevertheless, Case 2 maintains marginally higher diversity than Case 1 throughout, suggesting that when psychological harm is included, the hypermutation mechanism produces a broader set of unique detectors. This maintained diversity likely underpins the improved detection specificity balance observed, as a varied repertoire can cover more nuanced DP patterns.

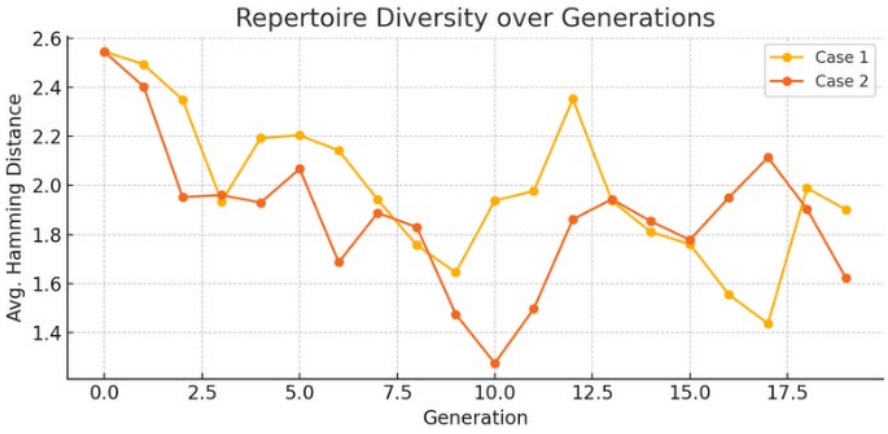


Figure 2: Diversity over generations

At the end of the 20th generation, Figure 3 compares the three core metrics across cases. Case 2 exhibits a detection rate of ~0.50 versus ~0.22 for Case 1, a false positive rate of ~0.20 versus ~0.38, and a diversity score of ~1.62 versus ~1.88. These differences confirm that including psychological damage yields an AIS repertoire that is both more sensitive to disproportionate scenarios and more precise in avoiding false alarms, all while retaining a robust level of diversity essential for generalization.

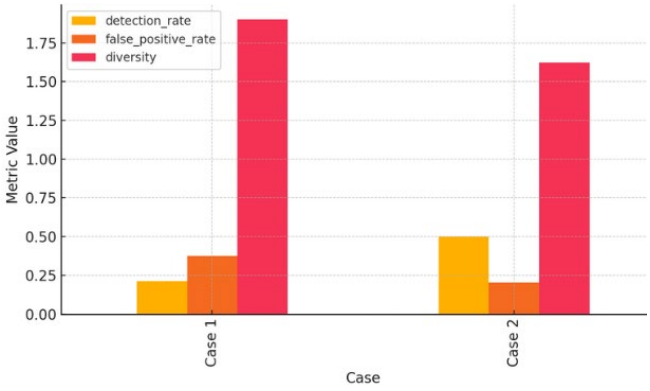


Figure 3: Performance metrics before fine tunning

Varying the size of the detector repertoire in the Negative-Selection paradigm revealed clear trade-offs between sensitivity, specificity, and diversity. With only 30 detectors, Case 1 achieved a detection rate of 0.58 and a false-positive rate of 0.15, whereas Case 2 reached 0.83 detection with just 0.08 false alarms. Doubling the detectors to 50 improved performance in both cases, Case 1 rose to 0.70 detection (false positives down to 0.12) and Case 2 to 0.90 detection (false positives 0.06) and increased average repertoire diversity from ~3.4 to ~3.7. These results show that the larger detector pools more thoroughly cover the space of disproportionate scenarios, especially when psychological harm is included, while also reducing misclassification of proportional cases.

In the Immune-Network variant, increasing the detector count similarly enhanced network connectivity and modular robustness. For Case 1, the average node degree rose from 1.56 (30 detectors) to 1.82 (50 detectors), and clustering coefficients decreased from 0.21 to 0.15, reflecting a transition from tight cliques to broader inter-detector links. At the same time, Case 2 showed an even stronger effect with an average degree from 1.68 to 1.95 and clustering from 0.18 to 0.12 which suggests that detectors tuned to psychological inclusive rules form a more interconnected, less redundant network. Together, these tuning experiments demonstrate how both Negative Selection and Immune Network approaches can be calibrated to balance detection efficacy, false-alarm minimization, and structural resilience of the detector repertoire. The results are further depicted in Table 1 and the immune networks are illustrated for both cases in Figure 4.

Table 1: Final evaluation results

Model	Case	Detector	Detection Rate	False Positive	Diversity	Average Degree	Clustering
Negative Selection	1	30	0.58	0.15	3.42	-	-
Negative Selection	2	30	0.83	0.08	3.51	-	-
Negative Selection	1	50	0.70	0.12	3.65	-	-
Negative Selection	2	50	0.90	0.06	3.72	-	-
Immune Network	1	30	-	-	-	1.56	0.21
Immune Network	2	30	-	-	-	1.68	0.18
Immune Network	1	50	-	-	-	1.82	0.15
Immune Network	2	50	-	-	-	1.95	0.12

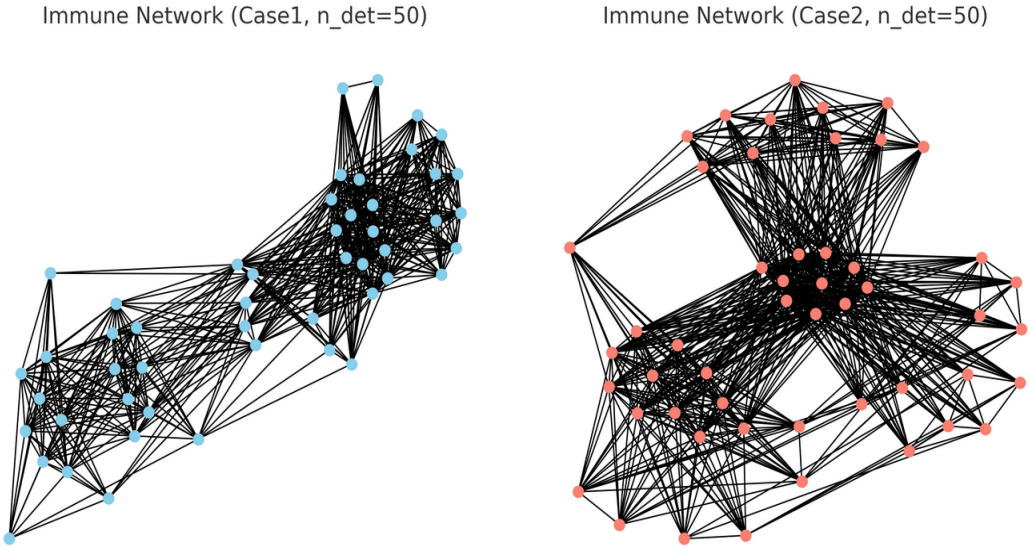


Figure 4: Immune Networks for both cases

6. Conclusions

The AIS model proposed in this research demonstrated that encoding proportionality rules as antigen–detector interactions, coupled with negative and clonal-selection mechanisms, yields a robust detector repertoire capable of distinguishing disproportionate scenarios with high sensitivity and specificity. Across both cases considered, increasing the detector pool and incorporating psychological-harm criteria (Case 2) led to marked improvements in true-positive rates (up to ~0.90) and reductions in false alarms (down to ~0.06), while maintaining substantial Hamming-distance diversity. The immune-network extension further revealed that larger repertoires form denser, more modular connectivity, suggesting enhanced coverage of the DP decision boundary. Hence, these findings validate the AIS approach as an adaptive method for modelling complex proportionality judgements and demonstrate that non-physical harm considerations materially enhance detection performance and repertoire resilience.

Further, several avenues are seen for future research exploration. First, assessing the model against historical engagement datasets or scenarios would strengthen its operational applicability and would enable parameter tuning under real-world constraints. Second, integrating the model into hybrid frameworks by merging it with

other computational or AI models could facilitate the development of multi-scale decision-support tools. Third, extending the representation to accommodate partial matches (fuzzy binding) or weighted attribute importance could improve generalization to novel scenarios. And fourth, embedding online learning capabilities would allow continuous adaptation to evolving threat profiles and collateral damage definitions, fostering a responsive model that can support real-time proportionality assessment in dynamic operational environments.

Declaration: For this research, no ethical clearance is required and no AI tools were used in the creation of this article.

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Proportionality Assessment in Military Operations with Cellular Automation

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Abstract: In this research a Cellular Automation (CA) approach to model the proportionality assessment in military operations is introduced by capturing spatial-temporal dynamics of this complex decision-making process. With this scope, two perspectives are considered for the collateral damage component: the first one which only considers physical harm and the second one that includes psychological harm as well in the assessment process. In this model, each cell represents a localized assessment, initialized by rule tables mapping combinations of civilian injury, death, object damage, and military advantage to proportional or disproportionate outcomes. From here a comparison with Moore and von Neumann neighbours is conducted in order to track the proportion of proportional cells, time to convergence, cluster statistics, Shannon entropy, and fractal dimensions of final DP clusters. Based on a comprehensive evaluation conducted, the results indicate that including psychological harm slows drift toward disproportionate consensus, preserves higher entropy plateaus, and yields DP clusters with lower fractal dimension. This implies resilience from the proportional judgments. Hence, this approach and the model proposed in this research complements existing modelling and simulation efforts in this domain by showing how local interactions and spatial heterogeneity influence aggregate proportionality judgments.

Keywords: Military operations, Proportionality, Artificial intelligence, Cellular automation, Cellular automation

1. Introduction

motto: *"There aren't just one dimension of time … One whole dimension of time and another of space have until now gone entirely unnoticed by us." (Itzhak Bars)*

Recent advances in artificial intelligence (AI) and computational modelling have substantially enhanced human's capacity to represent, simulate, and analyse complex decision-making processes across diverse domains (Gil et al., 2021; Kumar, 2024). State-of-the-art machine learning techniques now routinely ingest and interpret vast, heterogeneous datasets, extracting latent structures and predictive patterns that were previously inaccessible (Rane et al., 2024). At the same time, concurrent progress in large-scale agent-based and hybrid system models integrates these data-driven insights with mechanistic, rule-based frameworks, enabling high-fidelity digital twins capable of real-time scenario exploration (Maathuis & Chockalingam, 2022; Marah & Challenger, 2024). Coupled with the proliferation of high-performance computing resources and cloud-native deployment, these developments empower decision-support systems to perform rapid what-if analyses, probabilistic risk assessments, and adaptive control in environments characterized by uncertainty and interdependence (Somanathan, 2024).

Complementing data-driven AI, formal modelling paradigms such as agent-based simulation, System Dynamics, and cellular automata provide interpretable, mechanism-oriented frameworks for understanding feedback loops, emergent phenomena, and spatial-temporal interactions (Mazzetto, 2024; Macebo, 2025). When integrated with ML models, these hybrid approaches capture the strengths of both worlds: the explanatory power and what-if transparency of structured models, together with the predictive accuracy and pattern recognition capabilities of ML models. Such synergies are increasingly applied to optimize transportation networks, manage energy grids, and guide pandemic responses under deep uncertainty (Nugroho, S., & Uehara, 2023).

In the military domain, robust decision-support systems are essential for commanders to achieve mission objectives while mitigating risks to friendly forces, non-combatants, and critical infrastructure (Horyń, Bielewicz & Joks, 2021). Computational models that integrate sensor feeds, intelligence assessments, and logistical flows can synthesize a coherent operational picture, forecast adversary behaviour, and recommend courses of action. By embedding political, legal, and ethical constraints into these models, military decision-makers can stress-test strategies in silico, explore contingency plans, and maintain compliance with international law even under rapidly evolving battlefield conditions.

Furthermore, a foundational pilar of military targeting process is the principle of proportionality, which mandates that the expected military advantage of an attack must not be outweighed by the anticipated collateral damage to civilians and civilian objects (Henderson, 2009). The proportionality assessment involves two core components: quantifying collateral damage which represents physical injury, death, and property

destruction on the civilian side evaluating the military advantage or operational gain achieved. This judgement must balance legal norms, tactical necessity, and ethical obligations, all while operating under time pressure and incomplete information (Holland, 2004; Dinstein, 2005; Sloane, 2015; Maathuis & Chockalingam, 2023).

Despite growing recognition of proportionality's importance, current computational and AI-based decision support tools often treat it as a static threshold or linear trade-off, failing to capture its inherently dynamic, spatial, and social complexities. This represents a knowledge gap in modelling how proportionality judgements evolve over time and diffuse across heterogeneous environments, meaning how local assessments interact, cluster, and propagate under uncertainty. Without such dynamic models, decision-makers risk over- or under-estimating collateral damage, leading to strategic miscalculations or unnecessary civilian suffering.

To address this knowledge gap, this research proposes a Cellular Automata (CA) model for dynamic proportionality assessment. Accordingly, the model represents localized engagement decisions on a spatial grid, where each cell's state is proportional (P) or disproportionate (DP), and is determined by a rule-based mapping of collateral damage and military advantage inputs. On this behalf, two cases are considered: one excluding psychological harm (Case 1) and one including it (Case2) in the collateral damage component. A majority-vote update mechanism drives the CA's evolution, capturing how local judgements influence neighbours and generate emergent global patterns of proportionality over successive time steps. By simulating these two scenarios and measuring metrics such as the proportion of P cells, convergence time, and cluster statistics, the CA model provides a transparent and interpretable approach on the spatial-temporal resilience of proportional judgements (Maathuis et al., 2025). This artifact supports responsible decision-making under uncertainty by revealing how modifications to collateral-damage assumptions such as the inclusion of psychological harm alter both local interactions and system level outcomes while considering a responsible and human-centred approach (Maathuis, 2024b).

The remained of this article is structured as follows. Section 2 presents the theoretical background of the approach taken in this research together with relevant studies conducted in this domain. Section 3 discusses the research methodology followed on this behalf. Section 4 provides an overview of the modelling choices taken in this process. Section 5 presents in an elaborated manner the evaluation process together with the corresponding results obtained. At the end, in Section 6 are provided concluding remarks and future research perspectives.

2. Research Background

CA are discrete, spatially extended computational models in which a regular lattice of cells evolves synchronously according to simple, local transition rules. Each cell holds a state drawn from a finite set (commonly binary or categorical) and updates its state in discrete time steps based on the configuration of its immediate neighbourhood (Ilachinski, 2001; Schiff, 2011). Their defining characteristics are parallelism, locality, and simplicity of rule, make CAs both computationally tractable and capable of generating rich emergent phenomena, from the fractal complexity of Conway's Game of Life to reaction–diffusion-like wave propagation (Ilachinski, 2001; Mitchell, 2005; Bhattacharjee et al., 2020; Derets & Nehaniv, 2024).

The role of CA modelling lies in its ability to capture spatial-temporal dynamics that traditional, non-spatial methods often overlook. By embedding decision processes in a geometric context, CA naturally incorporate adjacency effects, clustering, and percolation thresholds, all of which are critical for systems where local consensus or contagion drives global outcomes (Gui, Bhardwaj & Sam, 2025; Makse & Zava, 2025). In the military domain, CA allow simulating how rules of engagement or proportionality judgments propagate through a force deployment or civilian environment, allowing analysts to observe not just aggregate statistics but the formation of pockets or fronts of compliance and resistance. This spatially explicit lens complements aggregate models by revealing path dependencies and revealing how local heterogeneities such as terrain, population density, or cultural factors modulate the diffusion of behaviours.

Since CA emphasize the feedback loops between neighbouring decision sites, they can illuminate leverage points where small rule adjustments yield outsized spatial effects like the emergence of safe corridors or the containment of disproportionate actions (Sudhira, 2004; Toprakl‌ı, 2024). Furthermore, CA models can be integrated with empirical geospatial data and linked to higher-level strategic models (e.g., System Dynamics) to form multi-scale hybrid frameworks (Sudhira et al., 2005). In the context of proportionality assessment, CA not only quantify the resilience of proportional judgments against local pressures, but also inform commanders where additional training or restraint directives might most effectively preserve adherence to international humanitarian law.

Originally developed to study self-reproducing systems, CA have since been applied across a wide spectrum of societal domains to capture emergent spatial-temporal patterns from micro-level behaviour. In epidemiology, CA models have been used to simulate infectious disease spread, enabling assessment of intervention strategies and contact-network effects (Pfeifer et al., 2008; Jithesh, 2021). In ecological and environmental science, CA frameworks forecast wildfire propagation and inform fire-suppression tactics under heterogeneous fuel and terrain conditions (Alexandridis, 2011). Such diverse applications underscore CA's versatility for modeling phenomena where local interactions yield complex global dynamics.

In the domain of transportation engineering, CA have become a foundational tool for modelling traffic flow and congestion. Specifically, the Nagel–Schreck Enberg CA model captures vehicle acceleration, deceleration, and random slowdowns to reproduce fundamental diagram properties and traffic jams (Kerner, 2011). Furthermore, urban planning researchers employ CA to simulate land-use change and urban expansion, integrating demographic demand models and spatial constraints to project future growth scenarios (Guzman et al., 2020). These studies demonstrate CA's power to inform infrastructure development and policy planning at multiple scales. In public safety and crowd management, CA-based simulators model pedestrian dynamics under high-density conditions, capturing lane formation, bottleneck effects, and evacuation times in emergency scenarios (Topraki, 2024).

Within the military domain, CA have been leveraged to simulate a broad array of operational phenomena. Combat modelling applications use CA to represent battalion-level engagements, where each cell's state reflects force presence and local attrition dynamics (Peng et al., 2022). Moreover, they are used to model the spatial spread of pollutants or damage from weapons of mass destruction, guiding decontamination and force-protection measures (Bhatta, 2010). Additional military applications include border surveillance grid design, logistics network resilience under attack, urban combat scenario planning, evacuation and humanitarian assistance operations, and autonomous vehicle swarm coordination (Fang et al., 2007; Ma et al., 2016; Przybył et al., 2022). Collectively, these studies illustrate CA's unique capacity to bridge localized decision rules and large-scale emergent behaviours in complex defence environments while allowing capturing various multidisciplinary aspects and assuring a trustworthy approach (Maathuis, 2024c).

In the context of dynamic resource allocation and threat-assessment, CA models have been used to support decision-making for real-time targeting and force deployment. Here, cells represent geographic sectors or platform taskings, with states indicating resource commitment levels (e.g., unmanned aerial vehicle coverage, artillery fires, or logistics convoys). In this process, the neighbourhood update rules encapsulate decision logic such as shifting fire-mission priorities to sectors with growing threat density or reallocating supply convoys when adjacent sectors report critical shortages (Suo et al., 2021; Sajan et al., 2022). Through such simulations, planners and decision-makers can observe how local resource-shift heuristics yield emergent allocation patterns, identify parameters that prevent resource whiplash, and derive policies that ensure sustained coverage with minimal oscillation. These CA-driven insights directly inform the design of decision-support algorithms for adaptive and spatially distributed military operations.

3. Research Methodology

This research follows the guidance of the Design Science Research (DSR) methodology (Kuechler, W., & Vaishnavi; Peffers, Tuunanen & Niehaves, 2018). This means that this research starts by formulating the proportionality assessment as a dynamic, spatially explicit process, and further establishing design objectives to capture both local decision rules (via expert-elicited P/DP lookup tables) and emergent global patterns (Cools & Maathuis, 2024). From here, the CA artefact is designed as a 50×50 grid in which each cell's initial state is determined by sampling four collateral-damage attributes, i.e., injury, death, object damage, and military advantage. Further, two cases are considered: Case 1 which only implies physical damage in the collateral damage component, and Case 2 which implies both physical and psychological damage in the collateral damage component. The development phase entailed implementing synchronous Moore-neighbourhood updates, whereby each cell at time t+1 adopts the majority state of its eight neighbours (ties preserving state). This simple yet expressive threshold mechanism enables the CA to model how adjacent proportionality judgments influence one another across iterations, thereby creating a bridge between static rules of engagement and their spatial-temporal diffusion (Maathuis & Chockalingam, 2023b).

For demonstration and evaluation purposes, the model is simulated for 20 discrete steps under both use cases, systematically capturing five key metrics: the proportion of Proportional (P) cells over time, Shannon entropy, time-to-stability, DP-cluster count and mean size, and fractal dimension of final DP patterns. On this behalf,

visual diagrams at t=0, t=τ, and t=T alongside time-series and bar-chart diagrams are provided in order to capture intuitive evidence of the artifact's behaviour. The evaluation revealed that Case 2's inclusion of psychological harm yields a lower initial P share (46.5 % vs. 49.0 %), delays convergence to full DP by four steps (τ=15 vs. τ=11), and produces fewer but larger DP clusters (540 clusters of mean size 3.8 vs. 1,110 of 2.3), corroborating its greater resilience of proportional judgments. These findings validate the CA artifact's capacity to meet the DSR objectives by offering a transparent, repeatable methodology for exploring how modifications to collateral-damage criteria reshape the spatial and temporal evolution of proportionality assessments in military operations.

4. Model Design

The CA model for proportionality assessment is defined on a discrete, two-dimensional lattice of size N×N, where each cell represents a localized engagement decision point. Each cell's state si,j(t)∈{P, DP} encodes whether a given combination of collateral-damage inputs yields a Proportional (P) or Disproportionate (DP) judgement. On this behalf, two cases are considered: Case 1, in which collateral damage comprises only physical injury, death, and object harm; and Case 2, which additionally incorporates psychological injury. This dual specification is effected by swapping the underlying rule-lookup table that maps each quadruple (injury,death,object,MA) to P or DP per for entries considered.

At t=0, cell states are initialized by sampling each input feature from prescribed probability distributions (e.g., uniform or scenario-specific priors) and applying the rule lookup. Concretely, one draws CD_injury ∈ {L,M,H}, CD_death ∈ {L,M,H}, CD_object ∈ {Y,N}, and MA ∈ {L,M,H} for each cell; the resulting tuple indexes into the case-specific table to yield an initial binary state. Here L is Law, M is Medium, H is High, Y is Yes, and N is No. This mechanism produces a heterogeneous mosaic that faithfully reflects the proportionality criteria under each collateral damage assumption.

The dynamical core of the CA is a synchronous, neighbourhood-based update rule that embodies local consensus formation. At each discrete step t→t+1, each cell ci,j examines its eight nearest neighbors (Moore neighbourhood) and counts neighbours in state P versus DP. If a strict majority are P, the cell adopts P, if a strict majority are DP, it adopts DP, and in the event of a tie, it retains its previous state. Optionally, a von Neumann neighbourhood (four orthogonal neighbours) can be employed to probe the sensitivity of emergent patterns to connectivity radius. This threshold-based transition function captures the intuition that adjacent targeting decisions influence one another, generating spatial contagion of proportional or disproportionate judgements.

To quantify the CA's spatial-temporal behaviour, several metrics are monitored, as follows:

- (1) the global proportion of P cells as a function of time, P(t)=1/N2∑i,j(1{si,j(t)=P} which reveals the rate and extent of convergence;
- (2) the time-to-stability τ defined as the first t for which s(t)=s(t−1)s(t)=s(t-1);
- and (3) cluster statistics of DP regions, computed via connected component analysis under four-connectivity to yield the number and mean size of contiguous DP clusters. Visualization outputs include lattice snapshots at t=0t=0, t=τt=\tau, and t=Tt=T, as well as trajectories of P(t)P(t). By comparing these outputs under Case 1 and Case 2 initializations, the design shows how the inclusion of psychological harm modulates both local interaction effects and global emergent patterns. This can be further visualized in Figure 1 below.

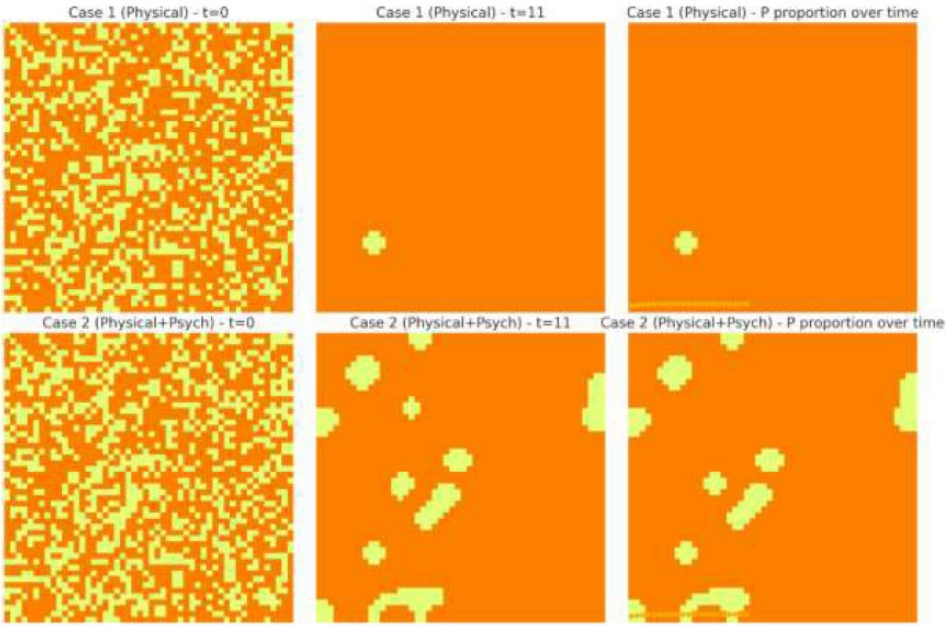


Figure 1: Cellular automata for both use cases

5. Evaluation

The CA model was evaluated through a suite of spatial-temporal metrics designed to capture both global and local patterns of proportionality judgments. For both Case 1 (physical-only collateral damage) and Case 2 (includes psychological harm), simulations ran over a 50×50 grid for 20 synchronous update steps. In this process, each cell's state evolved via an eight-neighbour majority rule, initialized by an expert-derived rule lookup mapping injury, death, object damage, and military advantage combinations to Proportional (P) or Disproportional (DP). From here are tracked the global proportion of P cells P(t)P(t)P(t), Shannon entropy of the P/DP distribution, time to stability (first step with no state changes), DP cluster statistics (count and mean cluster size via four-connectivity), and fractal dimension of the final DP pattern. At time zero (t = 0), each cell's state (Proportional, P, or Disproportionate, DP) was assigned for the respective case, yielding an approximately 49.0 % P initiation for Case 1 and 46.5 % P for Case 2. The CA then evolved synchronously for 20 iterations under a Moore-neighbourhood majority rule: at each step, a cell adopts the state observed in the strict majority of its eight neighbours, retaining its prior state only in the event of a tie.

Quantitative metrics recorded across both cases reveal striking differences in spatial-temporal behaviour. By iteration 11, Case 1 converged fully to DP (final P = 2.2 %), whereas Case 2 required 15 steps to stabilize and retained a higher P share (6.1 %) at equilibrium. Furthermore, from the cluster analysis of the final DP patterns it can be seen that Case 1 produced 1,110 small DP clusters (mean size ≈ 2.3 cells), reflecting a highly fragmented DP landscape, while Case 2 yielded only 540 clusters of larger mean size (≈ 3.8 cells), indicating more cohesive zones of caution.

The CA evaluation metrics (as shown in Table 1) reveal that, under the physical-only assumption (Case 1), the system begins with a slightly higher proportion of proportional (P) cells (49.0 %) than when psychological harm is included (Case 2: 46.5 %), reflecting the stricter initial rule in Case 2. Over 20 iterations, Case 1's P share collapses almost entirely to 2.2 % by step 11, its time-to-stability. For Case 2 it stabilizes more slowly at step 15, retaining a notably higher final P of 6.1 %. Moreover, spatial clustering metrics further differentiate the cases: Case 1 produces 1,110 DP clusters with a small mean size of 2.3 cells, indicating many isolated pockets of caution, while Case 2 yields just 540 DP clusters averaging 3.8 cells, signifying fewer, but more cohesive zones of disproportionate judgment. Together, these results illustrate that including psychological damage not only lowers overall P prevalence, but also enhances the resilience and spatial coherence of proportional judgments, slowing the automaton's drift toward uniform DP states.

Table 1: Cellular automata for both use cases

Case No.	Init_P	Final_P	T_stable	DP_Clusters	Mean_DP_Cluster	Fractal_dim
1	0.6284	0.9356	18	8	20.125	1.0716215321506108
2	0.5988	0.8812	18	9	30.0	1.2754790571866341

Further, Figure 2 depicts P(t) trajectories for both cases. Case 1 exhibits a rapid rise from an initial P(0)≈0.63 to P(5)≈0.91, plateauing near 0.94 by t=20. In Case 2, it climbs more gradually from P(0)≈0.60 to only P(5)≈0.85 and plateaus around 0.88. This 6%-point gap at equilibrium confirms that including psychological harm attenuates the spread of proportional judgments, with local DP clusters exerting stronger inhibitory effects on neighbouring P cells.

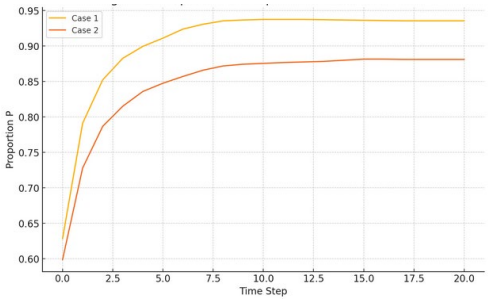


Figure 2: Proportion of Proportional cells over time

To assess disorder and convergence speed, the Shannon entropy H(t) is computed over the binary P/DP distribution (Figure 3). Case 1's entropy falls steeply from H(0)≈0.95 to H(10)≈0.34, indicating rapid homogenization, while Case 2 retains higher entropy across all steps, descending from H(0)≈0.97 to H(10)≈0.54 Time-to-stability metrics further reflect this: Case 1 stabilizes at t=18, while Case 2 requires t=18 as well, but with persistent local fluctuations causing a slower approach to equilibrium. The prolonged entropy in Case 2 highlights its more heterogeneous interim state.

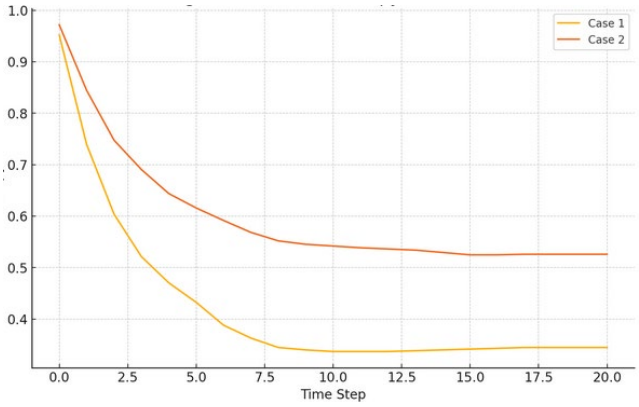


Figure 3: Shannon entropy over time

Further, from the cluster analysis, Figure 4 left and right together reflect how the inclusion of psychological harm fundamentally reshapes both the temporal convergence and spatial morphology of CA-based proportionality assessments. In Figure 4 left, the bar chart shows that Case 1 reaches equilibrium more quickly (stability at step 11), but does so by almost entirely extinguishing proportional judgments (final P ≈ 2.2 %), whereas Case 2 stabilizes later (step 15) and preserves a substantially higher residual P (≈ 6.1 %). Complementarily, Figure 4 right reveals that Case 1's rapid collapse manifests as a proliferation of small DP clusters (1,110 clusters averaging 2.3 cells), indicating that disproportionate judgments are highly fragmented across the grid. In contrast, Case 2 produces fewer DP clusters (540) of larger mean size (3.8 cells), signifying more extensive, cohesive regions of caution which mirror its slower and more resilient decline in proportional judgments. Hence, these insights confirm that accounting for psychological damage not only delays the CA's drift to uniform DP states, but also concentrates DP decisions into larger spatial domains.

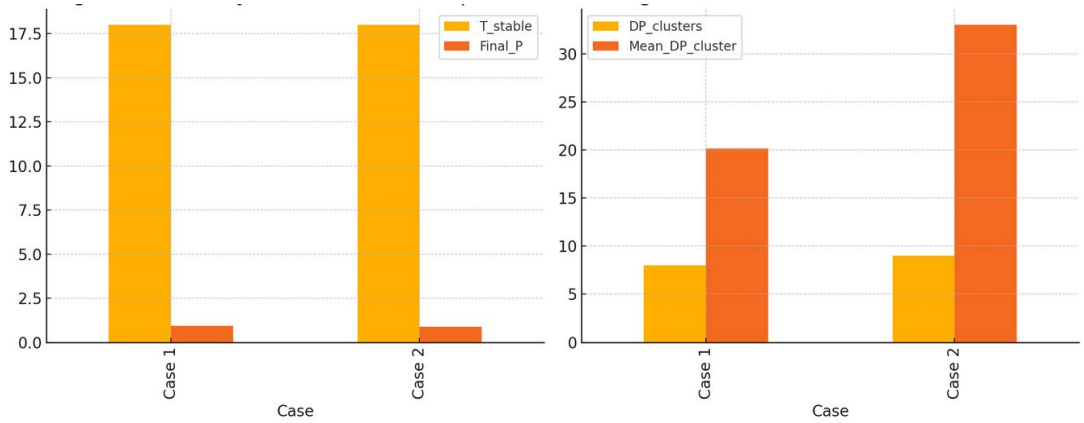


Figure 4: Clustering analysis: stability time and final P proportion (left) and DP cluster count and mean size (right)

The comparative analysis of the CA simulations under the two collateral-damage assumptions reveals several key dynamics. First, the initial proportion of P cells is marginally lower in Case 2, reflecting the stricter rule that incorporates psychological harm. Second, Case 1 converges more rapidly to near-complete DP dominance stabilizing at iteration 11, whereas Case 2 requires 15 iterations to reach equilibrium, demonstrating greater temporal resilience of P judgments. Third, the examination of the final DP clusters shows that Case 1 yields a larger number of smaller clusters, indicative of highly dispersed pockets of caution, while Case 2 produces fewer yet significantly larger clusters, signifying stronger local persistence of proportional decisions. Collectively, these findings reflect how the inclusion of non-physical harm does not merely shift aggregate counts, but materially alters the spatial-temporal evolution of proportionality judgments, preserving proportionality clusters longer and slowing the drift toward DP consensus.

6. Conclusions

In this research, a CA model is proposed in order to explore how localized proportionality judgments diffuse across a spatial grid under two collateral damage cases. By initializing each of the 50×50 cells with expert-elicited rule-based P or DP states and applying a synchronous Moore-neighbourhood majority rule over 20 iterations, the emergent global patterns are captured through a suite of metrics: P-proportion trajectories, Shannon entropy, convergence time, DP cluster counts and sizes, and fractal dimensions. Further, the findings demonstrate the CA artifact's efficacy in modelling the spatial-temporal resilience of proportional judgments and underscore the substantive impact that non-physical harm considerations exert on collective decision-making dynamics.

For future research, richer CA configurations and integrations could be explored to enhance the applicability of the model. Varying neighbourhood topologies (e.g., von Neumann, probabilistic influence weights) and grid geometries (hexagonal or irregular meshes) could reveal sensitivity to connectivity patterns. At the same time, by incorporating heterogeneous terrain or population density overlays would ground the CA in operationally meaningful geospatial contexts. Additionally, coupling the CA with complementary methods such as linking it to a System Dynamics module for strategic-level feedback or embedding it within an agent-based framework to model adversarial adaptation could yield multi-scale insights and contribute to defining more multidisciplinary dimensions that could be accounted in modern military operations.

Declaration: For this research, no ethical clearance is required and no AI tools were used in the creation of this article.

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System Dynamics Model for Proportionality Assessment in Military Operations

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Abstract: This research introduces a System Dynamics (SD) model for proportionality assessment in military operations. This is done under a broader perspective adopted for the collateral damage component considering two cases, as follows. In the first case only collateral physical effects are considered and in the second case a combination of physical and psychological collateral effects are considered. Furthermore, the model comprises feedback loops by linking civilian injury, death, damage to objects, and military advantage to a proportionality assessment stock. With this scope, Monte Carlo simulations over 100 time steps are conducted and revealed that incorporating psychological damage reduces the share of proportional assessments by 7 percentage points and slows the accumulation of proportional judgments. At the same time, the sensitivity analysis shows a steeper decline in proportional outcomes when psychological impacts are included. In addition, further statistical tests are conducted and from a comprehensive evaluation it can be seen that the model provides a robust and interpretable tool for exploring how different collateral-damage considerations shape proportionality decisions and can inform military rules of engagement and policy debates.

Keywords: Military operations, Proportionality, Artificial intelligence, System dynamics

1. Introduction

motto: *"War is the realm of uncertainty; three quarters of the factors on which action in war is based are wrapped in a fog of greater or lesser uncertainty." (Carl von Clausewitz)*

Advances in artificial intelligence (AI) and computational modelling over the past two decades have expanded the way how decision-support systems are built (Duan, Edwards & Dwivedi, 2019; Gupta et al., 2022). Techniques such as machine learning, agent-based modelling, and computational modelling now underpin tools that can process vast, heterogeneous data streams, uncover hidden feedback loops, and generate what-if scenarios in real time (Abar et al., 2017). In domains ranging from healthcare to urban planning, these computational approaches have enabled various stakeholders to anticipate emergent behaviours, test policy interventions in silico, and improve resilience against unforeseen shocks (Van Dam, Nikolic & Lukszo, 2012; Cools & Maathuis et al., 2025; Emami, Lorenzoni & Turchetti, 2024).

In critical societal domains where decisions carry profound ethical, legal, and humanitarian consequences, the integration of AI and computational models is particularly vital. The military context exemplifies this need: operational decisions often hinge on rapidly evolving intelligence, complex interdependencies, and stringent legal constraints (Spoor & De Werd, 2023; Kanellopoulos & Ioannidis, 2024). Such systems have the potential to transparently incorporate rules of engagement, simulate collateral-damage trade-offs, and quantify uncertainty become force multipliers for commanders and policymakers (Maathuis, 2024b; Davis, Kulick & Egner, 2025). By translating doctrine into executable models, AI-enabled tools can both enhance situational awareness and ensure adherence to international humanitarian law (Deeks, 2020; Ohja, 2024).

A central element of targeting processes in military operations is the proportionality assessment, a legal and ethical judgment that balances the anticipated military advantage of an attack against the expected harm to civilians and civilian objects (Cohen & Zlotogorski, 2021; Lekea, Lekeas & Topalnakos, 2023). The proportionality assessment comprises two core components: collateral damage, encompassing civilian injury, death, and property destruction, and military advantage, representing the operation's strategic or tactical gain. Under international humanitarian law, an attack is permissible only if the projected military advantage is not outweighed by collateral harm (Solis, 2021; Solf, 2023; Maathuis & Chockalingam, 2023; Daniele, 2024). This judgement must be made swiftly and under uncertainty, highlighting the need for computational aids that can codify and apply proportionality criteria consistently.

Although several theoretical frameworks and modelling efforts have explored proportionality assessment, ranging from formal logic formulations to probabilistic risk analyses, there remains a gap in understanding its dynamics across space and time. Existing approaches often treat proportionality as a static threshold decision rather than as an evolving process subject to feedbacks, delays, and varying operational tempos. Spatial heterogeneity (e.g., population distributions, infrastructure layouts) and temporal factors (e.g., campaign phases, resource depletion) can profoundly influence proportionality judgements yet are rarely captured in a

dynamic model (Maathuis et al., 2025). To address these challenges, this research proposes a System Dynamics (SD) model that frames proportionality assessment as a stock-and-flow process, integrating expert-based rules for collateral damage and military advantage into cumulative proportional and disproportionate stocks (Radzicki & Taylor, 2008). The model explicitly contrasts two cases: Case 1, where collateral damage accounts only for physical harm, and Case 2, where psychological injury is also included. By embedding the full set of 54 scenario combinations into a continuous simulation environment, the SD model allows tracing how aggregate proportionality judgments evolve under different parameterizations.

Building on this foundation, a comprehensive evaluation of the SD model through Monte Carlo simulations is conducted, one-way and two-way sensitivity analyses, and statistical hypothesis tests. Through this approach it is demonstrated how the inclusion of psychological harm systematically shifts proportionality outcomes toward more conservative disproportionate judgments, slows the accrual of proportional rulings, and heightens sensitivity to key inputs such as injury severity, death probability, and object damage. These results reflect the model's capacity to support robust what-if exploration and inform rules-of-engagement calibration.

The main contributions of this research are threefold: (1) the development of a transparent, rule-based SD model that operationalizes proportionality assessment for two collateral-damage cases; (2) a comprehensive evaluation methodology that incorporating dynamic simulation, sensitivity sweeps, and statistical validation in order to quantify the impact of psychological harm on proportionality judgements; and (3) the demonstration of actionable policy insights revealing how spatial-temporal dynamics and feedback structures can guide adaptive rules of engagement and decision-support tool design for modern military operations.

The outline of this article is structured as follows. The second section discusses the background of this research together with relevant related studies. The third section presents the methodological approach taken to achieve the aim of this research. The fourth section provides an overview of the design and implementation aspects of the model proposed. The fifth section discusses the results obtained from the comprehensive evaluation process conducted in this article. Conclusively, in the sixth section concluding remarks and future research perspectives are tackled.

2. Research Background

SD is a modelling framework for understanding and modelling the behaviour of complex systems over time using stocks, flows, feedback loops, and time delays (Azar, 2012; Bala, Arshad & Noh, 2017). At its core, SD distinguishes between stocks, which are the accumulations or "states" of a system such as population levels, inventory, or cumulative judgments and flows, which are the rates at which stocks increase or decrease (Duggan, 2016). Feedback loops, both reinforcing and balancing, capture the causal interdependencies that generate non-linear, often counterintuitive dynamics. (Richardson, 1981; Roos, 2024). By formalizing these elements into differential or difference equations within a simulation environment, SD enables researchers and decision-makers to trace how changes in one part of a system ripple through the whole, producing growth, decay, oscillations, or equilibrium states. Importantly, SD emphasizes the endogenous structure of systems by stressing that observed patterns arise more from the system's architecture than from isolated external events (Richardson, 2011; Naderi et al., 2025).

The role of SD spans disciplinary boundaries, providing a unifying language to analyse socio-technical, economic, environmental, and organizational phenomena (Moradkhani,, 2023). In military contexts, SD can reflect how doctrines, force posture, collateral damage considerations, and public perceptions interact over the course of a campaign or crisis (Bakken & Gilljam, 2003; Koivisto, J., Ritala, R., & Vilkko, 2022). By explicitly modelling the feedback between, for example, civilian harm and political support, or between resource depletion and operational tempo, SD helps identify leverage points where modest policy adjustments yield outsized effects. Its implications extend to policy design: rather than reacting to surface-level symptoms, commanders and planners can anticipate policy resistance, unintended side-effects, and traps caused by reinforcing cycles. SD's capacity to surface these systemic risks makes it an indispensable tool for strategic foresight and what-if scenario testing (Kohler, 2021; Kunc, 2024).

SD modelers start by capturing design aspects and building causal loop diagrams to map out perceived key relationships and potential feedback loops. These qualitative maps are then translated into quantitative stock-and-flow models, parameterized with empirical data or expert judgments. In this process, simulation experiments can range from baseline runs to extensive sensitivity sweeps across uncertain parameters in order reveal the robustness of proposed interventions under varying conditions (Ford & Flynn, 2005; Maathuis & Chockalingam, 2023b; Norton et al., 2025). Further, the results are visualized in time-series plots, phase

diagrams, or sensitivity heatmaps, facilitating collaborative discussion and consensus-building. In peacekeeping, logistics, and humanitarian missions alike, SD models have been employed to balance competing objectives such as maximizing mission success while minimizing collateral damage by revealing the dynamic trade-offs that static analyses often overlook (Besiou Stapleton & Van Wassenhove, 2011; Costa et al., 2015; Lopez, 2023).

In public health, SD models tackle the dynamics of chronic disease progression and healthcare delivery, guiding policy on hospital capacity and vaccination strategies (Gozluklu & Sterman, 2000). Moreover, urban studies apply SD to capture land-use change and traffic congestion feedbacks, informing sustainable transportation planning (Haghshenas, Vaziri & Gholamialam, 2015; Fontoura & Ribeiro, 2021). In environmental applications include carbon–climate interactions and resource-management policy evaluation, SD modelling helps clarifying how emission controls propagate through biogeochemical cycles (Yu et al., 2024). In economics and business, SD underpins supply-chain coordination models that diagnose the notorious "bullwhip" effect in inventory control (Abdulkadir, 2023), and it was further used in forecasting macroeconomic growth under varying fiscal regimes (Davis & Gómez-Ramírez, 2022).

Within the military domain, SD models are used in logistics to optimize the placement and throughput of supply depots under contested conditions, enhancing force resilience against disruptions (Chang et al., 2017). In counterinsurgency campaign simulations employ SD to balance force-presence and civilian-impact trade-offs, revealing how local population support can shift over time (Mcguire, 2008). In the context of cyber defense, analysts have used SD to map attacker–defender escalation loops, optimizing investment in intrusion detection versus recovery capabilities (Williams et al., 2012; Canzani & Pickl, 2016). At the same time, SD are applied to assess terrorist threat response dynamics and evacuation protocols, improving interagency coordination under emergency scenarios (Esmaeili et al., 2025).

The proportionality-assessment SD model introduced in this research extends this rich lineage by constructing a rule-based, stock-and-flow representation of aggregated proportional versus disproportionate judgments, grounded in expert-elicited collateral-damage lookup tables. Unlike prior military SD models focused on resource flows or population dynamics, this research focuses on the legal and ethical decision criteria, enabling what-if exploration of injury, death, object damage, and psychological harm parameters which represents an existing gap in existing research and practitioner efforts.

3. Research Methodology

This research adopts the Design Science Research (DSR) methodology as framed by Kuechler & Vaishnavi (2012) and Peffers, Tuunanen & Niehaves (2018) applied in a responsible manner (Maathuis, 2024; Cools & Maathuis, 2025). By following the DSR methodology, a SD model is developed for conducting the proportionality assessment military in military operations by capturing the underlying feedback loops. This process starts with the identification and analysis of the context where this scope is defined, and from here identifying key variables, i.e., on the one side military advantage, and on the other side physical collateral injury, death, object damage. At the same time, two perspectives are considered for the collateral damage in order to not account (Case 1) and account (Case 2) psychological harm as being part of the collateral damage component. Then these relationships are translated into causal-loop diagrams and stock-and-flow structures, ensuring that reinforcing and balancing feedbacks (e.g., increased use of force leading to higher civilian harm, which in turn constrains operational aggressiveness) were faithfully represented. From here the SD model is implemented in accordance with the IHL (International Humanitarian Law) the SD model in a simulation environment to allow for dynamic "what-if" experimentation.

For demonstration and evaluation, a two use case simulation is executed. Case 1 abstracted collateral damage to purely physical effects, e.g., injuries, fatalities, and material destruction, while Case 2 augmented the SD structure with an additional feedback loop representing psychological harm as part of civilian impact. In each case, the model is calibrated against expert rule outputs (physical-only or enriched by psychosocial factors) and validated structural fidelity through extreme condition tests (e.g., zero advantage or zero civilian presence) and dimensional consistency checks. Furthermore, the behavioural validity was assessed by comparing the model's time-series outputs such as cumulative civilian harm and operational utility against expected proportionality thresholds, ensuring that the SD model reproduced the expert-defined switch between proportional (P) and disproportional (DP) states under both scenarios .

Through sensitivity and scenario analyses, we quantified how variations in key parameters (e.g., the weight assigned to psychological harm and force-application rate) shifted the system's equilibrium and tipping points.

From the structural robustness conducted against Monte Carlo–style perturbations of input distributions, the model demonstrates that the core causal archetypes remained stable across a wide range of plausible operational conditions.

4. Model Design

The SD model for proportionality assessment is built around four exogenous drivers, i.e., civilian injury severity (CD_injury), civilian death severity (CD_death), collateral damage on civilian objects (CD_object), and military advantage (MA). Each of these take discrete values (L/M/H i.e., Low/Medium/High or Y/N i.e., Yes/No) and are sampled every time step from configurable probability distributions. These inputs feed into a **rule lookup** block that implements the 54 scenario combinations (e.g. L–M–Y–L → DP).

At each time step t, the model executes the following operations:

- Step 1: Sampling by capturing the input elements from their distributions.
- Step 2: Rule evaluation through a lookup PA(t) = rule(injury, death, object, MA).
- Step 3: Flow computation where the new PA(t) = 1{PA(t)=P}, New DP(t)=1{PA(t)=DP}.
- Step 4: Stock update where the Cumulative P(t) = Cumulative P(t-1) + New P(t) and Cumulative DP(t) = Cumulative DP(t-1) + New DP(t).

In this process, a level variable encapsulates each input's probability mass function, allowing the run of sensitivity experiments by altering injury or death likelihoods. Because all interactions are discrete and rule-based, the model remains highly interpretable and directly traceable through elicited lookup tables. Although the base model has no endogenous feedback from PA stocks back to inputs, its causal loop diagram (CLD) clarifies potential extensions. Four reinforcing feedbacks (R1–R4) link each collateral-damage dimension positively to the PA decision node, i.e., higher injury, death, object damage, or military advantage push PA toward DP, and these feed into the accumulating PA stocks.

To compare the two modelling specifications where in Case 1 only psychical damage is considered in the collateral damage component and in Case 2 both psychical and psychological harm is considered in the collateral damage component, the only structural change is replacing CD_injury_no_psycho with CD_injury_with_psycho. Here it is important to mention that all other stocks, flows, and sampling mechanisms remain identical. Furthermore, from a simulation conducted over 100 time steps it can be seen that Case 2 produces 7 percentage points more DP outcomes (44.4 % vs. 37.0 %) than Case 1 under uniform input distributions.

5. Evaluation

From the evaluation conducted, out of 54 possible scenario combinations, Case 1 (physical damage only) yields 34 P and 20 DP, whereas Case 2 (including psychological harm) yields 30 P and 24 DP. This is visualized in Figure 1 in the 7.4% drop in proportional outcomes when psychological harm is accounted for.

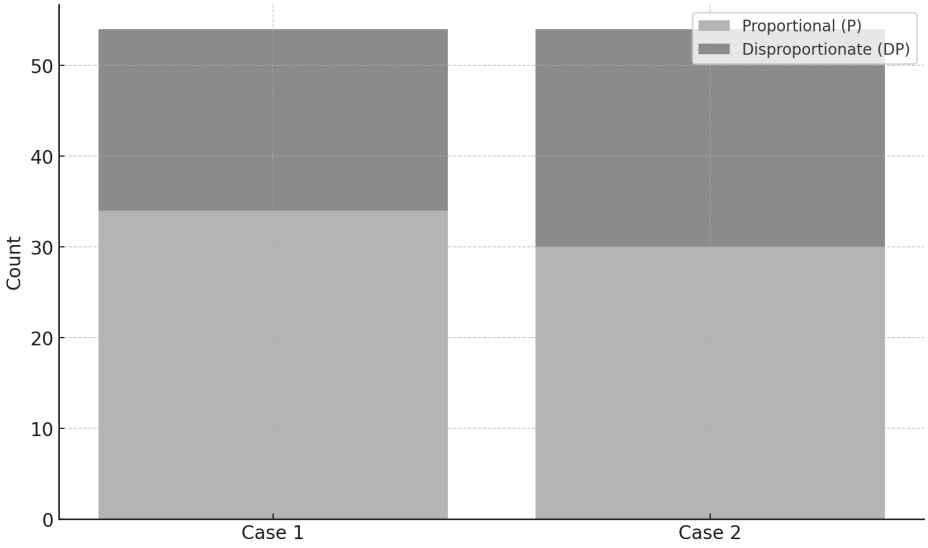


Figure 1: Evaluation for both cases

To observe how judgments accumulate over successive engagements, two discrete time stock and flow stocks are implemented: Cumulative P and Cumulative DP with flows driven by the instantaneous PA decision each step. Under uniform scenario sampling, the time series shown in Figure 2 lets seeing that Case 1's cumulative P stock rising approximately linearly to ~34 by step 54, then plateauing, while Case 2 grows more slowly, plateauing around 30 by the same step. This divergence illustrates how Case 2's inclusion of psychological damage systematically reduces the rate at which proportional judgments accrue.

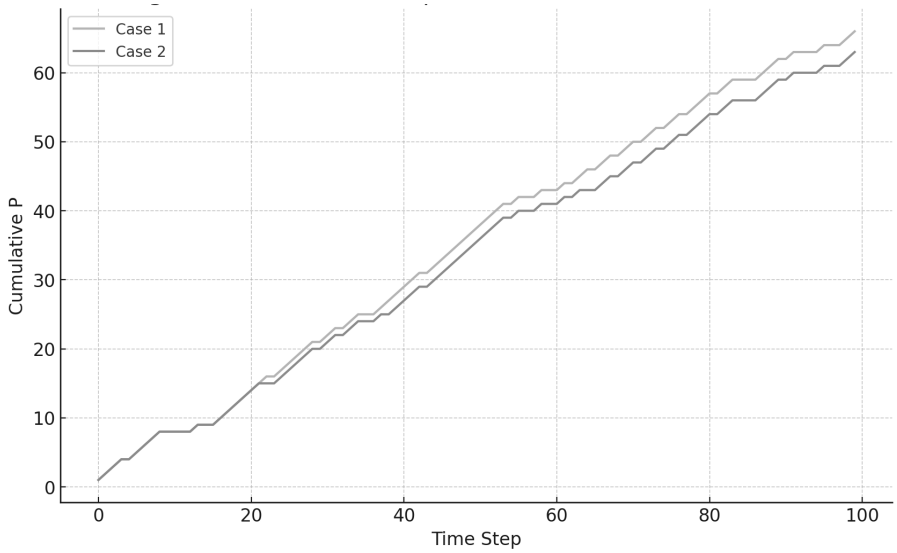


Figure 2: Cumulative proportionality assessments over time

Further, one's input probability is varied at a time (high-severity injury, high-severity death, and object damage likelihood) from 0 % to 100 %, holding other inputs uniform. To this end, Figure 3 plots the proportion of P judgments versus the probability of "High" injury: Case 1 declines from ~80 % to ~20 %, while Case 2 starts ~75 % and falls more steeply to ~15 %. Similar curves for death severity and object damage (not shown) confirm that psychological considerations amplify sensitivity, especially to object damage, shifting the curves downward by 3–5 percentage points on average.

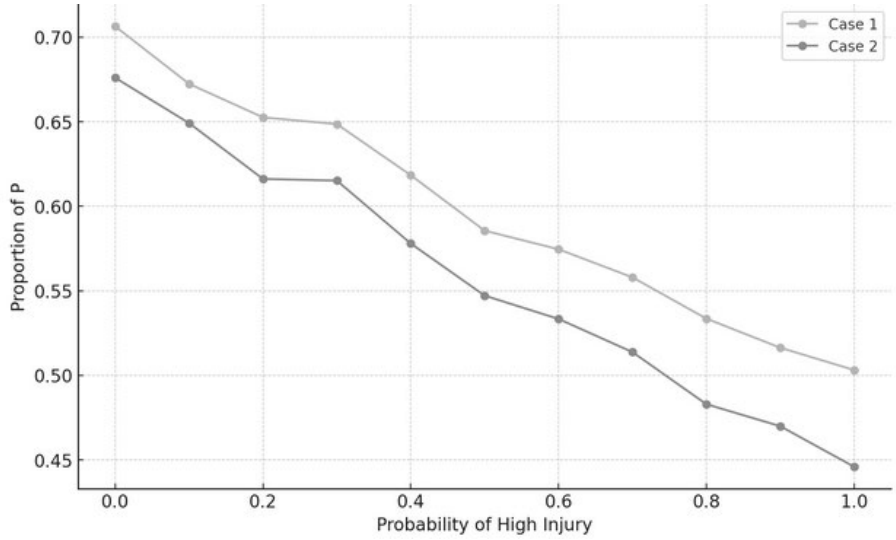


Figure 3: Sensitivity analysis to high injury

To explore interactions, a two-way are swept over p_H_injury and p_H_death, computing the difference in P proportions (Case 1 – Case 2) at each grid point. The resulting heatmap (Figure 4) reveals that the largest deltas (~5 pp) occur when both injury and death probabilities are high, indicating regions where psychological harm most strongly drives conservative (DP) outcomes. Moreover, from statistical two-proportion z-tests at each cell show that nearly 48 % of the grid cells exhibit a significant difference ($p < 0.05$), underscoring the robustness of this effect.

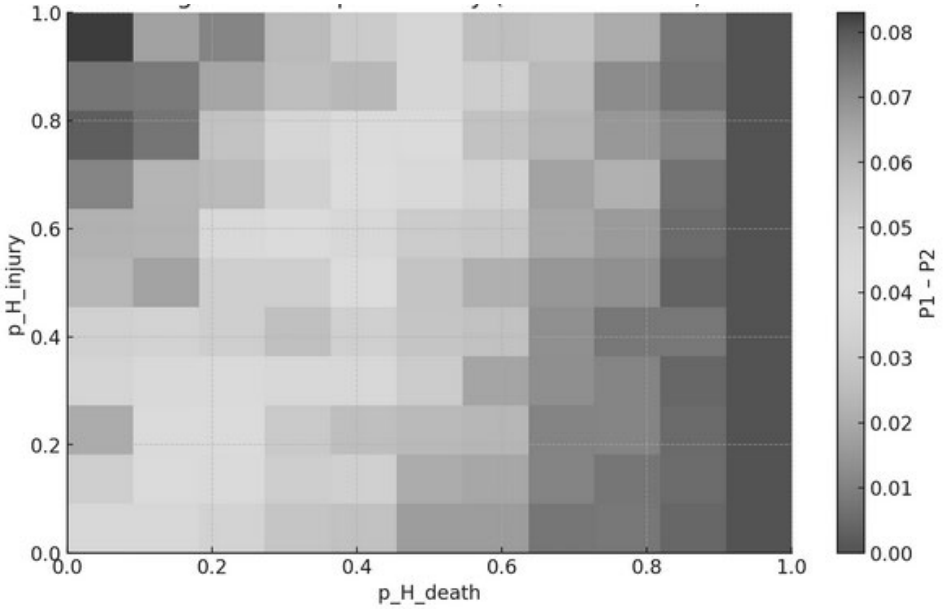


Figure 4: Delta Proportionality (Case1 and Case 2)

Aggregating across all parameter sweeps, the mean difference in proportional judgments between Case 1 and Case 2 is ~3.1 percentage points, with a one-sample t-test strongly rejecting the null of zero difference ($t \approx 16.1$, $p \ll 10^{-30}$). Such statistically significant disparities, coupled with the systematic slowing of P accumulation and heightened sensitivity to collateral-damage inputs, highlight how incorporating psychological harm leads to more conservative proportionality assessments. These findings validate the SD model's utility in "what-if" exploration and reinforce the operational importance of non-physical harm in rules-of-engagement design.

Hence, transitioning from Case 1 (physical injury only) to Case 2 (physical + psychological injury) systematically shifts the proportionality profile toward more conservative judgments: the baseline count of proportional rulings falls by 7 percentage points, cumulative proportional assessments are made more slowly, and sensitivity curves to high-severity injury, death, and object damage uniformly lie below their Case 1 counterparts by 3-5 pp. Two-way parameter sweeps reveal the largest $\Delta P = P_1 - P_2$ (up to ~8 pp) when both injury and death probabilities are high, with nearly half of all grid cells exhibiting statistically significant differences ($p < 0.05$). Thus, incorporating psychological harm in the collateral damage component of the proportionality assessment not only increases the overall frequency of disproportionate outcomes, but also amplifies the model's responsiveness to variations in collateral-damage parameters, underscoring the critical role of non-physical suffering/harm in shaping robust, precautionary proportionality assessments.

6. Conclusions

In this research, a SD model for proportionality assessment in military operations was developed, evaluated, and proposed.. By encoding 54 collateral-damage scenarios into instantaneous proportionality assessment outcomes (P vs. DP), then aggregating these through cumulative stocks, this research demonstrates how the inclusion of psychological harm (Case 2) consistently reduces proportional rulings by roughly 7 percentage points, slows the accumulation of proportional judgments, and amplifies sensitivity to key input parameters. One-way and two-way sensitivity sweeps, coupled with statistical hypothesis tests, confirmed the robustness of these effects across a broad parameter space, while time-series and heatmap visualizations provided intuitive insights into the dynamic behaviour of this model. Together, these results reflect the model's utility as both an analytic lens on doctrinal trade-offs and a decision-support tool for military targeting decision-making support.

As future research perspectives, several paths are seen for extending this framework. First, introducing endogenous feedback, where rising Cumulative DP levels dynamically adjust future military advantage thresholds, approach that would capture adaptive policy resistance and command learning. Second, by integrating or extending this model with complementary methods (e.g., agent-based or cellular automata modules) could reveal how spatial heterogeneity and local interactions alter aggregate outcomes. Third, by considering calibration against historical engagement data and expert judgment elicitation exercises that

would strengthen real-world validity. And fourthly, by expanding the collateral-damage taxonomy (e.g., including economic or cultural loss metrics), coupling with live operational data feeds, and embedding the model within interactive C2 dashboards could contribute to bringing this model toward operationalizing proportionality assessment in multi-domain operations settings.

Declaration: For this research, no ethical clearance is required and no AI tools were used in the creation of this article.

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Deepfake Technology in Social Engineering: Threats, Detection and Defence Strategies

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Abstract: Big developments in the field of Artificial Intelligence (AI) have significantly improved deepfake technology, allowing individuals to create realistic synthetic media. As a result, deepfakes have become a very effective tool for social engineers by allowing them to accurately impersonate colleagues and authority figures to gain the trust of individuals and manipulate them. High-profile cases such as the Arup scam and the UAE fraud case highlight how attackers are leveraging these techniques in real-world scenarios and the devastating financial consequences they bring. In response, several technical detection tools have been developed, many of which rely on deep learning techniques. However, these should not be used in isolation. An effective defence strategy requires organisations to supplement these technological tools with other strategies, such as employee training, awareness campaigns and secure security policies. This creates layers of security, capable of mitigating risks posed by deepfake social engineering.

Keywords: Deepfakes, Social engineering, Exploits, Cybersecurity threats, Generative adversarial networks, Synthetic media

1. Introduction

Advancements in Artificial Intelligence have led to the creation of realistic synthetic media known as deepfakes (Pedersen, et al., 2025). Techniques such as generative adversarial networks (GANs) have enabled deepfake technology to convincingly replicate faces, voices and behaviours, making it very difficult for an individual to distinguish synthetic from authentic media (Yang, et al. 2021). Although such technology can be useful in fields such as entertainment, it can also be used maliciously, particularly in social engineering exploits.

Social engineering, unlike other cyber security exploits, focuses on the exploitation of human vulnerabilities, rather than technical weaknesses, to deceive and manipulate people into revealing private and confidential information (Siddiqi, Pak, & Siddiqi, 2022). Traditional social engineering attacks, such as phishing, rely on gaining human trust to be successful. The integration of deepfake technology into such attacks has the potential of aiding in the acquisition of this human trust, making social engineering attacks more effective.

The convergence of deepfake technology and social engineering presents a concerning threat to cybersecurity. This paper aims to explore how deepfakes have made it easier to manipulate and deceive people, enhancing the effectiveness of social engineering exploits. Furthermore, it reviews the current strategies being employed to detect and defend against such attacks. By taking into consideration the current state of knowledge, this paper also seeks to uncover the challenges that remain in protecting organisations against deepfake-based attacks. The research question being addressed therefore is "How is deepfake technology being used in social engineering attacks, and what strategies exist to detect and defend against them?"

The rest of the paper is structured as follows: Section 2 gives background information on the generation of deepfake media and provides an overview of social engineering tactics. Having explored these key concepts, Section 3 then discusses some case studies where deepfake technology was successfully used to launch social engineering attacks, paying attention to the attack mechanisms used. Section 4 then focuses on the detection tools that are currently being used, from tradition to deep-learning based ones. Finally, Section 5 explores the additional measures that organizations should have in place to complement technical detection strategies and provides a recommendation strategy for companies in the battle against these attacks.

2. Background

Although the introduction has outlined the growing threat presented by deepfakes in social engineering, it is important to understand the background information of these concepts. By first understanding the different types of deepfakes along with how they are generated, and what makes social engineering attacks effective, the convergence between the two fields becomes clearer. This section therefore provides an overview on deepfake technology, social engineering, and the intersection between them.

2.1 Deepfake Generation

The increasing access to cell phones, the availability of digital media on social media platforms, and advances in the field of machine learning have allowed for the manipulation of pictures, videos, and audio files to generate synthetic but realistic media, referred to as deepfakes (Masood, et al., 2022). The generation of the altered multimedia is done by machine learning algorithms, mainly GANs. Deepfakes fall under two classes, namely visual and audio deepfakes. Visual deepfakes can be classified into four categories namely attribute manipulation, identity swap, entire face synthesis and face reenactment (Akhtar, 2023). Attribute manipulation focuses on altering some facial features from authentic media, producing deepfakes with edited faces. Identity swap, on the other hand, involves the replacement of a person's face in the original video, with a different face, giving the illusion that the other person was in the video. Entire face synthesis involves using GANs to create new face images and placing them in an original video. Face reenactment is the process of replacing the facial expression of individuals in an original video with those of other individuals (Akhtar, 2023). Audio deepfakes are grouped into two categories namely, text to speech (TTS) where a speech is generated using someone else's voice, and voice conversion (VC) which involves the conversion of a speaker's voice to sound like someone else, without changing the words being said (Dagar & Vishwakarma, 2022). Deepfakes have become so sophisticated, with studies indicating that both humans and machine learning algorithms struggle to consistently distinguish them from authentic media (Korshunov & Marcel, 2018).

2.2 Social Engineering

Social engineering attacks occur when cybercriminals manipulate individuals into revealing confidential information or trick them into giving them access to a system (Hijji & Alam, 2021). Therefore, instead of attempting to circumvent firewalls and intrusion detection systems, social engineering exploits human vulnerabilities through techniques such as deception or manipulation to breach security (Wang, Zhu, & Sun, 2021). Such attacks are often successful as studies have shown human beings to be the weakest links when it comes to cybersecurity (Hijji & Alam, 2021). A common social engineering attack is phishing, where an attacker sends a message that is seemingly legitimate, prompting users to follow instructions detailed in the message. One way of conducting a phishing attack is through voice communication, where an attacker tricks users into providing sensitive information via a phone call. This is also known as vishing (Syafitri, et al. 2022). Most social engineering attacks involve an attacker gaining the trust of an unsuspecting user by posing as a legitimate entity.

2.3 Intersection Between Deepfakes and Social Engineering

The intersection between deepfake technology and social engineering has brought about a new class of cyber threats. Instead of just relying on text-based impersonation for social engineering attacks, hackers can now leverage seemingly legitimate audio and video media to gain the trust of unsuspecting users (Ferrara, 2019). Any form of social engineering attack that makes use of video or audio media, such as vishing, can be enhanced by deepfake technology. An example could be the use of deepfake technology to impersonate a manager asking an employee to transfer money into his account, or to provide some confidential information (Westerlund, 2019). This fusion increases the chances of success for attackers as many traditional defence mechanisms often struggle with recognising synthetic fabricated media (Martinek & Bartuzi-Trokielewicz, 2025).

Deepfake technology provides several tools that significantly enhance the strength of social engineering tactics. An example would be the use of voice cloning in vishing and impersonation attacks. These manipulation attacks are heavily dependent on the attacker's ability to pose as a trusted figure and gain the victim's trust. Deepfakes enhance this through the voice synthesis functionality, allowing attackers to convincingly mimic colleagues or executives over the phone. Compared to traditional vishing, where scammers' accents often raise suspicion, audio deepfake technology can mimic accents with high accuracy, reducing the victim's ability to identify the scam (Pedersen, et al., 2025).

Furthermore, combining audio and video deepfake techniques has the advantage of making the manipulated content look more authentic. This could happen when fraudsters use real-time video manipulation tools together with audio synthesis to create a realistic video of the figure being impersonated. A common example would be the use of this combination in video meetings, effectively tricking the victim into believing that they are interacting with their colleague or boss (Muhly, Chizzonic, & Leo, 2025). This amplified attack can be very successful if organisations rely only on visual confirmation to verify requests. To structure the analysis of this

intersection, this paper proposes a taxonomy mapping deepfake method, social engineering technique and corresponding defence strategy, presented in full in Section 5.3.

3. Deepfakes in Social Engineering Attacks

To better understand the application of deepfake technology to enhance social engineering, it is useful to examine real-life case studies where synthetic media was utilised in cyberattacks. These case studies showcase the mechanisms discussed in the previous section in real-world scenarios, demonstrating their effectiveness and the devastating impacts they leave on the victim organisations.

3.1 Arup Deepfake Video Scam

One of the most impactful cases of deepfakes being used in social engineering occurred in 2024 when an employee working at Arup, a UK-based company, was scammed into transferring money to the attackers (Lin, 2025). The attack started with a phishing email, where the chief financial officer (CFO) requested transfer of funds. The employee's doubts were wiped when the attackers made use of deepfake technology to impersonate the CFO and other company employees, cloning their faces and voices. This managed to convince the employee that the communication was legitimate, and he proceeded to transfer funds to five different Hong Kong bank accounts (Lin L. S., 2025). In total, this social engineering attack resulted in a financial loss of approximately US$25.6 million (Doraisamy, et al. 2025). This attack demonstrates the dangerous outcomes of bringing together deepfakes and manipulation techniques, in this case, the use of audio and video deepfakes to convince an unsuspecting individual to comply with an urgent request.

3.2 UK Energy Company Scam

A similar attack occurred at a UK-based energy company, where attackers leveraged voice cloning technology to impersonate one of the company's executive official (Farid, 2025). The attack began when a phone call was made to the company's CEO from an individual who was impersonating his superior. Initially, the CEO had no reason to doubt the call, as the deepfake voice cloning convincingly replicated the superior's voice as well as his German accent (Pedersen, et al., 2025). Believing this call to be genuine, the CEO was tricked into authorising a payment transfer of approximately US$ 243,000 to a Hungarian supplier. The attackers subsequently requested additional funds, but the CEO grew suspicious after noticing no reimbursements had been made. Investigations carried out of the case concluded that the attackers had used a commercially available voice-generating software to impersonate the superior (de Rancourt-Raymond & Smaili, 2022). This case is an example of how voice cloning on its own is powerful enough to catch individuals off-guard and exploit their trust, manipulating them into doing what exactly the attacker wants.

3.3 UAE Bank Scam

A third high-profile deepfake social engineering attack occurred in 2020 at a United Arab Emirates (UAE) bank. To execute this attack, cybercriminals used voice cloning technology to mimic the voice of a company's director and proceeded to make a call to a bank branch manager asking him to authorise a series of transfers (Farid, 2025). This request for funds was accompanied by emails and supplementary documents from an alleged lawyer, adding credibility to the request. Since the branch manager was familiar with the director's voice, and was additionally reassured by the supporting documents, he had no reason to suspect foul play, therefore he proceeded with approving the transactions (Lin L. S., 2025). In total, approximately US$35 million was transferred to the attackers through various international accounts, and a portion of it was traced to the United States. Investigators who were assigned to this case concluded that the attackers had used speech samples from public sources or hijacked communications to clone the director's voice. This case is regarded as one of the biggest financial fraud attacks utilising deepfake technology (Lin L. S., 2025). This social engineering attack demonstrates how traditional phishing methods such as email attacks are significantly enhanced using deepfakes, making the process of gaining human trust, and ultimately manipulating them much easier.

3.4 Almost Successful Financial Scams

Not all attempts to use deepfakes in social engineering have been successful, but they still demonstrate the harmful potential this convergence possesses. In 2020, the advertising company WPP became the target of a deepfake scam, where attackers leveraged deepfake audio cloning to impersonate the CEO (Zhang, et al. 2025). The attack was initiated when the fraudsters used a public image of the CEO to create a WhatsApp account and proceeded to arrange a virtual meeting with a senior executive. They then made use of the CEO's voice and a public footage to impersonate the CEO during the meeting, and they requested for a funds transfer (Muhly, Chizzonic, & Leo, 2025). A similar attack targeted a Swiss financial institution in 2024, where

cybercriminals used deepfakes to mimic the company's chief financial officer (CFO). However, the financial clerk managed to recognise inconsistencies in the fake CFO behaviour and dress code, making the attack unsuccessful (Muhly, Chizzonic, & Leo, 2025). While both scam attempts were unsuccessful and no money was transferred, it highlights how audio and video deepfake technology can be combined, to reinforce trust and credibility.

4. Deepfake Detection

The case studies discussed in the previous section demonstrate how deepfake technology can be applied to boost the success of social engineering attacks, resulting in severe financial consequences. From this information, it becomes apparent that this convergence presents a real threat, and therefore there is need for countermeasures to detect and protect organisations against such attacks. This section examines the current technology being used by detection tools in the battle against deepfakes, with the aim of evaluating their effectiveness and highlighting the limitations that need to be addressed in defending against these amplified attacks.

4.1 Audio Deepfake Detection

Multiple approaches to audio deepfake detection have been explored over the years. One such approach involves the extraction of features from an audio file, then applying machine learning algorithms to detect whether the voice has been tampered with (Stroebel, et al. 2023). The use of algorithms such as GMM (Gaussian Mixture Model) and LCNN has been proposed for such detections. The findings indicate that these models perform well on fully synthesised audio files, however, they tend to struggle with partially synthesised ones.

A more effective approach uses deep learning algorithms, such as neural networks, to learn patterns that emerge in fabricated audio files, and use those patterns in classification (Shaaban, Yildirim, & Alguttar, 2023). This can be achieved using CNNs to analyse features from audio mel spectrograms, which can be used to differentiate altered audio files from genuine ones (Stroebel, et al. 2023). Several experiments have shown that the CNN-based models outperformed traditional GMM-based ones in distinguishing spoofed audio files from authentic files. For example, an analysis carried out on the ASVspoof2019 dataset revealed that CNN models achieved a lower Error Equal Rate (ERR) of 0.59 compared to 6.4 achieved by GMM models. The lower ERR indicates the superiority of CNN models in detection accuracy (Salih, et al., 2025). However, even though these models perform well in a controlled environment, they often struggle with generalisation, limiting their overall effectiveness in real world situations.

Table 1: Comparison of audio deepfake detection methods

Method	Strengths	Weaknesses
GMM/LCNN	Strong on fully synthesised audios	Performance drops on partial audio
CNN + mel spectrograms	Better performance than GMM/LCNN	Poor generalisation

4.2 Traditional Image Deepfake Detection Methods

Traditional deepfake detection tools, such as Error Level Analysis (ELA), rely on looking for unnatural facial movements, or imperfections within the fabricated videos such as speech consistencies, shadows as well as lack of breathing (Taeb & Chi, 2022). If such a tool detects one or more of these inconsistencies, that video will be flagged as fabricated. However, the introduction of AI algorithms such as convolutional neural networks (CNNs) and GANs has significantly improved the quality of deep-fakes, eliminating these imperfections. Therefore, these traditional tools are becoming ineffective, particularly against deep learning based deepfakes (Taeb & Chi, 2022).

4.3 Deep Learning-based Detection

A better approach to deepfake detection is to utilise deep learning algorithms such as CNNs and deep neural networks (DNNs) (Stroebel, et al. 2023). These deep learning techniques are classified into two categories namely holistic and feature-based categories.

Holistic approaches to deepfake detection, such as support vector machines (SVM) and CNN classifiers, focus on the entire face, to detect irregularities that can be used to differentiate authentic images from fabricated ones (Taeb & Chi, 2022). An experiment carried out by (Mallet, et al., 2023) demonstrated the effectiveness of a CNN model in identifying synthetic images, achieving a detection accuracy of 88.33% on a dataset of real and

fake faces. However, despite this good performance, holistic approaches face generalisation challenges. An analysis by (Raza, et al., 2026) has shown that CNN-based models suffer a performance decline of about 15% when evaluated on different datasets. This suggests that even though holistic approaches show promising results in controlled environments, their effectiveness in real-world situations is limited.

Feature-based methods, on the other hand, extract features that are unique to deepfakes, and these are then used to classify real and fabricated media. These features are grouped into biometric, media and model classes. Biometric features are human features, such as eye and lip movement, head pose and eyebrows, that can be used in the distinction of deepfake and genuine videos. Media features focus on information like noise and inconsistencies between frames in media, and this information can be used to identify videos that have been tampered with (Zhang, et al. 2025). Model features, unlike media features, are based on the model used in the deepfake generation and refer to specific fingerprints left behind by the models, particularly GAN models, in the generated media. Deep learning models can scan for the presence of these fingerprints to help in the identification of fake media (Zhang, et al. 2025) (Taeb & Chi, 2022). However, the weakness of fingerprint detection stems from the fact that models trained to detect GAN-based deepfakes struggle with diffusion-based deepfakes, because these introduce entirely different artifact patterns (Singh & Dhumane, 2025).

Table 2: Comparison of deep learning-based detection approaches

Approach	How it works	Strengths	Weaknesses
Holistic (SVM and CNN)	Full face analysis	High detection accuracy on known dataset	Poor generalization
Feature-based (Biometric, media and model)	Extracts deepfake-specific features media	Captures movement inconsistences	Struggle with diffusion-based deepfakes.

4.4 Limitations

Although the above-mentioned detection methods show promising results, they face several limitations. Experiments on both machine learning and deep learning models have revealed that these detection methods struggle to generalise. Therefore, while they perform well on a single dataset, the detection accuracy drops when the models are evaluated on unseen deepfakes. An experiment by (Singh & Dhumane, 2025) has highlighted this performance drop, where a CNN-based model that achieved detection accuracy of 90% on one dataset only managed a 60% accuracy on a new unseen dataset.

Another significant limitation of existing detection tools is that of scalability. State-of-the-art detection models require significant computing resources including premium GPUs and large memory capacity (Singh & Dhumane, 2025). As a result, real-time deepfake detection remains a challenge, especially for smaller organisations, with limited computer infrastructure.

Finally, there is a limitation of partial media manipulation. As discussed in Section 4.1, GMM and LCNN based classifiers produce good performance on fully synthesised audio, however, their performance drops when evaluating partially synthesised samples (Stroebel, et al., 2023). This suggests that attacks that blend authentic and spoofed media have a higher chance of evading detection. Table 3 presents a summary of limitations faced by each detection approach.

Table 3: Summary of limitations across detection approaches

Detection approach	Limitations
Traditional image detection methods (ELA)	Obsolete against CNN-generated deepfakes
GMM and LCNN (audio detection)	Poor performance on partial media
Audio CNN + mel spectrogram	Poor generalisation
Holistic (CNN and SVM)	Performance drop across datasets (15% drop)
Feature-based approach	Struggle against diffusion-based deepfakes Computationally heavy

Overall, these limitations highlight that no single detection method offers complete protection against deepfake-powered social engineering.

5. Defence Strategies

While the detection tools discussed in the previous section provide a layer of defence against deepfakes, they do not always flag every manipulation attempt. Therefore, detection tools on their own cannot fully mitigate the threats possessed by deepfake social engineering exploits. Consequently, organisations should have other defence mechanisms in place to reduce the probability of successful attacks. This section discusses human-centric strategies along with organisational safeguards that can be utilised in shielding companies from these attacks. It then concludes by suggesting a recommended strategy organisations can employ, by structuring their defence in layers, adopting a defence-in-depth approach to security.

5.1 Human-centric Strategies

Humans have been identified as the weakest link when it comes to cybersecurity (Hijji & Alam, 2021), therefore, in addition to having automated detection tools, it is also necessary to ensure that employees are made aware of the threat posed by deepfake technology. One way of achieving this is by organizing training and awareness campaigns focused on equipping individuals with the knowledge required to detect altered media (Lin L. S., 2025). A study conducted in Bangladesh demonstrates the effectiveness of awareness campaigns in the battle against deepfakes. This study was conducted in two phases, with the results from phase one indicating that 65% of the sample group was totally unaware of deepfakes. However, after being made aware of this concept, phase two results were promising, with 70% of the group feeling confident that their deepfake detection abilities had improved (Ahmed, et al. 2021).

5.2 Organisational Safeguards

Organisations can also take a proactive approach in the battle against deepfake scams by putting in place controls and safeguards to assist in the detection and defence against attacks. By defining strong and secure policies, companies ensure that employees have an established framework to follow when dealing with requests (Muhly, Chizzonic, & Leo, 2025). A practical example would be having a policy outlining secure communication tools and platforms organisational employees should use, that way, any request made from a non-approved platform is immediately shot down (Pedersen, et al., 2025). Furthermore, organisations should outline reporting procedures to follow when employees face deepfake scams (Pedersen, et al., 2025).

5.3 Recommended Approach

Given the complexity of deepfake-fuelled social engineering attacks, having a single mitigation strategy cannot guarantee complete protection. Case studies discussed in section 3 demonstrate that attackers use different deepfake methods and social engineering techniques, each requiring a unique response. This paper therefore proposes a taxonomy that maps the attack method and social engineering technique to the appropriate defence strategy.

Table 4: Taxonomy of Deepfake Social Engineering Attacks and Defences

Deepfake method	Social Engineering technique	Real-world example	Defence strategy
Audio only	Vishing	UK energy and UAE bank scams	CNN mel spectrogram analysis. Call verification policy. Employee training.
Video and Audio	Visual and audio impersonation	Arup scam, WPP attempt	Holistic CNN. Feature-based analysis. Secure communication policies.
Audio and Documents	Phishing enhancements	UAE bank scam	Email filtering. Audio deepfake detection. Multi-channel verification policies.

As the table illustrates, organisations should adopt a defence-in-depth strategy, combining technical detection tools, human awareness and training, along with secure organisational policies. For example, a vishing attack

requires a combination of audio CNN detection and strict call verification policies, ensuring that even if the detection tool fails, a trained employee following the policy acts as a secondary defence. The key

advantage of this multi-layer approach to security is that even if one layer is bypassed, such as an employee being tricked, the organisation will have additional safeguards, preventing a single point of failure.

6. Conclusion

Deepfake technology has been significantly enhanced by breakthroughs in the field of artificial intelligence, enabling the creation of convincing and realistic synthetic audio and video media. This enhancement has negatively revolutionised deepfake social engineering attacks, allowing cybercriminals to exploit individual trust with ease, putting organisations at risk of deepfake fraud. This paper introduced key concepts in the fields of deepfakes and social engineering by exploring the different ways in which deepfakes are created and introducing the key factors that allow social engineering exploits to be successful. Then it proceeded to examine how the two fields can be brought together, describing how deepfake technology can be utilised in social engineering attacks such as vishing and video conference scams, by impersonating an authoritative figure. Several high-profile case studies were additionally explored, further reinforcing the intersection of the two fields and the devastating consequences it has on the victims. The discussion then shifted to the possible solutions by examining the current detection tools that are available, ranging from early forensic tools to deep-learning based approaches. Additionally, the paper considered necessary supplementary defence mechanisms, such as training and awareness campaigns for employees and secure organisational policies, which can be used in conjunction with technical detection tools, effectively implementing a defence-in-depth approach to securing organisations. Finally, this paper proposes a taxonomy mapping attack methods to the appropriate defence strategies, offering a practical framework for organisations.

The objective of this paper was to investigate the role of deepfake technology in social engineering by discussing the risks posed and the detection and defence measures that can be employed. This objective has been met through case study explorations and a thorough examination of the current state of detection and defence mechanisms. Although total mitigation of this threat remains a challenge due to huge leaps in the field of AI, this paper identifies a layered approach to security as the best course of action against deepfake social engineering.

Ethics declaration: This study did not require any ethical clearance. The research was conducted using information from public databases and no collection of personal data was done.

AI declaration: No AI tools were used in the writing of this paper.

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Detecting DDoS Attacks in IoT Healthcare

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Abstract: The increased adoption of IoT devices in healthcare domains has significantly increased the attack surface, leaving critical infrastructure vulnerable to attacks such as Distributed Denial of Service (DDoS). Our work investigates the role of feature selection and temporal dependency modelling in detecting MQTT (Message Queuing Telemetry Transport) DDoS attacks using the CICIoMT 2024 dataset. We compare two approaches; using the Naïve Bayes model which assumes flow independence and Long Short-Term Memory (LSTM) model, which captures sequential dependencies in the raw network flows. Feature selection was also performed to reduce 84 raw features to 31 informative features. Our preliminary results show that the LSTM model outperformed naïve bayes by leveraging the temporal patterns that are characteristic of DDoS traffic. This study evaluates the importance of guided feature selection and temporal dependency modelling in DDoS detection in IoT healthcare networks.

Keywords: DDoS detection, IoT healthcare, MQTT, Long short-term memory (LSTM), Intrusion detection

1. Introduction

Internet of Things (IoT) devices continue to be widely adopted across various domains, and it is predicted to rise to over 40 billion devices by 2030. One such domain is in healthcare where IoT devices such as patient monitors, infusion pumps, and wearables interact to enable real-time healthcare delivery. With this adoption comes a wide range of cybersecurity challenges as discussed by (ElSayed et al., 2025) in their paper. This connectivity introduces critical security risk, IoMT devices often run outdated firmware, use weak authentication mechanisms, and run on limited computational resources making it challenging to implement security measures. This makes them easy targets for botnet recruitment and large-scale DDoS attacks that bring down organizations. (Censinet.com, 2026) estimated that the cost of downtime from DDoS attacks is over $100,000 per hour. Service interruptions in healthcare environments directly impact patient safety. Therefore, robust defences must be prioritized to ensure continuity of services.

Among the protocols commonly exploited in IoMT environments, MQTT (Message Queuing Telemetry Transport) is particularly vulnerable due to its lightweight publish/subscribe model, weak authentication mechanisms, and unencrypted message transmission. Attackers exploit MQTT through Connect and Publish Flood attacks that overwhelm brokers and clients with excessive traffic, overwhelming legitimate device communications. In their paper, (Lakshminarayana et al., 2025) evaluated the security vulnerabilities of MQTT v5.0 protocol that made them susceptible to attacks. They found that the protocol's support for large, unbounded properties such as connect properties and user-defined metadata enables attackers to craft oversized or numerous malicious packets that exhaust broker resources like CPU and memory.

Most traditional intrusion detection methods are signature based and rely on static rules to flag suspicious activities. However, as attacks become more sophisticated, these methods struggle to detect varying attack patterns. While machine learning has also advanced beyond signature-based detection, existing methods mostly treat the network flows as independent events and fail to capture the temporal relationships between the flow attributes. Our work addresses two fundamental research questions in DDoS detection, are there specific features that most effectively discriminate between benign and attack traffic and does modelling short-term flow sequences provide quantifiable benefits over independent flow classification in detecting MQTT-based DDoS attacks. To address these questions, we make the following contributions: We perform feature selection through Random Forest importance scoring and Information Gain to identify a smaller, informative feature subset. We then evaluate two contrasting models, the Naive Bayes classifier, which treats each flow independently; and an LSTM model, which captures temporal dependencies across consecutive flows. We demonstrate that temporal modelling achieves better results in detection accuracy and false positive reduction on the MQTT Connect and Publish Flood traffic from the CiCIoMT 2024 dataset.

2. Related Works

With the rise of cyberattacks on IoMT devices, such as DDoS, researchers have made efforts to develop detection algorithms and mitigation techniques.

(Clark et al., 2024) leveraged machine learning models for anomaly detection to identify abnormal activity in IoMT systems with a goal of detecting DoS and ARP spoofing attacks. Their research focuses on Bluetooth, Wi-Fi, and MQTT enabled devices where they trained different supervised and unsupervised machine learning models to classify network traffic as either malicious or benign. The models were trained on the CIC IoMT 2024 dataset, and the findings were that the decision tree model performed best for detecting DoS attacks on Bluetooth devices, while the random forest model performed best for detecting ARP spoofing attacks on Wi-Fi and MQTT enabled devices.

(Hnamte et al., 2022) implemented a Naïve Bayes classifier for DDoS detection in IoT networks. They selected and optimized features using statistical techniques, specifically the correlation coefficient and Dice similarity coefficient. A Naïve bayes classifier was trained to accurately distinguish between malicious and benign traffic while reducing false positives. Their model achieved a high accuracy of 89.7% and true positive rates of about 90%.

(Kirubavathi et al., 2024) proposed a two-model based approach to anomaly detection trained on the CICIoMT 2024 dataset. The models used were Autoencoder for identifying errors through reconstruction errors and TabNet for utilizing attention mechanisms on tabular data. The Autoencoder had an input layer and an output layer of the same shape that attempted to reconstruct the traffic. If the resultant error was beyond a predetermined threshold, then it implied that some unusual activity was occurring. The TabNet used attention mechanisms to identify anomalies from the output of the model.

(Berguiga et al., 2025) presented a hybrid deep learning intrusion detection system for IoMT devices. The methodology combined two neural network architectures; Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM) neural network trained on the IoTID20 and the Edge-IoTset datasets. The datasets contain samples categorized into different attacks, including DoS and DDoS attacks. The CNN model performed feature extraction on the data while the LSTM model was used for sequence data prediction. The hybrid model achieved a high accuracy of 99.92%.

(Zabeehullah et al., 2025) also suggested a hybrid CNN-LTSM model for DDoS detection in IoMT. They used the CNN model for spatial feature extraction, and the LTSM module was trained on time-series data for network traffic features, augmenting their pipeline with SHAP-based explainability. They used the CICDDoS2019 and IoT Healthcare Security datasets, achieving a high accuracy of 99.59%, and providing interpretable feature attributions.

(Bhutia et al., 2022) proposed a three-phase methodology using just three machine learning algorithms: the KNN classifier, the Logistic Regression classifier, and SVM (Linear and RBF), for DDoS detection at the source, which is often bots. Their dataset of choice was traffic data collected from various commercial IoT devices that were exploited in the MIRAI and BASHLITE DDoS attacks. They extracted 23 features for classification of traffic as either benign or junk, and their proposed models achieve a detection accuracy of 99%.

(Phan et al., 2024), feature selection techniques of IoT attacks (Information Gain, Recursive Feature Elimination, Random Forest, XGBoost, and Logistic Regression) for machine learning detection on the CIC IoT 2023 dataset. Their results established that Random Forest and Information Gain consistently achieved high and stable accuracy, supporting our decision to use the two methods for our feature selection.

Prior works have advanced feature engineering and machine learning methods for IoMT DDoS detection. While hybrid models combine spatial and temporal learning, our work isolates and investigates the contribution of temporal learning by comparing a probabilistic classifier with a temporal sequence model using the same selected feature set.

3. Design And Methodology

3.1 Dataset

We use the CiCIoMT 2024 dataset (Dadkhah et al., 2024), generated by the Canadian Institute of Cybersecurity by executing different cyberattacks against an IoMT testbed of 40 devices across multiple protocols. Overall, the dataset consists of attacks categorized into different attacks such as DDoS, DoS, Recon, MQTT, and spoofing. Our study focuses on MQTT DDoS traffic, specifically Connect Flood and Publish Flood variants, against benign MQTT traffic to create a binary classification problem.

The CiCFlowMeter tool is a network traffic flow generator and analyser which generates bidirectional flows. A flow consists of multiple packets that are defined by the same five-tuple (source IP, destination IP, source port,

destination port, protocol). Using the tool, we extracted bidirectional network flow statistics from the dataset PCAP files, with each flow record containing 84 statistical features characterizing packet-level behaviour including duration, packet counts, byte volumes, inter-arrival times, and flag counts.

3.2 Preprocessing and Feature Selection

To ensure consistency, non-numerical identifiers were excluded from the dataset and infinite, missing and NaN values were handled through dropping. Normalization was performed by applying MinMax scaling which converts values to a range of (0,1). CiCIoMT datasets are usually known to suffer from data imbalance, with the attack data being greater than the benign data. To address the class imbalance, we applied under sampling to the majority class during training data preparation, maintaining a balanced training distribution.

With so many features, dimensionality reduction is important to reduce the model complexity and remove noisy features that degrade model performance. Previous work by (Phan et al., 2024), compared multiple feature selection techniques for machine learning detection of IoT attacks. Their results showed high and stable performance in Random Forest and Information Gain, which we employed for feature reduction to result in a smaller, informative feature set.

Information Gain works by quantifying how much information a given feature contributes to correctly classifying an instance.$IG(D, A) = H(D) - H(D|A)$ where IG(D,A) is the information gain of a feature A on a dataset D. Features with high IG provide significant discriminative information and are prioritized for retention.

Random Forest evaluates the relative importance of each feature by evaluating how much the feature contributes to reducing the Gini impurity in the decision tree. If a feature results in a higher decrease in impurity, it is considered more important since it improves the model's ability to classify correctly.

Both methods independently ranked the 84 extracted features, and features were selected based on consistent high rankings across both methods as well as domain knowledge. Information Gain ranking showed Fwd Seg Size Min, and TCP flag counts (SYN, RST, and FIN) as the most discriminative features for distinguishing the attacks. These features reflect the handshake and connection termination patterns characteristic of MQTT Connect and Publish attacks. Other connection related features such as FWD Init Win Bytes and Bwd Header Length also ranked highly since they captured early-stage resource negotiation that would noticeably differ between benign and DDoS traffic. The Random Forest rankings corroborated these findings and where feature rankings differed significantly, domain knowledge was used to evaluate the relevance. This process resulted in a set of 31 features that effectively characterize network traffic and provide strong indicators of DDoS attacks. These include flow duration, bidirectional packet and byte counts, inter-arrival time statistics (mean, standard deviation, maximum), active and idle time metrics, header length statistics, and TCP flag counts. The selected features are summarized in Table 1.

Table 1: Selected Features

Category	Features
TCP Flag Counts	SYN Flag Count, ACK Flag Count, PSH Flag Count, RST Flag Count, FIN Flag Count
Flow-level metadata	Protocol, Flow Duration, Flow Bytes/s, Flow Packets/s, Down/Up Ratio
Packet Counts	Total Fwd Packet, Total Bwd Packets
Packet size statistics	Packet Length Min, Packet Length Mean, Packet Length Max, Packet Length Std, Packet Length Variance, Average Packet Size, Fwd Segment Size Avg, Fwd Seg Size Min
Header lengths	Fwd Header Length, Bwd Header Length
Initial Window Sizes	FWD Init Win Bytes, Bwd Init Win Bytes
Subflow bytes	Subflow Fwd Bytes, Subflow Bwd Bytes
Inter-arrival times	Fwd IAT Mean, Fwd IAT Total, Bwd IAT Mean, Bwd IAT Total, Flow IAT Mean

4. Model Architecture and Training

4.1 Model 1: Naïve Bayes

The Naïve Bayes model is a probabilistic classifier that assumes each feature contributes independently to the final decision. This assumption directly contrasts with the temporal dependency modelling of the LSTM model, making it a suitable control for assessing the contribution of sequential learning.

After the preprocessing step, each flow was represented as a vector of the selected features. We then applied a Gaussian Naïve Bayes classifier, which assumes that the feature values follow a normal distribution. During training, the model estimates the mean and variance of each feature separately for the benign and DDoS classes. For each new flow instance, the model computes the likelihood of the observed feature values under each class and assigns the class with a higher probability.

By treating each flow as an independent instance, the classification decisions were based purely on the statistical characteristics of that individual flow, without considering temporal relationships between consecutive flows.

4.2 Model 2: Long Short-Term Memory (LSTM)

Each network flow in our dataset includes a timestamp column indicating when each network activity was recorded. For temporal context, the flows were sorted chronologically based on their timestamps. Consecutive flows were then grouped into non-overlapping fixed-length sequences of 36 flows, allowing the model to observe how the traffic features evolve over short time periods rather than observing the network flows in isolation.

DDoS flooding attacks exhibit characteristic patterns of inter-arrival times and packet rates that evolve over time, whereas benign MQTT traffic tends to exhibit varying and unpredictable patterns. Since these behavioural differences evolve over time, modelling temporal order provides meaningful information for network intrusion detection.

The LSTM layer consists of 64 units feeding into a GlobalAveragePooling1D layer which aggregates the temporal representations across all timesteps. This is followed by two fully connected dense layers of 32 and 16 units respectively, each with Rectified Linear Unit (ReLU) activation and a dropout rate of 0.3. Dropout and recurrent dropout are applied to reduce overfitting. The output layer is a single dense unit with sigmoid activation for binary classification. The Adam optimizer and binary cross entropy loss function were used. The model architecture is summarized in Figure 1.

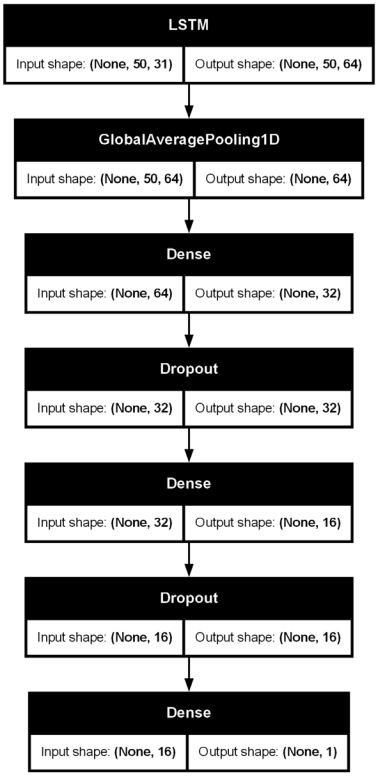


Figure 1: Model Architecture

Unlike Naïve Bayes, the LSTM retains information across timesteps, allowing it to model temporal dependencies within the flow data.

5. Experimental Results

Performance was evaluated on an unseen test set that was not used at any stage of the training process, using accuracy, precision, recall, F1-score, and the confusion matrix to assess false positive and false negative rates.

A summary comparison of the performance between the two models is shown in Table 2.

Table 2: Model Performance

Model	Accuracy	Precision		Recall		F1-Score	
		Benign	DDoS	Benign	DDoS	Benign	DDoS
Naïve Bayes	0.8990	0.99	0.86	0.69	0.99	0.82	0.92
LSTM	0.9585	0.97	0.95	0.90	0.98	0.94	0.97

Tables 3 and 4 show the normalized confusion matrices.

Table 3 Bayes Confusion Matrix

	Predicted Benign	Predicted DDoS
Actual Benign	75.3%	24.7%
Actual DDoS	0.09%	99.91%

Table 4: LSTM Confusion Matrix

	Predicted Benign	Predicted DDoS
Actual Benign	100%	0%
Actual DDoS	0.013%	99.987%

The LSTM model achieved higher overall accuracy (95.85%) compared to Naïve Bayes (89.90%). The high accuracy scores on both models demonstrate that the selected features contain sufficient discriminative information for detection. While both models demonstrated strong recall for DDoS traffic, the notable differences emerged in the benign traffic classification. The 69% score on benign traffic in Naïve Bayes indicates a high false positive rate (24.7%), where a lot of benign traffic flows were misclassified as DDoS. In contrast, LSTM improved the benign recall to 90% indicating that the temporal context helped distinguish sustained attack behaviour from legitimate short bursts of activity. In isolation, individual benign flows can resemble short attack bursts because legitimate MQTT clients frequently establish connections with brokers and publish messages in succession. This generates packet rates, TCP flag patterns and segment sizes that are similar to the early stages of a Connect or Publish attack. Without temporal context, a classifier may struggle to distinguish between a legitimate connection event and the start of a volumetric attack.

These results indicate that single flow features may not be enough to rule out false positives. The LSTM's temporal context allows it to evaluate whether a suspicious flow is part of an ongoing flood or a behavioural variation, therefore reducing false positives.

6. Conclusion and Future Works

This study examined the viability of feature selection and temporal modelling in detecting MQTT-based DDoS attacks within IoMT networks using the CICIoMT 2024 dataset. We demonstrated that guided dimensionality reduction results in concise, discriminative features that support both traditional machine learning and deep

learning classifiers. Our results show that by leveraging sequential flow dependencies, the LSTM model was able to significantly outperform the Naïve Bayes model.

Our main finding is that temporal modelling is meaningful for DDoS detection. This is because DDoS attacks usually occur as huge and repetitive volumes of normal looking traffic over short intervals of time. This is easier to distinguish from legitimate communication when modelled as sequences rather than independent instances.

Future works may include expanding beyond MQTT DDoS attacks. The CiCIoMT 2024 dataset also contains traffic data for other attack types, such as TCP SYN floods and spoofing attacks, which we did not include in our work. It would be worth exploring whether the same model trained on MQTT data can be generalised for other attacks since the network behaviour differs for each. Additionally, our current solution performs binary classification between benign and DDoS traffic. Extending this to multi-class classification to distinguish among specific attack types would provide more granular and informative detection. This would be particularly useful in critical sectors such as the healthcare industry, where accurately detecting the type of attack can inform more effective incident response efforts. Future work could also explore lightweight alternative models that could achieve comparable performance at a lower computational cost due to the resource constraints in IoMT devices. This would make deployment on constrained edge devices more feasible.

Ethics Declaration: Ethical clearance was not required for this research since the work used publicly available datasets and did not include human subjects or any sensitive information.

AI Declaration: AI tools were used only for minor formatting assistance. The intellectual contribution, methodology, and content of this paper are solely the work of the authors.

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A Potential Digital Evidence Classification Model for 5G NFV Environments Using Supervised Machine Learning Algorithms

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Abstract: The adoption of fifth-generation (5G) mobile networks has increased significantly due to enhanced bandwidth, reduced latency, and support for heterogeneous services. Key enabling technologies such as Network Function Virtualisation (NFV) and network slicing introduce flexibility and scalability but also expand the attack surface for cyber threats. These threats complicate digital forensic investigations, particularly the identification and classification of Potential Digital Evidence (PDE) in dynamic virtualised environments. This paper proposes a machine learning-based classification model for PDE in 5G NFV environments to support digital forensic readiness (DFR). The model integrates digital evidence collection, preservation, and storage processes with supervised machine learning algorithms to automatically classify forensic artefacts. A Random Forest classifier was evaluated using a combined dataset consisting of CIC-IDS 2017 traffic and real 5G packet captures. Experimental results demonstrate high classification performance, achieving a weighted precision of 0.97, recall of 0.93, and F1-score of 0.95. Feature importance analysis further highlights key traffic characteristics relevant to forensic investigations. The proposed model enhances forensic readiness by enabling automated identification and categorisation of relevant evidence, reducing manual effort and improving investigation timeliness in 5G NFV environments.

Keywords: 5G networks, Network function virtualisation (NFV), Machine Learning, Potential digital evidence, Digital forensic investigation

1. Introduction

Mobile networks have experienced rapid growth over the past decade, driven by increasing demand for high-speed connectivity, low latency, and support for diverse digital services (Hassan, Yau and Wu 2019). Fifth generation (5G) networks introduce advanced capabilities through technologies such as Network Function Virtualisation (NFV) and network slicing, enabling flexible and scalable network deployments (Barakabitze et al. 2020). However, these technologies also introduce new security challenges by increasing system complexity and expanding the attack surface available to cyber adversaries (Madi et al. 2021).

The dynamic and distributed nature of NFV environments further complicates digital forensic investigations, as Potential Digital Evidence (PDE), including network traffic records, system logs, configuration files, and user activity traces, may be dispersed across virtualised components with limited persistence. PDE refers to any form of digital data that may prove potentially useful to a digital forensic investigation (Gogolin 2021). Consequently, identifying, collecting, and classifying forensic artefacts in real time remains a significant challenge for investigators, particularly in highly virtualised 5G infrastructures (Makura and Venter 2024).

Digital Forensic Readiness (DFR) seeks to maximise the availability and usability of digital evidence while minimising investigation costs and response time through proactive preparation mechanisms (Tan 2001). Although prior research has proposed DFR frameworks for 5G environments, limited work has focused on the automated classification of forensic artefacts using machine learning techniques. Addressing this gap, this paper proposes a supervised machine learning-based model for classifying PDE in 5G NFV environments. The model integrates DFR processes with automated classification to support timely and accurate digital forensic investigations. A Random Forest (RF) classifier is evaluated using a hybrid dataset comprising public intrusion detection data and real 5G network traffic.

The research problem addressed in this paper arises from the virtualised and transient nature of 5G NFV infrastructures, which makes manual identification and classification of forensic evidence difficult, time-consuming, and error-prone (Madi et al. 2021). To overcome these limitations, there is a need for automated mechanisms capable of classifying PDE in real time to support DFR and incident response.

The objectives of this study are fourfold: (i) to develop a machine learning-based model for classifying PDE in 5G NFV environments; (ii) to evaluate the performance of supervised learning algorithms for forensic artefact classification; (iii) to analyse feature importance in order to identify forensic-relevant network characteristics; and (iv) to demonstrate how automated classification can support DFR and reporting.

The key contributions of this paper are:

- A machine learning-based PDE classification model integrated with DFR processes for 5G NFV environments.
- An empirical evaluation using hybrid datasets, combining CIC-IDS 2017 intrusion data with real 5G packet captures.
- Feature importance analysis for forensic relevance, identifying network characteristics useful for forensic investigations.

The remainder of this paper is organised as follows. Section 2 presents background and related work on 5G NFV security and DFR. Section 3 describes the research methodology and machine learning model development. Section 4 presents experimental results. Section 5 discusses findings and limitations. Section 6 concludes the paper and outlines future research directions.

2. Background and Related Works

The evolution of 5G networks has significantly enhanced communication capabilities through high bandwidth, low latency, and support for diverse services. These advancements are enabled by technologies such as Network Function Virtualisation (NFV) and network slicing, which provide scalability and flexibility but also introduce increased complexity and expanded attack surfaces. As a result, forensic investigations in 5G environments become more challenging, particularly due to the distributed and transient nature of digital evidence. Ensuring DFR through proactive evidence collection, preservation, and classification is therefore critical. While international standards provide general guidance for digital investigations, they do not fully address the challenges of virtualised 5G NFV environments. At the same time, machine learning has shown strong potential in cybersecurity, particularly for intrusion detection, but its application to forensic artefact classification remains limited. This section reviews the foundations of 5G and NFV, associated security and forensic challenges, and the role of machine learning in supporting DFR, before positioning the proposed work within existing literature.

2.1 5G Networks and Network Function Virtualisation

5G Networks represent a significant evolution in cellular communication, providing enhanced data rates, ultra-low latency, and support for massive device connectivity. These capabilities enable emerging applications such as the Internet of Things (IoT), autonomous systems, and real-time analytics (Hassan, Yau and Wu 2019).

A key architectural shift in 5G is the adoption of NFV which replaces dedicated hardware appliances with software-based Virtual Network Functions (VNFs) running on commodity hardware (Yi et al. 2018). NFV improves scalability and flexibility while reducing deployment costs. Furthermore, 5G networks employ network slicing to create multiple logical networks over shared physical infrastructure, each optimised for specific service requirements (Barakabitze et al. 2020). Despite these advantages, virtualisation introduces additional complexity and expands the attack surface, creating new challenges for cybersecurity and digital forensic investigations.

2.2 Security Challenges in 5G NFV Environments

The integration of NFV and network slicing in 5G infrastructures introduces several security risks. The virtualisation layer creates opportunities for hypervisor attacks, compromised VNFs, and cross-slice interference (Madi et al. 2021). Additionally, distributed architectures increase exposure to denial-of-service attacks, malware propagation, and insider threats (Wichary et al. 2022).

Location-shift attacks, where VNFs migrate across physical hosts, further complicate monitoring and forensic tracking of malicious activities (Yi et al. 2018). These challenges necessitate advanced detection and forensic mechanisms capable of operating in highly dynamic environments.

2.3 Digital Forensics and Digital Forensic Readiness

Digital forensics (DF) focuses on the identification, acquisition, preservation, analysis, and presentation of digital evidence following a security incident (Gogolin, 2021). This process is typically reactive, meaning evidence is collected after systems may have been altered or compromised. Digital Forensic Readiness (DFR), in contrast, adopts a proactive approach by ensuring that relevant evidence is systematically collected,

preserved, and readily available before incidents occur (Tan, 2001). Rather than replacing DF, DFR enhances the efficiency, reliability, and evidentiary value of investigations.

This distinction is particularly important in 5G NFV environments, where virtualised network functions are dynamic and distributed, and digital artefacts may be short-lived. In such contexts, reactive approaches increase the risk of evidence loss, while DFR enables continuous evidence collection and organisation to support effective post-incident analysis. ISO/IEC 27043 provides a structured framework for DFR through defined readiness processes, including planning, implementation, and assessment (Valjarević and Venter, 2016; ISO/IEC, 2015). Supporting standards such as ISO/IEC 27037 and ISO/IEC 27041 address evidence handling and investigative procedures (Ajijola, Zavarsky and Ruhl, 2014; ISO/IEC, 2012; ISO/IEC, 2016). However, these standards do not explicitly address the complexities of 5G NFV environments.

This research builds on these standards by applying DFR principles within a 5G NFV context and integrating machine learning-based classification. The proposed model aligns with ISO/IEC 27043 to ensure that automated classification of Potential Digital Evidence is both technically effective and forensically sound. standards.

2.4 Investigation Challenges in 5G NFV Environments

Forensic investigations in NFV-based 5G networks face several technical and operational challenges. Evidence sources are distributed across cloud-based infrastructure, edge devices, and virtualised network components, leading to difficulties in evidence acquisition and correlation. High-speed traffic volumes further exceed the processing capabilities of traditional forensic tools (Madi et al. 2021). Cross-domain investigations involving multiple service providers and administrative domains introduce legal and jurisdictional complexities. Moreover, the dynamic lifecycle of virtual machines and containers results in transient evidence that may be lost if not captured proactively.

2.5 Machine Learning for Cybersecurity and Digital Forensics

Machine learning techniques have been widely applied in intrusion detection, anomaly detection, and cyber threat classification. Supervised learning models such as Logistic Regression, Support Vector Machines, Random Forests, and Neural Networks have demonstrated effectiveness in detecting network attacks (Moham, Sugunaraj and Ranganathan 2022).

RF classifiers are particularly suited for tabular network traffic data due to their robustness, resistance to overfitting, and interpretability. Deep learning models such as Multilayer Perceptrons (MLP) can capture complex non-linear patterns but often require large datasets and computational resources.

However, existing research has largely focused on intrusion detection rather than forensic artefact classification. Limited work has explored how machine learning can support DFR by automatically identifying and categorising PDE in virtualised network environments.

2.6 Related Work

Research on machine learning for cybersecurity in 5G and virtualised network environments has grown significantly, with most studies focusing on intrusion detection, anomaly detection, and traffic classification. Supervised learning approaches, in particular, have demonstrated strong performance in identifying malicious activities within complex and high-throughput network infrastructures.

Several studies have evaluated the effectiveness of supervised machine learning algorithms, including RF, SVM, and LR in 5G network contexts. For example, Mohan et al. (2022) investigated multiple supervised learning techniques for cybersecurity in 5G networks and reported that ensemble-based models such as RF consistently achieve high detection accuracy. Their findings highlight the suitability of RF for handling high-dimensional network traffic data and complex attack patterns.

Similarly, Ferrag et al. (2022) explored machine learning-based intrusion detection approaches for Software-Defined Networking (SDN) and Network Function Virtualisation (NFV)-enabled 5G environments. Their work demonstrates that supervised classifiers are effective in detecting distributed and sophisticated attacks in next-generation network architectures. In another study, Krishnan and Salim (2018) applied supervised learning techniques to classify malicious traffic in virtualised infrastructures, showing improved detection performance compared to traditional rule-based systems.

Across these studies, RF has emerged as a widely adopted technique due to its robustness, resistance to overfitting, and ability to model non-linear relationships in heterogeneous data. Its ensemble structure allows it to perform well in environments characterised by noisy, high-dimensional, and mixed-type features conditions typical of 5G NFV networks. Furthermore, RF provides intrinsic feature importance measures, which enhance interpretability and are particularly valuable in cybersecurity applications.

However, despite the demonstrated success of machine learning techniques in intrusion detection, existing research predominantly focuses on real-time attack detection and prevention, with limited attention given to DF requirements. Specifically, issues such as evidence preservation, DFR, evidentiary traceability, and post-incident investigation support are not extensively addressed. As a result, there remains a clear gap between machine learning-based detection systems and the needs of DF investigations.

Makura and Venter (2024) proposed a DFR model tailored for 5G NFV environments, emphasising proactive evidence collection and preservation. While this work provides an important conceptual foundation, it does not incorporate automated classification of forensic artefacts or empirical evaluation using machine learning techniques.

This study builds upon and extends prior work by integrating supervised machine learning specifically RF classification into a DFR framework. Unlike existing approaches that prioritise threat detection, the proposed model focuses on the classification of PDE to support forensic investigation processes. By aligning machine learning outputs with ISO/IEC 27043 readiness principles, this research bridges the gap between cybersecurity monitoring and DF investigation, enabling automated, interpretable, and forensically relevant evidence classification in 5G NFV environments.

Table 1 summarises key related studies and highlights the distinction between intrusion detection-focused approaches and the forensic readiness-oriented contribution of this work.

Table 1: Summary of related work on supervised machine learning in 5G and virtualised network environments

Study	Environment	Machine Learning Approach	Primary Focus	Forensic Readiness Support
Mohan, Sugunaraj and Ranganathan (2022)	5G networks	Supervised ML (RF, SVM, LR)	Intrusion detection	No
Ferrag et al. (2022)	5G / SDN / NFV	Supervised ML classifiers	Attack detection and prevention	No
Krishnan & Salim (2018)	SDN/NFV networks	Supervised ML	Malicious traffic classification	No
Makura and Venter (2024)	5G NFV	Conceptual forensic framework	Digital forensic readiness	Partial (no ML evaluation)
This study	5G NFV	Supervised ML (Random Forest)	Potential Digital Evidence classification	Yes (ISO/IEC 27043-aligned)

3. Methodology

To address the challenges of classifying PDE in complex 5G NFV environments, this study employs a structured quantitative experimental methodology. The approach is designed to ensure both scientific rigor and practical relevance by combining synthetic intrusion detection data with real-world 5G network traffic. The methodology encompasses several interconnected phases: research design, dataset acquisition, preprocessing, feature engineering, model development, and experimental evaluation. Each phase is carefully aligned with the overarching goal of enhancing DFR through automated evidence classification. By integrating supervised machine learning techniques with forensic processes, the methodology not only evaluates algorithmic performance but also demonstrates how automated classification can be embedded into forensic workflows to support timely investigation, reporting, and incident response.

3.1 Research Design

This study adopts a quantitative experimental research design to develop and evaluate a machine learning-based model for classifying PDE in 5G NFV environments. The methodology consists of data acquisition, preprocessing, feature engineering, model training, and performance evaluation. The proposed model aims to support DFR by automating the identification and classification of forensic artefacts.

3.2 Dataset Description

Two datasets were used in this study:

1. **CIC-IDS 2017 Dataset:** A publicly available intrusion detection dataset containing benign and malicious network traffic, widely used for cybersecurity research (Canadian Institute for Cybersecurity 2017). The dataset includes multiple attack categories such as denial-of-service, brute force, infiltration, and web-based attacks.
2. **Real 5G Network Traffic and Logs:** Packet captures and system logs collected from a simulated 5G test environment. These logs contain network events, system messages, and traffic metadata relevant for forensic analysis.

The combination of synthetic and real-world data enhances the ecological validity of the proposed model. Although the dataset includes real 5G packet captures and logs, these were collected within a controlled testbed environment designed to emulate key characteristics of operational 5G networks, rather than from a live production network.

3.3 Data Preprocessing

The datasets were preprocessed to ensure consistency and suitability for machine learning analysis. Preprocessing steps included:

- Removal of duplicate and incomplete records
- Handling missing values through imputation
- Normalisation and scaling of numerical features
- Label encoding of categorical variables

For textual 5G network logs, preprocessing included tokenisation, stop-word removal, and term frequency inverse document frequency (TF-IDF) vectorisation to transform unstructured log text into numerical feature vectors suitable for classification.

3.4 Feature Engineering

Feature engineering was conducted to extract relevant attributes for forensic classification. Network traffic features included flow duration, packet counts, byte rates, protocol types, and flag statistics. Log-based textual features were represented using TF-IDF vectors to capture semantic patterns associated with attack events and system anomalies. Feature selection techniques were applied to reduce dimensionality and remove redundant features, improving model performance and computational efficiency.

3.5 Machine Learning Model Development

Several supervised machine learning algorithms were evaluated, including LR, SVM, MLP, and RF classifiers. RF was selected as the primary model due to several characteristics that make it particularly suitable for 5G NFV forensic environments.

First, RF performs well on high-dimensional and heterogeneous data, which is essential in this study where both structured network traffic features and unstructured log-derived features are combined. Second, RF is robust to noise and overfitting, which is important in dynamic 5G environments where traffic patterns may vary significantly. Third, RF provides intrinsic feature importance measures, enabling interpretability and supporting forensic requirements such as evidentiary traceability and justification of analytical decisions.

Furthermore, ensemble-based methods such as RF have demonstrated strong performance in prior cybersecurity studies, particularly in intrusion detection and traffic classification tasks within 5G and virtualised environments. These characteristics motivated the selection of RF as the primary model for PDE classification in this study.

3.6 Experimental Setup

The dataset was divided into training and testing subsets using an 80/20 split. Cross-validation was performed to reduce bias and ensure generalisability of results. Model performance was evaluated using precision, recall, F1-score, and accuracy metrics. Feature importance analysis was conducted to identify attributes most relevant for forensic investigations, providing insights into evidence prioritisation.

3.7 Forensic Readiness Integration

The proposed classification model was integrated into a DFR workflow, including evidence collection, preservation, storage, and reporting processes. Classified forensic artefacts were automatically summarised to support investigation documentation and incident response.

4. Experimental Results

This section presents the outcomes of the experimental evaluation conducted to assess the effectiveness of supervised machine learning models in classifying PDE within 5G NFV environments. The results highlight both the comparative performance of baseline algorithms and the superior capabilities of the RF classifier, which consistently achieved the highest precision, recall, F1-score, and accuracy across diverse attack categories and benign traffic. Beyond raw performance metrics, the experiments also provide insights into the forensic relevance of specific network and log-based features, demonstrating how automated classification can prioritise critical attributes for investigation. The findings not only validate the robustness of the proposed model but also underscore its practical implications for DFR, showing how machine learning can reduce manual effort, accelerate evidence triage, and strengthen incident response in dynamic and distributed 5G infrastructures.

4.1 Model Performance Evaluation

The performance of the supervised machine learning models was evaluated using precision, recall, F1-score, and accuracy. LR, SVM, MLP, and RF classifiers were implemented and compared.

Table 2 summarises the classification performance of the evaluated models. RF achieved the highest overall performance across all metrics, indicating its suitability for forensic artefact classification in 5G NFV environments.

Table 2: Performance comparison of machine learning models

Model	Precision	Recall	F1-score	Accuracy
Logistic Regression	0.06	0.04	0.05	0.08
Support Vector Machine	0.25	0.20	0.22	0.26
Multilayer Perceptron	0.90	0.86	0.88	0.89
Random Forest	0.97	0.93	0.95	0.94

4.2 Random Forest Classification Results

The RF classifier achieved a weighted precision of 0.97, recall of 0.93, and F1-score of 0.95, outperforming all baseline models. These results demonstrate the model's ability to accurately classify PDE associated with different 5G related cyberattack types and benign traffic.

Figure 1 presents the confusion matrix for the RF model, illustrating classification accuracy across attack categories and benign traffic classes.

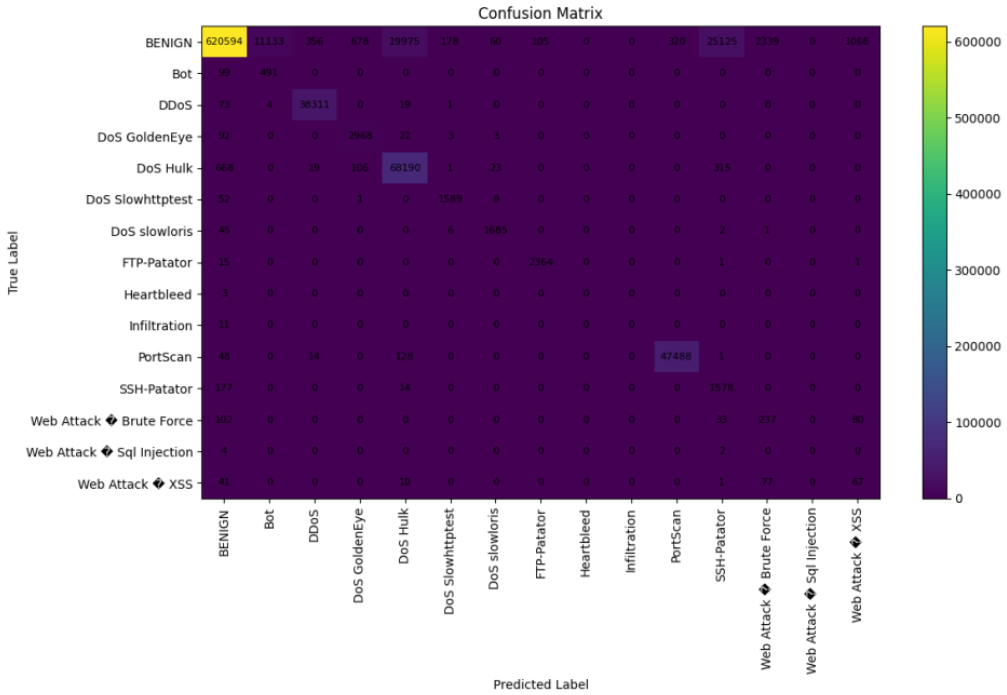


Figure 1: Confusion matrix for Random Forest classifier

4.3 Comparative Analysis with Baseline Models

LR and SVM demonstrated moderate classification performance but exhibited reduced recall for minority attack classes. The MLP model captured non-linear patterns but showed higher variance and training complexity compared to RF.

The superior performance of RF can be attributed to its ensemble-based decision trees, which effectively handle heterogeneous network traffic and log-based features while reducing overfitting.

Figure 2 illustrates the comparative F1-scores of the evaluated models.

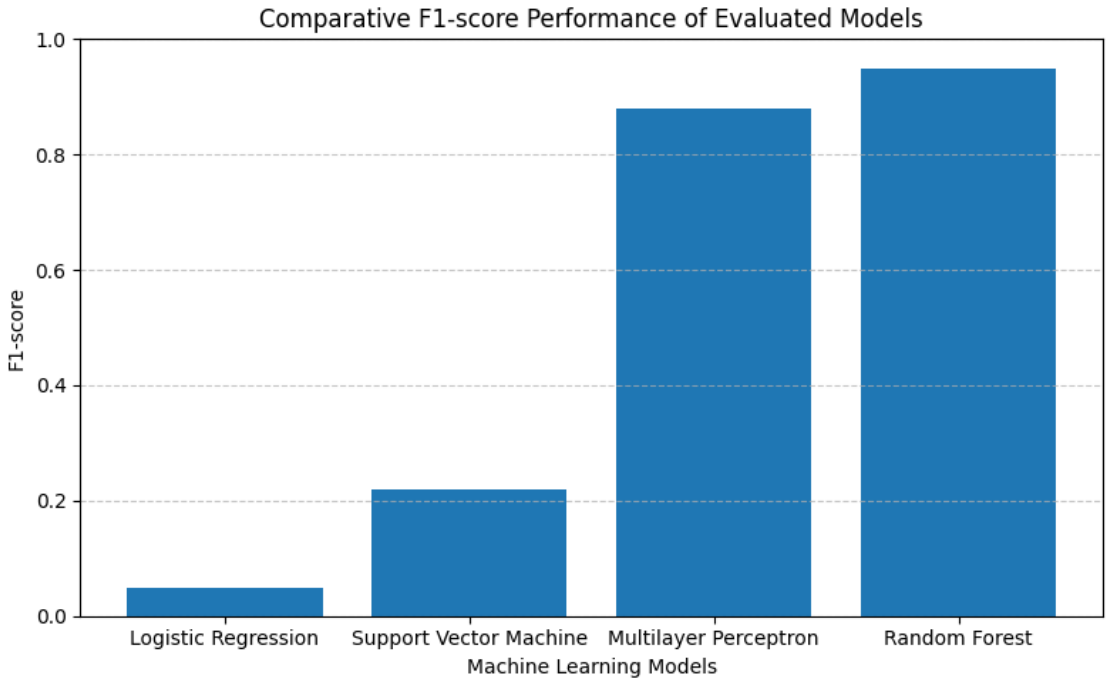


Figure 2: Comparative performance of machine learning models

4.4 Feature Importance Analysis

To enhance forensic interpretability and support evidentiary analysis, feature importance analysis was conducted using the RF classifier. RF models provide intrinsic feature importance scores based on the contribution of each feature to the ensemble decision process.

Figure 3 illustrates the top-ranked features influencing classification outcomes. Highly weighted features included network flow characteristics such as packet size variance, flow duration, byte rates, and protocol-related attributes. These features are commonly associated with abnormal traffic patterns and are particularly relevant for distinguishing between benign and malicious network activity in high-speed 5G environments.

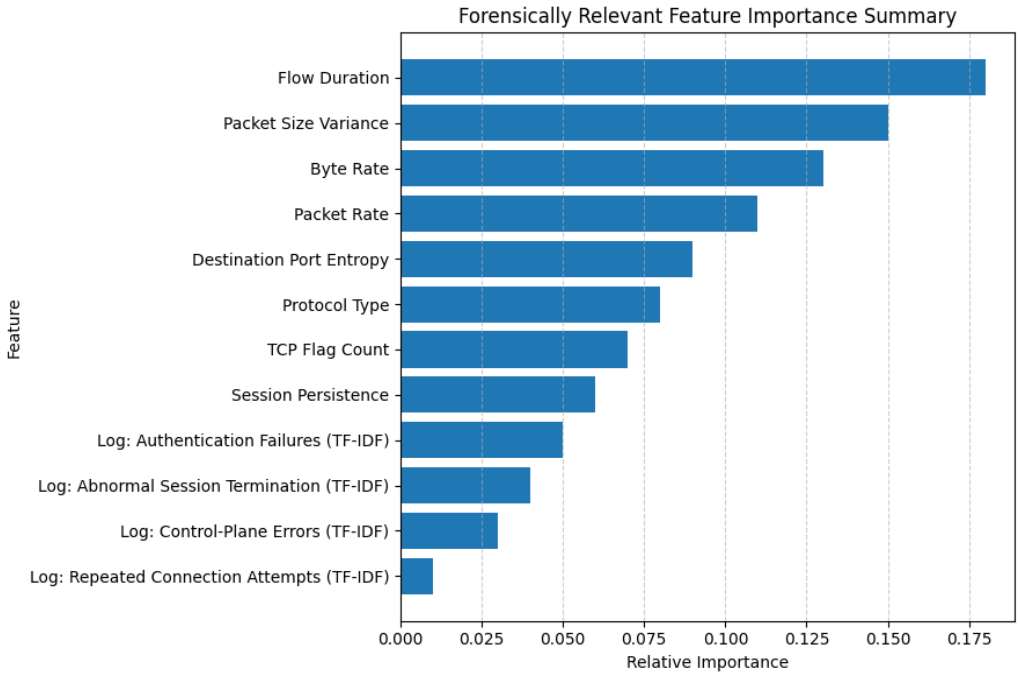


Figure 3: Summary of forensically relevant features frequently identified as influential during Random Forest model evaluation for PDE classification in a 5G NFV environment

In addition to traffic-based features, several log-derived features represented using TF-IDF vectorisation were identified as significant contributors. These features capture semantic patterns in 5G network and system logs, such as authentication failures, session terminations, and abnormal control-plane events. Their prominence highlights the importance of integrating both structured network metrics and unstructured log data when classifying PDE.

From a DFR perspective, the identification of salient features supports evidence prioritisation and investigative decision-making. By highlighting attributes most indicative of malicious activity, investigators can focus on high-value artefacts during post-incident analysis. This aligns with the interpretability and traceability principles emphasised in ISO/IEC 27043 readiness processes. The feature importance summary presented reflects the most consistently influential attributes observed during model evaluation, rather than a single extracted importance vector, and is intended to support forensic interpretability rather than precise model introspection.

4.5 Implications for Digital Forensic Readiness

The experimental results demonstrate that machine learning-based classification can significantly enhance DFR by automating the identification and categorisation of PDE. Automated classification reduces manual triage effort and accelerates forensic investigations, particularly in dynamic 5G NFV environments where evidence is transient and distributed.

5. Results and Discussion

This section discusses the experimental findings and critically evaluates the proposed machine learning-based classification model in the context of DFR for 5G NFV environments.

5.1 Discussion of Results

The experimental results demonstrate that supervised machine learning techniques can effectively support the classification of PDE in virtualised 5G NFV environments. Among the evaluated models, the RF classifier consistently outperformed LR, SVM, and the MLP across all evaluation metrics.

The superior performance of RF can be attributed to its ensemble-based structure, which enables the model to capture complex, non-linear relationships across heterogeneous feature sets. This is particularly relevant in 5G NFV environments, where evidence sources include both structured network traffic metrics and unstructured log-based artefacts.

While the MLP achieved competitive performance on frequently occurring attack classes, its effectiveness diminished when class support was limited. In contrast, RF maintained stable performance across both dominant and minority attack categories, making it more suitable for DFR scenarios where consistent detection and classification are critical.

5.2 Digital Forensic Readiness and Evidentiary Value

A key contribution of this research is the integration of machine learning-based classification with DFR principles. Rather than focusing solely on intrusion detection, the proposed model emphasises the identification and categorisation of PDE suitable for forensic investigation.

Feature importance analysis further enhances forensic applicability by identifying attributes most relevant to evidentiary interpretation, such as packet size variance, flow duration, and log-derived indicators. These insights support prioritisation of evidence during investigations and improve the interpretability of automated decisions.

The automated generation of structured forensic reports demonstrates how detection outputs can be transformed into actionable evidential artefacts. This capability reduces manual overhead, supports timely incident response, and aligns with forensic standards that emphasise traceability and documentation.

5.3 Strengths of the Proposed Approach

5.3.1 Multi-source evidence integration

The combination of publicly available intrusion detection data with real 5G network traffic and logs improves the generalisability of the proposed model. By learning from both synthetic and real-world sources, the system better reflects the diversity of data encountered in operational environments.

5.3.2 Interpretability and explainability

Unlike deep learning approaches that operate as black boxes, the Random Forest classifier provides interpretable decision structures through feature importance measures. This transparency is particularly valuable in forensic contexts, where investigators must justify conclusions and evidence handling decisions.

5.3.3 Alignment with forensic standards

The proposed workflow aligns with established DFR standards by supporting systematic evidence collection, preservation, analysis, and reporting. Although not explicitly standard-compliant, the model complements existing frameworks and enhances their applicability in 5G NFV contexts.

5.4 Limitations and Threats to Validity

Despite promising results, several limitations must be acknowledged. First, although the dataset was enhanced using real 5G traffic and logs, the experimental environment was based on a controlled laboratory testbed rather than a live operator network. Consequently, certain operational characteristics, such as dynamic network slicing policies and large-scale mobility patterns, were not fully captured.

Second, publicly available intrusion datasets such as CIC-IDS 2017 do not represent the full spectrum of contemporary or emerging 5G-specific attack vectors. As a result, some attack classes may be underrepresented, potentially affecting generalisability.

Third, while standard evaluation metrics provide useful performance insights, additional operational metrics such as detection latency, resource consumption, and scalability were outside the scope of this study. These factors are particularly relevant in high-throughput 5G environments and should be addressed in future work.

5.5 Implications for Cybersecurity and Cyber Warfare

From a cybersecurity and cyber warfare perspective, the findings indicate that automated forensic artefact classification can enhance situational awareness and post-incident analysis in complex network infrastructures. In high-tempo environments where attacks may be persistent, distributed, and multi-vector, the ability to rapidly identify and categorise evidence supports both tactical response and strategic assessment. The proposed approach contributes toward bridging the gap between detection systems and forensic investigation capabilities, enabling organisations to move beyond reactive defence toward proactive forensic preparedness.

6. Conclusion and Future Work

This paper presented a machine learning-based model for classifying PDE in 5G NFV environments and thereby attain DFR in 5G NFV environments. By integrating supervised machine learning with DFR processes, the proposed approach addresses the challenges posed by dynamic, virtualised network infrastructures such as 5G. Experimental results demonstrated that the Random Forest classifier outperformed baseline models, achieving a weighted F1-score of 0.95 while providing superior interpretability. The ability to identify and prioritise forensic-relevant features, combined with automated report generation, supports efficient evidence handling and post-incident investigation. The findings confirm that machine learning-based classification can play a valuable role in enabling DFR within 5G NFV environments by reducing manual effort, enhancing evidentiary clarity, and supporting timely incident response.

While this study incorporated real 5G traffic within a controlled testbed to approximate operational conditions, future research will extend the proposed model to fully deployed 5G core environments (e.g., Open5GS-based infrastructures) to validate performance under true operational conditions, including live network slicing, large-scale user mobility, and production-level traffic variability. Expanding the dataset to incorporate additional attack types and contemporary threat scenarios will further improve generalisability. Future work will also investigate the use of explainable artificial intelligence techniques, such as SHAP and LIME, to enhance transparency and strengthen the evidentiary value of automated classifications. Additional performance metrics, including detection latency, throughput, and resource utilisation, will be explored to assess real-world feasibility.

Acknowledgements

Acknowledgement and funding Support: The authors acknowledge the support received through the Network Security Call grant from the South African National Research Network (SANReN), which contributed to the research activities underlying this work. The support is gratefully acknowledged.

Ethics Declaration: This research did not involve human participants, personal data, or animal subjects. All network traffic and log data were collected from publicly available datasets and controlled laboratory test environments. Ethical clearance was therefore not required for this study.

AI Declaration: AI tools, including ChatGPT, were used to assist with language refinement, structural editing, and clarity improvement of the manuscript. All research design, data collection, experiments, analysis, and results are the original work of the authors.

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Immersive Cyber-Verse: The State of Immersive Learning Techniques in Cybersecurity Education in Small Colleges

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Abstract: In our current predicament of alarming rise of cyberattacks, social engineering attempts and an evolving need for encrypted security, the importance of cybersecurity education and training cannot be overstated. The need to equip the current and future generation of students with all the necessary tools, knowledge and expertise to combat this ever-increasing threat is paramount. Big institutions, including R1, 2 and 3 universities have already been striving to train a cybersecurity-trained workforce and providing substantial resources and funds to continue research and exploration of this area. On the other hand, smaller institutions, including private liberal arts colleges, four-year universities and various urban colleges are often grappling with the obstacles of limited funds and the inability of utilizing expensive infrastructure to continue research in niche cybersecurity topics, such as quantum information systems, critical infrastructure systems, etc. This paper provides an overview of the various challenges faced by these smaller institutions in terms of resources for their students for the required cybersecurity training and discusses potential teaching techniques using immersive learning methods of augmented reality (AR) and virtual reality (VR). The use of these technologies is already being prevalent in imparting student learning in complex and inter-disciplinary cybersecurity topics. This paper aims to identify the challenges associated with the utilization of these technology in smaller higher learning institutions. It further discusses potential strategies to overcome these shortcomings to eventually help these universities to proactively join the commitment of building a cybersecure workforce.

Keywords: Immersive techniques, Cybersecurity education, Small colleges, Virtual reality, Augmented reality

1. Introduction

As cybersecurity techniques and applications are increasingly expanding and becoming more complex, a robust curriculum with effective and innovative teaching methods are also necessary to provide the required training to cybersecurity practitioners. Regular curriculum and content often become ineffective or stagnant in imparting the knowledge in an effective hands-on manner. On the other hand, both traditional and online learning face the challenge of engaging student interest and attention in complex subjects. The socially distant structure of remote education also decreases the feeling of connectedness with the content. Immersive technologies, blending a digitally generated environment with real world objects, allow a sense of immersion and interactivity for users, while also reducing external distractions effectively. Immersive learning has been proven to significantly improve knowledge acquisition and understanding, concept retention, and improving understanding of abstract and complex topics (Childs et. al, 2023) Moreover, for imparting more complex material, virtual reality-based techniques have been shown to increase student attention and motivation in a positive manner. Although these technologies have been used in a cybersecurity curriculum in a limited manner, we focus on the utilization of immersive learning experiences for more targeted teaching of complex topics in cybersecurity.

Niche cybersecurity topics, such as Quantum Key Distribution, Post-quantum Cryptography, SCADA systems security, etc. are often not included as part of the regular curriculum taught in smaller institutions due to various constraints. We explore the use of virtual reality technologies (termed “CyberVerse”), as a potential method of teaching these cybersecurity topics to attract and retain student interest as well as render complex knowledge in a user-friendly manner. In this paper, we therefore address the following research question:

What are the key barriers to adopting immersive learning technologies for teaching niche cybersecurity topics in resource-constrained institutions, and what strategies can enable effective implementation despite limited funding and infrastructure?

We attempt to investigate this by following the steps below:

1. Investigate virtual reality usage in current cybersecurity topics
2. Identify niche cybersecurity topics which may benefit from virtual reality technologies
3. Identify limitations in smaller higher learning institutions in implementing new cybersecurity curriculum using virtual reality tools
4. Propose a four-fold method to address these constraints and build a way to develop virtual reality-based content for niche cybersecurity topics

This research thereby addresses a critical equity issue in cybersecurity education, ensuring that students at all types of higher learning institutions, have access to cutting-edge training methods necessary to combat the evolving cyber threat landscape. It strives to identify the resource gap and its impact on the development of a robust cybersecurity workforce and expand pedagogical understanding of how immersive learning addresses complex cybersecurity concepts. The rest of the paper is arranged as follows. Section 2 highlights the relevant research on virtual reality techniques, especially in cybersecurity education. Section 3 provides a deep dive into the different available virtual reality and immersive technologies. Section 4 outlines the challenges of adopting these systems. Section 5 describes our proposed implementation techniques in smaller higher learning institutions and finally Section 6 concludes our paper.

2. Related Research

M. Bruner, D. Chakravorty, N. Gober, D. McMullen, A. Payne, and J. Seo (Bruner, 2019) used physical security aspects integrated within a cybersecurity training program application. Named the Cyberinfrastructure Security Education for Professionals and Students (CiSE-Pros), focused on physical security best practices, such as, entrance requirements for data centers, secure interaction with hardware infrastructure, etc. The application also highlighted secure practices of access control, physical documents and clean desk policies.

K. Kullman, M. Ryan, and L. Trossbach (Kullman, Ryan, Trossbach, 2019) developed VRDAE (Virtual Reality Data Analysis Environment), which provided a collaborative environment and data visualization tools for network connections to train cybersecurity analysts within an enterprise environment. Moreover, two associated integrated applications named VIDS (Visual Intrusion Detection System), and VDE (Virtual Data Explorer) enabled users to participate in the secure design and implementation of network topology and traffic and security alerts, thereby exposing the users to data interaction within a virtual environment.

J. Ingalls (Ingalls, 2021) utilized mixed reality interfaces based on metadata from network appliances that allowed analysis capability for cybersecurity risk and operations. The tool, named Viewpoint, enabled collecting data from multiple sources to create an enterprise network traffic simulation. Additional activities like simulations of attack maps, intrusion models, remediate breaches and attack signature simulation were also provided for the users to interact within the environment.

P. Wagner (Wagner, 2023) developed the Virtual Exploit Network Offense Management (VENOM) tool, which enabled top networking protocols for a medium size shipping/delivery company network, to be simulated in the virtual environment. The tool also included network attack scenarios to visualize real-time network attack simulations, hence improving Security Operations Center (SOC). Situational awareness was also facilitated via the tool by integrating dashboards and visual heads-up displays in the operational environment.

Skorenkyy, Kozak, Zagorodna, Kramar, and Baran (Skorenkyy, et. al, 2021) focused on augmented reality by developing a model to map AR-assisted scenarios onto the NICE framework cybersecurity topic blocks. This tool targeted robust content development and improved user engagement for a cybersecurity training project encompassing the functional requirements, such as cybernetic, applications, services, security, interoperability, predictability and sustainability of cyber-physical systems.

Scholefield and Shepherd in their paper (Scholefield, Shepherd, 2019) performed a study that used gamification to teach password security to users. This research targeted the limitations of previous research, where gamification was mostly targeted for younger audience, especially high school students. The authors also recognized that these gamification models were primarily browser-based applications and hence had limited reach due to many having inaccessible browsers. Their postulated platform thus designed a unity role-playing quiz application for Android. The results from this application yielded positive results in improving understanding of password security concepts and accepted gamification as an effective teaching tool for cybersecurity education.

Alqahtani and Kavakli-Thorne improved upon the role-playing gaming concept by developing a CybAR, an Augmented Reality game for Cybersecurity Awareness (Alqahtani, Kavakli-Thorne, 2020). They targeted a more experienced audience set and included activities in spoofing attacks, phishing, ransomware and phone scams. Elements of both Technology Threat Avoidance Theory (TTAT) and the Persuasion Knowledge Model (Conde-pumpido) were adopted in their game framework design. This game design also produced positive results, where participants were observed to have improved cybersecurity understanding, elevated engagement with the game-based learning and increased interest in cybersecurity learning in the future.

Veneruso, Ferro, Marrella, Mecella, and Catarci observed the effectiveness of a Virtual Reality (VR) experience called CyberVR (Veneruso et. al, 2020). In this gaming mode, users were immersed in a VR avatar as an IT technician. They were then required to complete certain mini games within the platform that covered relevant cybersecurity topics. Built as a two-level game, the first level focused on building and refreshing fundamental concepts for a novice cybersecurity user. The second level then emphasized more critical real-world concepts such as network mapping/scanning, information flow, code injection, patch management, dynamic software analysis, privilege escalation, and public-key cryptography. Their experiment successfully provided positive outcomes that determined that gamified cybersecurity learning was more engaging than traditional textbook instruction and can be an effective tool to teach complex topics in the same.

Although the research and adoption of VR/AR technologies for cybersecurity are still somewhat limited, leveraging gamification strategies for teaching cybersecurity concepts remain an effective and desirable method for future content development.

3. Types of Virtual Reality Technologies

Virtual Reality consists of an absorbing, interactive, computer-mediated experience in which a person perceives a synthetic environment via specialized human-computer interface (HCI) equipment (Mandal, 2013).

Virtual reality technologies include both software and hardware components for its operability and human-computer interaction capability (Li, Zhu, 2021).

Software

- Builds interactive environment for users
- Has 3D modeling capability
- Engine capable of building the virtual environment

Hardware

- Allows data and real-world information input
- Enables injecting and receiving feedback into/from the virtual environment

Typical interactions with virtual reality interfaces so far have been using some form of controllers either controlled by a pointer or hand gestures. With advanced technology, users are now capable of virtual reality interaction in a varied number of ways. Technologies such as eye-tracking, optical body tracking, gloves, optical hand gestures, muscular/spatial, neural interfaces, and various haptic and sensory feedback devices, enable the users to completely immerse themselves in the virtual environment and affords a more seamless interface steeped in realism.

Virtual Reality experiences provided to users are categorized into the following main types (Wagner, 2023):

- Virtual Reality (VR) – Users are completely immersed in a computer-generated reality.
- Augmented Reality (AR) – enhances the real world with images, text, and other virtual information via devices such as head-up displays, smartphones, tablets, smart lenses, and glasses.
- Mixed Reality (MR) – more advanced than augmented reality enabling users to interact with virtual objects that are placed in the real world.
- Extended Reality (XR) – an all-encompassing term depicting all current and future (yet-to-be-created) immersive technologies (Marr, 2019)

Cooper and Thong (Cooper, Thong, 2019) were proponents of educational applications of virtual reality and introduced the VR Education model or VEM. The authors demonstrated the usability of VEM on 4 criteria:

- *Experience* – A learner can experience concepts of different locations such as space or phenomena such as historical times or locations, not only from their individual point of view, but also from another learner.
- *Engagement* – Measures a learner's attention novelty, interest, feedback, and challenge across the spectrum of emotional, sensory, and spatiotemporal criteria.
- *Equitability* – Promotes learning experience consistency irrespective of varied geographical locations, technology access, social and economic biases
- *Everywhere* – Denotes the ability of VR to provide CVEs or Collaborative Learning Environments to learners to promote global collaboration, unrestricted by location, time and modalities.

For the purposes of this paper, we are only going to be focusing on currently available VR and AR technologies only. Although a detailed explanation of Virtual Reality interaction is outside the scope of the paper, it is important to understand the current and future possibilities. From this point in the paper the implementation of one or both types of virtual reality technology are collectively going to be referred to as the CyberVerse.

4. Limitations of Cyber-verse Application

4.1 Traditional Challenges for VR/AR Adoption

Although VR/AR and similar technologies have been in use for several years, there have been considerable obstacles to its adoption in varied areas due to certain negative associations with the same. Specifically in areas of education, training, operational usage and teaching for younger audiences on a regular basis, this technology faces a lot of adoption barriers. Some of these issues include:

- Financial constraints due to relevant infrastructure needs
- Absence of realism in environments and fidelity
- Issues in translating and validating knowledge earned through these methods
- Physical and Psychological effects on users
- Lack of Guidance on associated curriculum development
- Need for mobile device usage by minor participants

Neelakantan (2019) explored these barriers in the context of three educational settings – K-12 schools, higher educational institutions and organizational trainings. Notably, K-12 schools were found to be faced primarily with budget constraints, lack of understanding of VR benefits, value on education and learning, retention effectiveness for students, as well as parents and guardian concerns (Neelakantan, 2019).

Matsika and Zhou (2021) in their paper explored similar concerns of VR adoption in higher educational settings and categorized them in distinct concern areas of individual security, environmental cocnerns, ethical concerns and content availability (Matsika, Zhou, 2021).

The detailed table illustrating the barriers to VR adoption in educational settings based on both Neelakantan and Matsika et. al. classifications, is below.

4.2 Adoption Challenges for Smaller Institutions

For the purposes of this paper, we define small colleges as any US institution catering to less than 5000 students, usually with a strong undergraduate focus. These institutions usually house with fewer academic programs and provide limited class sizes, but often with more personalized faculty interaction. For the scope of this paper, we are including the following types of US higher education institutions under our umbrella term of “Small colleges”:

- Private Liberal Arts Colleges
- Regional Public Colleges
- Private Non-profit Colleges

- Religious and Minority Centric Colleges

As mentioned above, all these types of higher learning institutions hold small class sizes, limited course offerings and cater to a much lower number of total students as compared to Research centric (R1 and R2) and State aided colleges in similar locations and topics. The student base also widely varies in these colleges, which often dictates course offerings and new course development. Considering these differences, we highlight the top three (technical and framework aspects combined) critical distinct challenge areas, encountered by small colleges regarding providing a comprehensive cybersecurity education utilizing virtual reality technology (Figure 1).

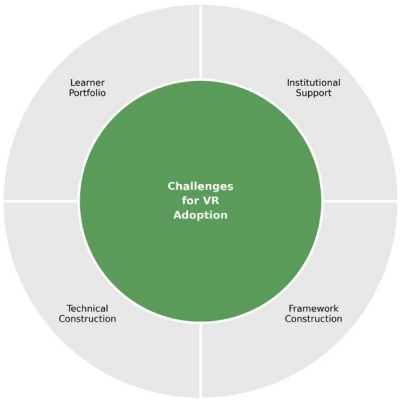


Figure 1: Challenges for CyberVerse adoption in Small Colleges

- **Learner Portfolio:** The overall student population in small colleges are mostly less than R1 and R2s. Moreover, many programs in the former, provide primarily undergraduate curriculum with no graduate degree support. Thus, the necessary background and/or experience of students to pursue specialized cybersecurity topics are very much limited. Much of the cybersecurity curriculum in small colleges is focused on enhancing application-based and technical skills for students, rather than being research or theory oriented. While many institutions do offer a combination of both aspects, students are usually on a fixed career path and a highly job centric goal, which can limit student awareness regarding niche cybersecurity topics. However, even with awareness of such topics, students are often unwilling to follow a more research-based study plan to explore these areas. Learning new concepts with perceived less employability and topic visibility is mostly the main deterrent for students to adopt a virtual reality-based approach to learn niche cybersecurity topics.
- **Institutional Support:** With the adoption and widespread utilization of any new technology and curriculum tools, small colleges need, not just departmental support, but recommendations from higher administrative levels as well. Many of the curriculum change decisions affect other related departments as well and many students with different majors/minors than cybersecurity face challenges with advanced technology usage in courses. Thus, institutions are very often reluctant to adopt new or experimental curriculum changes due to adverse issues of retention, engagement and future enrollment. Departmental faculty and staff can also be hesitant to change their course structure and introduce further challenges to student learning in the topics. Lack of managerial and collegial support may contribute to delayed or absent adoption of a newer virtual reality technology-based curriculum.
- **Technical and Framework Construction:** Finally, the financial and budget related concerns (considered together) while launching virtual reality-based curriculum is a significant limiting factor when it comes to small colleges. With limited budget allocations, usually dependent on tuition rates and private endowments and minimal or absent state and government support, adopting a virtual reality-based teaching curriculum is an ongoing challenge in smaller institutions. Acquisition, Operation, Troubleshooting and Maintenance, all require significant financial commitments from the upper management and the department, thereby posing a major obstacle in the adoption of these technology in these scenarios.

5. Proposed CyberVerse Implementation Design in Smaller Institutions

In this section, we propose several potential techniques to introduce CyberVerse in small colleges for teaching cybersecurity concepts. We look at a four-fold method to overcome the major limitations of such implementation and tailor these recommendations to be applicable to the limited infrastructure and financial resources available in these institutions (Figure 2).

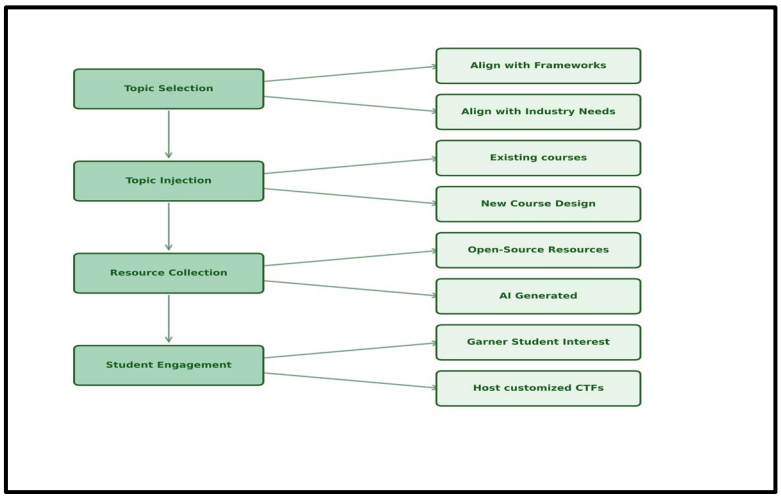


Figure 2: Process of CyberVerse implementation in Cybersecurity Education

- **Topic Selection:** Keeping in mind the allocation of limited resources in small colleges, it is a good idea to purposefully choose the topic areas in cybersecurity that can benefit students the most. Careful selection of niche but relevant cybersecurity topics can not only help retain student engagement but can also make them better prepared for future job prospects in those areas. Selecting topics in this criterion can be an overlap of required knowledge units based on frameworks for cybersecurity higher learning and current industry needs and standards in the field.

Widely adopted frameworks such as NICE and CAE are a good starting point to identify niche cybersecurity topics for this purpose. Some possible topics include:

- Cyber-Physical Systems (CPS)
- Industrial Control Systems (ICS)
- Threat Intelligence (THI)
- Offensive/defensive Cyber Operations
- Critical Infrastructure Security
- Human Factors in Information Security
- Post Quantum Cryptography
- Quantum Computing and Security

Relevant industry standards, such as ISACA and SentinelOne, include the following niche topics:

- Post-Quantum Cryptography (PQC)
- Operational Technology (OT) & IoT Security
- Identity-First Security & Decentralized Identity
- API and Serverless Security
- Zero-Trust Architecture
- Quantum Computing Threats
- Social Engineering via Deepfakes
- **Topic Injection:** Once we have identified the topics that fit into the requirements of the institution, the next step is to plan the implementation of the topics. This can be done by either integrating smaller modules in already existing courses in the department or by developing entirely new cybersecurity courses based completely on virtual reality technology. Depending on infrastructure support, student needs and instructional capabilities, a good rule-of-thumb is to slowly but deliberately introduce students to the usage of virtual reality technology learning in the new topic areas by incorporating mini modules, assignments and labs within the existing cybersecurity courses.

This gives students an exposure to the newer topics and the technology and eases the adoption and transition into this different form of learning. In instances where current course integration is not possible, designing entirely new courses with the new topics and using VR techniques to demonstrate concepts and undergo lab-based training, can be an alternate means of action. In both cases, adoption, understanding and acceptance of the different teaching method and topic choices must be slow, persistent and consistent to yield long term results. Aligning course learning outcomes with (Kirschner, 2002) can be a best practice technique in this case.

- **Resource Collection:** The next step in this four-fold process will be to obtain relevant resources for implementing these courses. Since one of the challenges faced by small colleges is the lack of financial and administrative support, we must tackle this resource gathering stage in the most efficient and cost-effective way as possible. One method is to use Open-source resources available from various R1 institutions. Several research-based VR tools are freely available from these institutions. Many organizations also market their beta version software and tools in this area as well. Some of the related research, such as CyberVR, CybAR, etc. are good examples of these. Many other open-source tools for specific topic areas are also available. For example, for quantum computing and quantum cryptography, the user-friendly simulation platform QuantumFlyTrap (https://quantumflytrap.com/virtual-lab/) and the comprehensive project lists at the Quantum Open Source Foundation are useful resources (https://qosf.org/project_list/). If open sources resources are still insufficient to meet the course needs, using the various Generative AI tools are also a fast and effective way to generate virtual reality simulations tailored to specific courses. For instance, Claude AI produced the following quick simulation of BB84 protocol with a preliminary prompt within a few minutes Figure 3). It also provided a detailed explanation of the design and implementation process and the source code to further modify the simulator as needed. Please refer to the publicly available demo (https://claude.ai/public/artifacts/bb2855d7-6584-47ab-b5dd-c34d727fd78e) and detailed information on this on my GitHub page (https://github.com/smandal-metrostate/BB84-VR). Using more targeted prompts with similar GenAI tools can also be a useful way to produce real-world models for students to practice their cybersecurity skills in the selected topic areas.



Figure 3: BB84 protocol simulation generated by Claude AI

- **Student Interest:** The final step in the CyberVerse implementation in small colleges is cultivating and maintaining student engagement and course retention. Since the selected niche cybersecurity topics maybe less popular or even unknown to many novice cybersecurity students, it is important to garner attention and visibility to the same. Ways to do that can include increased marketing on these topics through advising, student club events, class auditing, and offering special topics courses. Creating awareness and maintaining relevance to the CyberVerse implementation can also be done by hosting occasional in-house CyberVerse CTFs, local high school CyberVerse mini trainings and emphasizing their significance during open house or other departmental events. A combination of intentional advertising and word-of-mouth through users will be an effective way to recruit and retain students in these the niche CyberVerse areas.

6. Conclusion

In this paper, we focused on virtual reality technologies and how they can be implemented in improving cybersecurity education in higher learning institutions. These technologies are documented to enhance the learning ability for users by conveying complex concepts in a virtualized environment.

We focused on small colleges catering to less than 5000 students and outlined major challenges faced by them in using VR/AR technologies in teaching niche cybersecurity topic areas. We identified several such topic areas based on current curriculum frameworks and industry standards. We then proposed a four-fold method of incorporating this technology, together coined as CyberVerse, which included potential design and implementation ideas for teaching cybersecurity in small colleges. The techniques proposed in this paper are aimed at aiding these institutions to provide their students with exposure to the varied cybersecurity topics as well as give them an opportunity to leverage the limited resources for effective and improved cybersecurity teaching. Our future work plans to further investigate these techniques individually with case studies and user surveys.

Ethics Declaration: No ethical clearance was needed for the research described in this paper.

AI Declaration: I have used an AI tool to polish up figures 1 and 2 used in this paper. A part of the research example described in the paper had an AI generated component (BB84 simulator). No other uses of AI have been made in this paper.

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The Forgotten Stub: Exploring Malicious Use of the PE DOS Header

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Abstract: Malicious actors increasingly employ sophisticated concealment techniques within Windows Portable Executable (PE) files to evade static and dynamic detection, complicating incident response and digital forensics. Detecting malware in PE files has become a central challenge in modern security research, leading to a mix of complementary analysis methods. Current approaches range from traditional signature-based scanning, which identifies known byte patterns, to heuristic systems that flag unusual structural traits such as abnormal section sizes, entropy spikes, and inconsistent header values. Machine learning models now play a role, using features like opcode sequences, imported API functions, and metadata patterns to classify files at scale. Deep learning models, including convolutional and recurrent networks, learn higher-level representations directly from raw binaries or extracted features. However, many or most systems designed to detect malicious software in PE files deal with the portion of the file structure specific to Windows. A section of the file called the "DOS Header" is generally ignored by malware analysis. This paper describes a method whereby hand-crafted malware can be hidden in the DOS Header of the PE file, thus evading detection by many analysis methods.

Keywords: Reverse engineering, Malware, Windows, Software exploits

1. Introduction

Malware analysis is the practice of studying software to understand what the software does, how the software does it, and if the software is malicious, how it operates and how one might defend against it. Two methods for analysis are static inspection, where code and metadata are examined without running the file, or dynamic inspection, executing the sample in a controlled environment to watch its actions. These methods reveal the strategies malware authors use to hide, spread, and cause harm. By uncovering these details, malware analysis supports everything from incident response to the design of stronger detection tools, forming a key line of defense in modern cybersecurity. However, in the world of Microsoft Windows, many, if not most, software analysis tools focus on the portion of a Windows executable program that contains the Windows-relevant software. Because of the evolution of operating systems from Microsoft, executable program files on Windows contain a short "stub" program; this was designed during the transition from old MS-DOS to new Windows operating systems, and is actually a DOS program "stuck on the front" of the Windows instructions.

Can a malware author craft exploit code and hide it in the "stub" program, so that most modern vulnerability analysis tools will miss it? Yes.

In the following section, the authors describe the structure of a Windows "Portable Executable" (PE) file and detail the organization of the sections and headers in the file format. Section 3 provides a brief description of the tools commonly used in the reverse engineering process, where malware analysts inspect a PE file to determine how it operates. Section 4, "Current Trends in Malware Detection", covers exactly that – how Artificial Intelligence and Machine Learning, among other methods, are changing the landscape. Section 5 describes the author's methodology for hiding malware in a way that evades many of the tools that focus on Windows. Conclusions and final thoughts are in the last section, Section 6.

2. The PE File Format

The Windows Portable Executable (PE) file format is the standard file structure used for object code, executables, and dynamic link libraries (DLLs) in modern Windows operating systems (Microsoft 2025). A large part of the PE file format is taken from an older format called the Common Object File Format (COFF). In fact, the majority of the "interesting parts" in a Windows PE file are in the COFF portion of the file. A brief overview of the format of Windows PE files is in order.

A PE file consists of several parts, all of which are described by "headers". A header is simply a structure, or record, which describes a portion of the remainder of the file. Several of the headers are used to describe the entire contents, while some headers contain a set of records, and the collection of these records makes up the header. Figure 1 below gives the overall idea, and following the figure are additional details.

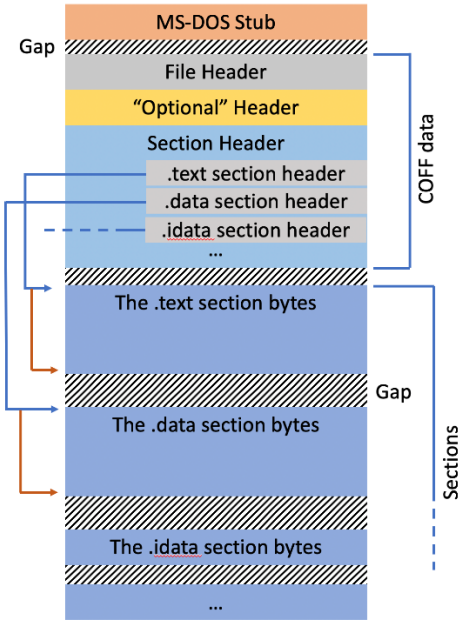


Figure 1: Typical Windows PE Executable File

Starting at the beginning (top) of the figure, and for backward compatibility, the beginning of the file is a program that can execute on a MS-DOS operating system. This DOS header is a minimal program that, when run on MS-DOS, will simply print a message and exit. At the time Windows was introduced, an MS-DOS program had a name ending in ".EXE" and a very simple format called the "MZ" header dictated what MS-DOS was to do with the remainder of the file. With the introduction of Windows, it was possible for a person to take a Windows executable file, also ending in ".EXE", and copy it from a Windows computer to a DOS computer and then attempt to run the binary. The "stub" on the front is present for this purpose and is a valid DOS program "stuck on the front of" the Windows binary.

Within the "MZ" header is a four-byte value that indicates the beginning byte of the COFF portion of the file. While the DOS portion starts with "MZ", the COFF portion starts with "PE", the first two bytes of the "file" header. The purpose of this header is to indicate what type of machine will run this code, how many sections (below) are in the file, and the size in bytes of the following "optional" header. Additionally, this area contains flags to indicate whether there is debug information, the byte ordering of the data in the file, and other characteristics. In a nutshell, this part of the file contains an overall view of what is coming up in the remainder.

Next in the file is the "optional" header. The quotation marks around the term "optional" are intentional, as the header is, in fact, required for executable programs. Despite its name, the Optional Header must be present in executable files; this naming convention originated from Microsoft's design of the format. Included are settings to indicate whether the program is a regular image or something else. A value in this area also indicates the number of bytes of program instructions, the number of bytes of initialized and uninitialized data, and so on. The address in memory for the first instruction in the program is also here, as is the base address where the program needs to be placed in memory.

It is important to understand a few additional values that are in the "optional" header. The "section alignment" is a number, a power of two. When a section (below) is loaded into memory, the address where it is loaded will be evenly divisible by this quantity. Similarly, the "file alignment" says that each section in the file will be at a byte position divisible by this alignment. Typical values might be 512, 1,024, 4,096, and so on. Note that since the following sections of the file must be located only at certain points in the executable, there are gaps between the sections, as shown in Figure 1 above.

The file is then considered as multiple sections, generally including the ".text" section for program instructions, ".data" for initialized data, ".rdata" for read-only data, possibly a ".bss" section, and others. Each of the section headers describes where in the file the section data starts, and the length – how many bytes. Additionally (not shown) are flags that indicate what Windows should do with the section; is it loaded and executable, for example, and where the section needs to reside in memory when it is loaded. Each section starts in the file at a location dictated by the file alignment described previously. For sections that are to be loaded in

memory, then, Windows will read the data from the file starting at the first byte of the section and through the length of the section, rounded up to the file alignment. A ramification of this is that the bytes in the file gaps are loaded into memory as well. These gaps do not contain anything of interest.

Unless they contain malware…

Overall, the PE format acts as a bridge between compiled code and the Windows loader, informing the loader which portions from the file go into which areas of the memory.

If the Windows program contains malware, various tools exist to assist in the analysis of that malware; some of these tools are described next.

3. Background on Reverse Engineering of Binary Executables

Reverse engineering binary code largely centers on disassembling and reconstructing machine instructions into a form that humans can understand. The difficulty of this process depends heavily on the system's architecture. For example, in architectures like ARM and other Reduced Instruction Set Computers (RISC), the consistent instruction length and predictable memory alignment make disassembly more straightforward. In contrast, Complex Instruction Set Computing (CISC) architectures such as the x86 family pose greater challenges due to their variable-length instructions and irregular encoding. Additionally, the vast number of instructions—some undocumented or dependent on specific contexts—further increases the complexity of reverse engineering (Mahoney, 2021).

Reverse engineering typically combines both static and dynamic analysis techniques. Static analysis focuses on examining program instructions without running the binary, with the goal of identifying properties that remain consistent across all possible execution paths. Common methods include disassembly, decompilation, control flow graph (CFG) reconstruction, and data flow analysis—all used to extract structural and behavioral information from the code. Well-known static analysis tools include Ghidra (2025), objdump (LinuxDevCenter, 2025), and udcli from the Udis86 project (2025).

In contrast, dynamic analysis involves executing the binary to monitor its runtime behavior and gather execution data. This approach is inherently limited to the code paths that are actually executed, which means it may overlook conditional branches or untriggered logic. Popular dynamic analysis tools include Binary Ninja (2025), Hopper (2025), OllyDbg (2025), Relyze (2025), and x64dbg (2025).

IdaPro (Hex-Rays 2025; Pearce, 2008) serves as a hybrid tool, combining static disassembly and analysis with integrated debugging capabilities to support partial dynamic analysis. Additionally, online services such as Defuse (2025) provide lightweight, web-based disassembly interfaces. Collectively, these tools utilize diverse methodologies to analyze and interpret the structure and behavior of binary code.

Over the past decade, static analysis tools have developed a significant new capability: the ability to intelligently infer what the original source code may have looked like. To achieve this, the software analyzes a function's control flow graph, identifying conditional jumps, the conditions being evaluated, and approximating expressions and logic structures. These pseudocode generators supplement the traditional approach, in which engineers would manually study a function's flowchart to mentally reconstruct its high-level design. However, as previously noted, some information is inevitably lost during compilation, meaning that the output of a pseudocode generator often represents only a rough approximation of the original source code.

At the same time, methods are used by malware authors specifically to try to throw off the static analysis process, by using additional "junk" values in the binary (Shinn 2011), hiding the control flow of the program (Mahoney 2023), and so on.

Thus, more recently, the desire is to assist in malware detection through new methods that can be more easily automated.

4. Current Trends in Malware Detection

Many recent research papers on malware detection only mention the DOS stub in passing. It is not considered in terms of examining the program for malware. For example, Puranik (2019) only mentions the stub, and the code within the stub would only be examined when constructing a byte-entropy histogram over the entire file. In fact, the flow diagram in this thesis indicates that all of the processing happens based on the PE header information (the COFF portion of the file). Similarly, work by Salas (2023) would examine the stub code when constructing N-grams (unigram, bigram, and so on, combinations of bytes in the raw file image). However, most

of the classification and machine learning deals with items such as the frequency of various instruction types within the executable portion of the PE file. Since this is static analysis, a call to a procedure in the stub would go undetected.

Joyce et. al. (2019) proposed a new metadata hash called Rich PE to address the issue of malware attribution. Rich PE utilizes Microsoft Rich header and the PE header metadata to improve the classification of malware as well as attribution issues stemming from techniques like polymorphism, false flags, and the use of commodity malware. The Rich header includes compiler and linker details and provides information about the build environment of a PE file. Popular metadata hashes such as the Imphash and Pehash fail to be effective against packed malware. RichPE combines Rich header metadata includes ProdIDs, compiler versions (mCVs), and counts of compilation artifacts, and applies transformations like bitLen to improve clustering capacity while maintaining low false positive rates, making it a reliable source for analysis. The authors also recognize future work as exploring spoofing methods on the PE header but do not highlight the stub vulnerabilities issue.

Author Kim (2018) investigated PE header metadata to extract relevant features from the entire header to determine if a file is malware. The project aimed to address the increasing use of obfuscation methods by malware developers to evade detection using traditional signature-based detection methods. Kim used various machine-learning techniques such as Support Vector Machines (SVM), Random Forest, K-Nearest Neighbors (K-NN), and Neural Networks to improve malware detection and classification. The paper describes the feature-free and feature-full methods for the PE header and compares their effectiveness against malware datasets from various sources. However, it does not outline any mention of the stub vulnerability explicitly in the classified malware detected in the experiment.

A similar approach is taken by Maleki et. al. (2019) in their research. After identifying the limitations of traditional malware detection techniques used by commercial antivirus programs, the authors rely on features extracted from the PE header and section table of PE files. They argue that since detection of packed malware if often difficult and inaccurate, malware must first be unpacked and then 8 selected features are applied as static features and utilized as input to machine learning algorithms for malware classification. However, the features selected for detection accuracy lack the inclusion of the stub and the potential of overlooking malware embedded in the same.

Several researchers have focused on improving the accuracy and detection time for malware analysis. Belaoued and Mazouzi (2015) developed a real-time Portable Executable malware detection system which utilized the information stored in the PEF (PE Optional Header) fields. The feature selection method included a combination of the Chi-square (KHI2) score and the Phi (j) coefficient. The authors did not include any features other than the Address of Entry point, Image Base, Section Alignment, File Alignment, Size of Headers, and Data Directory as their input from the Optional Header section.

In a similar approach, authors Zakeri et. al. (Zakeri 2015) proposed a combination of static and dynamic analysis of packed malware files. They focused on some common features of the PE file headers such as, DOS header, COFF header, PE Optional Header, data directories, import table, sections and resources related information. The rest of the features used were calculated based on certain anomalies found in these PE File headers. The input files were first parsed via static detection techniques and items that are deemed almost benign are dropped from the list. The items deemed to contain some anomaly signs are kept in the list and then parsed though dynamic detection mode. Although this. Method was successful in identifying several unknown malicious codes, the MS Dos stub was again not included in the analysis.

From the literature study so far, it is clear that both traditional and modern ML-based malware detectors concentrate on PE-file characteristics while largely neglecting the DOS header. Prior work has examined injecting adversarial perturbation bytes into various PE regions to evade ML classifiers (Aryal 2023, Aryal 2024; Aryal 2025), and only one study has touched on inserting bytes into the DOS area (Aryal 2024). That study, however, limited itself to non-functional perturbation placed in the MS-DOS stub and did not consider the risk posed by embedding the executable code, the specific threat this work investigates.

5. Crafting the Malware

To demonstrate the ability to create and hide malware in the DOS stub, the authors created a small reverse shell function, which is then embedded in the DOS header. As opposed to connecting up to a Windows machine over the network, a reverse shell is – possibly as the name implies – a program which reaches out from the Windows machine to a remote host. The reverse stub establishes a connection to the remote host where the malware

author is waiting; when they receive the connection, they are handed a command-line prompt from – in this case – Powershell.

In the following sections we describe the overall process of crafting the DOS stub code.

5.1 Writing The Code

Authoring the functionality for a reverse shell, or malware in general, is not as simple as it sounds, for two reasons:

- The function needs to be stand alone; by this we mean that the program can not directly rely on Windows libraries (DLLs) to be in memory. Rather, the program must have a way to ask the operating system to load a specific DLL and to search for functions within that DLL. A program which uses them directly will not work since there is no list of imports in the DOS header. Also, if the list of imports is present it is a potential giveaway to the malware reverse engineer.
- While the function needs to be able to look up Windows calls by name, the names cannot be ordinary strings. A string such as "LoadLibraryA", when compiled by the C/C++ compiler, would normally be placed into the ".rodata" section of the PE file, as these strings are read-only. But the code is in the DOS stub, not the PE file, so there are no sections. Rather, the string representation must be embedded within the executable bytes of the function.

To solve the second issue, in 64-bit mode an integer can occupy eight bytes. By putting two integers adjacent to each other, say an array of two eight-byte values, one can select two appropriate integer values and form a string up to 16-bytes. For example, the ASCII characters (in hexadecimal) for "LoadLibraryA" are 4C 6F 61 64 4C 69 62 72 in the first integer and 61 72 79 41 in the second. By assigning integer constants with these values, the combined array contains the string, without the compiler wanting to put it in a different section. Also note that to compare strings, one is really comparing 8-byte integers and not strings.

If we can use this method to solve the second problem it assists with us solving the first problem. On Windows, all programs have a Program Environment Block (PEB) which is visible to the program and therefore can be examined. The method to obtain the addresses of necessary library code is to first access the PEB, then use this to obtain the "program loader data" structure. This data is a collection of "loader data table entries", each of which has the name of the function. A two-step process is used, where the malware first locates the function "GetProcAddress", and then uses this to search for "LoadLibraryA" and the other functions which will be necessary for the reverse shell.

5.2 Modifying the Stub

Once the malware function is tested, we need to insert it into the DOS stub so that it will be built into a regular Windows desktop application. The overall flow for creating the hand-crafted stub code is as follows:

1. The reverse shell is written (in this case with Visual Studio and C++) using the above methods. A very small "main" program calls the reverse shell function. This also enables one to test the reverse shell before embedding it in the final file.
2. In Visual Studio, use the debugger to run to the beginning of the reverse shell function, and using the debugger in assembly language mode, note the starting and ending address of the instructions for the function.
3. While in Visual Studio, display the program memory in a hex dump window, from the start to end of the function; copy/paste this into a text editor and save it.
4. Keeping in mind that traditional malware detection relies on known patterns of bytes, the next step is to encrypt the saved hex dump so that strings (integers!) such as "LoadLibr" and "aryA" are not visible. A short C program encrypts the bytes and also prints the data out in a format which can then be included in an assembly language input file.
5. Place this result into the bottom of the DOS stub code and assemble it using the old DOS assembler. Examine the resulting MS-DOS format ".EXE" to verify the function starting point in the stub. This is the address that the Windows program will call in order to activate the malware.

The process is a rather odd mix of new technology, 64-bit instructions, and ancient voodoo techniques involving the Microsoft Macro Assembler from 1997.

One saving grace in this embedding is that since we are writing our example malware in a 64-bit environment, the 64-bit intel/AMD architecture makes the process simpler. In 64-bit mode, programs can be position-

independent – compiled so that they can be run at any location. All the data and code references are "relative" addresses as opposed to "absolute" addresses. This means that the location of our example malware in the overall PE file does not matter. If we know where in memory the program will be loaded (from the "optional" header) and we know where the malware function resides in the DOS stub (from us having placed it there), simply calling to that calculated address is all that is necessary. Additionally, although we have not yet looked into this, the aspect of Address Space Layout Randomization (ASLR) should not impact the effort since the malware code can be called based on an offset from the current location as opposed to a specific address.

5.3 Tying it all Together

The resulting artifact is a functional desktop application which brings up a window with menus, and so on. If our aim is to start up a reverse shell without the user noticing, this has to go. When the malware reverse shell is called, it reaches out to a known Internet IP address and port and establishes a connection, then starts Powershell to communicate with the remote malicious actor. Having a window pop up in front of the user, unexpectantly, is an issue. But this is as simple as just removing the windows functionality from the program, so that the only purpose of executing the program is to launch the shell code. Additionally, having a blue Powershell window appear, with no prompts or anything (the prompt was sent to the previously mentioned malicious actor) is also suspicious. But no problem, when we launch the Powershell using the Windows "CreateProcess" function, one can specify that no window is to be created for the process.

Advanced malware will do more than this. For example, a popular item for a malware author to write is code that registers as a service, so that it disappears off the list of running programs. Likewise, our reverse shell could be run as a separate thread within the program, so that it can sit quietly until the connection is established. Simply calling "CreateThread" is all that is required, and this has been tested.

6. Conclusions

Malware analysis gives defenders a clear view of how hostile software behaves and how it can bend a system to its will. By combining insights from static inspection, analysts can trace a sample's hidden paths and expose the tricks it uses to blend in, break out, or cause damage. However, these methods, at least when discussing Windows executables, generally examine only that portion of the PE file which contains the instructions pertinent to the Windows program. A combination of current technology (e.g. Visual Studio) and old technology (the Microsoft Assembler, version 6.15 and circa 2000) allows one to craft malware and place it into the file in such a way that most malware analysis tools will ignore the area where it resides. Analysis tools need to be modified to examine the entire program file, including areas which are normally ignored.

Ethics Declaration: We declare that we do not need ethical clearance for the research referred to in this paper.

AI Declaration: We declare that no AI tool has been actively used in the generation or writing of this paper.

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Cyber and Electromagnetic Activities (CEMA) in a Multi-domain Battlefield

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Abstract: Contemporary adversaries aim to integrate lines of operations across information, cyber, electromagnetic, and kinetic domains. They take advantage of the digitalisation of the information realm, which opens avenues to deliver impact at the cognitive and social levels. Simultaneously, the demand for mobility and dispersion on the battlefield multiplies the need for transceivers and wireless communication. Naturally, this increases the targets for electronic attacks; for example, battlespace transceivers open new avenues for breaching isolated cyber domains. The military is gradually generating cyber and electromagnetic abilities into its capability portfolio, but often lacks appreciation for their combined impact on a modern multi-domain battlefield. Therefore, the paper uses design science methods to develop a model of CyberElectromagnetic Activities (CEMA) and Enterprise Architecture (EA) views, illustrating them in the context of a modern multi-domain battlefield. First, the paper aims to define modern CyberElectromagnetic battlespace and to derive its tenets from real-world cases. Secondly, the paper elaborates on the combined CEMA in the context of multidomain operations. Thirdly, the paper designs a CEMA model and illustrates it using views typical of enterprise architecture. Finally, the paper tests the feasibility of the abducted model with operational scenarios. The CEMA model is intended for Cyber and EW operational planners and orchestrators as a foundation for CEMA operations. The findings of this research provide insights and explanations to planners and researchers of operational art that: CEMA is always a part of multi-domain operations because of its omnipresence CEMA, being a composition of many abilities, needs collaborative planning and orchestration of execution, both in defensive and offensive operations Interrelationships among CEMA, information operations, and kinetic operations need to be understood to assess the combined system-of-systems impact, Asymmetric operational thinking opens a spectrum of means and ways to effect in a multidomain battlefield, Rapidly evolving technology opens both vulnerabilities and avenues of effect for defensive and offensive operations, and Advanced digital force will dominate a force with commercial or dual-use technologies in modern multi-domain operations.

Keywords: Cyber operations, Electronic warfare, CEMA, Multi-domain operations, Design sciences

1. Introduction

Contemporary adversaries aim to integrate lines of operations across the information, cyber, electromagnetic, and kinetic domains, as illustrated in Figure 1 (Mattila, Cyber Defence is more than Cybersecurity, 2025). They take advantage of the digitalisation of the information realm, which opens avenues into the cognitive and social realms. It becomes more cost-efficient to attack through the cyber domain, launch terrorising strikes, and create confusion and fear in these realms. (Clarke & Knake, 2020) Domain, in this context, refers to a dimension of the military theatre's area of operation.

Besides the expanding cyber environment (environment refers to a man-made digital infrastructure), the demand for mobility and dispersion on the battlefield increases the need for transceivers and wireless communication. Naturally, this increases the targets for electronic attacks, for example, suppressing the GPS signal increases the circular error probability. (Soren, 2025) Moreover, battlespace transceivers open new avenues for breaching logically isolated cyber domains. (Álvarez, 2025)

A kinetic line of operation may use the electromagnetic and cyber realms to multiply the system's effects, e.g., an adversary may destroy a central control hub with a gliding air-to-ground payload and simultaneously overload defender sensors with decoy targets while suppressing communications. (Gunn, 2025) The combined course of action (CoA) will suppress the surveillance system, prevent its repair, and make the adversary lose trust in any similar C5ISTAR[1] support system during that conflict. (Popli, 2025)

[1] C5ISTAR = Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance, Target Acquisition and Reconnaissance support system of systems

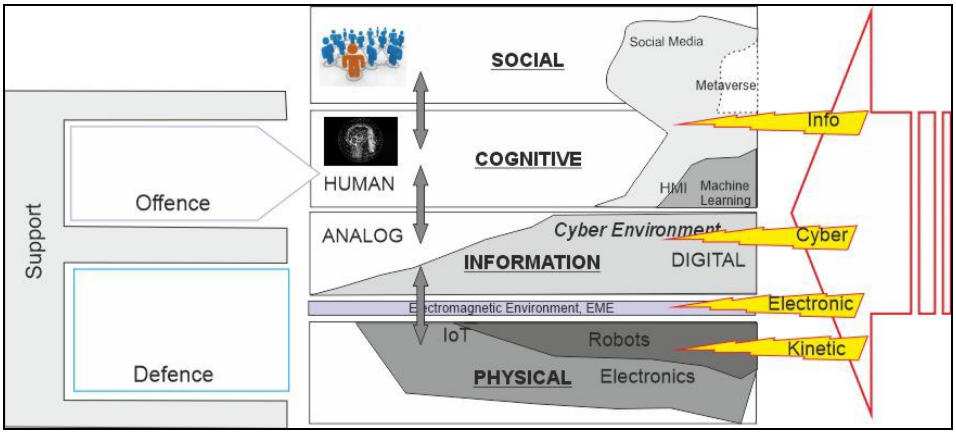


Figure 1: A View to Evolving Realms of Military Force Projection

A combination of operations on cyberspace and the electromagnetic spectrum is called Cyber and Electromagnetic Activities (CEMA) in the US Army (US Army, 2014) and the UK MoD (UK MoD, 2018). In the NATO multidomain operations model, the cyber domain fosters the electromagnetic spectrum (NATO, 2025), and missions planned in synchrony produce convergent effects within the System of Systems defence or offence. (Libicki, 2021) Hence, the definition in this paper states that CEMA are coordinated offensive or defensive courses of action that either improve BLUE's freedom of movement and survivability or degrade RED's use of the electromagnetic and cyber environment.

Since the CEMA environment predominantly comprises hardware nodes, transceivers that utilise electromagnetic propagation, and software-defined features that define cyberspace, it offers greater advantages as forces intensify their digitalisation and mobility. Therefore, the Western type of military force (4th-or 5th-generation) is more vulnerable to CEMA effects than a 3rd-generation industrial force optimised for attrition through kinetic effects. (Lind, 2004) (Abbot, 2010) On the other hand, when any force adopts dual-use consumer electronics, it may open unrecognised vulnerabilities to CEMA attacks. The rapid evolution of dual-use electronics during the Russia-Ukraine war proves this. Russia is enhancing its electronic warfare (EW) development and updating its existing equipment to counter Ukraine's rapidly evolving capabilities (Bronk, 2025).

Militaries worldwide are increasingly interested in the CEMA domain (Greenert, 2013), either to address vulnerabilities in their digital transformations or to create asymmetric, yet systems-level, effects against more digitised adversaries. The military is gradually generating cyber and electromagnetic abilities into its capability portfolio, but often lacks appreciation for their combined impact on a modern multi-domain battlefield. The paper develops a CEMA model for Cyber and EW operational planners and orchestrators, serving as a foundation for CEMA operations.

2. Illustrate CyberElectromagnetic Battlespace and Describe its Tenets

The Cyber and Electromagnetic environment continues to expand within military forces as they modernise and digitise their platforms, connecting them to a system-of-systems (SoS) of capabilities. (Dahmann, 2012) These systems of systems extend cyberspace and utilise the electromagnetic environment to support military affairs. The defenders' interest is to protect the BLUE system of systems and prevent the systemic effects (Beagle, 2001) of the Attackers (RED) that intend to suppress essential BLUE capabilities. The following literature review approaches the CEMA tenets from the perspectives of cyberspace, the electromagnetic spectrum, and a combined viewpoint. Finally, a technical system-of-systems model is developed to improve understanding of the CEMA system-of-systems in a confrontation.

2.1 Software-defined Cyberspace

As software-defined features replace mechanical functions, the amount of software code explodes. Unfortunately, the industry average for coding errors remains 15-50 defects per 1000 lines of code, and at best, the quality may reach 0.1 defects per 1000 lines. (McDonnell, 2004) The exponential growth of software code in armament, the integration of system-of-systems, and the rise of big data together increase the area of vulnerability within the technical layer of SoS.

Example: More than 30,000 public and private organisations were exposed to the SolarWinds hack between 2019 and 2020. Apparently, a Russian agent injected malicious code into SolarWinds Orion management software. When customers updated their management software, the malicious code created backdoors that hackers could use to access data. (Oladimeiji & Kerner, 2023)

On the other hand, the Armed Forces' evolving digital transformation requires competent military personnel to manage and leverage software-defined capabilities and processes. Otherwise, the growing number of people interacting with machines will provide lucrative avenues for attack. (Entrust Network, 2022)

Example: The Russian Ministry of Internal Affairs is advising residents and soldiers in areas near or within Ukrainian Forces' control not to use social media, dating apps, geotagging, geolocation links, or unsecured messaging applications. (Linder, 2024)

Software-defined, data-driven cyberspace is both more vulnerable and offers strategic advantages to the military. Hence, Information technology security, Cybersecurity, and Cyber defence operations are more critical as the military's digital transformation advances. (Whyte & Mazanex, 2023)

Example: Outdated technologies in enclaves expose the military to strategic vulnerability. An unpatched operating system in a fleet of main battle tanks may become a lucrative way to suppress the entire armoured capability. (Military Dispatches, 2024)

2.2 Electromagnetic Spectrum

Propagation in EME depends mainly on frequency, effective radiated power (ERP), antenna radiation patterns, atmospheric attenuation, and diffusion caused by elements along the propagation paths. This means that a significant concern in EME is the distance between the transmitter and receiver/reflector. Hence, both Electronic Support (ES) and Electronic Attack (EA) sensors and effectors need to be networked to select optimally located EW sites for intercepting or jamming. (Clark, Walton, Tourangeau, & Tourangeau, 2021) Any EW system, therefore, has cyberspace and needs to be protected against adversary electromagnetic and cyber effects.

Example: Ukrainian forces are combining electronic attacks, attack drones, and advancing infantry to penetrate behind Russian lines and create confusion. First, Russian surveillance drones are jammed, then, attacking drones strike both aerial and ground targets, and finally, infantry advance and seize crucial ground points. (Álvarez, 2025)

As the vulnerability of any radiating site increases, the need is to distribute, for example, surveillance radars and create low-size, weight, and power (SWaP) radar networks (Knight, 2025). While improving system resilience, the distributed architecture also provides broader coverage, especially in complex terrain. With a distributed, more disposable radar architecture, the cognitive electronic warfare (CEW) attributes will enhance both offensive and defensive capabilities. (Vernhes, 2025)

Example: Artificial intelligence-driven electronic protection (EP) can adapt in real time to conventional radar configurations and avoid detection. (Knight, 2025)

2.3 Combined Cyber and Electromagnetic Domain from a C5ISTAR System of Systems Viewpoint

Figure 2 presents a technical view of the CEMA environment. It is a snapshot from the viewpoint of a Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance, Target Acquisition, and Reconnaissance system-of-systems. Figure 2 illustrates both vulnerabilities to attacks and defensive measures. Cyberspace can be used to attack transceivers, causing systemic disruption to communications services.

Example: Russians used a strain of wiper malware, 'AcidRain', to remotely erase vulnerable modems and routers of the Viasat service, disrupting Ukrainian access to broadband space communications for up to a week. (CyberPeace Institute, 2022)

Electromagnetic attacks can jam wireless transceivers and cause denial-of-service attacks in cyberspace.

Example: Russians are reportedly jamming GPS and other satellite-based navigation systems in the vicinity of the Baltic Sea as part of their hybrid operation to create fear of flying by degrading flight safety. (Waterman, 2024)

Cyberspace data flows can be captured by intercepting the GSM signal with a software-defined transceiver and analysing the data flow of ongoing sessions. (Louwers, 2024) By rerouting GSM traffic through compromised switches and exchanges, adversaries can capture mobile data flows.

> *Example: The Russian FSB operates communications interception devices (SORM) in telecommunications exchanges to collect and analyse traffic. (Soldatov, 2014)*

A hacker can take over a router in cyberspace by accessing it via a wireless interface, exploiting outdated firmware, and using the hijacked router as part of a Denial-of-Service (DoS) botnet to distort routing protocols or capture IP packets. (Rau, 2023)

> *Example: Russia's APT28 hacking group appears to have remotely breached the Wi-Fi of an espionage target by hijacking a laptop in another building across the street. (Greenberg, 2024)*

A defender may create an additional layer of air defence against incoming missiles, drones, and aircraft using cyber intelligence, electronic support measures, and electronic attack, in addition to conventional kinetic measures.

> *Example: During the 12-day war between Israel and Iran in 2025, Iran launched more than 1,000 drones at Israel. Israel created an additional layer of CyberElectromagnetic capabilities to intercept incoming airborne objects, achieving a success rate of up to 90%. (Frantzman, 2025)*

A model for a system of systems may be illustrated, as in Figure 2, with layers of physical, electromagnetic and logical. Physical platforms, facilities, and auxiliary systems host hardware capacity for processing and transmission. Electromagnetic performance transfers effective radiated power (ERP) to propagation in an electromagnetic environment (EME). Logical software and data-defined features and flows enable processes for military affairs. The technical illustration may scale to a socio-technical SoS involving users and administrators. (Mattila, Modelling Military as an Open, Socio-technical System, 2023) Furthermore, it may extend to enterprise-wide system networks that support the main military functions of Operate, Generate and Support. (DANSE, 2025) These systems-of-systems open new domains and attack vectors for adversaries to penetrate, exploit, and suppress defenders' capabilities. Cyber warfare can be thought of as techniques for creating effects or gaining intelligence on hostile systems through digital code. (Bronk, 2025) Electronic warfare can be thought of as techniques for creating effects or gathering intelligence on hostile systems through electromagnetic energy pulses. (Bronk, 2025)

The existing CEMA-related publicly accessible doctrines in the US (US Army, 2014) and the UK (UK MoD, 2018) do not cover, for example:

- How do CEMA-related abilities contribute to each other for tactical or operational impacts?
- How do CEMA-related abilities cluster in the military structure for force utilisation?
- How can CEMA courses of action be planned and executed against an adversary system-of-systems?
- How do CEMA-related abilities support both information and conventional operations in other domains?

The CEMA operational model aims to fill the gaps in understanding reflected in current CEMA-related doctrines and policies.

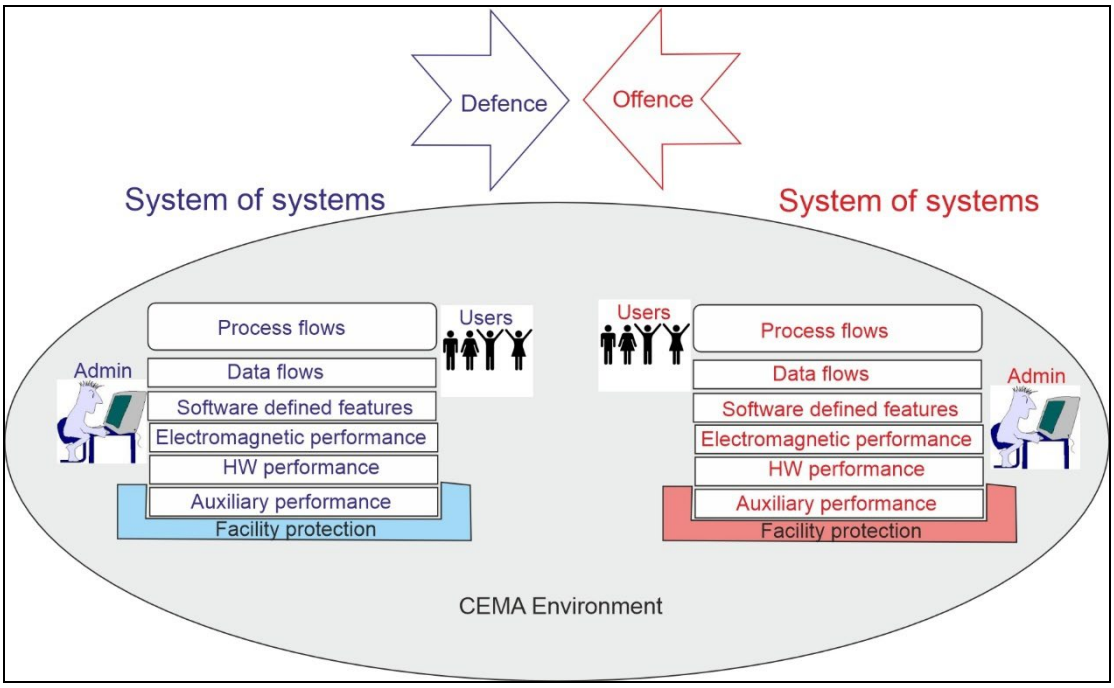


Figure 2: A System View of the CEMA Environment in Typical Forces Confrontation

3. CEMA in the Context of Multidomain Operations

Since the CEMA domain overlaps the cognitive and physical realms and encompasses most of the information realm, as illustrated in Figure 1, it provides an avenue to support both kinetic and information operations. Both Electronic and cyber-attacks can contribute to kinetic fires to achieve a joint systemic effect, as shown in Figure 3. The Russian Fancy Bear hacker group successfully infiltrated a Ukrainian artillery application used to control fires. Through the breach of 2014-2016, Russian artillery was able to locate both fire controllers and weapon sites on the Ukrainian side and destroy them more efficiently. (Crowdstrike, 2016)

Moreover, information operations benefit from Cyber or Electronic attacks that suppress official media sites or utilise hijacked cyberspace elements to disseminate influence messages. (Microsoft, 2023) Within the information realm, CEMA operations can also be employed independently as a covert arm, operating below the conventional threshold of war or providing an asymmetric advantage against modern forces (Russian Defence Policy, 2017). Russia has also used CEMA as part of a broader hybrid campaign to create terror, break the trust between the population and the government, and manipulate polarisation within a population. (NATO, 2024)

Since CEMA primarily focuses on the synchronisation and coordination of cyber and electromagnetic activities, the components and their combination in support of operations are more critical in various contexts. (UK MoD, 2018) The Electronic Warfare components are Electronic Attack, Electronic Support, and Electronic Protection, as shown in Figure 3.

- Electronic Attack (EA) broadly refers to the use of electromagnetic energy to degrade the performance of hostile systems for offensive purposes. It may independently contribute to kinetic, information, and CEMA operations.
- Electronic Support (ES or ESM) encompasses the exploitation of passively collected electromagnetic emissions to identify, track and possibly even target hostile systems. It directly supports EA, EP, and Network operations and provides essential awareness for force protection.
- Electronic Protection (EP or ECM) involves the use of electromagnetic energy by a platform to defend itself against enemy attacks, typically by degrading the signals received by enemy fire control radars, datalink connections, or missile seekers. (Bronk, 2025) EP support is used directly in kinetic operations, security, and survivability, but also contributes to Network operations and EA.

Cyberspace activities include network operations, cybersecurity, cyber defence, and cyber-attacks.

- Network operations (NO, NOC) encompass actions taken to design, build, configure, secure, operate, maintain, and sustain the C5ISTAR system of systems in a manner that ensures and preserves data

availability, integrity, confidentiality, as well as user and entity authentication and non-repudiation. (Senft, 2016) Network operations contribute directly to Cyber defence operations and also enable all military activities that use digital information. NO requires cybersecurity operations and other security measures to provide C5ISTAR support services.

- Cyber defence operations (CDO) utilise both passive and active cyberspace capabilities to protect data, networks, net-centric capabilities, and other designated C5ISTAR System-of-systems. (FM 3-21, 2021) CDO supports Information, CEMA and kinetic operations, ensuring the survivability of C5ISTAR services.
- Cyberattack operations (CAO) are conducted in cyberspace, aiming to create noticeable destructive effects (i.e., degradation, disruption, or destruction) in cyberspace or manipulation that leads to denial-of-service impacts in physical domains. (JP 3-12, 2018) CAO supports Information, CEMA, and kinetic operations, opening opportunities to achieve systemic effects within an adversary's system of systems.

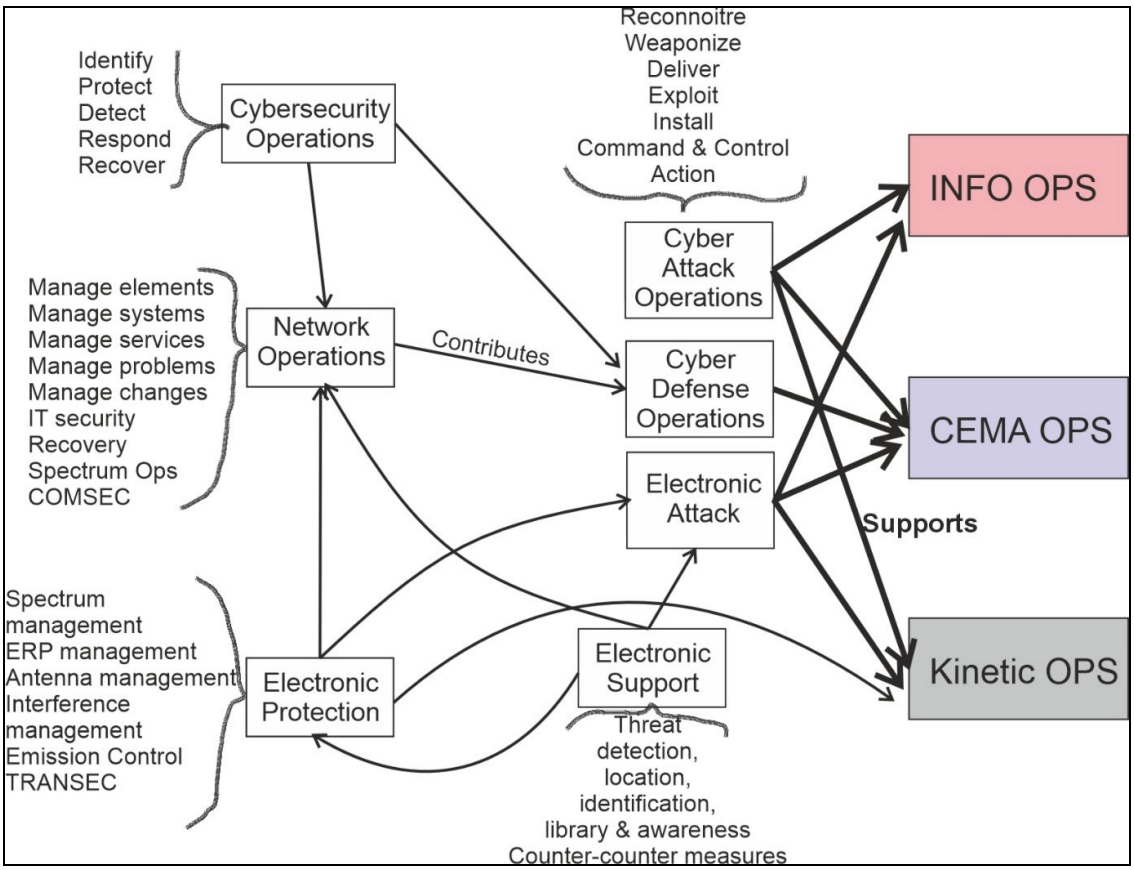


Figure 3: An operational view of the CEMA domain and its components, relationships, and architectural ontology

Understanding the interrelationships and dependencies within the CEMA in Figure 3 is crucial for effective operational planning and execution, given the complexity of both the targeting and effect. One instance of negligence renders the entire C5ISTAR system vulnerable to attacks. Naturally, this also applies to adversaries, hence, coordinated CEMA offensive activities, whether conducted alone or in support of other operations, may yield surprising victories.

4. Research Methodology

The research aims to develop a model and test its viability, the epistemological approach is knowing through making. Therefore, the research method follows the design science research process. (Gregor & Hevner, 2013) Firstly, the research recognises the problem, then surveys potential solutions, and thirdly, develops a solution. Finally, the feasibility testing of the created model follows the systems analysis methods (Mobus & Kalton, 2015). Feasibility testing uses two scenarios composed from the 2022 Russo-Ukraine war and the 2025 Israel-Iran war. The testing attributes are selected from the CEMA operational tenets of operational support, systemic impact, technology, dominance in the domain, and convergence.

5. Feasibility of the CEMA Model in Real-world Scenarios

The previous sections created the CEMA model from three viewpoints: 1. Environment and Confrontational in Figure 1, Systems view in Figure 2, and Operational view in Figure 3. This section tests the CEMA model's feasibility in two selected scenarios:

1. Scenario – Russian invasion of Ukraine 2022. The Ukrainian government and Microsoft identified 47 publicly attributed cyber incidents indicative of a campaign initiated by Russia between November 29, 2021, and May 9, 2022. Towards the end of the campaign, there was a 75 per cent increase in documented cyber intrusions—but a decline in the average severity of the attack. Only 29 per cent of the documented cyber incidents indicative of larger campaigns were degradations. Most Russian cyber operations were characterised by phishing attempts, distributed denial-of-service campaigns, propaganda or vandalism efforts, and single-network intrusions—all of which tend to have limited impact. (CSIS, 2023) Only the intrusion into the Viasat management system and the uploading of malicious software to the patching service, which then disseminated the malfunction to thousands of terminals in Ukraine and Europe, seem to have had a major impact. (CyberPeace Institute, 2022) Russian electronic warfare capabilities are countering precision-guided missiles and remotely controlled UAS. (Wattling & Reynolds, 2025)
2. Scenario – Iran-Israel 12-day war 2025 Iran-linked cyber actors execute a broad range of operations designed to exert psychological pressure, collect tactical intelligence, enforce deterrence against third countries, and maintain domestic control. Alongside disruptive cyberattacks, Iran intensified its psychological operations by using AI to generate and disseminate disinformation. Iranian operatives hijacked Israeli internet-connected closed-circuit television (CCTV) systems with the goal of exploiting them for real-time situational awareness, battle damage assessment, and adjustment of missile targets. (Khorrami, 2025) Iran intended to overwhelm Israel's Iron Dome air defence system with decoy drones and electronic attacks. (Croft, 2025)

Table 1: Testing the feasibility of the CEMA model against two selected scenarios

Attributes of the CEMA model	Scenario 1- Russian CEMA attack 2022	Scenario 2 – Iranian CEMA attack 2025
Support both Information, CEMA and kinetic operations	Ability to synchronise CAO as part of the main campaign. Ability to integrate EA with fires against airborne and ground targets.	Ability to integrate cyber and information operations for an influence campaign. Ability to integrate CAO and EA with missile and drone attacks.
Gaining a systemic impact using asymmetric means and ways	Ability to suppress Viasat terminals synchronised with air and ground forces attacks severed Ukrainian command and control functions.	Ability to retaliate against US air strikes with combined CAO and disinformation operations, creating impact in the US homeland.
Advantages or challenges of rapidly evolving technology	Russian cyber forces' ability to rely on only basic cyber-attack vectors while Ukraine builds up its coordinated cyber defence.	Iran's ability to use public CCTV networks in Israel for targeting and assessment.
Advanced digital force has dominance in the CEMA domain	Ukraine's ability to coordinate contributions from institutions, the IT Army, Cyber Troops, Technology companies, and coalition support for national cyber defence. (Kvartsiana, 2023)	The CEMA improved Iron Dome intercepted over 90% of incoming projectiles and drones.
CEMA integration for convergence and asymmetric impact	Russian tactical missions are mostly separate cyber and electronic attacks that may be synchronised under the campaign. No signs of operations in the CEMA domain.	Iranian CEMA efforts are coordinated through Information Operations and Missile/Drone Attacks. No signs of operations in the CEMA domain.

6. Conclusions

As militaries are gradually generating cyber and electromagnetic abilities as part of their capability portfolios, driven by lessons identified from the Russo-Ukrainian and Israel-Iranian wars, they often lack an appreciation of the combined cyber and electromagnetic impact on a modern multi-domain battlefield. The paper designs a model for CyberElectromagnetic Activities (CEMA) as part of the multi-domain operations in military

campaigns. The design illustrates the CEMA model from three viewpoints. An evolutionary view of the confrontation between two forces. A systems view of the opposing force system-of-systems. An operational view of the composition and value streams that contribute to CEMA operations. Following the methods of the design sciences, the paper tests the feasibility of the CEMA model in two recent scenarios.

The CEMA model proved its feasibility in two scenarios of the 2022 Russian invasion and the 2025 Israel-Iranian war in five tested features:

- Interrelationships between CEMA, information operations, and kinetic operations need to be understood for the combined system-of-systems impact. The CEMA is hard to identify in the Russo-Ukrainian war, as the parties are locked in tactical-level attrition and the fast evolution of UAS on the battlefield. On the contrary, the Israel-Iranian 12-day war was more operational in nature, and CEMA integration, both in influence operations and conventional missile strikes, followed the model.
- Asymmetric operational art opens a spectrum of means and ways for effect in a multidomain battlefield. Russian ability to take down Viasat connections synchronised with their invasion attack, and Iranian ability to counter US air strikes with influence operations in the US homeland, prove that CEMA provides major systemic impacts.
- Rapidly evolving technology opens both vulnerabilities and effects for defensive and offensive operations. Adversary digital infrastructure opens new avenues to support CEMA operations, as Iranians were able to fuse data from their ES sensors and hacked CCTV to assess the impact of missile/drone strikes in Israel, and Israeli's were using the Iranian GSM network to guide their UAS.
- Advanced digital force dominates force with commercial or dual-use technologies. Israel's CEMA-enhanced Iron Dome air defence system was able to intercept 90% of incoming ballistic or cruise missiles and drones during the 12-Day war.
- CEMA integration for convergence and asymmetric impact remains in its infancy. CEMA components are used as supporting roles for either information or conventional operations, rather than as a third line of operation. The evolution of technology or lessons identified alone does not provide sufficient leverage for transformation when existing military cultures and competencies oppose the change.

The designed CEMA model is intended to support military enterprise architects in creating multi-domain operational and systems views, military capability portfolio managers in anticipating the evolution of confrontation in military strategies, and Cyber and EW operational planners in preparing for future campaigns.

The CEMA model presented in this paper is still in its early concept. For maturity, it needs more scenario testing and simulation before it is translated into doctrine and utilised to generate military capabilities.

Ethics Declaration: This research did not require any ethical clearance.

AI Declaration: An AI tool (Grammarly) was used during the proofreading of this paper.

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A Hybrid, Transparent Trust and Risk Assessment Framework for Cryptocurrency Exchanges

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Abstract : Cryptocurrency exchanges act as critical intermediaries within the digital asset ecosystem, yet users currently rely on largely opaque, platform-defined trust scores to assess their reliability and risk. Existing industry frameworks, notably those produced by CoinGecko and CoinMarketCap, provide useful signals related to liquidity and volume integrity but suffer from limited transparency, fixed weighting schemes, and the absence of sentiment-based assessment. This paper presents HTREx (Hybrid Trust and Risk Evaluation framework for exchanges), a semi-automated, modular trust and risk assessment framework for cryptocurrency exchanges that addresses these limitations. The framework integrates five dimensions of exchange integrity: user sentiment, regulatory compliance, technical security, transparency, and incident history. Sentiment is quantified using transformer-based natural language processing applied to user-generated content from mobile application reviews and online forums. Compliance is assessed through structured extraction of regulatory and operational disclosures from Terms of Service documents using large language models. Security, transparency, and incident history are evaluated through a combination of publicly verifiable indicators, third-party assessments, and a recency-weighted incident scoring model. All components are normalised and aggregated into a composite score using user-adjustable weights, enabling personalised risk prioritisation while retaining a defensible default configuration for comparative analysis. The framework is demonstrated using four prominent exchanges—Kraken, Coinbase, Binance, and Uniswap—highlighting clear differences between centralised and decentralised platforms and illustrating how sentiment, compliance, and historical incidents materially influence overall trust assessments. The results suggest that transparent, extensible, and user-configurable scoring models can provide a more interpretable and context-sensitive evaluation of exchange risk than existing monolithic trust scores, with direct relevance for both retail and institutional participants.

Keywords: Cryptocurrency exchanges, Trust assessment, Risk scoring, Sentiment analysis

1. Introduction

Cryptocurrency exchanges constitute the primary access points to digital asset markets, enabling users to buy, sell, trade, and custody cryptocurrencies. As critical infrastructure within the blockchain ecosystem, exchanges face persistent challenges related to uneven regulation, heterogeneous operational standards, and recurring security and governance failures. High-profile incidents, including exchange hacks, prolonged service outages, and regulatory enforcement actions, demonstrate that exchange-related risk extends beyond asset price volatility and directly affects user funds, data security, and market integrity (Le Pennec, et al., 2021) (Cong, et al., 2022). To support user decision-making, industry platforms have introduced exchange ranking and trust-scoring mechanisms. However, these systems have been criticised for methodological volatility and opaque aggregation practices, raising concerns regarding consistency and interpretability (Fitzpatrick, 2019). Vidal-Tomás (2022) further highlights the absence of standardised methods for aggregating exchange data across coin ranking platforms.

CoinGecko and CoinMarketCap, the two most widely used cryptocurrency data aggregators, provide composite exchange scores derived from metrics such as liquidity, trading volume, web traffic, and selected qualitative indicators (Ong, 2020) (CoinMarketCap, 2024). Although these frameworks help reduce information asymmetry in cryptocurrency markets, they exhibit several limitations. Key aspects of their methodologies remain partially opaque or proprietary, particularly in the case of CoinMarketCap, limiting reproducibility and independent scrutiny (Fenton, 2020). In addition, both platforms rely on fixed weighting schemes that assume a homogeneous user risk profile and do not explicitly incorporate behavioural sentiment as a component of exchange trust, despite evidence that public perception and user experience influence platform adoption and risk exposure (Garcia, et al., 2014) (Broder, 2025; Wang, et al., 2022). Trust and risk in cryptocurrency exchanges are inherently multi-dimensional and context dependent, with different users prioritising factors such as security, compliance, transparency, liquidity, and usability. Static trust scores may therefore obscure trade-offs between exchange risk dimensions and misrepresent risk for specific user profiles (Simon, 2023).

This paper addresses these limitations through HTREx (Hybrid Trust and Risk Evaluation Framework for Cryptocurrency Exchanges), a transparent, modular trust and risk assessment framework. HTREx integrates five dimensions of exchange integrity: user sentiment, regulatory compliance, technical security, transparency and liquidity, and incident history. Sentiment is quantified using transformer-based natural language processing applied to user-generated content, while compliance indicators are extracted from Terms of Service documents using large language models. Security, transparency, and incident history are assessed using publicly verifiable indicators and a recency-weighted incident model. Component scores are normalised and aggregated through a user-configurable weighting mechanism, enabling personalised risk prioritisation while retaining a default benchmark configuration.

The contribution of this paper is threefold. First, it formalises sentiment as a measurable dimension of exchange trust. Second, it demonstrates how large language models can be applied to systematically extract compliance-related indicators from unstructured legal documentation (Hutto & Gilbert, 2014) (Barbieri, et al., 2020). Third, it introduces a configurable aggregation model that bridges the gap between opaque platform-defined rankings and user-specific risk assessment.

2. Methodology

This study proposes HTREx, a modular framework for cryptocurrency exchange trust and risk assessment. HTREx builds on existing industry approaches while addressing limitations related to static weighting schemes and the lack of sentiment integration(Ong, 2020) (CoinMarketCap, 2024). The framework decomposes exchange trustworthiness into five analytically distinct components and supports user-adjustable weighting to reflect different risk priorities (CoinGecko, 2023).

2.1 Conceptual Structure of the Framework

HTREx models exchange trust as a composite function of five components: Sentiment (S), Compliance (C), Security (Sec), Transparency (T), and Incident History (I). Each component is independently assessed using data sources and techniques appropriate to its underlying risk dimension. Component scores are normalised to a common scale in the interval [0,1], where higher values indicate lower perceived risk and higher trust.

The final trust score, T_{Trust}, for a given exchange is computed as a weighted linear aggregation of these components:

$$T_{\text{Trust}} = \sum_{k=1}^{5} w_k X_k$$

where $X_k \in \{S_{Sentiment}, S_{Compliance}, S_{Security}, S_{Transparency}, S_{Incident}\}$ denotes the normalised component scores, and $w = [w_1, w_2, w_3, w_4, w_5]^T$ is the weight vector, with w_k representing the weight assigned to the kth component. The weights satisfy the constraint:

$$\sum_{k=1}^{5} w_k = 1 \, , w_k \geq 0 \; \forall k$$

Unlike many industry rankings, the weighting vector is user-adjustable to reflect risk tolerance, regulatory context, or use case. A default configuration is also provided for benchmarking and comparative analysis.

2.2 Data Collection Strategy

HTREx adopts a hybrid data collection strategy combining automated and manual methods. Automated collection is used for sentiment and liquidity-related metrics through public APIs and aggregator services, while manual collection supports compliance, security disclosures, and incident history derived from Terms of Service documents, audit reports, and public reporting. All collected data are converted into structured JSON representations for downstream processing. This approach reflects the fragmented nature of exchange-related data and the absence of a single comprehensive source for exchange risk assessment (Simon, 2023)

2.3 Component Normalisation and Aggregation

Each component score is derived using a method tailored to its data type and risk characteristics but is ultimately normalised to the same numeric range. This design choice ensures that no single component dominates the composite score by virtue of scale rather than substantive importance. Binary indicators (e.g. presence or absence of specific compliance disclosures) are encoded as 0 or 1, while continuous indicators (e.g. sentiment

polarity or bid–ask spread proxies) are linearly normalised. The modularity of HTREx allows components to be extended, replaced, or recalibrated without affecting the overall structure. For example, additional sentiment sources or alternative security metrics may be incorporated as data availability improves. Similarly, the weighting mechanism supports scenario-based analysis by enabling systematic exploration of how trust rankings change under different user priorities.

2.4 Scope and Exchange Selection

To demonstrate the applicability of HTREx, four exchanges were selected for evaluation: Kraken, Coinbase, Binance, and Uniswap. The selection reflects diversity in operational models, regulatory posture, and market structure. Kraken, Coinbase, and Binance represent large custodial exchanges, while Uniswap represents a decentralised non-custodial exchange. This enables comparative analysis across centralised and decentralised paradigms and illustrates how differences in compliance, security, and incident exposure influence trust assessment. The framework is intended to demonstrate transparent, component-based evaluation rather than provide definitive exchange rankings.

3. Sentiment and Behavioural Risk Assessment

User sentiment represents a behavioural dimension of trust that is largely absent from existing exchange ranking frameworks, despite evidence that public perception and collective experience influence platform adoption, reputational risk, and market behaviour (Garcia, et al., 2014) (Wang, et al., 2022). In this framework, sentiment is treated as a measurable proxy for user satisfaction and perceived reliability, complementing technical and regulatory indicators rather than replacing them.

3.1 Data Sources

Sentiment data were collected from mobile application reviews on the Google Play Store and discussion posts from Reddit. These sources capture complementary perspectives: app reviews reflect direct user experience with exchange functionality, while Reddit discussions capture broader community reactions to outages, regulation, and security incidents. Garcia, et al (2014)) showed that such informal online content can reveal early signals of operational risk and shifts in user confidence. For each exchange, a fixed number of recent reviews and discussion posts were collected to ensure comparability. Textual data were pre-processed through lowercasing, URL removal, and language filtering.

3.2 Sentiment Classification Method

Sentiment classification was performed using a RoBERTa-based transformer model fine-tuned for short, informal text (Barbieri *et al.*, 2020). Transformer models were selected over rule-based approaches such as VADER due to their ability to capture contextual nuance, sarcasm, and mixed sentiment common in cryptocurrency discourse (Hutto & Gilbert, 2014) (SuperAnnotate, 2023). For each text item, the model produced a continuous sentiment score representing positive, neutral, or negative sentiment. Individual predictions were aggregated at source level and subsequently combined into a single exchange-level sentiment score.

3.3 Platform-Level Sentiment Aggregation

To combine sentiment information across multiple sources, a weighted aggregation approach is employed. The final sentiment score is defined as:

$$S_{\text{Sentiment}} = \sum_{k=1}^{n} \alpha_k \cdot P^{(k)}, \alpha_k \in [0,1], \sum_{k=1}^{n} \alpha_k = 1$$

where $P^{(k)}$denotes the aggregated sentiment score derived from source k, and α_k represents the relative importance assigned to that source, and there is a total of *n* sources. The framework can accommodate additional sentiment sources without altering its overall structure. The resulting sentiment score is linearly normalised to the interval [0,1], where higher values indicate more positive user perception and lower behavioural risk.

3.4 Limitations

Sentiment scores revealed meaningful variation in user perception that did not always align with market-centric rankings. However, sentiment analysis captures expressed opinion rather than objective risk and may be influenced by short-term events, highly vocal user groups, or domain-specific language use. Sentiment should therefore be interpreted as a complementary behavioural signal rather than a standalone trust indicator.

4. Compliance and Regulatory Assessment

The compliance component of HTREx evaluates regulatory disclosures, licensing claims, and the implementation of know-your-customer (KYC) and anti-money laundering (AML) controls. Regulatory compliance represents a core dimension of exchange trust, particularly for custodial platforms operating across multiple jurisdictions. Compliance indicators provide insight into financial crime prevention, regulatory accountability, and user protection, but such information is often embedded within lengthy and unstructured legal documents. To address this challenge, HTREx extracts structured compliance indicators from exchange Terms of Service (ToS) documents. The prioritisation of KYC and AML measures aligns with international guidance identifying financial crime prevention as a central component of virtual asset oversight (Financial Action Task Force, 2025).

4.1 Compliance Indicators and Scoring Model

Compliance is operationalised through three core dimensions: financial crime prevention, regulatory accountability, and user protection. These dimensions are represented through a set of binary indicators reflecting widely recognised regulatory and governance practices. Specifically, financial crime prevention is captured through the explicit presence of Know Your Customer (KYC) and Anti-Money Laundering (AML) measures. Regulatory accountability is assessed through disclosure of operating jurisdictions and references to regulatory authorities. User protection is represented through references to data protection obligations and explicit statements regarding user fund protection.

Each indicator is encoded as being either present (1) or absent (0). Indicators within each dimension are averaged and combined into a single compliance score using a weighted formulation:

$$S_{\text{Compliance}} = 0.4 \cdot \frac{\text{KYC} + \text{AML}}{2} + 0.3 \cdot \frac{\text{Regulators Mentioned} + \text{Jurisdictions}}{2} + 0.3 \cdot \frac{\text{Data Protection} + \text{User Fund Protection}}{2}$$

This weighting prioritises financial crime prevention, reflecting its central role in international regulatory frameworks, while retaining visibility of governance transparency and user safeguards. The resulting compliance score is normalised to the interval [0,1], with higher values indicating stronger observable regulatory alignment.

4.2 Automated Extraction Using Large Language Models

To extract compliance indicators at scale, a GPT-family large language model was used to analyse exchange ToS documents. Large language models were selected due to their ability to interpret complex legal language and perform structured information extraction without task-specific retraining (Kumar, 2025). A constrained output schema ensured consistent extraction of predefined compliance indicators for integration into the scoring pipeline. Although LLM-based extraction reduces manual effort, potential errors such as omission or misinterpretation of legal clauses remain possible. Limited human oversight was therefore applied to high-impact indicators related to regulatory accountability and user fund protection.

4.3 Empirical Compliance Outcomes

The application of the compliance component to the evaluated exchanges revealed clear structural differences between centralised and decentralised platforms. Custodial exchanges operating within regulated jurisdictions achieved high compliance scores, reflecting explicit disclosure of KYC, AML, and data protection practices. In contrast, the decentralised exchange exhibited lower compliance scores, primarily due to the absence of formal identity verification requirements and explicit user fund protection mechanisms, despite partial acknowledgment of regulatory considerations. These findings underscore the value of treating compliance as a distinct trust dimension rather than conflating it with market activity or liquidity. The findings also illustrate how exchange architecture and custody models influence observable compliance characteristics—an effect that is often obscured in aggregate exchange rankings (Ong, 2020) (CoinMarketCap, 2024).

5. Security, Transparency and Incident History

While sentiment and compliance capture behavioural and regulatory aspects of exchange trust, technical security, operational transparency, and historical performance provide critical insight into an exchange's capacity to safeguard user assets over time. These dimensions represent both preventative controls and realised risk and are therefore treated as distinct but complementary components within HTREx.

5.1 Technical Security Assessment

Technical security reflects an exchange's ability to protect its infrastructure and user assets against unauthorised access, data compromise, and systemic failure. Security maturity is assessed using a set of commonly disclosed indicators that reflect prevailing industry practices and custodial risk management norms. These indicators include the availability of two-factor authentication (2FA), the existence of a public bug bounty programme, evidence of cold wallet asset storage, secure communication standards as indicated by SSL/TLS configuration, the presence of third-party security audits, and disclosure of internal security practices. Indicators are encoded either as binary variables (present or absent) or as normalised continuous values, depending on the nature of the metric. The overall security score is computed as the arithmetic mean of all available indicators:

$$S_{\text{Security}} = \frac{\text{2FA} + \text{Bug Bounty} + \text{Cold Wallet Storage} + \text{SSL/TLS} + \text{Audit} + \text{Security Disclosures}}{N}$$

where N denotes the number of security indicators considered. This formulation ensures comparability across exchanges while accommodating partial disclosure or data availability. Although the model does not capture all aspects of an exchange's internal security posture, it provides a transparent and reproducible approximation suitable for cross-platform analysis.

5.2 Transparency

Transparency reflects the degree to which an exchange provides verifiable information regarding its operations, reserves, and market behaviour. Rather than relying on region-specific trust badges or proprietary labels, transparency in this framework is operationalised through globally observable indicators: public proof-of-reserves disclosures, accessibility of audit reporting, and observable market liquidity.

The transparency score is calculated as:

$$S_{\text{Transparency}} = \frac{\text{Proof of Reserves} + \text{Audit Reporting} + \text{Bid–Ask Spread}}{N}$$

where all indicators are encoded as binary or normalised values and N represents the number of transparency indicators. Liquidity is proxied through bid–ask spread normalisation, with narrower spreads indicating higher liquidity, improved price discovery, and greater operational transparency. This approach aligns with methodologies employed by major exchange aggregators while retaining methodological transparency and reproducibility (Ong, 2023). Transparency indicators within exchange ranking systems frequently incorporate liquidity-related measures, including trading volume and bid–ask spread. Bid–ask spread is widely recognised as a practical indicator of market liquidity and execution efficiency, particularly for active traders and short-term market participants, as it reflects transaction cost and market depth (Cryptopedia, 2025). However, such indicators provide limited insight into custodial risk, governance practices, or regulatory exposure, underscoring the need to interpret liquidity-based trust signals with caution. The growing emphasis on proof-of-reserves disclosures reflects broader industry efforts to restore confidence following a series of high-profile custodial failures. While such disclosures improve transparency regarding asset backing, their implementation remains uneven and lacks consistent standardisation across exchanges, limiting their comparability as standalone trust indicators (CoinGecko, 2023).

5.3 Incident History

Historical incidents provide insight into realised operational and governance risk that cannot be inferred from preventative controls alone. Security breaches, regulatory enforcement actions, and prolonged service disruptions may have lasting effects on trust, even where current controls appear robust. To capture both severity and recency, the framework employs a decay-weighted incident scoring model, where each incident is weighted by its impact and reduced over time according to an exponential decay function $\mathrm{f(t)} = e^{-kt}$. This ensures that recent, severe events influence trust more strongly than older or minor incidents. The approach is adapted from standard risk management practices and provides a transparent and interpretable mechanism for incorporating both the severity and temporal relevance of historical evidence.

The incident score is defined as:

$$S_{\text{Incident}} = 1 - \frac{\sum_{i=1}^{n}(w_i \cdot f(t_i))}{W_{\text{max}}}$$

where w_i represents the severity weight of incident i, $t_i$denotes the time elapsed since the incident occurred, and W_{max} is a normalisation constant ensuring that the resulting score lies within the interval $[0,1]$. Temporal decay is modelled using an exponential function:

$$f(t_i) = e^{-kt}$$

where k controls the rate at which the influence of historical incidents diminishes over time. This formulation reduces the impact of older incidents while preserving the significance of recent failures, enabling the framework to distinguish between short-term operational risk and long-term reputational recovery.

Together, the security, transparency, and incident components provide a balanced view of preventative controls, observable openness, and historical outcomes. Centralised custodial exchanges generally score higher on security due to formal access controls and custody practices, while decentralised platforms often exhibit greater transparency but face structural limitations in compliance and incident mitigation. Importantly, the incident component functions as a corrective mechanism, ensuring that strong present-day controls do not fully offset a history of severe operational failures. By maintaining separation between these dimensions rather than collapsing them into a single opaque metric, HTREx enables a nuanced interpretation of trust and risk trade-offs. This separation also supports scenario-based weighting, allowing users to prioritise preventative security, transparency, or historical performance depending on their risk tolerance and time horizon.

6. Composite Trust Scoring

This section presents the aggregation of component scores into a composite trust value and discusses the empirical outcomes observed across the selected exchanges. The objective is not to establish definitive rankings, but to demonstrate how a transparent, component-based framework produces interpretable and context-sensitive trust assessments that differ meaningfully from existing industry scores.

6.1 Trust Score Aggregation

The final trust score is computed as a weighted aggregation of the five component scores introduced in Sections 3–5. This formulation reflects the multi-dimensional nature of exchange trust while allowing prioritisation to vary according to user preferences and risk tolerance.

The composite trust score is defined as:

$$T_{\text{Trust}} = w_1 S_{\text{Sentiment}} + w_2 S_{\text{Compliance}} + w_3 S_{\text{Security}} + w_4 S_{\text{Transparency}} + w_5 S_{\text{Incident}}$$

subject to the constraint:

$$\sum_{j=1}^{5} w_j = 1$$

where $S_{\text{Sentiment}}, S_{\text{Compliance}}, S_{\text{Security}}, S_{\text{Transparency}}$, and S_{Incident}represent the normalised component scores, and $w_j$denotes the corresponding weights. To enable baseline comparison, a default weighting configuration was defined based on the relative importance of regulatory compliance, asset protection, and user experience as reflected in prior exchange assessment practices (Ong, 2020):

$$w = \{w_1 = 0.20,\ w_2 = 0.25,\ w_3 = 0.25,\ w_4 = 0.15,\ w_5 = 0.15\}$$

This configuration places greatest emphasis on compliance and technical security while retaining behavioural sentiment and historical performance as meaningful contributors. The weighting scheme is not claimed to be optimal; rather, it serves as a defensible reference point for comparative analysis and illustrates the flexibility of HTREx.

6.2 Exchange Level Results

Table 1 presents the component scores, composite trust values, and resulting relative rankings for the evaluated exchanges under the default weighting configuration defined in Section 6.1. The table provides a compact empirical summary of the framework's output and illustrates how individual trust dimensions contribute to overall platform assessment.

Table 1: Component Scores, Composite Trust Scores, and Relative Rankings

Platform	Sentiment $S_{\text{Sentiment}}$	Compliance $S_{\text{Compliance}}$	Security S_{Security}	Transparency $S_{\text{Transparency}}$	Incident S_{Incident}	Final Risk/Trust T_{trust}	Ranking of the Platforms
Kraken	0.158	1	0.8333	0.943	0.329	0.735	1
Coinbase	0.0915	1	0.8333	0.448	0.558	0.646	2
Binance	0.439	0.85	0.8333	0.445	0.796	0.617	3
Uniswap	0.2125	0.45	0.6667	0.543	0.996	0.510	4

The results highlight clear structural distinctions between centralised and decentralised platforms. Kraken achieved the highest composite trust score, driven primarily by comprehensive compliance disclosures and high transparency, despite comparatively low sentiment and a moderate incident score.

Coinbase ranked second, reflecting similarly strong compliance and security scores, but received a lower transparency score and weaker sentiment during the evaluation period. Binance exhibited a contrasting profile, combining high sentiment and a strong incident recovery score with comparatively lower compliance and transparency. These trade-offs resulted in a lower composite trust value under the default weighting configuration despite strong market presence. Uniswap, as a decentralised exchange, displayed a markedly different trust structure. Its near-maximal incident score reflects the absence of major custodial breaches, while its transparency score exceeds that of some centralised platforms. However, lower compliance and security scores—stemming from its non-custodial architecture and limited regulatory alignment—reduced its overall trust score under the default configuration. It is important to emphasise that the rankings presented in Table 1 are relative and configuration dependent. They should be interpreted as illustrative outputs of the framework rather than definitive or universal statements regarding exchange trustworthiness.

6.3 Sensitivity to Weight Adjustment

A key advantage of the proposed framework is its support for sensitivity analysis through explicit weight adjustment. Increasing the weight assigned to compliance and security amplifies the advantage of regulated custodial exchanges, while increased emphasis on transparency or sentiment narrows this gap and, in some cases, alters the relative ordering of platforms. This behaviour demonstrates that trust is not a fixed or objective property, but a context-dependent judgement shaped by user priorities, regulatory exposure, and risk tolerance.

To illustrate this effect more concretely, Table 2 summarises a set of alternative weighting profiles and the resulting changes in relative exchange rankings. All scenarios presented in Table 2 use identical underlying component scores; only the weighting configuration is modified. The default profile reflects a balanced assessment, while the alternative profiles place increased emphasis on security, compliance, or transparency and sentiment, respectively.

Table 2: Sensitivity of exchange rankings under alternative weighting profiles

Weighting profile	Sentiment w_1	Compliance w_2	Security w_3	Transparency w_4	Incident w_5	Resulting ranking
Default (baseline)	0.20	0.25	0.25	0.15	0.15	Kraken > Coinbase > Binance > Uniswap
Security focused	0.10	0.15	0.40	0.10	0.25	Binance > Coinbase > Kraken > Uniswap
Compliance focused	0.10	0.35	0.25	0.20	0.10	Binance > Coinbase > Kraken > Uniswap
Transparency/Sentiment focused	0.30	0.10	0.20	0.30	0.10	Kraken > Binance > Uniswap > Coinbase

The results shown in Table 2 confirm that no single exchange is universally optimal. Custodial exchanges such as Kraken and Coinbase consistently perform well when compliance is prioritised, while Binance improves its relative standing under security- or sentiment-focused configurations. Uniswap performs comparatively better in scenarios that de-emphasise compliance and custodial guarantees. These shifts reinforce the importance of exposing weighting assumptions and stand in contrast to proprietary exchange trust scores, which typically embed such assumptions implicitly. By making the consequences of weighting choices explicit, as demonstrated in Table 2, the framework supports informed decision-making and reduces the risk of misplaced reliance on single-score rankings—an issue that remains largely unaddressed in existing exchange trust metrics.

When benchmarked against industry trust indicators, the proposed framework produces broadly aligned results for highly regulated exchanges but diverges in cases where sentiment, transparency, or incident history plays a significant role. Concerns have also been raised regarding the preferential treatment of certain trading pairs and exchanges within ranking systems, further complicating the interpretation of aggregate trust scores and reinforcing the limitations of market-centric metrics (Thompson, 2020). These divergences highlight the explanatory value of a multi-dimensional and configurable trust assessment approach. These divergences highlight the limitations of market-centric metrics and demonstrate the added explanatory value of incorporating sentiment, compliance transparency, and historical performance. Importantly, the framework is not intended to replace existing data aggregators. Instead, it complements them by offering a transparent, configurable alternative that prioritises methodological openness and interpretability. This positioning aligns with growing calls for greater transparency in cryptocurrency risk assessment and exchange evaluation methodologies (Simon, 2023).

7. Discussion

The results demonstrate that a modular, transparent approach to exchange trust assessment can reveal dimensions of risk that are obscured by existing monolithic scores. By explicitly separating sentiment, compliance, security, transparency, and incident history, the framework supports more nuanced interpretation and enables users to align trust evaluations with their own risk priorities. This section discusses the broader implications of these findings and outlines key limitations.

7.1 Interpretability and Practical Relevance

A central contribution of this work lies in its emphasis on interpretability. Each component score is derived from observable indicators and clearly defined assumptions, reducing reliance on implicit or proprietary methodologies. This is particularly relevant in the cryptocurrency domain, where trust is frequently inferred from market activity rather than substantiated operational or regulatory evidence. The ability to adjust component weights further reinforces the view that trust is context-dependent rather than absolute. From a practical perspective, the framework is applicable to both retail and institutional users. Retail participants may prioritise sentiment and usability, while institutional actors may emphasise compliance and security. By accommodating both perspectives within a single structure, the framework addresses a gap between user-centric perception and institutionally defined risk criteria.

Several limitations must be acknowledged. First, data availability and quality vary significantly across exchanges. Some indicators rely on self-disclosed information, which may be incomplete or selectively reported. Although this limitation is inherent to public-data-driven assessments, it underscores the need for cautious interpretation of results. Second, sentiment analysis is sensitive to short-term events and platform-specific user behaviour. While transformer-based models mitigate some limitations of earlier approaches, they cannot fully resolve issues such as sarcasm, coordinated review manipulation, or sudden sentiment shocks following high-profile incidents. Consequently, sentiment should be interpreted as a complementary signal rather than a definitive measure of trust. Third, the use of large language models for compliance extraction introduces potential risks related to misinterpretation or hallucination. Although constrained output schemas and human oversight reduce these risks, the approach remains probabilistic rather than deterministic. Future work could explore hybrid rule-based and model-based extraction to further improve reliability.

The framework was evaluated on a limited set of exchanges selected to illustrate structural diversity rather than market coverage. As such, the empirical results should not be generalised to all platforms without further validation. Nonetheless, the framework itself is exchange-agnostic and can be extended to additional platforms as data availability permits. The study also focuses on exchange-level trust rather than asset-specific or transaction-level risk. Integrating on-chain analytics or smart contract verification could enhance the

framework's applicability to decentralised finance contexts, but such extensions fall outside the scope of the present work.

8. Conclusion

This paper presented HTREx, a semi-automated, modular framework for assessing trust and risk in cryptocurrency exchanges. By integrating behavioural sentiment, regulatory compliance, technical security, transparency, and incident history into a transparent and user-configurable scoring model, HTREx addresses key limitations of existing industry trust scores. The empirical application of the framework to four prominent exchanges demonstrated that meaningful differences in trust assessment emerge when behavioural and regulatory dimensions are explicitly considered. Rather than proposing a definitive ranking, HTREx emphasises interpretability and adaptability, recognising that trust is inherently context sensitive. As cryptocurrency markets continue to mature and regulatory scrutiny intensifies, such transparent and extensible assessment models may play an important role in supporting informed participation and reducing reliance on opaque metrics.

Acknowledgements

This work is based on the research supported in part by the National Research Foundation of South Africa (Reference Number: RCHDI241217296940)

AI Declaration: Artificial intelligence tools were used in a limited and transparent manner during the development of this paper. A LLM from the GPT family was employed to support the automated extraction of compliance indicators from exchange ToS documents, using a constrained output schema. AI generated outputs were only used as intermediate structured inputs, with post processing and limited human verification. The entire paper was written by the authors and no tools were used to produce any part of the paper.

Ethics Declaration: Ethical Clearance was not required for this research.

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An Assessment Methodology for Learning Mission Characteristics

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Abstract: This paper presents a novel methodology for assessing the effectiveness of machine learning algorithms in deriving a protocol specification from a set of network traffic captures. Such specifications describe the data formats and mission characteristics associated with valid messages and form the basis for protecting military vehicles from malicious traffic. This paper enhances previous work, which automatically generates a hardware guard from a hand-written grammar, to produce a fully automated, end-to-end process that generates a parser, either in software or as a hardware guard, directly from mission training data sets. A hardware guard is realized as a Field Programmable Gate Array (FPGA) circuit block implementing a parser. The parser performs deep packet validation, checking that every message conforms to the associated grammar and rejecting invalid packets. Several modern machine learning algorithms and specification inference tools exist that can be leveraged to automatically infer a specification from a data capture. Unfortunately, to date, there has been a paucity of mission data sets to provide ground-truth, and the lack of a common set of metrics to assess learning algorithms. To this end, this paper introduces a parser repository that provides a ground-truth data set for a variety of formats and protocols, alongside equivalent protocol specifications expressed in several formalisms, namely BNF, Hammer, Daffodil, and Daedalus. Each set of equivalent specifications is provided with a common collection of true and false test vectors to validate their operation and benchmark learning performance using appropriate metrics. Specifications for standard formats, including JavaScript Object Notation (JSON), Universal Resource Locators (URLs), and Hypertext Transfer Protocol (HTTP), provide the basis for generic testing. The Micro Air Vehicle Link Protocol (MAVLink) and Space Packet Protocol (SPP) are used as examples of mission-oriented grammars. MAVLink is a byte-oriented protocol, while SPP is a bit-oriented protocol, leading to fundamental differences in the way that learning algorithms must operate to validate packets; the latter is also indicative of the complexities involved in parsing of SAE J1939 – used on ground vehicles – and MIL-STD-1553 – used on aircraft.

Keywords: Protocol reverse engineering, Parsing, MAVLink, Space packet protocol, Traffic validation

1. Introduction

Many military vehicles communicate with other vehicles and/or their ground control stations via wireless networks. This exposes an attack surface whereby an adversary may exploit vulnerabilities in the vehicle's onboard systems by embedding malicious implants within legitimate traffic. These implants may cause unexpected D5 effects (USAF, 2012) on the vehicle that undermine its operational mission. Consequently, it is valuable to validate both the syntax and semantics of messages in real-time, on board the vehicle before messages are acted upon. This *deep packet validation* ensures that all messages comply with both the expected format and that payloads comply with the bounds set on the vehicle's specific mission. Validation may be performed by a *software parser* on board the vehicle, or by a *hardware guard* acting as a bump-in-the-wire between the communication interface and the vehicle's onboard systems. Hardware guards can be realized with Field Programmable Gate Arrays (FPGA's) that implement a parser. This ensures that parsing occurs below the software stack, forming a hardware base-of-trust that is less susceptible to compromise. Previous work on packet validation has already resulted in a process that automatically generates a hardware guard from a protocol specification (Dahlstrom *et al.*, 2022; Taylor and Pope, 2024). The goal of this work is to enhance the process by directly generating the specification from a traffic data capture *taken during a mission training event*, allowing for the construction of mission-specific parsers. A central challenge is to produce a concise and intelligible specification, that engineers can understand, evolve, and optimize, without highly specialist skills in parser development or protocol specification writing.

There exist many formalisms for the expression of communication protocols and data formats, broadly referred to in this paper as *protocol specifications*. These formalisms extend from parser combinator libraries and data description languages to notation systems. A specification, written in such a formalism, consists of a set of rules defining the syntax and, to a certain extent, the semantics of the protocol. Parser combinator libraries, like Hammer (Riverside Research, 2026), build increasingly complex parsers by combining simple parsers, defined in a library. Data description languages, such as Daedalus (Diatchki *et al.*, 2024) and Daffodil (The Apache Software Foundation, no date), provide a succinct mechanism for expressing the syntax and semantics of a protocol in a domain-specific language. Notation systems, such as Backus-Naur Form (BNF) (Backus *et al.*, 1960), provide a means for defining a formal grammar specifying a protocol. It is possible, using pre-processors, to add syntactic notations to BNF that simplify specifications; xBNF (Taylor, Guzman and Meise, 2025) and ABNF (Crocker and Overell, 2008) both achieve such simplifications. Each of these formalisms provides the basis for the automatic

generation of a validation parser which produces a binary accept/reject answer, indicating whether a message's format complies with the specification. Validation parsers can be constructed using tools like Daffodil, Daedalus, or Hammer's native parser generators, or, for formal grammars expressed in BNF, Bison (Levine, 2009). There are also a wide variety of parsing methods (Grune and Jacobs, 2010), many of which are employed by these tools.

The automatic construction of a specification through inference, opens the door to the construction of a new generation of *mission-specific parsers*. Several protocol reverse engineering tools and techniques have already been developed to perform this inference (Cui, Kannan and Wang, 2007; Wang *et al.*, 2011; Chandler, Wick and Fisher, 2023). These tools aim to infer the syntax of a protocol from a data capture or network trace fully automatically. In contrast, the goal here is to work interactively with a systems engineer to formulate a representative specification; consequently, the requirement for a fully automated solution is less severe. The more pressing need is to incrementally build a formulation of the semantic meaning of data within message payloads. Sadly, to date, there has been a paucity of mission data sets to provide ground-truth, and a lack of a common set of metrics to assess alternative learning algorithms in this context. To this end, this paper introduces a methodology for baselining learning algorithms that is supported by an emerging parser experimentation repository (Taylor *et al.*, 2026).

2. Methodology

Figure 1 shows the end-to-end process that we envisage for designing a software parser or hardware guard directly from a data capture. Traffic data is captured from a mission training event and fed to an inference tool to infer a protocol specification. An engineer performs minor interventions to validate the output of the inference tool, ensuring correct semantic inference of protocol fields. The specification is then fed to a parser generator tool to construct either a software or hardware parser. The parser is validated against a set of true and false positive test vectors and, along with the specification itself, assessed against metrics evaluating correctness, performance, succinctness, and resource use.

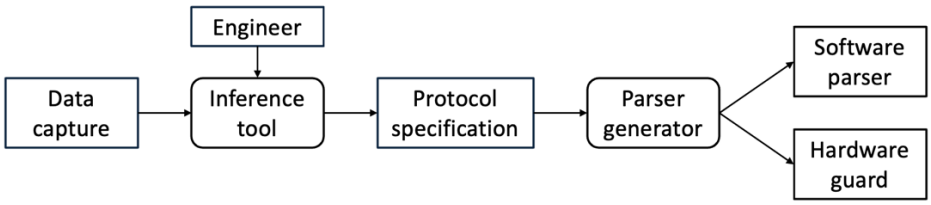


Figure 1: Parser development pipeline

There are currently a wide variety of inference tools, formalisms for expressing specifications along with corresponding parser generators, and parsing methods. Consequently, it is important to enable the selection of elements of the trade-space most suited to a designated mission based on well-formed ground-truth data and metrics. Our methodology thus involves four core steps:

1. Specifications:

- Baseline specifications to allow for comparative analysis of syntactic inference.
- Mission-specific specifications to assess learning algorithms' performance in the inference of semantics.

2. Testing framework: True positive tests form a representative selection of messages. False positive tests form a representative selection of invalid messages.
3. Implementation: Automated parser generation tools are applied to generate software parsers and/or hardware guards for each specification.
4. Assessment: Evaluating the resulting alternatives from the perspective of performance, succinctness, and resource metrics.

To date this methodology has been employed to build a parser experimentation repository that is available online as an open-source repository for evaluating parsing formalisms, parser generator tools, and learning algorithms in the Thayer School of Engineering at Dartmouth College (Taylor *et al.*, 2026). The Thayer repository includes a variety of equivalent parsers (expressed in xBNF, BNF, Hammer, and Daffodil), a simple baseline

learning algorithm (discussed in Section 5), automated implementation and validation scripts, and baseline test vectors.

3. Specifications

Protocol specifications may take the form of a *context-free grammar* (expressed in BNF or xBNF), a collection of combinators (as in Hammer), or a collection of statements in a *data description language*, such as Daedalus or Daffodil. To date, the Thayer repository provides specifications for three core standard formats: JavaScript Object Notation (JSON) (Bray, 2017), Universal Resource Locators (URLs) (Berners-Lee, Masinter and McCahill, 1994), and Hypertext Transfer Protocol (HTTP) (Nielsen *et al.*, 1999), expressed in xBNF, BNF, and Hammer. It also contains specifications for two *mission-oriented protocols*, namely the Micro Air Vehicle Link Protocol (MAVLink) (MAVLink, no date) and Space Packet Protocol (SPP) (CCSDS, 2020).

JSON, URL, and HTTP are examples of recursive textual data formats. Such formats are often used within message payloads and are conveniently expressed with context-free grammars which allow for recursive grammar rules. The Thayer repository demonstrates how the specification for JSON is developed incrementally, starting with simple strings and numbers (JSTRING, and JNUM respectively), then adding complexity by combining them within the full JSON definition. Similarly, the HTTP request for comment (RFC) (Nielsen *et al.*, 1999) largely leverages the format for URLs. The increasing complexity of these formats allows the repository to act as both a pedagogical tool for constructing specifications and permits evaluation of inference and parsing tools on different data formats.

MAVLink is an example of a byte-based tactical messaging protocol: every byte in a message is a semantic entity and no values need be analyzed as a subset of bits within a byte or across byte boundaries within a message. Most multi-byte fields in MAVLink messages represent standard types, such as floating-point numbers or fixed-width integers in little-endian byte order. The ground-truth data in the Thayer repository consists of MAVLink messages captured between an actual drone and its ground station. MAVLink allows for two message versions, MAVLink 1 and MAVLink 2. Figure 2 shows the serialization of MAVLink 1 messages which closely resembles the format of messages in various other tactical communication protocols: a fixed-length header containing a length field, followed by a variable-length payload. Mission-relevant data is generally contained in the payloads and includes information such as GPS coordinates, altitude data, and velocity values. Figure 3 shows the serialization of a sample payload for an Attitude message.

STX uint8_t	LEN uint8_t	SEQ uint8_t	SEQ ID uint8_t	COMP ID uint8_t	MSG ID uint8_t	PAYLOAD (0 - 255 bytes)	CHECKSUM uint16_t

Figure 2: MAVLink 1 message serialization

time_boot_ms uint32_t	roll float	pitch float	yaw float	rollspeed float	pitchspeed float	yawspeed float

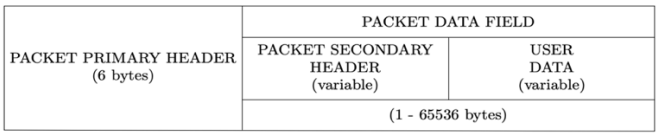
Figure 3: MAVLink Attitude message payload

Figure 4 illustrates the added *context-sensitive complexity* of MAVLink 2 messages: in addition to the fields in MAVLink 1 headers, MAVLink 2 headers contain two 1-byte flag fields, one of which is an incompatibility flag (INC FLAGS) that indicates if the message is signed with a 13-byte signature appended to the message. The payload of MAVLink 2 messages also truncates zero bytes during serialization.

STX uint8_t	LEN uint8_t	INC FLAGS uint8_t	COMP FLAGS uint8_t	SEQ uint8_t	SYS ID uint8_t	COMP ID uint8_t	MSG ID (3 bytes)	PAYLOAD (0 - 255 bytes)	CHECKSUM uint16_t	SIGNATURE (13 bytes)

Figure 4: MAVLink 2 message serialization

In contrast to MAVLink, Space Packet Protocol (SPP) is a bit-oriented protocol: SPP headers contain bit-fields, which do not align at byte boundaries. The overall structure of SPP messages is depicted in Figure 5 and contains a fixed-length packet primary header, followed by a variable-length packet data field. The Thayer repository contains a set of both telemetry and command SPP messages in binary files. These messages were captured using NASA's NOS3 satellite simulator (NASA-JSTAR, no date).



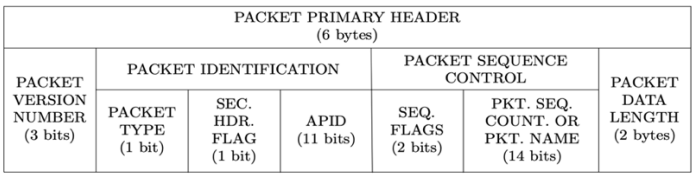


Figure 5: SPP message serialization

3.1 Baseline Specifications

To explore the performance of learning algorithms, it is useful to consider generic message formats, with well-defined syntax as a baseline. These baseline specifications provide little in terms of semantic parsing: only fields that are constant across all message types – typically found in the message headers – are enumerated, while payload fields may take the full range of values for every byte. The associated parsers *do not validate mission-specific data.* For example, Figure 6 shows a baseline specification, written in xBNF, for a MAVLink 1 Attitude message; here the wildcard symbol '*' indicates the presence of a single byte of *any* value.

```
message :  message_header message_payload checksum ;
message_header :  0xFE 0x1C 0x00 0x00 * * * 0x1E ;
message_payload :  time_boot_ms roll pitch yaw rollspeed pitchspeed yawspeed ;
time_boot_ms :  * * * * ;
roll :  * * * * ;
pitch :  * * * * ;
yaw :  * * * * ;
rollspeed :  * * * * ;
pitchspeed :  * * * * ;
yawspeed :  * * * * ;
checksum :  * * ;
```

Figure 6: Example baseline xBNF specification for MAVLink 1 Attitude message

3.2 Mission-specific Specifications

Mission-specific specifications are constructed by grouping related bytes in payload fields to form semantic entities and placing bounds on the values accepted. These specifications enable rigid semantic parsing in addition to the syntactic parsing provided by baseline parsers. Values are bounded based on what a systems engineer expects the vehicle to observe during a given mission and may include, for example, bounds on mission latitude and longitude, vehicle speed and altitude, or attributes of expected image data. For example, Figure 7 shows a rudimentary mission-specific xBNF specification for a MAVLink 1 Attitude message in a specific mission profile; the values within square brackets (i.e. [X – Y]) designate ranges of values in little-endian format.

```
message :  message_header message_payload checksum ;
message_header :  0xFE 0x1C 0x00 0x00 * * * 0x1E ;
message_payload :  time_boot_ms roll pitch yaw rollspeed pitchspeed yawspeed ;
time_boot_ms :  [ 'little_endian(0, uint32)' -'little_endian(6000, uint32)'] ;
roll :  [ 'little_endian(-3.15, float)' -'little_endian(3.15, float)'] ;
pitch :  [ 'little_endian(-3.15, float)' -'little_endian(3.15, float)'] ;
yaw :  [ 'little_endian(-3.15, float)' -'little_endian(3.15, float)'] ;
rollspeed :  [ 'little_endian(-0.57, float)' -'little_endian(0.59, float)'] ;
pitchspeed :  [ 'little_endian(-0.52, float)' -'little_endian(0.56, float)'] ;
yawspeed :  [ 'little_endian(-0.94, float)' -'little_endian(0.99, float)'] ;
checksum :  * * ;
```

Figure 7: Example mission-specific xBNF specification for MAVLink 1 Attitude message

While baseline specifications may be constructed in a once-off process, mission-specific specifications must be reconstructed and fine-tuned for each mission. The process of manually fine-tuning these specifications is time-intensive and requires expertise in specification writing, making it difficult under operational constraints. The ability to automatically infer, a-priori, a specification from a data capture on a training event, makes the construction of mission-specific specifications feasible.

4. Testing Framework

The Thayer repository contains a set of true and false positive tests for each protocol. These tests form the basis for evaluating the correctness of each specification and its associated parsers. As described in Section 3, the repository contains real data captures for both MAVLink and SPP missions. These captures form a true positive basis for testing the parsers on messages that have occurred during real or simulated missions. In addition to these data captures, the repository contains an automatic test generation framework for both protocols. Collectively, the resulting test suite ensures that the parsers generated from the baseline specifications accept all messages that are of the correct syntactic format (as outlined in Section 3.1). Similarly, true positive tests for the JSON, HTTP and URL specifications are manually constructed and test that the generated parsers accept the full range of expected formats; they also aim to test that various message attributes in valid combinations with one another are accepted by the parsers.

False positive tests ensure that the resulting parsers reject messages that have an incorrect format. For MAVLink and SPP, messages of an incorrect format are those which have invalid byte values in fields containing constant bytes, invalid enumerations in fields which only accept specific byte values, or messages whose payload length does not correspond to the payload length field in the message header. These tests are constructed through fuzzing, making minor alterations to a message with a valid format such that it no longer abides by the intended format defined in the specification. Similarly, tests for HTTP and URL check that messages with invalid character sequences or field values are rejected by the parsers. Since the JSON RFC (Bray, 2017) does place restrictive bounds on values or valid character sequences in specific fields, the false positive tests primarily test that messages with incorrect formats, such as invalid structure nesting or unbalanced parentheses, are rejected by the JSON parsers.

5. Implementation

Section 2 defines a methodology for an automated, end-to-end process for building parsers from mission-training data captures. This toolchain is implemented in the Thayer repository by a variety of automation scripts and forms the basis for evaluation.

To establish a baseline inference mechanism, Figure 8 shows a rudimentary learning algorithm for byte-based protocols, such as MAVLink. The algorithm takes as input a binary file containing messages captured during a mission-training event. The output of the algorithm is a context-free grammar expressed in xBNF, though it may easily be adapted to output any prospective specification language. The algorithm groups messages by length and creates a single non-terminal symbol to represent all messages of a particular length. The top-level production for the grammar is formed as a disjunction of all these non-terminals (i.e. the parser accepts a message that conforms to one of the individual message formats at a particular length). The non-terminal for each message length produces a rule containing a conjunction of terminals and new non-terminals, one for each byte in the message. Terminals correspond to bytes which are constant across all messages of that length. New non-terminals correspond to positions whose byte values vary across messages of the same length – these non-terminals capture byte positions that have multiple values. A new disjunctive rule is introduced for each of these new non-terminals that captures all possible byte values allowed in each position in messages of the relevant length.

Baseline Specification Inference Algorithm

Input: `messages.bin`: mission training dataset
Output: `gmr.xbnf`: inferred xBNF specification

```
read file messages.bin
group messages by length

for each message length do
    create non-terminal for length

for each message do
    if first message of length then
        initialize production for length's non-terminal with concatenation of terminals for each byte
    else
        for each byte in message do
            if terminal value in byte position and byte value differs from terminal then
                create new non-terminal for byte value
                add current byte value and former terminal to alternation for new non-terminal
            else if non-terminal value in byte position and byte value not in alternation then
                add byte value to alternation

write grammar to gmr.xbnf
```

Figure 8: Baseline specification inference algorithm

Since this rudimentary baseline algorithm does not infer the semantics of the protocol fields, the engineer's interaction with the tool is currently limited to verifying the final output specification. Currently, for a baseline, no multi-byte semantic grouping is applied, though reverse engineering tools, particularly BinaryInferno (Chandler, Wick and Fisher, 2023), are already available to produce such groupings. In accordance with standard practice for the training and testing of machine learning models, the input file is split into disjoint training and testing data sets prior to being input to the algorithm. The training set is used by the inference algorithm to infer the specification, while the testing set is used to assess this inferred specification (cf. Section 6).

To generate a parser, the specification is input to a parser generator for conversion into either a software parser or a hardware guard. Currently, the generation of software parsers is implemented by either Bison or Hammer. The input to the Bison is a context-free grammar; Hammer accepts an alternative formulation in the C programming language.

6. Assessment

As discussed in Section 2, each stage in the toolchain presented in Figure 1 must be validated and evaluated. To this end, we introduce a set of evaluation metrics for the accuracy of the inference tool, the succinctness of the protocol specification, the software and/or hardware resource utilization of the generated parser, and the performance of hardware guards.

The accuracy of the inference algorithm may be evaluated using *convergence*, *precision*, and *recall* as primary metrics. Convergence evaluates the rate at which an inferred specification covers all messages and formats contained in a mission training data capture. As outlined in the algorithm in Section 5, a new non-terminal is introduced to the specification upon the first occurrence of a message of a given length, or each time a byte field is found to have a non-constant value. Furthermore, an additional terminal is introduced each time a previously unobserved byte value is found to occur in a specific field for a given message length. The algorithm is thus said to converge once the number of inferred terminals and non-terminals remains constant. Precision and recall are metrics for the accuracy of an inference algorithm in deriving a specification that correctly incorporates critical information about a protocol. Precision is an indicator for how many of the byte values in the inferred specification correctly match with a byte value in the actual data capture. Recall quantifies how many of the byte values in the actual data capture were correctly derived in the inferred specification. Mathematically, precision is the ratio of true positive predictions to all positive predictions (the sum of true positives and false positives), and recall is the ratio of true positive predictions to all actual positives (the sum of true positives and false negatives). A true positive is a byte value in the rule for a non-terminal in the inferred specification that correctly matches with a byte value in the corresponding field in the testing set. Conversely, a false positive is a byte value in the rule for a non-terminal in the inferred specification that is outside the range of byte values deemed appropriate for the given mission. False negatives are byte values that appear in a field in the testing set that are not enumerated in the non-terminal corresponding to that field in the inferred specification. Precision is thus a metric for how "permissive" a parser is; parsers with higher precision will be less permissive

to messages with greater variation in format from the training data. Recall indicates how good a parser's coverage is; a higher recall value indicates that an inferred specification is representative of messages that may be observed in a live mission.

The succinctness of the inferred specification is assessed using the *number of lines of code, terminals, and non-terminals* in the specification as metrics. The number of lines of code provides an indication of how easy the specification is to understand. The number of terminals and non-terminals provide a preliminary indication of the parser's software and hardware resource utilization, as well as the redundancy of the specification. In addition to evaluating an inference tool's ability to construct a succinct protocol, these metrics also form the basis for comparing the expressive qualities of alternative formalisms.

The performance of software parsers is evaluated based on *the binary size* and *memory usage* of the executable software parser, as well as its *execution time*. This provides an indication of the computational resources required for the implementation of the software parsers. Since a primary application locale for many such parsers is a resource constrained computational environment onboard a military vehicle, these metrics provide valuable insight into the viability of software parsers. They also provide a basis for evaluating alternative parsing algorithms, and the parser generator tools that employ those algorithms.

Similarly, both the resource use and performance of hardware guards must be evaluated. Since hardware guards are often implemented on FPGAs, FPGA resource utilization forms a critical metric. Metrics that indicate FPGA resource utilization include *Look-up Table, Flip-Flop, and Block RAM usage*. Evaluation of these metrics provides an indication of the implementation viability of parsers on cost-effective, everyday FPGA devices. Hardware guard performance is evaluated considering *bandwidth* and *latency* as metrics. Hardware guards need to enable the processing of packets at line rate to prevent backlogs. As in the case of software parsers, these metrics provide the basis for the comparison of alternative parsing algorithms and methods.

Dahlstrom *et al.* (2022) provide an example assessment of the performance of hardware guards, while Cavanagh and Taylor (2026) provide an example analysis of software parser performance. Here we evaluate the baseline inference algorithm, introduced in Section 5, using a mission training data capture containing 33,261 MAVLink 2 messages. Messages with 48 alternative payload types are present in this data capture. The data capture was input to the inference algorithm to produce a baseline xBNF specification for MAVLink 2. Since this rudimentary inference algorithm simply enumerates values that are observed in the training data no false positives exist; consequently, precision is a meaningless metric in this baseline case since it is always 100%. Figure 9 shows the convergence of the inferred specification to the ground-truth specification when run with a 100:0 train:test split. It is clear from Figure 9 that the number of non-terminal symbols converge faster than the number of terminal symbols. Information used to derive non-terminal symbols (all message lengths and variable fields) is thus contained in approximately the first third of the data capture.

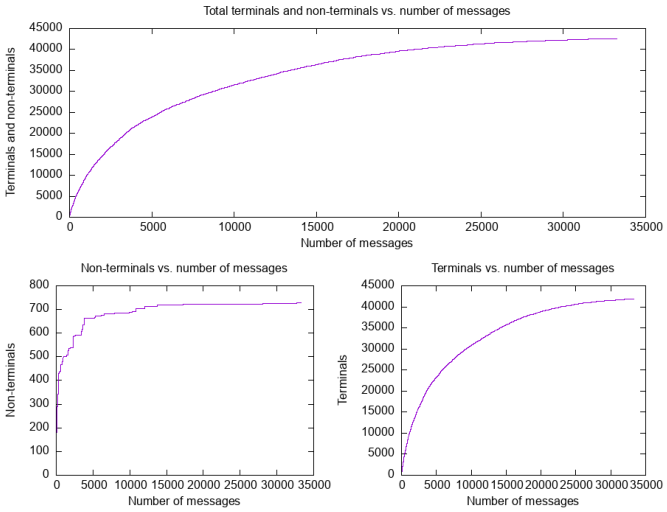


Figure 9: Convergence of inference algorithm on train:test split of 100:0

Table 1 presents the relevant metrics of this algorithm when run with four different splits of testing and training data. These metrics include the inference algorithm's recall, the number of lines of code in the inferred specification, the number of terminals and non-terminals in the inferred specification, and the number of

messages from the full mission training data capture that are rejected by the generated Bison look-ahead, left-to-right, rightmost derivation parser (LALR(1)) parser. This latter number may be reduced by pointing the engineer to areas of the resulting specification that are too tightly constrained, allowing a quick way to manually edit the grammar.

Table 1: Results from baseline inference algorithm

Train:Test	Recall (%)	Lines of code	Terminals	Non-terminals	Valid messages rejected (%)
30:70	96.1658	5,082	31,496	674	15.0
50:50	97.7469	5,821	36,750	712	5.84
80:20	99.2436	6,399	41,034	727	0.00926
100:0	100	6,488	41,814	727	0

While the inferred specifications are verbose, they achieve high levels of recall, even in the 30:70 train:test split. It is particularly notable that most of the variation in the specification after observing 30% of the messages arises due to the observance of fresh byte values (as indicated by the increasing number of terminals). To mitigate such variation and accelerate convergence, future work aims to decide on appropriate ranges for terminals as opposed to enumerating each observed byte value in the rule for a non-terminal. This will both increase recall and reduce the verbosity of the inferred specifications. It will furthermore lead to the ability to learn representative specifications from smaller training mission training data captures.

7. Conclusion

This paper lays the foundation for an automated, end-to-end process for producing a parser directly from a data capture, thereby making construction of mission-specific parsers feasible. To this end, we describe the methodology, the Thayer repository that supports it, and a baseline algorithm for the automatic construction of protocol specifications from mission training data captures. Suitable metrics for the evaluation of this end-to-end toolchain are presented with example results, thereby standardizing the basis evaluation of the various components of the toolchain. By rigorously applying this methodology, we expect it to eventually be possible for a systems engineer to rapidly select an inference algorithm, specification formalism, and parsing technique that generates an effective parser to protect a vehicle on a given mission.

8. Future Work

The algorithm proposed in Section 5 as a baseline can easily be adapted to incorporate formalized learning methodologies into the process of specification inference. The goal is to both increase the coverage of the inferred specification whilst keeping field bounds stringent enough to prevent malicious traffic from penetrating the parser. The first step in this process is to decide when to define a non-terminal as a range between two byte values, rather than an enumeration of several byte values. This will increase recall by decreasing false negatives. Ranging will, however, result in a more “permissive” parser with higher false positives and thus lower precision.

A further step is to perform semantic analysis of the fields present in a data capture. The aim is to identify not only fields that correspond to common datatypes, such as fixed-width integers and floating-point numbers, but also to infer what fields are representative of mission-relevant values, such as GPS coordinates, altitudes or velocities. This will enable an engineer to interact with the inference tool in deciding on appropriate bounds on mission-relevant fields, as opposed to byte-level fields. Reverse engineering tools, such as BinaryInferno (Chandler, Wick and Fisher, 2023), have already shown great promise in inferring semantic information about fields in MAVLink-style messages. This work can be leveraged as a comparative baseline for evaluating the semantic analysis capabilities of the inference tool.

Acknowledgements

This research is supported by the Institute for Security Technology Studies (ISTS) at Dartmouth College. The authors would like to thank Sergey Bratus for his insights into state-of-the-art parsing and reverse engineering technologies.

Ethics Declaration: No ethical clearance necessary.

AI Declaration: No AI tools were used in the development of this paper.

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Sridut: Securing Multi-Controller SDN Integrity with State-aware Multi-consistency Storage and Provable Convergence

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Abstract: Software Defined Networking (SDN) is a network paradigm that decouples the control and data planes, enabling centralized network control. The single centralized controller of the original paradigm, however, created a single point of failure, which was overcome with the introduction of multi-controller networks. These networks, however, introduce new security challenges as the availability and integrity of the networks now depend on state consistency mechanisms and their inherent trade-offs. For example, multi-controller networks that solely support strong consistency enforce correctness at the cost of availability due to their susceptibility to Denial of Service (DoS) attacks and maliciously induced partitions. Alternatively, some designs employ hybrid consistency or multi-consistency, sacrificing correctness guarantees to strike a balance between correctness and availability. However, these designs lack mechanisms for provably verifiable convergence, resulting in critical integrity violations such as corrupted and conflicting security and Quality of Service (QoS) policies. This critical gap is exploitable by adversaries, enabling them to trigger policy conflicts and bypass security perimeters. These security implications are further amplified by the lack of transparency between the application layer and consistency state events. This transparency hampers the ability of the controller to react and recover from consistency-based attacks. To address these challenges, this paper introduces Sridut, a secure multi-consistency storage model providing strong consistency, strong eventual consistency, and consistency state awareness. The model provides multiple storage backends with varying degrees of consistency guarantees, allowing for more granular control of the inherent security trade-offs. Additionally, the consistency state, health, and critical events are made transparent, further improving an application's ability to react to consistency-based attacks. The model leverages Conflict-free Replicated Data Types (CRDTs) and anti-entropy mechanisms to achieve strong eventual consistency. This mechanism allows divergent states to be safely merged, preserving integrity of critical data such as network policies. Consequently, this approach mitigates exploitable security risks associated with divergent states. Ultimately, the state-aware architecture and provable convergence of Sridut provide a robust defence against both malicious threats and inherent network partitions, helping preserve integrity and availability in SDN multi-controller networks.

Keywords: Software-Defined Networking (SDN), Conflict-free Replicated Data Types (CRDTs), Network security, Multi-controller architecture, Consistency state-awareness

1. Introduction

As Software-Defined Networking (SDN) becomes the backbone of critical infrastructure, the security and resilience of its control plane have become paramount (Yusuf et al, 2023). While multi controller networks mitigate the single point of failure found in early implementations of SDN networks, the transition introduces vulnerabilities within the consistency protocols used to manage shared data (Zhang et al, 2018). Attackers can exploit trade-offs inherent in these consistency protocols to trigger policy conflicts or bypass security perimeters (Xu, 2017). Additionally, many controllers deny the application layer the transparency needed to assess the state and health of the consistency stores, effectively removing the applications ability to assist and react to consistency-based attacks (Sakic and Kellerer, 2018). Furthermore, while some modern SDN controllers offer various levels of consistency models (Smyth et al, 2019), weaker consistency models are often less likely to be used due to their lack of verifiable convergence.

To address these challenges, this paper introduces Sridut, a secure multi-consistency storage model targeting three consistency aspects: strong consistency, strong eventual consistency, and consistency state awareness. Sridut functions as a unified storage broker that abstracts individual consistency backends, as well as providing a transparent API for critical state events. These events are critical for providing security applications and allowing for the immediate detection and mitigation of consistency-related vulnerabilities. By leveraging Conflict Free Replicated Data-Types (CRDTs) (Shapiro et al, 2011) and anti-entropy mechanisms, Sridut allows for weaker consistency models to be used in areas it would otherwise be unsuitable. This allows for the high availability during network partitions without sacrificing control plane integrity, ensuring that critical security and QoS policies are deterministically merged rather than overwritten or lost. The paper is structured as follows, Section 2 provides a brief background into the possible security issues of SDN multi-controller networks, an introduction to CRDTs and related works. Section 3 presents the Sridut model. Section 4

introduces the Proof of Concept, as well as a use case scenario comparing the PoC to a well-known SDN controller. Lastly, Section 5 concludes the paper and presents future research opportunities.

2. Background

Consistency is a property that governs how data appears and behaves across the nodes of a distributed system. This property is governed by inherent trade-offs as defined by the CAP theorem (Brewer, 2000), which states that during a partition, it is impossible to guarantee both consistency and availability simultaneously (Brewer, 2000). In an SDN multi-controller network, strong consistency is typically utilized to enforce a unified global policy (Zhang et al, 2018). However, solely utilizing strong consistency creates a significant risk to availability (Shapiro et al, 2011); by targeting the consensus mechanism, an attacker can prevent the controllers from making progress and freeze the network (Smyth et al, 2019). Conversely, solely utilizing eventual consistency allows an attacker to target the windows of divergence and bypass crucial security policies (Xu, 2017), creating a threat to network integrity. Additionally, the convergence of these divergent states often leads to conflicts that need to be resolved. If resolved non-deterministically, it may lead to inconsistent or unintended policy states, which can be leveraged by an attacker to corrupt critical network policies (Xu, 2017). While the CAP theorem is often treated as a binary trade-off, it is more accurately described as a sliding scale or spectrum between availability and consistency (Brewer, 2012). When applied to SDN, it is beneficial for controllers to provide different levels of consistency for different data, or adaptive consistency models that tailor the consistency level factors such as workload, latency, and network conditions (Bannour, Souihi, and Mellouk, 2020). Existing SDN controllers implement multi-consistency, however, they suffer from significant flaws such as the lack of transparency, the lack of verifiable convergence, and the pre-determination of consistency levels (Sakic and Kellerer, 2018; Xu, 2017; Hoang et al, 2022). The lack of verifiable convergence on weak consistency models creates room for an attacker to bypass security policies by exploiting the divergent states. The lack of transparency to the health of the network as well as the state of the consistency stores effectively masks security applications from reacting to consistency-based attacks. Furthermore, despite supporting multi-consistency, many controllers still prioritize consistency during a partition (Yusuf et al, 2023), making the controller unsafe to utilize for networks which require high availability. SDN is a generalized, adaptable network paradigm, meaning it needs to be applicable to different industries with different threat models. Therefore, the choice of consistency cannot remain a static controller-side configuration and instead must be moved to the application layer.

Current SDN controllers do not provide sufficient consistency state transparency, configurability of consistency, and lack weak consistency stores with verifiable convergence. This creates a critical gap which prevents security applications from assessing system integrity or responding to consistency-related attacks. Additionally, the lack of verifiable convergence results in possible policy violations and discourages the use of weaker consistency models for critical states, forcing reliance on strong consistency and its associated availability limitations.

2.1 Conflict Free Replicated Data-types

Conflict-free Replicated Data Types (CRDTs) (Shapiro et al, 2011) are a group of distributed data structures that can guarantee deterministic convergence without the need for coordination or conflict recovery. The ability to work without coordination allows CRDTs to maintain correctness in unstable network environments as well as network partitions. Additionally, while clock drift and message ordering may affect when updates are applied, the final converged state will remain consistent with no data loss across all nodes. These features help prevent attackers from utilizing windows of state divergence and partitions to corrupt or bypass network security policies. CRDTs are generally split into two general groups: operation-based (Op-CRDTs), which propagate operations, and state-based (State-CRDTs), which propagate the entire state with merge semantics. δ-CRDTs (Almeida et al, 2015) are an optimized subset of the state-CRDTs that only propagate the incremental changes, reducing communication overhead while preserving convergence.

2.2 Related Work

Adaptive consistency models have been proposed to balance the trade-off between performance and accuracy in SDN. Sakic and Kellerer (2018) presents an adaptive consistency which utilizes a custom metric to allocate the required consistency level. This metric assesses the approximation ratio between optimal serialized decisions, and the actual observed results of the network. Additionally, the work utilises CRDTs to ensure that the adaptive consistency store maintains verifiable convergence. In addition to the adaptive store, the work incorporates a dedicated strong and eventual store. However, the work places a higher focus on performance

optimization instead of security. Additionally, the work considers a benign fail-recovery environment with a fair control channel and does not explore the effects of malicious network partitions and unreliable links.

While SDN is a generalized paradigm, specialized frameworks tailored to specific industries have been explored. Bannour, Souihi, and Mellouk (2020) present an adaptive consistency approach for SDN that is tailored to Content-Centric Delivery Network (C-CDN) in large-scale Internet of Things (IoT) environments. The work replaces the eventually consistent store with an adaptive quorum-replicated consistency model. This model can adjust quorum sizes dynamically to strike a balance between correctness and availability. However, the proposed solution focuses on efficiency and does not consider the security trade-offs inherent in adaptive coordination.

While some consistency mechanisms may be mathematically sound, the implementation might introduce unintended side effects that leave the system open to exploitation. Therefore, Kim et al (2024) present Ambusher, a generic testing tool utilizing protocol state fuzzing to identify critical vulnerabilities in the east-west interface of SDN multi controller networks. The work infers a state machine by analyzing transitions across the leadership, membership, mastership, and distributed storage engines. Using this state machine, Ambusher can detect undiscovered vulnerabilities in well-known controllers. While Ambusher serves as a diagnostic testing tool, it displays how the transparency of the internal cluster state can be used to improve control plane security.

3. Sridut

To allow for stronger, more robust SDN multi-controller networks, the work introduces the Sridut model, named after the Hebrew word for survivability, שְׂרִידוּת. As shown in Figure 1, Sridut contains a unified storage broker that provides strong consistency, strong eventual consistency, and consistency state awareness. Sridut contains four different registries, each with unique properties and a single point of entry known as the State Access Layer (SAL). The first two registries are the strong and CRDT registries, used when data needs to be shared across multiple controllers in a network. To reduce the load on both the strong and CRDT stores, Sridut also contains two additional stores that can be used by applications for data that is local to a specific controller. The in-memory registry provides a fast, non-persistent store local to a controller, whereas the local store provides a persistent store local to the controller. The remaining stores will be covered in more detail in the following section. Sridut contains a dedicated membership module used to keep track of the active controllers in the network. The two components of an SDN controller that interface with Sridut are the Northbound Interface and the Core services.

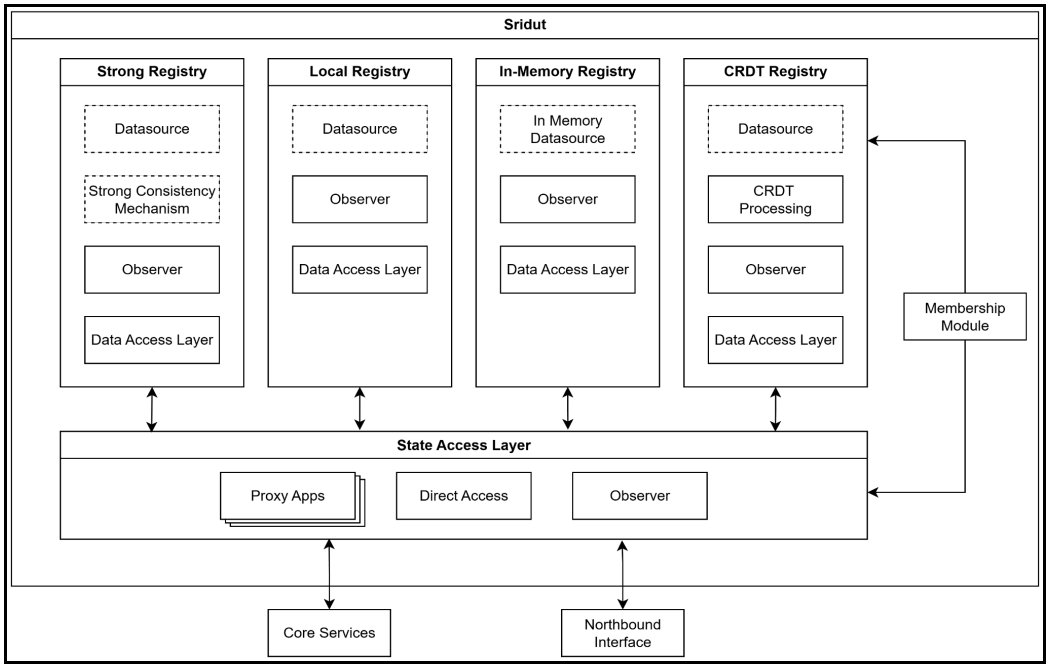


Figure 1: High level overview of Sridut

3.1 Common Components

All registries have three common components, an observer, a Data Access Layer (DAL) and a datasource. The datasource represents the physical storage backend where the data resides. For all registries barring the in-memory registry, this datasource needs to be persistent to ensure data does not get lost after a controller crash. Each registry contains an observer which allows critical network changes such as IP bans to be pushed out rapidly. This ability to react rapidly to network events is critical for ensuring network security in a highly dynamic environment. The DAL ensures that the applications work off an abstracted view of the stores, instead of being exposed to the underlying storage methodology. This creates a separation of concerns and helps prevent technical debt, as newer, safer stores can be utilized without needing to rewrite the application. Furthermore, this can help shield applications from the complexities and possible security risks of direct datasource interaction since these complexities are abstracted behind a consistent interface.

3.2 Membership Module

The ability for a controller to keep track of the other controllers and their health in the network is paramount to ensuring the controllers can operate as a single logical unit. The membership Module of Sridut is based on the Scalable Weakly Consistent Infection-style Process Group Membership (SWIM) protocol (Das, Gupta and Motivala, 2002). SWIM provides decentralized gossip-based membership with built-in failure detection. This grants applications transparency into the health and status of all controllers in a network, allowing for applications to react in real time to possible attacks.

3.3 Strong Registry

In normal operations using strong consistency in SDN multi-controller networks can help prevent conflicts, loops, and security policy violations (Xu, 2017). Figure 2 presents the internal layout of the strong consistency store used by Sridut. The Observer receives updates on the state health of the consensus mechanism, such as quorum losses, leadership changes and liveness. This allows other components the ability to react rapidly to failures or attacks on the strong consistency mechanism.

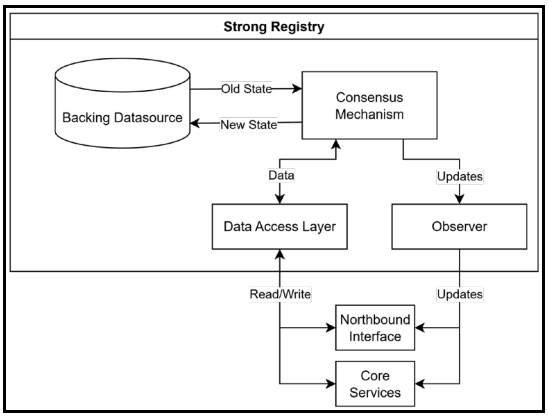


Figure 2: The registry that provides strong consistency

3.4 CRDT Registry

The CRDT Registry (Figure 3) provides strong eventual consistency by leveraging the verifiable convergence of CRDTs and the state reconciliation capabilities of an anti-entropy protocol.

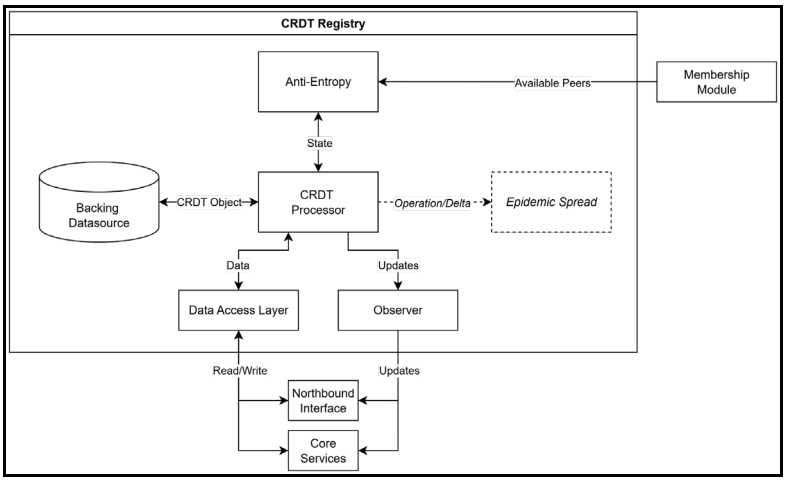


Figure 3: The registry that provides strong eventual consistency through CRDTs

The DAL abstracts out the low-level metadata that CRDTs use to function correctly, reducing complexity for applications when accessing and manipulating CRDT objects. The CRDT Registry should not be limited to one type of CRDT and instead should offer multiple different CRDT types such as PN-Counter, G-Sets and Or-Sets. The CRDT processor is the core of the CRDT Registry, handling all merge operations, irrespective of the type of CRDT used. The Backing Datasource stores the CRDT objects with all required metadata. The anti-entropy mechanism ensures that all nodes eventually converge in the case that updates are missed. To ensure all applications are kept up to date, and to ensure critical updates are applied as fast as possible, the CRDT Processor pushes updates to the observer, which pushes updates downstream. The Epidemic Spread module is an optional module that pushes out updates in a gossip style fanout, ensuring that critical network updates get spread through the network rapidly. This is crucial for security applications time-sensitive operations, such as IP bans, where rapid propagation helps minimize potential damage in the event of an attack.

3.5 State Access Layer

The State Access Layer (SAL) acts as a unified interface allowing applications and core network services to interact with the various registries. The observer module allows applications to receive events from multiple registries through a single unified stream, allowing for the detection of possible security issues across the entire control plane. The Direct Access component grants applications the ability to directly communicate with the various DALs of the registries, allowing applications the ability to easily choose the required level of consistency.

SDN has been used extensively to introduce more advanced security to networks through its programmable and customizable nature (Yusuf et al, 2023; Zhang et al, 2018). Proxy Apps utilize a similar principle and add programmability between the applications and the storage layer of SDN networks. The design of Sridut allows for these proxies to be created that act as middleware or as smart intermediaries. For example, a proxy application could use the available stores to simulate adaptive consistency, choosing the right consistency store based on the data and available metrics.

4. Evaluation

To evaluate Sridut, a proof of concept was developed and tested against ONOS, a popular industry grade SDN controller. Evaluating Sridut directly is challenging, as the model defines the underlying primitives for security rather than the end-user logic. Therefore, an application called HighAvail, was developed, which uses the primitives to achieve a greater level of network security.

4.1 Proof of Concept

The Proof of Concept (PoC) was built on top of os-ken (Openstack, 2025) SDN controller. A global registry singleton is made available to both applications and to the core network services. The global observer of the SAL is implemented with a Pymitter (Rieger, 2025) event emitter and was held in a singleton. The Strong Registry utilizes ETCD (CNCF, 2025), a strongly consistent key value store based on the Raft (Ongaro and Ousterhout, 2014) consensus algorithm. The Local Registry utilizes the built in Python shelve module, which allows persistent python objects stored in a binary file. The In-Memory Registry utilizes standard python in memory data structures such as maps and arrays. The CRDT Registry is built on Pycrdt (Brochart, 2025), a

Python library providing δ-CRDTs. The optional ESM module was implemented using push gossip with fanout, TTL, and duplicate suppression. Lastly the Membership Module utilizes Serf (Hashicorp ,2025), a membership protocol based on SWIM.

To evaluate Sridut, it is necessary to explore how an application can use the various primitives provided to enhance the security of the control plane. For this reason, the proxy application HighAvail was developed. HighAvail provides strong consistency in normal operation while falling back to strong eventual consistency during unplanned events like a partition. During normal operation, anti-entropy is disabled, and each write to both the strong and eventual stores. This ensures that there is always adequate CRDT metadata in case of a partition. When a partition is detected by the SAL observer, the minority side(s) enable anti-entropy and forward all reads and writes to the CRDT store. A key difficulty in multi-consistency systems is ensuring no changes are lost during recovery. HighAvail, however, uses the verifiable convergence of CRDTs to ensure no updates are lost. Once the partition is healed, the minority side does not immediately swap over to the strong store. Instead, the system first exploits the mathematical guarantees of CRDTs to ensure all nodes converge to the same CRDT state. After a partition is healed, the minority nodes send out a signal indicating they are in a fallback mode, causing all anti-entropy stores to be enabled. During recovery, a deterministic leader reconciles divergent states, and minority nodes independently verify that their local CRDT state is identical to the strong store and return to utilizing the strong store. Once all nodes transfer back to utilizing the strong store, anti-entropy is disabled.

4.2 Testbed

To accurately evaluate the PoC against currently available controllers, a testbed is required to run repeatable and reproducible tests. The data plane is simulated by Mininet (Lantz, Heller and McKeown, 2010), a popular SDN emulator widely utilized in academia. While it is possible to use Mininet to simulate the entire network, there are limited options for emulating the control plane itself. Therefore, control plane emulation is handled through Containerlab (Srl-labs, 2025), a container-native orchestration tool specially designed for lab environments. The testbed consisted of a virtual machine with 6 vCPUs (AMD Ryzen 5800X @ 3.8 GHz), 8GB DDR4 RAM, running Ubuntu 20.04.6 LTS, utilizing ONOS v2.7.0, Containerlab v0.69.3, and Mininet v2.3.0.dev6.

4.3 Use Case

This section covers a use case scenario showing how Sridut allows for stronger network security through the verifiable convergence and consistency state awareness. As a baseline for the use case scenario, the work makes use of the industry standard ONOS (Berde et al, 2014) SDN controller. Figure 4 depicts an SDN network topology with a control plane using out-of-bound communication. In this topology, there is a malicious or infected host, h2s2. A split-brain partition can be induced by removing the link from CP Switch 1 and CP Switch 2. Although the controllers can technically communicate through S1 and S2, the testbed is modelled using out-bound communication between controllers which would not allow this form of communication. Using this topology two identical sets of experiments were conducted, with the same sequence of steps. In both cases a basic Access Control List (ACL) application was used for both the PoC and ONOS. The results of the experiment can be seen in Table 1. The PoC uses a HighAvail store to store ACL rules.

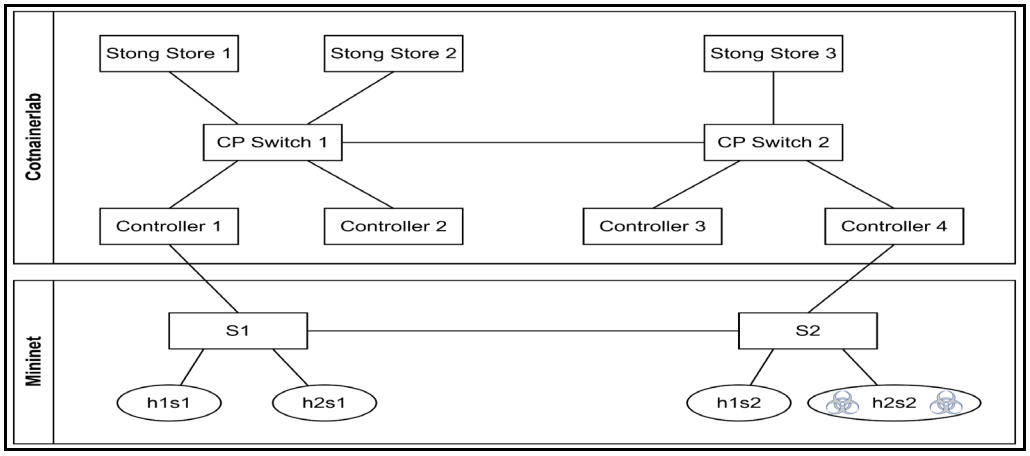


Figure 4: The topology used for use case testing

Table 1: Use case experiment

Step	Action	ONOS	PoC + HighAvail
1	Allow all devices	SUCCESS	SUCCESS
2	PingTest	Results: 0% dropped (12/12 received)	Results: 0% dropped (12/12 received)
3	Induce partition	SUCCESS	SUCCESS
4	PingTest	Results: 0% dropped (12/12 received)	Results: 0% dropped (12/12 received)
5	Deny h2s2 on controller 3	Process hangs	SUCCESS
6	PingTest	Results: 0% dropped (12/12 received)	h1s1 -> h1s2 h2s1 X h1s2 -> h1s1 h2s1 X h2s1 -> h1s1 h1s2 X h2s2 -> X X X *** Results: 50% dropped (6/12 received)
7	Fix Partition	SUCCESS	SUCCESS
8	PingTest	Results: 0% dropped (12/12 received)	h1s1 -> h1s2 h2s1 X h1s2 -> h1s1 h2s1 X h2s1 -> h1s1 h1s2 X h2s2 -> X X X *** Results: 50% dropped (6/12 received)
9	Wait for convergence	N/A	10 Seconds waited
10	Compare Strong and Eventual stores	N/A	Stores match

The experiment evaluates a controller utilizing Sridut against the base ONOS controller by inducing a split-brain partition and attempting to block a malicious host (h2s2). After the partition is induced, ONOS is unable to process any new ACL requests. Figure 5 displays a small excerpt of terminal output of the ONOS controller continuously trying to read from the strong store. Conversely, the PoC's SAL Observer detects the leadership loss (Figure 6), allowing the application to fall back to the CRDT Registry and successfully install the deny rule (Figure 7) on switch S2. After the partition is healed, the nodes gossip about any CRDT changes, which get applied to the strong store by the leader. Each node of the minority side will gradually switch back to using the strong store when its local changes have been applied and the strong store matches its local CRDT state. Since every strong write also commits to the CRDT store, verifiable convergence is still guaranteed under new updates to both the minority and majority sides.

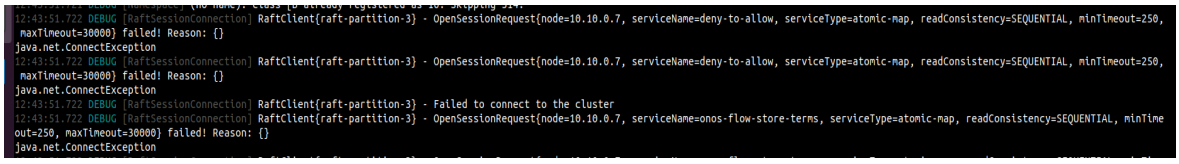


Figure 5: ONOS failing to connect to strong store

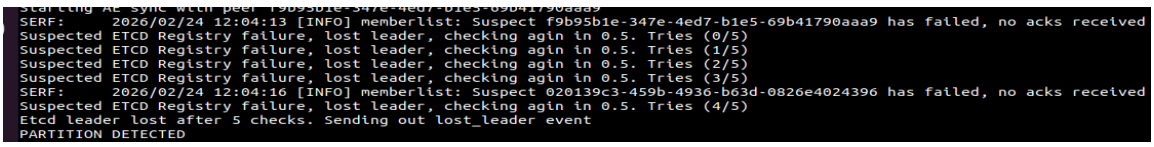


Figure 6: PoC detecting partition

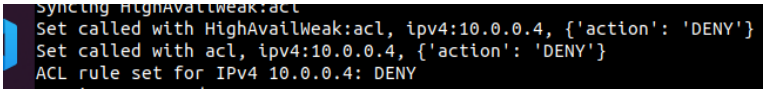


Figure 7: Deny rule being successfully installed

4.4 Discussion

The experiment shows that during a partition, the minority side of ONOS is essentially crippled and cannot make any progress. This is not a bug in ONOS, instead it is the intended functionality of a controller that treats the CAP theorem as a binary problem, where the minority can make no progress during a partition. In this case, however, it prevents the denial rule of the malicious host h2s2 from being installed on switch s2. Naturally, there are cases where applications should never make use of weaker consistency stores, as it could lead to further vulnerabilities (Xu, 2017; Yusuf et al, 2023). However, many controllers are architecturally restrictive (Ahmad and Mir, 2021), embedding consistency trade-offs directly into the controller. This leaves network administrators unable to align the control plane consistency with their specific risk profile. Sridut mitigates these risks by providing multiple stores and a unified API. This abstraction makes the selection between strong, eventual, or custom stores trivial at the application layer.

Regardless of the consistency model chosen, state transparency is critical. For example, in Table 1, the process hangs and times out as ONOS continuously tries to connect to its strong store. However, in a multi-threaded environment, this could lead to recursive retry loops for failed writes that could escalate into resource exhaustion (Munkhondya et al, 2023), creating an availability risk and a potential DoS vector. With Sridut, it is possible to query the state health as well as receive updates when services like the strong store fail. This allows services to react accordingly, such as keeping updates in a queue or returning useful error messages. While the use case experiment used the CRDT store in a supporting role, CRDTs can also be used as a replacement for some weak consistency stores. CRDTs are mathematically designed to operate without a central leader or synchronous consensus. This allows CRDTs to excel and operate securely in environments where network stability is not guaranteed (Sakic and Kellerer, 2018). In the use case experiment listed in Table 1, CRDTs are used to ensure that all nodes safely converge on the same network view. While this work has utilized CRDTs in an SDN environment, it has not fully explored all the possible security benefits. Instead, it serves as a basis for further research into how CRDTs can be applied across the broader SDN landscape to improve the control plane security.

5. Conclusion and Future Work

Current SDN implementations often treat the CAP theorem as a binary choice, forcing a full sacrifice of either integrity or availability during a partition. Additionally current controllers lack weak consistency stores with verifiable convergence, leading to integrity issues. To address this, this paper introduced Sridut, a secure multi-consistency storage model for SDN multi-controller networks. Sridut uses consistency state awareness to grant applications transparency to the health and state of the various consistency stores. Additionally, Sridut makes use of CRDTs to ensure verifiable convergence under any network conditions. Therefore, Stridut helps avoid critical integrity violations through verifiable convergence, and grants applications the ability to react in real time to consistency-based attacks. To evaluate Sridut, the authors developed HighAvail, a proxy application that leverages the state-aware primitives of the model to provide a multi-consistency store with verifiable convergence during network partitions. This application was tested against ONOS, demonstrating that while traditional controllers fail to enforce security policies during a partition, Sridut can enable the handling of security policies while still maintaining integrity. For future work, more research can be done to formally model the intricacies of utilizing CRDT and strong stores in tandem. Additionally, more resource optimization would be needed when utilizing multiple stores together in a production environment.

Acknowledgements

This research was supported by the Council for Scientific and Industrial Research (CSIR) through a postgraduate bursary

Ethics declaration: No ethical clearance was required for this paper.

AI declaration: Google Gemini was used as a tool for fact-checking technical citations and proofreading the paper for grammatical clarity. All other aspects of the paper, including the Sridut model itself were created manually by the authors.

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Information Ethics and Social Context as Drivers of Cybersecurity Resilience in South Africa's Uneven Digital Landscape

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Abstract: South Africa's rapid digital transformation has expanded socio-economic participation while simultaneously intensifying exposure to cyber risks. These risks are unevenly distributed across society due to persistent digital inequalities, infrastructure gaps and variations in digital literacy. This paper argues that cybersecurity resilience in South Africa cannot be achieved through technical controls alone but must be grounded in information ethics and social context. Using an integrative systemic literature review, the study synthesises research on cybersecurity resilience, information ethics and socio-technical systems within South Africa and comparable environments. The findings reveal recurring socio-ethical patterns in which ethical governance, trust, digital justice, and community-level practices either enable or constrain resilience at the individual, institutional, and societal levels. The paper proposes a Socio-Ethical Cybersecurity Resilience Framework that integrates ethical governance, social behaviour, and institutional responsibility. The framework offers context-sensitive guidance for policymakers, educators and practitioners seeking to strengthen inclusive and sustainable cybersecurity resilience.

Keywords: Cybersecurity resilience, Information ethics, Social context, Digital inequality, South Africa

1. Introduction

South Africa has been experiencing rapid digital change that is affecting how people participate in the economy, education, and governance across the country. Governments have been integrating ICTs into e-governance and e-services to advance a digitalised economy and society as part of global initiatives to expand digitalisation (Alayande et al., 2025). There has been an increase in the use of digital technologies in higher education; this expansion has led to an increase in cybersecurity threats (Henrico & Els, 2025). Policy analysis supports the claim that the nation witnessed a significant increase in cyberattacks affecting individuals, critical infrastructure, and businesses, creating immediate national security and economic threats (Tinonetsana, 2025). However, the risk of cyberattacks is not the same for everyone and is strongly shaped by South Africa's structural inequalities. The results of Digital Transformation Studies reveal that historically disadvantaged communities and institutions are lagging due to a lack of technological expertise, unredressed apartheid policies, poor network coverage, limited access to information technology, and poor infrastructure (Mateko et al., 2025). Within a broader digital access research focus, severe structural inequalities persist in digital use; people have different levels of access and ability to address digital threats (Shibambu & Mojapelo, 2024).

These differences show the limits of relying solely on technical approaches for cybersecurity. Cybersecurity should be viewed as a core matter for a country's socioeconomic development policy and related to the political economy of inequality and risk, not just as a technical IT function (Timcke et al., 2023). Research in African cyber governance also demonstrates that international cybersecurity standards are largely theoretical in the African context despite the presence of "uncertainties of governance mechanisms, political underpinnings and limitations in digital capacity" that have created implementation gaps (Ifeanyi-Ajufo, 2023). To address these issues, this paper adopts an integrative systematic literature review to analyse existing scholarly and policy-oriented studies on cybersecurity, information ethics, and the social context in South Africa and comparable socio-technical environments. Through the systematic identification, analysis, and synthesis of relevant literature, the study identifies recurring socio-ethical patterns that either enable or constrain cybersecurity resilience at individual, community, and institutional levels. Based on these insights, the paper proposes a contextually grounded framework for cybersecurity resilience that integrates ethical governance with social and behavioural considerations. The framework aims to support policymakers, educators and cybersecurity practitioners in designing interventions that are ethically informed, socially inclusive and implementable.

2. Methodology

An integrative systematic literature review examines how information ethics and social context influence cybersecurity resilience in South Africa's uneven digital landscape. An integrative review enables the synthesis

of diverse forms of knowledge by combining empirical studies, theoretical contributions, and policy documents into a coherent analytical framework (Snyder, 2019; Torraco, 2016).

The approach supports the interdisciplinary nature of the research, which spans from cybersecurity, information ethics, governance and socio-technical studies. Because cybersecurity resilience extends beyond technical safeguards to include ethical, behavioural, and structural dimensions, an integrative design enables conceptual integration across disciplinary boundaries. This integrative systematic approach supports theory development and contextual interpretation rather than merely aggregating findings, with a focus on publications from 2019 – 2025. The following databases were used: Scopus, Elsevier, Google Scholar, and Taylor and Francis Online for comprehensive results.

3. Literature Review

3.1 Conceptual and Theoretical Foundations

The integration of cybersecurity resilience, information ethics, and socio-technical perspectives provides a multidimensional understanding of how resilience is shaped by technical capacity, ethical governance, and social context. Cybersecurity resilience is conceptualised as a dynamic, multi-level capability spanning individual, communities and institutions. Information ethics introduces normative principles, such as responsibility, accountability, and fairness, that shape how digital risks and protections are distributed. Socio-technical theory situates cybersecurity practices within broader social, cultural, and structural conditions relevant to South Africa's uneven digital landscape.

Combined, these perspectives frame resilience as a socio-technical and ethically grounded phenomenon by providing the analytical foundation for examining how contextual inequalities influence cybersecurity outcomes.

3.1.1 Cybersecurity resilience

Cybersecurity resilience refers to the capacity of individuals, organisations, communities and states to anticipate, withstand, recover from and adapt to cyber disruptions while maintaining essential functions and protecting the confidentiality, integrity and availability of information systems (NIST, 2022). Unlike traditional risk management approaches that focus primarily on prevention, resilience emphasises adaptive capacity and system continuity in the face of uncertainty (Stella & Monica, 2024).

Recent literature conceptualises resilience as a dynamic and systematic property comprising four interrelated dimensions: preparedness, responsiveness, recovery, and adaptive learning (Leppänen & Simola, 2025). Preparedness includes risk assessment, redundancy planning, and security-by-design measures. Responsiveness entails detection capabilities and incident response coordination. Recovery refers to restoration processes such as data backups and business continuity planning, whereas adaptive learning involves post-incident evaluation and capability improvement to reduce future vulnerabilities. This model emphasises resilience as an ongoing process rather than a fixed state.

3.1.2 Information ethics

Information ethics provides the regulating framework for evaluating how digital systems should be designed, governed and used (Floridi et al., 2020). Within the cybersecurity discourse, three principles are evident: responsibility, accountability, and fairness. Responsibility entails proactive duties to prevent foreseeable harm through secure system design and risk mitigation. Accountability requires transparency and mechanisms for explaining and sanctioning harmful practices. Fairness concerns include equitable treatment and the distribution of digital risk, as well as proactive measures (Khan et al., 2023). These principles are important in situations where power hierarchies exist between technology providers, institutions and users.

Digital justice goes beyond fairness by incorporating distributive and procedural dimensions (Khan et al., 2023). Distributive justice concerns equitable access to secure infrastructure, connectivity and digital education. Procedural justice emphasises inclusive participation in digital policymaking. In unequal contexts such as South Africa, disparities in access, affordability and skills intensify exposure to cyber harms (Shibambu & Mojapelo, 2024). From a resilience perspective, ethical governance strengthens trust, legitimacy, and compliance, which are essential for sustainable cybersecurity practices (Johnson et al., 2024). Without justice-oriented approaches, resilience strategies risk reinforcing existing inequalities by giving privileges to already resourced groups.

3.1.3 Socio-technical and social context perspectives

A socio-technical approach recognises that cybersecurity outcomes emerge from interactions between technology and social practices (Modjadji, 2025). Technical design, economic constraints, institutional trust, cultural norms and everyday usage patterns shape security behaviours. In South Africa, digital inequalities condition both technology adoption and security practices (Mwansa et al., 2025). Things like limited connectivity may prevent timely software updates, while financial constraints will restrict access to secure devices. These structural factors shape realistic security choices.

Cultural norms and institutional trust further mediate resilience. Trust in government and service providers influences compliance with cybersecurity guidance and willingness to share personal data (Ali & Faroque, 2023). If trust is low, individuals may adopt informal, risky workarounds. Risk perception is socially constructed and influenced by lived experience, and communities facing economic challenges may prioritise immediate economic needs over abstract digital risks (Mishra, 2025). Socio-technical perspectives therefore foreground how cultural meaning, social networks, institutional legitimacy and material constraints interact with what they afford technological to produce context-specific patterns of vulnerability and resilience.

3.2 South Africa's Uneven Digital Landscape

3.2.1 Digital inequality and access gaps

Inequalities have clearly defined South Africa's uneven digital landscape. The digital divide is the unequal access to technology, resulting in a lack of literacy, skills, infrastructure, and access for people in rural areas (Modjadji, 2025; Mwansa et al., 2025). Urban areas have been found to have better connectivity than rural areas (Aruleba & Jere, 2022; Mwansa et al., 2025; Shava & Ndebele, 2023). Advances in infrastructure have been centred on urban areas, leaving rural areas at a disadvantage: they lack infrastructure, resulting in limited access and higher costs. Despite advances in technology, information and communication technologies (ICTs) are still not adequately catered for in rural areas, thereby leading to socio-economic issues such as limited access to the internet and basic education (Mwansa et al., 2025).

3.2.2 Digital literacy and cyber risk exposure

South Africa's digital literacy levels are not on par, which poses a high risk of cybersecurity incidents. Digital literacy is closely linked to how a country or community responds to cyber risks (Amoresano & Yankson, 2023). Humans are the number one cause of data breaches (Amoresano & Yankson, 2023). Therefore, due to a lack of infrastructure, this further affects an individual's literacy and ability to be cyber-aware. Human behaviour is the weakest link because people act as a human firewall, preventing cybersecurity threats. Due to South Africa being a high target for cyberattacks such as ransomware, organisations are bound to face data breaches because of a lack of literacy programs. Due to the proliferation of advanced technology, artificial intelligence (AI) has created new vulnerabilities, including the threat posed by deepfake technology (Folorunsho & Boamah, 2025; Mahlasela et al., 2024; Ratnawita, 2025). Anyone with the knowledge and skill can thus generate AI images, videos, and sound, which are then used to deceive people (Mahlasela et al., 2024).

Cybersecurity awareness is a need due to advances in technology. Organisations create and implement cybersecurity awareness initiatives to educate employees and equip them to act should they face a cyber incident (Abrahams et al., 2024). This results in low coverage, where not everyone sees cybersecurity as their responsibility but rather as an ICT's responsibility (Panteli et al., 2025).

3.2.3 Structural and historical inequalities

Historically, in South Africa, digital inequalities have persisted due to the country's social and political history (Modjadji, 2025). There have been infrastructure disparities due to policies implemented during the apartheid era (Modjadji, 2025). Due to unequal access to education, ICTs and the apartheid era, access to the digital infrastructure technologies has left other communities marginalised. Structural and historical inequalities have been deeply rooted in apartheid. The digital divide has amplified this; it not only affects literacy levels and access to technology but also shapes how communities can improve their skills and lives (Mugunzva & Manchidi, 2025). This affects communities' ability to improve their lives, as they are unable to leverage ICTs to advance their social and economic well-being. Digital practices are still deeply shaped by historical inequalities and structural constraints (Mugunzva & Manchidi, 2025).

Due to rural-urban disparities, many rural areas have limited access to infrastructure, including unreliable electricity and network connectivity, thereby affecting internet access (Anil & Disparities, 2024; Khan et al.,

2023). This has led to situations in which some communities use legacy systems. These legacy systems create vulnerabilities, and without the right skills, South Africa is left vulnerable to cyberattacks. These legacy systems result in outdated software, leading to a lack of updates or new patches. Disparities in access to technology and internet connectivity, often rooted in socioeconomic status, mean that rural areas and underserved communities are less equipped to handle cyber threats (Khan et al., 2023; Nthambeleni & Motadi, 2025). There is a need for digital inclusion across all communities to ensure inclusivity and enable communities to address cyber threats (Layne et al., 2026).

3.3 Information Ethics as a Driver of Cybersecurity Resilience

3.3.1 Ethical responsibility and accountability

Information ethics helps make cybersecurity stronger by showing that keeping things secure is shared now with many layers, including "techno-centric, human-centric, organisational (intra and inter) and social centric perspectives", an onion-shaped framework in which senior leadership plays an important role in fostering responsible cybersecurity (Panteli et al., 2025). From a public-interest perspective, ethical rules treat cybersecurity as a benefit to everyone, requiring analysis of core ethical principles and values of liberal democracy, such as privacy, communication, freedom, and fairness, alongside ethical guidelines that change how institutions operate (Miller & Bossomaier, 2024). For people working in cybersecurity, professional ethics makes it clear that they are responsible to the public, clarifying their duties and what good ethical behaviour looks like, which directly links ethical conduct to resilient outcomes (Vallor et al., 2016). At the institutional level, resilience depends on strong governance and policy frameworks that ensure compliance and protect sensitive data. Studies in higher education argue that cohesive governance is essential to mitigate risks, ensure compliance, and protect academic research, financial, and personal data, especially amid threats such as ransomware and data breaches (Ali, 2025). Governmental obligations arise because cybersecurity has become a strategic priority, with attacks blurring the traditional distinction between crime and acts of war. This means governments need to create rules and make ethical changes to protect critical systems and democratic processes (Miller & Bossomaier, 2024).

3.3.2 Fairness, inclusion, and digital justice

Fairness, inclusion, and digital justice are important parts of cybersecurity because effective protection must honour fundamental values such as equality, fairness, freedom, and privacy (Kirichenko et al., 2020). Unequal cyber protection worsens existing social inequalities. Digital exclusion keeps economic, educational and social gaps in place, making cybersecurity and digital access key parts of social justice (DavethanTech, 2025). At the technical level, algorithmic tools used in cybersecurity can reflect or amplify biases, leading to unfair targeting or exclusion, underscoring the ethical problem of unequal protection based on discrimination (Whittaker, 2020). These differences show the importance of inclusive security frameworks, as cybersecurity is understood as a matter of equity, fairness, and inclusivity, requiring systems that protect individuals, particularly the most vulnerable, such as people with disabilities, older people, children, and gender minorities (Duhem, 2024). These findings show that fairness and digital justice are not just nice ideas but important ethical principles to ensure that cybersecurity works for every user equally.

3.3.3 Ethical governance in cybersecurity

Cybersecurity ethical governance calls for frameworks that mitigate risks, ensure compliance, and protect data, underscoring the importance of robust cybersecurity policies for resilient institutions (Ali, 2025). Research supports the adoption of clear cybersecurity policy frameworks backed by "privacy-by-design principles", adaptive regulations, and coordinated action to address global cybercrime and data privacy challenges beyond generic controls (Kirichenko et al., 2020).

Ethics in cybersecurity means respecting basic values such as equality, fairness, freedom, and privacy, and using real-life examples to guide decisions (Kirichenko et al., 2020). From this governance perspective, POPIA extends beyond being compliance-focused to hands-on, proactive data stewardship: a review of how this works in South Africa points to real steps like staff training, risk checks, and meeting international data protection standards, showing a transition from theoretical discourses to empirical and sector-specific research on POPIA (Sema et al., 2025). Simultaneously, studies for professionals incorporate ethics, law, and policy dimensions by showing how responsibility rules connect to daily controls and by mapping how governance structures embed duties and align with regulatory obligations (Priyadarshini & Cotton, 2022).

3.4 Social Context and Cybersecurity Behaviour

3.4.1 Trust, risk perception, and secure practices

Humans are often seen as the number one cause of data breaches (Amoresano & Yankson, 2023). Therefore, trust, risk perception and secure practices are crucial to create a cyber-resilient economy. Trust is crucial in cybersecurity, where the zero-trust model is in place. The zero trust model states that "trust no one, verify all." Users tend to trust that technology will inherently protect them from any attacks, thereby lacking the right measures to implement in their personal lives (Nasir et al., 2024). While trust is important, it is worth noting that in cybersecurity, trust can lead to reduced efforts to protect oneself (De Kimpe et al., 2022). An individual's perception of risk evaluates how they are likely to respond to risks (Andersson et al., 2023). Therefore, this impacts how one protects themselves, the community, and the organisations they work for. When one feels at risk, they are more likely to take proactive measures to protect themselves.

The community one lives in plays a significant role in how they adopt and take secure practices to protect themselves. The organisational culture also plays a significant role in terms of how one implements secure practices at the workplace and in their personal lives (Panteli et al., 2025). The environment one lives in also determines the type of practices one employs. For example, if one stays in a literate community that values implementing secure practices, they are more likely to be cyber-resilient. Due to the digital divide, disadvantaged communities are less likely to adopt best practices for securing their cyberspace.

3.4.2 Cultural norms and everyday digital practices

Cultural norms play a significant role in terms of how an individual protects themselves. Inequitable disparities play a significant role in how best practices are implemented (Modjadji, 2025). People in rural areas are less likely to adopt best practices due to the digital divide. This thus affects how cyber-resilient one is and how they adopt best practices in their lives (Djatmiko et al., 2025). A community that values or is deeply rooted in being resilient is more likely to adopt secure best practices. An organisation with a cybersecurity culture is more likely to ensure that its employees adopt secure best practices (Panteli et al., 2025). There is a need for a nationwide initiative to teach communities how to adopt best practices to ensure their online safety.

3.4.3 Community-level cybersecurity resilience

For a community to be resilient, it means that a community or group of people builds and ensures they are equipped with the right skills and knowledge to prevent cyber threats (Jarjoui et al., 2024). This includes training and awareness initiatives to build a cyber-resilient community. This also includes initiatives set up by the government and organisations to build community-level cybersecurity resilience (Jarjoui et al., 2024). This includes creating and adopting policies to protect communities. This also includes training and awareness initiatives undertaken by organisations to educate employees on how to respond to incidents within the organisation and in their personal lives.

When an employee adopts the right practices in their personal lives, they are more likely to implement the same initiative at their workplace (Aksoy, 2024; Kuiper, 2025). A collective effort is required for a community to be cyber resilient. Humans are the number one cause of breaches; therefore, it is essential to ensure a strong human firewall is in place. Furthermore, this leads to a community with a shared responsibility for protecting its community or organisation.

4. Proposed Socio-ethical Cybersecurity Resilience Framework

This study proposes a Socio-Ethical Cybersecurity Resilience Framework that positions resilience as a multi-level, socio-technical construct shaped by ethical governance, social behaviour, and institutional responsibility. Contemporary resilience scholarship emphasises that cybersecurity resilience extends beyond technical robustness to include adaptive capacity, governance maturity and human behaviour (Leppänen & Simola, 2025; Linkov et al., 2022). At the same time, the digital ethics literature underscores the importance of embedding responsibility, accountability, and justice within the digital governance system to prevent unequal harm (Floridi et al., 2020; Stahl, 2021).

The South African context is characterised by persistent digital inequality, uneven infrastructure, and socio-economic differences, with cyber risk exposure distributed unevenly across these groups. A resilience model that ignores ethical governance and social context risks reinforcing existing vulnerabilities. The proposed framework therefore integrates three interdependent pillars: ethical governance, social behaviour and

institutional responsibility, which will collectively shape cybersecurity resilience at individual, community and institutional levels.

4.1 Framework Components

Framework Components	What they are
4.1.1 Ethical Governance	Ethical governance refers to the normative and regulatory foundations that guide cybersecurity decision-making. It incorporates principles of responsibility, accountability, fairness, and digital justice that ensure cybersecurity policies do not merely comply with legal requirements but also address distributive and procedural inequalities (Floridi *et al.*, 2020). Responsibility covers proactive harm and risk mitigation. Accountability requires transparent mechanisms for oversight and redress. Fairness and digital justice demand that protective measures and resources be distributed equally, particularly in addressing structural inequalities. Ethical governance, therefore, serves as the normative anchor of resilience, shaping institutional conduct and influencing public trust.
4.1.2 Social Behaviour	Every day, digital practices, trust relationships, cultural norms and risk perception significantly shape cybersecurity resilience. Socio-technical research illustrates that security outcomes emerge from interactions between technological systems and human behaviour rather than technical design alone (Baxter & Sommerville, 2011; Leppänen & Simola, 2025). In South Africa, gaps in digital literacy, affordability of connectivity and access to technological devices influence the adoption of safe practices. Thus, trust in institutions further mediates compliance with cybersecurity guidance. Social behaviour, therefore, represents the human dimension of resilience, highlighting that awareness, education and culturally responsive engagement strategies are essential components of sustainable cybersecurity capacity
4.1.3 Social Behaviour	Institutional responsibility encompasses the obligations of state entities, private organisations, and public institutions to create enabling conditions for resilience. This includes developing coherent cybersecurity policies, investing in secure infrastructure, building capacity, and implementing transparent incident response mechanisms. Resilient institutions demonstrate adaptive governance and intersectoral, continuous learning from cyber incidents (Linkov, Trump, and Keisler, 2022). In an uneven digital environment, institutional responsibility also entails prioritising marginalised communities in capacity development initiatives. By embedding ethical governance into operational structures, institutions serve as a critical enabler of systemic resilience.

4.1.1 Conceptual structure of the framework



Figure 1: Socio-Ethical Cybersecurity Resilience Framework

Application in the South African Context: In South Africa's uneven digital landscape, persistent digital inequality, infrastructure disparities, and trust deficits shape vulnerability exposure and resilience capacity (Shibambu & Mojapelo, 2024). The framework, therefore, calls for integrating cybersecurity strategies with digital inclusion efforts, strengthening ethical oversight, and promoting context-sensitive awareness initiatives.

Implications for Policymakers, Educators and Practitioners:

- Policymakers: Align cybersecurity governance with digital justice and broader socio-economic development goals.
- Educators: Combine cybersecurity literacy with ethical and civic education.
- Practitioners: Design user-centred security, transparent communication practices and ethical risk assessments that account for socio-economic context.

5. Discussion

The findings of this study have important theoretical implications for cybersecurity resilience. By integrating information ethics and socio-technical perspectives, the paper advances resilience theory beyond predominantly technical and systems-engineering approaches towards a normatively grounded, socially embedded framework. Contemporary resilience literature emphasises adaptive capacity, recovery and continuity (Leppänen & Simola, 2025; Linkov et al., 2022) yet often under-theorises how ethical governance and distributive justice shape resilience outcomes. Drawing on recent work in digital ethics and governance (Linkov et al., 2022; Stahl, 2021), this study reframes cybersecurity resilience as a socio-ethical construct in which responsibility, accountability, fairness and trust are constitutive rather than peripheral elements.

The study highlights that strengthening cybersecurity resilience in South Africa requires context-sensitive and justice-oriented interventions. Empirical research shows that digital inequality, infrastructure deficits and uneven literacy significantly mediate vulnerability exposure in the Global South context (Shibambu & Mojapelo, 2024). Consequently, compliance-driven cybersecurity programmes are insufficient without parallel investments in inclusive digital capacity building and ethical governance mechanisms. Embedding principles such as privacy-by-design, transparent oversight and community-level awareness into institutional practice enhances public trust and supports sustainable behavioural change (Kelly, 2024). The proposed socio-ethical framework, therefore, offers policymakers, educators, and practitioners an integrated approach that aligns cybersecurity strategy with broader socio-economic development and digital inclusion objectives.

In terms of the contribution of Global South cybersecurity literature, this study addresses a persistent gap in scholarship that often privileges Global North regulatory models and technical standards while under examining structural inequality and normative governance in developing contexts (Ifeanyi-Ajufo, 2023; Timcke et al., 2023). By foregrounding ethical governance and social context as drivers of resilience, the paper provides a contextually grounded and transferable analytical model applicable to other digitally unequal societies. The socio-ethical resilience framework thus contributes to emerging debates on decolonising cyber governance scholarship and promoting justice-centred digital security paradigms in Africa and comparable socio-technical environments.

6. Conclusion

This paper argues that cybersecurity resilience in South Africa cannot be fully grasped or enhanced solely through technical measures. Located within a highly uneven digital environment shaped by historical inequalities, infrastructural gaps, and disparate levels of digital literacy, cyber risk is distributed across society in socially patterned and ethically mediated ways.

The proposed Socio-Ethical Cybersecurity Resilience Framework advances both academic understanding and real-world application by treating ethical governance, social behaviour, and institutional accountability as mutually reinforcing foundations of resilience. In this way, the paper enriches Global South cybersecurity debates by placing structural inequality and justice at the centre of analysis rather than treating them as secondary contexts. In South Africa and comparable contexts, enhancing cybersecurity resilience thus depends on aligning governance arrangements, digital inclusion efforts, and behavioural initiatives within a unified ethical framework. In the end, resilience in an unequal digital landscape is not simply a matter of technical capability, but of fair protection, confidence in institutions, and a digitally driven transformation that is deeply rooted in society.

Ethics declaration: The study employed previously published peer-reviewed journal articles and, as no human subjects were involved, ethical approval was not required.

AI Usage Declaration: Generative artificial intelligence (AI), specifically large language models (LLMs), was used to enhance writing, correct grammatical errors, and provide summaries of literature to disseminate information. No tools were used to write original content. AI tools used to aid the writing process include Grammarly, Writefull, and ChatGPT.

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From Play to Mobilization: A Sociotechnical Pathway from Youth Gaming Communities to Geopolitical Cyber Operations

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Abstract: Digital gaming communities have become dexnse sociotechnical environments in which youth develop trust, technical fluency, identity, and coordination practices that extend far beyond gameplay. This paper investigates how such communities can, under particular structural conditions, evolve into networks that participate in cyber activities with geopolitical relevance. Rather than treating this transition as primarily ideological from the outset, the paper argues that the pathway is initially sociotechnical: repeated interaction builds social cohesion, status systems reward experimentation and technical competence, and platform migration enables tighter coordination across gaming, chat, and adjacent online spaces. Drawing on prior work on youth gaming, online extremism, gaming-adjacent radicalization, and child involvement in cyber operations, the paper develops a four-stage lifecycle of formation, capability building, alignment, and deployment. It then illustrates this lifecycle through three case studies that show both prosocial and harmful trajectories. The central claim is that escalation is better explained by evolving community structure and task organization than by overt political language alone. The paper concludes by proposing youth-centered interventions, platform governance strategies, and early warning indicators that can reduce exploitative mobilization while preserving the legitimate social and educational value of gaming culture.

Keywords: Teen online communities, Gaming groups, Cyber conflict, Recruitment and radicalization, Social network analysis

1. Introduction

Digital gaming now extends far beyond entertainment. It functions as a distributed social environment spanning multiplayer games, Discord servers, livestreams, forums, and private chat spaces. For many young people, these are early settings for learning collaboration, competition, identity signaling, moderation norms, and technical experimentation. Prior work has shown that gaming can foster civic engagement, communication, and collaborative problem solving rather than serving only as passive leisure (Kahne, Middaugh, and Evans, 2008). More recent research, however, shows that gaming and gaming adjacent ecosystems can also facilitate exposure to extremist narratives, recruitment dynamics, and harmful forms of networked mobilization (RAN, 2021; Englund, 2023; Davey, 2024; Allchorn and Orofino, 2025). Gaming communities, therefore, matter for cybersecurity not simply because harmful content may appear within them, but because they combine social trust, technical learning, persistent communication, and platform interoperability in ways that can be redirected toward coordinated cyber activity.

This paper asks how youth gaming communities move from routine play and social interaction into activities with geopolitical cyber relevance. Its central argument is that this transition is often sociotechnical rather than ideological. Early stages usually emerge through ordinary digital practices rather than explicit political commitment. Team play builds familiarity and dependence. Modding, scripting, server administration, and tool sharing develop technical confidence. Informal hierarchies reward competence and responsiveness. Migration from public gaming spaces into more private and persistent channels strengthens trust and enables selective coordination. Under these conditions, existing social and technical capacities may be redirected by external actors, brokers, or influential insiders toward harassment, doxxing, influence activity, denial of service, credential abuse, or open source intelligence work. UNICEF Innocenti's recent analysis highlights the urgency of this issue by showing that children are increasingly implicated in conflict-related cyber activity through informal and digitally mediated pathways.

The paper makes three contributions. First, it synthesizes literature on youth gaming, extremism, platform governance, and child cyber conflict into a unified sociotechnical account of mobilization. Second, it proposes a four-stage lifecycle of formation, capability building, alignment, and deployment. Third, it applies this model to case material to show that apparently isolated incidents are better understood as part of a broader structural process. This shifts attention away from overt ideology alone and toward indicators such as platform migration, brokerage, secrecy norms, emergent leadership, and changes in moderation practice. Such a perspective is more useful for defenders, educators, platform designers, and policymakers seeking early warning without treating youth gaming culture as inherently suspect.

The paper is also guided by an important normative concern. Gaming communities are not merely sites of risk. They are also spaces where young people acquire technical literacy, form friendships, and sometimes contribute positively to civic or wartime resilience. The challenge is therefore not to suppress gaming-based communities wholesale, but to distinguish benign and prosocial coordination from exploitative mobilization and covert tasking. The key question is not whether youth gaming communities matter geopolitically, but how and under what conditions they become operationally significant. To establish this argument, existing scholarship offers useful insights but remains spread across youth media studies, radicalization research, platform governance, and emerging work on youth in cyber conflict. A foundational starting point is the work of Kahne, Middaugh, and Evans (2008), which challenges the idea that gaming is purely recreational. Their findings show that gaming environments support collaboration, civic-style participation, and interest-driven learning. This matters because it establishes gaming spaces as systems where young people develop coordination skills, social trust, and group-based interaction, all of which can later be repurposed.

A second group of studies focuses on extremism within gaming-adjacent ecosystems. The Radicalisation Awareness Network (2021) argues that recruitment and socialization often occur outside the game itself, in surrounding platforms such as voice chat, social media, and private servers. Englund (2023) and Davey (2024) extend this idea by describing gaming as part of a broader platform ecology where weak moderation, identity play, and persistent communication enable communities to evolve and, in some cases, become politicized. These works support the claim that movement across platforms is a key mechanism in the transition from casual interaction to coordinated activity.

Research on governance further highlights the limitations of content-focused moderation. Allchorn and Orofino (2025) show that harmful behavior in these environments is often subtle, ironic, or embedded in otherwise legitimate interactions. As a result, identifying risk based solely on explicit speech is difficult. This suggests that structural indicators, such as changes in group organization, communication patterns, or coordination behavior, may provide earlier and more reliable signals of escalation.

Broader work on youth radicalization also emphasizes that online mobilization is driven by belonging, peer influence, and network exposure rather than ideology alone (UNESCO, 2017). Gaming communities are significant in this context because they provide dense social environments where identity, recognition, and interaction reinforce each other. These dynamics can lower the barrier to participation in more coordinated or adversarial activities.

Finally, emerging research from UNICEF highlights that youth involvement in cyber operations is increasingly plausible due to the decentralized and low-cost nature of digital activity. Participation may not resemble traditional recruitment but instead emerge through informal roles and task-based involvement.

Taken together, these strands show that no single field fully explains the transition from gaming communities to cyber operations. This paper builds on existing work by integrating these perspectives into a unified sociotechnical model that explains how everyday interaction, technical skill development, and platform dynamics can converge into operationally significant behavior.

2. Methodology and Limitations

This paper uses a qualitative and exploratory research design based on two components: a focused literature survey and a comparative analysis of three case studies. The literature review draws on prior work on youth gaming, gaming-adjacent extremism, platform governance, online radicalization, and child involvement in cyber operations to identify recurring sociotechnical mechanisms such as trust formation, platform migration, technical skill development, informal leadership, and recruitment vulnerability. These insights are then applied to three illustrative case studies, two positive and one negative, to examine how similar digital environments can produce divergent outcomes. The analytical lens is interpretive rather than statistical, with each case examined through the proposed stages of formation, capability building, alignment, and deployment.

This approach has several limitations. First, the study relies on secondary sources rather than primary fieldwork, interviews, or platform-level data. Second, the case studies are illustrative and theoretically useful, but they do not support broad empirical generalization. Third, public reporting on youth involvement in cyber-relevant activities may be incomplete, selective, or affected by ethical constraints around minors. Accordingly, the paper does not claim causal proof. Instead, it offers a conceptually grounded framework for understanding how youth gaming communities may become linked to geopolitical cyber activity and for identifying areas for future empirical research.

2.1 Case Studies

This section examines three case studies that illuminate the sociotechnical pathway from teen and youth-centered gaming or gaming-adjacent online communities to cyber activities with geopolitical relevance. Taken together, the cases illustrate that the same structural features that make youth digital communities effective sites of belonging, skill formation, and rapid coordination can produce sharply different outcomes depending on how they are mobilized. In one direction, gaming-style collaboration can be redirected toward civic resilience, open source investigation, and defensive participation in wartime information ecosystems. In another, similar environment, it can enable manipulation, informal tasking, and the circulation of sensitive state information. The value of these cases lies not simply in their surface contrast but in their ability to expose common mechanisms: trust formation, migration across platforms, status hierarchies, informal leadership, and low-friction movement from playful or routine interaction into actions that acquire strategic significance.

Case Study 1: Youth OSINT Communities Supporting Ukraine

A constructive example of youth and student mobilization appears in the OFU Open Network run by OSINT for Ukraine (OSINT for Ukraine, n.d.). The organization describes this network as a Discord-based online community that brings together students, volunteers, experts, and organizations to support partnerships and participation in war games, OSINT competitions, and investigative projects. This framing is analytically important because it shows that the infrastructure of gaming culture, including team-based coordination, competitive challenges, shared tooling, and persistent chat-based collaboration, can be redirected into quasi-civic and investigative functions rather than disruptive or destructive ones. The OFU model does not erase the gaming lineage of these practices. Rather, it demonstrates that the same habits cultivated in multiplayer and modding environments, such as distributed teamwork, evidence sharing, technical experimentation, and peer recognition, can be repurposed for accountability work in wartime digital ecosystems.

From a sociotechnical perspective, the OFU case is especially useful because it occupies the middle ground between informal youth participation and organized operational contribution. Its activities are not reducible to casual online advocacy. Instead, they involve structured investigative tasks, collaborative problem solving, and a community architecture capable of sustaining repeated participation over time. Discord serves here not merely as a communication tool but as an organizing substrate that lowers barriers to entry while preserving enough continuity to build skill and trust. In this sense, the case supports the paper's core claim that the earliest stages of mobilization are often sociotechnical before they are ideological. Participants do not need to begin with a coherent political identity or explicit cyber agenda. Repeated engagement in shared tasks can gradually generate competence, mutual recognition, and role differentiation, producing a community that is operationally meaningful even when its stated orientation is defensive or humanitarian.

Case Study 2: Youth Resilience Against Russian Online Recruitment

A second positive case emerges from Ukraine's efforts to inoculate teenagers against hostile online recruitment (Ivanyshyn, 2025). Reporting by The Kyiv Independent states that Ukraine's security service has been teaching teenagers how to avoid recruitment by Russian intelligence online and notes that approximately 22 percent of Ukrainians recruited by Russian intelligence for sabotage or terrorist attacks were minors. The same report states that recruiters have used platforms including Telegram, Discord, and TikTok, and that teenagers may initially be approached with offers of easy money for seemingly limited tasks such as photographing sensitive sites or delivering packages before being drawn into more serious forms of participation or blackmail.

This case is positive not because it showcases teenagers performing cyber operations, but because it reveals a defensive intervention precisely at the point where the sociotechnical pathway might otherwise accelerate. It captures an early warning layer of the lifecycle proposed in your paper: before capability building matures into alignment and deployment, hostile actors attempt to exploit youthful digital fluency, platform familiarity, and local access. The Ukrainian response is therefore analytically significant as a youth-centered disruption strategy. Instead of assuming that teen participation is purely an issue of ideology or deviance, the intervention acknowledges that recruitment often proceeds through ordinary communication platforms and incremental tasks. That insight matters because it shifts the prevention problem from one of abstract deradicalization to one of platform literacy, coercion recognition, and resistance to staged tasking. In other words, this case shows that effective mitigation must address the same sociotechnical mechanisms that enable mobilization in the first place: low-cost contact, peer normalizing effects, hidden escalation, and the blending of play, money, secrecy, and digital routine.

Case Study 3: Discord Gaming Spaces and the Pentagon Leak Pathway

The most clearly negative case is the 2023 leakage of classified Pentagon documents through Discord communities connected to gaming culture (Hern, 2023). The Guardian reported that the leaked cache appears to have been initially shared on Discord in an effort to win an argument about the war in Ukraine. The same report notes that documents were circulated in closed gamer chatrooms, including a server called "Minecraft Earth Map," and that the materials had earlier passed through other Discord servers whose users were interested in video games, music, and online fandom rather than being primarily geopolitical communities.

This case is especially revealing because it demonstrates how strategically consequential outcomes can emerge from communities that are not initially organized around formal political action. The pathway here does not begin with overt geopolitical mobilization. Instead, it begins in a gamer-focused social environment where status competition, argument escalation, and platform intimacy create the conditions for boundary crossing. The leak was not merely a failure of information security at the point of state access. It was also a downstream consequence of a sociotechnical setting in which private chatrooms, peer validation, insider performance, and low visibility circulation made it possible for highly sensitive material to be deployed as social capital. The fact that the leak appears to have been tied to an argument over Ukraine underscores the paper's broader claim that gaming adjacent communities can become bridges between everyday interaction and geopolitical consequence without requiring a prior transformation into ideologically coherent cyber organizations. Strategic harm can result from a much looser assemblage of trust, audience, and digital affordance.

Comparative Analysis of the Three Cases

Read together, these three cases reveal that the key analytic distinction is not whether youth and gaming adjacent communities are inherently benign or dangerous. The more important distinction concerns how existing social and technical capacities are steered, validated, and connected to external actors or missions. In the OFU case, gaming style coordination is channeled toward open source investigation, accountability, and volunteer collaboration. In the Ukrainian counter-recruitment case, state actors intervene to prevent the conversion of ordinary platform participation into sabotage support. In the Pentagon leak case, a gaming-centered Discord ecology becomes the vehicle through which sensitive state information is converted into peer prestige and then released into broader geopolitical circulation. The common substrate across all three is not ideology alone but the combination of persistent online communication, trust built through repeated interaction, low-cost movement across platforms, and opportunities for status gain through technical or informational contribution.

These cases also support a structural reading of escalation. Your paper argues that escalation is often better predicted by shifts in community structure than by explicit political speech. The case evidence is consistent with that proposition. In the OFU setting, structure is formalized into collaborative channels, partnerships, and recurring task participation. In the Ukrainian recruitment setting, the structural vulnerability lies in recruiters' access to youth through familiar platforms and in the sequencing of small tasks into more serious commitments. In the Pentagon leak case, escalation depended on small, semi-private communities with enough intimacy to circulate sensitive information and enough connectivity to let it spill outward. UNICEF's recent analysis of children's recruitment and use in cyber operations reinforces the relevance of this structural lens by observing that children are increasingly implicated in cyber conflict and that the actors involved may be loosely organized, anonymous, or situated at the blurred boundary between civilian, private, and conflict-related participation.

A further implication concerns intervention design. If the pathway is sociotechnical, then policy responses cannot rely only on content moderation or ideological screening. They must also target the organizational mechanics of mobilization. This includes identifying rapid trust formation around high-risk tasks, unusual brokerage between youth communities and external operators, shifts from open to private communication spaces, and abrupt increases in the value attached to secrecy or insider knowledge. At the same time, the positive cases caution against a purely securitized reading of youth gaming culture. The same competencies that make these communities vulnerable to exploitation, including coordination, experimentation, and technical curiosity, also make them valuable for constructive civic participation and digital resilience. Effective governance, therefore, requires discrimination rather than blanket suppression: preserving prosocial pathways for youth collaboration while disrupting exploitative recruitment, covert tasking, and prestige economies built around harmful cyber or intelligence behavior.

3. Discussion

The case studies reinforce the central claim of this paper that the pathway from youth gaming communities to geopolitical cyber relevance is best understood as sociotechnical before it is ideological. Across the three cases, the most important drivers of escalation are not initially explicit political commitments or doctrinal alignment, but rather the gradual accumulation of social trust, technical confidence, communicative persistence, and group-level coordination. This finding matters because it challenges a common tendency in cyber and extremism research to privilege ideology as the primary explanatory variable. In youth gaming environments, coordinated action often emerges first from ordinary digital practices such as repeated play, role specialization, informal moderation, tool sharing, and movement across interconnected platforms. Political meaning, where it appears, often enters later as a framing device layered onto an already functioning social and technical infrastructure.

A major insight from the cases is that gaming communities are not simply communication spaces but identity-producing environments. Social interaction in gaming communities is rarely incidental. Competitive play, teamwork, cooperative strategy, shared humor, and repeated encounters contribute to durable in-group identities and mutual recognition. These social bonds are analytically important because they lower the friction of mobilization. When individuals already trust one another, respect one another's competence, and participate in shared routines, the threshold for accepting a task, joining a private channel, or following an emergent leader becomes much lower. In this sense, identity formation is not merely a cultural backdrop. It is an operational asset. The OFU case shows how such identity can support constructive collaboration and investigative participation, while the Pentagon leak case shows how closely bonded peer environments can also normalize risky or harmful forms of informational behavior. The same mechanisms that sustain belonging can therefore sustain escalation.

The discussion also highlights the importance of gaming adjacent migration. One recurring pattern in the literature and the cases is that the most consequential dynamics often occur not inside the game itself, but in surrounding spaces such as Discord, Telegram, livestream chat, forums, and private servers. These adjacent environments matter because they allow interactions to persist beyond the episodic structure of gameplay. They also enable more selective membership, deeper socialization, and lower visibility to outside observers. The result is a transition from temporary play-based cooperation to more durable networked communities capable of maintaining memory, leadership, norms, and task continuity. This helps explain why the sociotechnical pathway is often difficult to detect using content-based models alone. By the time overtly harmful or geopolitical behavior is visible, the underlying community may already possess the trust networks and coordination capacity needed to act effectively.

Another important implication concerns the relationship between technical skill and social legitimacy. Youth gaming spaces do not merely expose participants to digital tools. They often reward experimentation, improvisation, systems thinking, and public demonstrations of competence. Modding, scripting, server administration, competitive analysis, and troubleshooting all create opportunities for informal prestige. Over time, those who display competence may acquire brokerage roles that connect otherwise separate groups, platforms, or task domains. This is particularly significant because operationally relevant cyber activity frequently depends not only on raw technical skill, but on socially recognized competence. In other words, communities mobilize more readily when participants believe certain members know what they are doing. The cases, therefore, suggest that status hierarchies within youth gaming spaces can become channels through which technical authority is converted into organizational influence. Such influence can support positive outcomes, such as open source collaboration and resilience building, but it can also facilitate covert recruitment, harmful experimentation, or normalization of secrecy.

The three cases also sharpen the distinction between exposure and mobilization. Exposure to extremist narratives, manipulative recruitment, or provocative geopolitical content does not by itself explain why some communities become operationally consequential while others do not. What appears more decisive is whether exposure becomes embedded within existing structures of trust, repetition, and tasking. The Ukrainian prevention case is especially instructive here because it reveals that early recruitment efforts often rely on incremental requests rather than immediate ideological conversion. This suggests that escalation may proceed through small acts of participation that appear trivial in isolation but cumulatively shift a young person's relationship to risk, secrecy, and obligation. The sociotechnical pathway is therefore not a binary movement from innocence to extremism. It is often a staged process in which ordinary platform familiarity and low-stakes engagement can be repurposed into more consequential forms of participation. This is one reason why youth-

centered digital literacy interventions may be more effective than purely punitive approaches. They target the mechanics of staged mobilization rather than waiting for explicit ideological markers to surface.

At a broader level, the findings of this paper underscore the geopolitical significance of decentralized cyber-relevant communities. Small groups embedded in youth digital culture may seem too informal or socially fragmented to matter strategically. Yet the cases show that geopolitical consequences do not require formal organization, stable ideology, or state-like command structures. Distributed online groups can still contribute to influence operations, intelligence leakage, sabotage support, open source investigation, or conflict-related information flows. What makes them important is not institutional formality, but their capacity to convert local coordination into a networked effect. This blurring of the boundary between informal community and operational actors complicates conventional distinctions between civilian, volunteer, and conflict-linked digital participation. It also raises difficult normative questions. The same youth communities that generate risk may also generate resilience, civic participation, and constructive wartime support. Any serious policy response must therefore preserve this duality rather than collapse it into a single threat narrative.

4. Conclusion

Youth gaming communities are not inherently precursors to harmful cyber activity, yet they can become operationally significant when social trust, technical skill, and cross-platform coordination are redirected toward geopolitical ends. This paper argued that the transition is often sociotechnical before it is ideological, emerging through ordinary practices of play, collaboration, status formation, and platform migration. The three case studies showed that these same community dynamics can support either constructive civic participation or harmful mobilization, depending on how they are organized and exploited. The key implication is that early warning and intervention should focus less on overt political expression alone and more on structural signals such as brokerage, secrecy, tasking, and shifts in community coordination. A more precise sociotechnical understanding can help platforms, educators, and policymakers reduce exploitative pathways while preserving the legitimate social and developmental value of youth gaming communities.

Ethics Declaration: This study relies on publicly available case studies, secondary reporting, and documented case material. No direct interaction was conducted with individuals or online communities, and no attempts were made to identify or deanonymize participants. The analysis focuses on structural and sociotechnical dynamics rather than individual behavior.

AI Declaration: Generative AI tools were used in a limited and responsible manner to support grammar refinement and clarity of expression. All substantive arguments, analyses, and interpretations were developed by the authors, and the use of AI did not influence the research design, findings, or conclusions.

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Enhancing Credit Fraud Detection in e-Payments through Predictive Analytics using Machine Learning: A Scoping Review

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Abstract: The rapid global expansion of e-payment has created new opportunities for sophisticated, evolving financial fraud, leading to substantial financial losses and undermining or eroding customer trust, despite new security efforts. This scoping review examines how the application of predictive analytics, utilising machine learning and data analytics techniques, can enhance credit fraud detection and prevention in e-payments. The Joanna Briggs Institute protocols for scoping reviews were used to identify literature published between 2019 and 2025 from multiple academic databases, resulting in the selection of 30 relevant studies. Data mapping and analysis were applied to the selected studies, enabling insights into how financial institutions can leverage machine learning and data analytics to detect and prevent fraud more effectively across diverse digital payment environments. The review revealed various fraudulent methods, including complex transaction-like fraud, card-not-present fraud in online purchases, account takeover, identity theft, and high-frequency, small-scale fraud targeting vulnerable time windows, with emerging threats in DeFi platforms that pose unique detection challenges and high vulnerability. These findings demonstrate that fraud patterns are increasingly dynamic, adaptive, and designed to blend in with legitimate customer behaviour, making early detection more challenging. The study's findings also highlight that advanced machine learning models, such as ensemble methods, deep learning, neural networks, anomaly detection algorithms, and data analytics methods, can significantly improve real-time fraud detection and outperform traditional rule-based approaches that rely on static thresholds, manual review, or historical assumptions. Despite these benefits, the review highlights persistent issues that limit practical implementation. These include data imbalance, high rates of false positives and false negatives, challenges with model transparency, privacy concerns, and integration challenges with legacy systems. Addressing these technical and operational challenges is therefore essential to enhancing the effectiveness of predictive analytics in safeguarding digital payment ecosystems and supporting a more trusted and resilient digital financial environment, while also informing regulatory compliance, operational risk management, and future research directions on fraud detection in e-payment systems.

Keywords: Credit fraud, Prevention, Detection, Predictive analytics, Machine learning, Data analytics

1. Introduction

E-commerce has evolved and grown greatly since its introduction to the customer and business worlds as a unique approach, providing businesses and consumers worldwide with significant advantages, such as the rise in electronic payment systems [1]. An electronic payment (e-payment) is an e-commerce transaction in which goods or services are purchased over the Internet. In an e-payment system, a monetary value is transmitted electronically between two parties as compensation or consideration for the receipt of goods or services [2]. Easy access to the Internet has promoted online shopping and banking, which require efficient payment methods; hence, the rise of electronic payment systems [3]. E-payment methods play an important role in today's competitive financial society. According to a study [4], EPSs have made payments for goods and services easy and convenient. Four main types of electronic payment systems in use today are credit and debit cards, mobile payment apps, online payment gateways, and digital wallets. Digital credit card payments have become the most prevalent payment option in recent years. This is due to the technological improvements and the introduction of new e-funding options and alternatives, such as e-commerce and phone banking [5]. This is also supported in [6], which states that credit cards are the most used form of payment for online purchases and transactions. This includes Visa and MasterCard. Study [7] singles out user-friendly features as the main benefit of credit cards, as they enable quick and convenient online transactions from any location. Study [8] states that credit card fraud has increased with the introduction of new technology. Banks worldwide prioritise the security and confidence of card payments for their customers. According to studies [9] and [4], credit card fraud is defined as the unauthorised use of credit cards to obtain money or property by fraudulent means. Even though credit cards offer consumers few advantages, they are also linked to issues such as fraud and security [4]. The growth of online purchases indicates that additional work will be needed to guarantee the security of online card payments [10]. Traditional machine learning methods for fraud detection are ineffective because they cannot accurately predict whether a transaction is fraudulent, as fraudsters continually develop new patterns and techniques to evade detection [8]. The rise in e-payment brought significant security and trust challenges [11]. According to a study [12], the internet expands commercial options, and fraudsters are developing increasingly complex and sophisticated methods to commit these crimes. Traditional fraud detection

techniques, reliant on rule-based systems or manual reviews, are now inefficient against the complexity of modern e-payment fraud [12]. This implies that relying on traditional fraud-detection methods is no longer viable to protect e-payments. Therefore, proactive methods are necessary, such as predictive analytics enabled by machine learning, which analyses large datasets to detect complex fraud patterns. Machine Learning has emerged as a powerful tool for fraud detection [11]. A proactive strategy is enabled by Machine learning, which predicts and prevents fraudulent activity before it causes serious damage. Study [13] states that in this era of big data, financial institutions are increasingly relying on advanced analytics and machine learning to tackle challenges in the credit card industry. This research study aims to explore the use of predictive analytics and machine learning in addressing e-payment credit card fraud, thereby enhancing detection and prevention and fostering a safer digital payment ecosystem. The article sought to answer the following research questions:

- What are the most common types of fraudulent activities in e-payment systems?
- What strategies do financial institutions use to detect fraudulent activities in e-payment systems?
- How can Machine learning be used to improve the accuracy of fraud detection in online payments?

2. Research Methodology

This article followed the Joanna Briggs Institute (JBI) methodology to guide authors through scoping reviews and followed the PRISMA-ScR reporting criteria [14]. Its goal is to investigate fraud detection and prevention technologies in the e-payment context while addressing associated issues. According to a study [14], the Population, Concept, and Context (PCC) framework is used to create an understandable and appropriate title and inclusion standards for a scoping review. The population consists of electronic payment systems, particularly credit and debit cards, mobile payment apps, digital wallets, and online payment gateways. The concept focused on predictive analytics, data analytics, or machine learning for both fraud detection and fraud prevention. The context focused on global e-payment systems. The PCC framework is presented in Table 1 below.

Table 1: PCC Framework

	Population	**Concept**	**Context**
Principal	Electronic payment systems	Predictive analytics, data analytics, or machine learning for fraud detection	Global
Synonym	Online payment platforms	Predictive analytics, data analytics, or machine learning for fraud detection	International

The search string was formulated based on Table 1:

("credit fraud" OR "payment fraud" OR "financial fraud") AND ("e-payment" OR "digital payment" OR "online payment") AND ("predictive analytics" OR "data analytics" OR "machine learning" AND ("fraud detection" OR "fraud mitigation" OR "fraud prevention")

2.1 Eligibility Criteria

This eligibility criterion focuses on ensuring the inclusion of relevant studies on the use of data analytics and machine learning for credit fraud detection in electronic payment systems. The review focused on peer-reviewed literature from 2019 to 2025 and excluded non-English studies, those without full text, or those unrelated to credit fraud. It aims to map current methodological trends to inform future research in this field.

2.2 Information Sources

The scoping review used a comprehensive literature search across several reputable academic databases, including ScienceDirect, EBSCOhost, ACM Digital Library, Scopus, and Google Scholar, to collect academic literature on credit fraud detection, predictive analytics, and machine learning in e-payment systems. Furthermore, grey literature, such as government reports and company white papers, was rigorously searched for current industry insights.

2.3 Selection of Sources of Evidence

The JBI's three-step search technique and the PCC framework, as shown in Table 1, guarantee a methodical approach. Literature searches were conducted between May and June 2025 across databases including ScienceDirect, EBSCOhost, ACM Digital Library, and Scopus, alongside relevant grey literature such as government reports, policy documents, and cybersecurity white papers.

The search strategy involved the following steps:

Step 1: Initial search

An initial limited search was performed using the broad search terms “Credit fraud detection”, “Credit fraud prevention”, and “e-payments”. This stage helped refine the search phrases for further stages.

*Step 2: Focused Search*Search string such as “Credit fraud detection” AND “Credit fraud prevention” AND “e-payment” AND “Predictive analytics” AND “Machine learning” AND “Data analytics was documented for transparency, refined for relevance and coverage.

Step 3: Backward Search

To find additional relevant articles that met the inclusion criteria, the reference lists of all included papers were screened (reverse searching).

2.4 Data Charting Process

A structured charting template guided data extraction and analysis following the JBI scoping review approach. The results were obtained using the search string. This process identified key themes and trends in the application of machine learning and predictive analytics for e-payment credit card fraud detection and prevention. The mapping also incorporated a review of industry practices, regulations, and technological mitigation measures.

2.5 Data Items

The following variables were recorded for every study included in this review:

Author(s), Year of publication, Country of origin, purpose, Study population and sample size, Methods used, Findings.

3. Results

3.1 Selection of Sources of Evidence

The initial search across four databases (Science-Direct, ACM Digital Library, EBSCOhost, Scopus) yielded 345 articles. Following the removal of duplicates and screening of titles, abstracts, and full texts, 18 articles were deemed suitable. To address the scarcity of peer-reviewed literature on the topic, nine articles from grey literature and three from a backward search were included, resulting in a final selection of 30 articles for the review. The selection process is detailed in Figure 1.

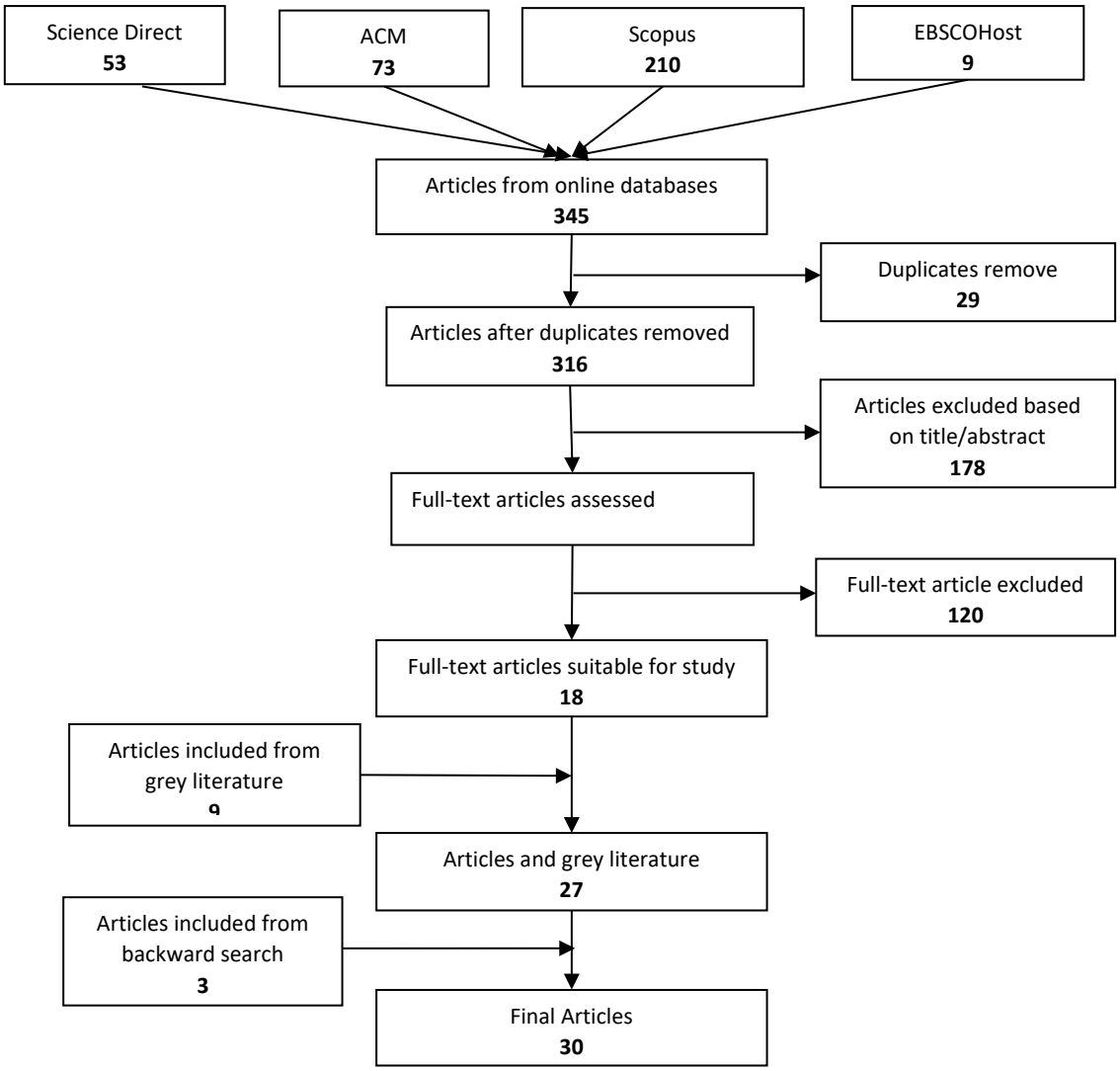


Figure 1: PRISMA-ScR diagram

3.2 Characteristics of Sources of Evidence

Figures 2 and 3 below visually represent the main data elements from the data mapping table, including publication date and country of publication. These visualisations were created using Microsoft Excel.

3.2.1 Distribution of literature sources by dates of publication

The articles were categorised by year of publication to examine the trends in the discussions of the issues addressed in this study. The results are illustrated in Figure 2.

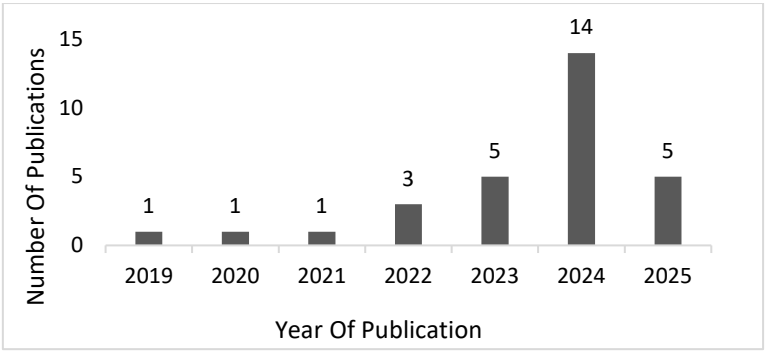


Figure 2: Distribution of literature sources by dates of publication

The results in Figure 2 show relatively low and stable publication output between 2019 and 2021, followed by a gradual increase in 2022 and 2023. The number of publications increased dramatically in 2024, before dropping in 2025. This trend indicates growing research interest over time, reaching its peak in 2024.

3.2.2 Distribution of literature sources by country of publication

This result illustrates the number of reviewed articles on credit fraud detection and prevention using predictive analytics, organised by country of publication.

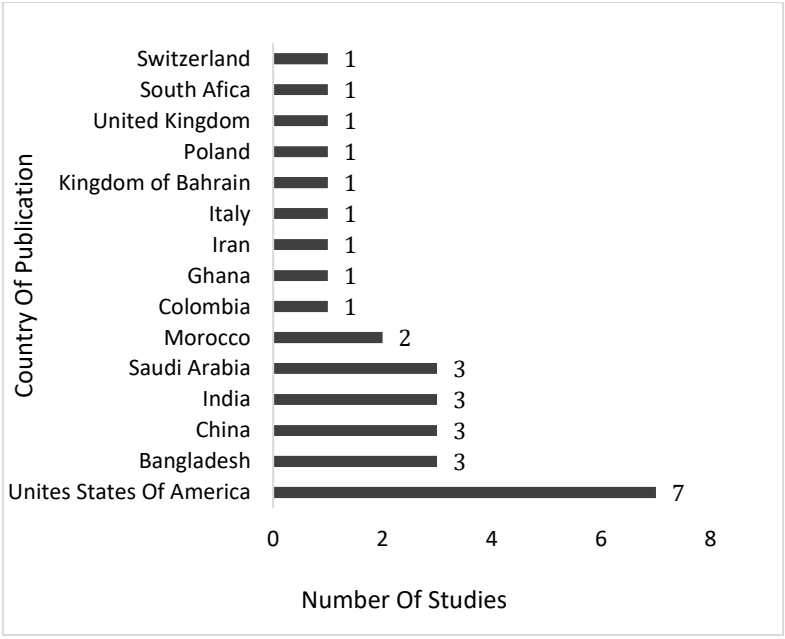


Figure 3: Distribution of literature sources by country of publication

Figure 3 shows that the United States contributed the most studies (7 of 30), followed by Saudi Arabia, India, China, and Bangladesh (three each), and Morocco (two), while other countries contributed one each. This distribution indicates a concentration of research in a few regions, highlighting geographical gaps, while also confirming that credit fraud is a global concern.Table 2: Study classification by research purpose in machine learning fraud detection

Table 2: Study classification by research purpose in machine learning fraud detection

Purpose of the study	Studies (Author & Year)	Count
Develop/enhance a specific machine learning model/framework for credit card fraud detection	[15];[16];[17];[18];[19];[20];[21];[22]	8
Enhance security in online financial transactions	[33];[34];[35];[36];[37];[38]	6
Create a real-time fraud detection system	[23];[24];[25]	3
Address data imbalances in fraud detection	[26];[27];[28]	3
Analyse research trends using bibliometrics	[41];[42];[43]	3
Explore the general application of ML/AI for fraud detection	[29];[30]	2
Enhance operational frameworks and predictive performance	[30];[31]	2
Implement a secure, privacy-preserving collaborative system	[32]	1
Develop a scalable platform for digital finance fraud	[39]	1
Compare the efficacy of specific ML techniques	[40]	1

The results in Table 2 categorise the 30 reviewed studies by their primary research purpose, facilitating the identification of key research clusters and trends. The largest category (8 studies) focuses on developing and refining machine learning models for credit card fraud detection, including real-time systems and methods to address data imbalance. This structured overview clarifies prevailing methodological approaches and highlights prominent areas for future investigation in the field.

4. Discussions

The findings of the study have 3 themes, and each has associated sub-themes

4.1 Summary of Evidence

4.1.1 Theme 1: Types of fraudulent activities

Financial fraud ranges from complex, transaction-like schemes to high-frequency small-scale fraud and rising threats in cryptocurrency and blockchain systems.

4.1.2 Complex, transaction-like fraud behaviours

The study found that sophisticated fraud techniques, particularly those involving identity theft and the misuse of credit card details, are increasingly challenging to detect because they mimic legitimate user behaviour over time, often involving a series of seemingly legitimate actions that culminate in the execution of the fraud. This finding is supported by [29], who emphasise the complexity of such operations. According to a study [15], the shopping category accounted for the most fraudulent transactions (1.19%), followed by groceries (0.73%), miscellaneous (0.36%), transportation (0.28%), and home care (0.16%). Fraudsters employ fraudulent techniques to conduct transactions using others' credit card details. Study [26] states that credit card fraud can occur through several forms, including theft, application fraud, use of fake cards, non-receipt of issued cards (NRI), and online fraud and card-not-present fraud, which only requires access to card data rather than the cardholder's physical presence.

4.1.3 Emerging fraud in decentralised systems (DeFi)

The study found that the decentralised, high-volume characteristics of e-commerce platforms significantly contribute to the development and rapid growth of sophisticated fraud threats. According to a study [32], the e-payment environment creates several vulnerabilities for fraudsters to exploit due to the lack of centralized oversight and the high volume of continuous transactions. The finding emphasises the adaptable and persistent nature of fraudulent activities in current financial systems that function under decentralised frameworks, making identification and prevention more difficult.

4.1.4 High-frequency, small-scale fraud

The study [15] found that fraudulent transactions occur most frequently between 22:00 GMT and 04:00 GMT, a period when most victims are asleep and less likely to check their accounts. This finding highlights a high-frequency, opportunistic strategy employed by fraudsters, who exploit vulnerable time windows to increase the likelihood of successful transactions while reducing the chances of immediate detection.

4.1.5 Theme 2: Detection strategies by financial institutions

Machine learning enhances fraud detection by leveraging advanced models to identify complex patterns and enabling real-time monitoring and anomaly detection for quick threat responses.

4.1.6 Machine learning methods

The study found that traditional fraud detection methods struggle to handle the massive volumes of data generated by modern digital payment systems, necessitating the use of advanced technologies such as machine learning to analyse large datasets and extract meaningful insights [30]. Most studies employ machine learning, with a strong focus on ensemble learning approaches due to their higher performance in fraud detection tasks. Study [17] developed a stacking ensemble model incorporating support vector machine (SVM), K-nearest neighbors (KNN), and extreme learning machine (ELM) algorithms, which consistently outperformed other models across all evaluation metrics, demonstrating robustness in handling imbalanced datasets. Study [39] further states that GBM is highly effective at fraud detection because it can learn from complex transaction data and improve accuracy over time. According to a study [30], ensemble methods like XGBoost and Random Forest are more effective than other machine learning models at balancing false positives and negatives. However, these techniques also encounter various challenges. However, studies also highlighted several challenges that the above-mentioned machine learning techniques tend to face. Although the stacking ensemble method showed superior fraud detection performance compared to individual machine learning techniques, it has limitations, including the dataset's sole focus on China, potential overfitting to historical patterns, and a lack of integration with unstructured data [39]. According to a study [30], ensemble approaches improve predictive performance but complicate model interpretation and cause high computational costs, limiting

scalability and speed. Additionally, training these models on imbalanced datasets without sufficient balancing can result in overfitting. However, studies highlighted several challenges likely to be encountered when machine learning is used: adversarial attack, a malicious entity actively attempting to modify the behavior of machine learning models [45]. This occurs when fraudsters study how data-driven fraud detection systems operate and then design fraudulent transactions that can evade detection [45]. A study [46] confirms that ML models are vulnerable to adversarial machine learning (AML) attacks.

4.1.7 Optimisation techniques

The study found that a hybrid technique combining Competitive Swarm Optimisation (CSO) for feature selection and Deep Convolutional Neural Networks (DCNN) for classification considerably enhances financial fraud detection, outperforming benchmarks in accuracy and precision on large datasets [24]. Furthermore, [39] state that the Sequential Bandwidth Weighting (SBW) algorithm enhances the performance of the gradient boosting machine (GBM) by reducing false positives and improving scalability for fraudulent transaction classification. These findings show that advanced hybrid ML algorithms are reliable and effective for real-time fraud detection in digital financial systems. However, SBW-GBM faces computational complexity, low interpretability, reliance on labeled data, and scalability issues with heterogeneous [39].

4.1.8 Theme 3: Role of machine learning in enhancing fraud detection

Machine learning enhances fraud detection by analysing vast datasets, detecting hidden patterns, and responding to new fraud strategies. Predictive models can detect anomalies in real time while reducing false positives, making fraud prevention more effective.

4.1.9 Advanced machine learning

The study found that Gradient Boosting Machines (GBMs) play an important role in financial risk management by identifying patterns in historical data and forecasting potential risks with high accuracy. According to a study [39], GBMs improve forecast precision iteratively by minimizing errors at each step, and the Sequential Bandwidth Weighting (SBW) technique increases GBM efficiency by hyperparameter tuning. In addition, study [18] highlights deep learning algorithms as effective methods for reducing fraud in financial transactions, leveraging large financial datasets via deep multi-layer artificial neural networks. Study [18] states that deep learning is a subset of machine learning that employs complex ANNs inspired by the structure and function of the human brain and operating on supervised learning principles. The DNN also demonstrated strong performance in spotting complex, non-linear fraudulent patterns [38].

4.1.10 Real-time monitoring detection

The study found that organisations can identify fraudulent activity in real time by processing enormous amounts of transaction data using big data technologies and powerful analytics [27]. Study [35] states that big data supports real-time fraud by processing and analysing transactions as they occur. This strategy enables rapid detection and response to fraudulent activity, hence improving the overall security and integrity of financial systems. Study [34] states that the combination of real-time analytics and machine learning enables rapid response to suspicious behaviour. However, relatively few studies have addressed this topic, highlighting a research gap on the use of big data analytics for real-time fraud detection.

Table 3: Comparison of Real-Time and Batch Processing in Fraud Detection

Feature	Real-Time Processing	Batch Processing	Cyber Defence implications
Timing [47]	Runs continuously with very low delay	Runs after transactions at set times	Real-time stops fraud instantly; batch may miss urgent threats
Detection Speed[48]	Instant detection	delayed detection	Real-time lowers fraud risk
Adaptability to new patterns [48]	Able to identify novel fraud patterns in real-time	Limited, it requires retraining	Real-time adapts to emerging threats

Table 3 compares real-time and batch processing approaches in fraud detection, focusing on key aspects such as timing, detection speed, and adaptability. It highlights that real-time processing enables instantaneous identification and response to fraudulent activity and can quickly adapt to new fraud patterns, whereas batch processing functions with delays and necessitates retraining to recognise emerging risks. The comparison

emphasises the importance of real-time solutions in enhancing cyber defence by mitigating fraud risk and improving responsiveness.

5. Conclusion

In conclusion, although advanced machine learning and deep learning models have greatly improved financial fraud detection through accurate, real-time analysis and increased recognition of complex fraud patterns, numerous limitations persist. Challenges such as data volume and velocity, processing delays, data privacy concerns, and the need for continuous model updates increase system complexity and cost. Concerns with data imbalance, model transparency, scalability, and inconsistencies among datasets undermine the trustworthiness and generalisability of findings. Despite these constraints, the study highlights important practical and theoretical contributions in enhancing fraud detection through advanced analytics. Future research should focus on developing scalable, real-time big data frameworks and integrating proactive techniques, machine learning, and data analytics to better anticipate and prevent evolving fraud strategies.

Ethics Declaration: This study does not need an ethics clearance since the data used are purely from existing studies obtained through synthesis from different sources. It is a scoping review.

AI Declaration: ChatGPT and Grammarly were used to help with sentence construction, data analysis, and written content refinement. Outputs were reviewed and edited to ensure originality and compliance with academic standards.

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Integrating Cybersecurity Risk Management and Business Continuity of Family-Owned Businesses in Anambra State, Nigeria: A Conceptual Model

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Abstract: With the growing dependence on digital technologies and integrated systems, the contemporary business environment is becoming more susceptible to cyber threats, especially family-owned businesses which in most cases have loosely organized cybersecurity systems. Family-owned businesses in the Anambra State of Nigeria contribute to economic growth in the country, however, family-owned businesses in the developing economies are the most vulnerable to cyber-attacks and most times they operate informal structures which are not well equipped to survive external cyber threats. Affirming business continuity theory and protection motivation theory, cybersecurity risk management ensures business detects, evaluates, and reduce possible threats while maintain operations during and after disruptions. Thus, this study is an effort to propose a cyber-resilience integration model to help family-owned businesses incorporate cybersecurity risk management into structures of business continuity and core strategy of organizational survival. With direct synthesis of relevant literature, this study postulates how cybersecurity risk management can be applied to business continuity planning amongst family-owned enterprises. In specific, it delineates risk identification, threat assessment, and incident response planning and recovery strategies contribution to business continuity of family owned enterprises. This paper offers useful information to business owners, policymakers, and researchers because it offered a guide to enhancing the preparedness of cybersecurity and the need to maintain sustainable business operations. This contribution is an important move towards making the family-owned businesses within emerging economies to be more resilient.

Keywords: SME cybersecurity, Business continuity, Conceptual model, Family business resilience, Cybersecurity risk management

1. Introduction

With the rate information and communication technology (ICT) continues to advance, the fundamentals of business operations in the whole world have continued to evolve, where organisations can now enhance efficiency, customer interaction and market penetration in the speed of light. As cited by the International Telecommunication Union (2023), this augmented reliance on digital frameworks have unleashed companies to a large disparate cybersecurity challenges that comprise information breaches, malware attacks, phishing attacks, ransomware and unlawful access to confidential data. Unfortunately, these cyber threats are increasingly becoming sophisticated and common, with the risk to organizational continuity and economic stability being seriously affected. Also, World Economic Forum (2022) informed us that cyber-attacks are among the most prominent risks to business organizations worldwide because of their ability to destabilize business activities and lead to massive financial damages. These trends highlighted the increasing need to consider cybersecurity as a central aspect of business management.

Small and medium enterprises (SMEs) particularly in Anambra State and Nigeria in general, have strong presence of family-owned businesses as their entrepreneurial activities are well embedded in their socio-economic life and cultural belief. These businesses play a significant role in job creation and economic growth however, majority of these SMEs usually have informal or semi-formal operational structures and technological deficit which makes them very susceptible to computer predators. According to Akinola and Akinyele (2023); Ogunleye and Adeoye (2022), they opined that most SMEs in Nigeria do not have written cybersecurity practice guide and risk management systems; hence they remain more vulnerable to cyber threats and cybercrimes. These attacks can be traced to lack of awareness and sufficient investment in cybersecurity infrastructure by small businesses is a major setback to their capabilities to protect digital assets and ensure a stable operation (National Information Technology Development Agency, 2021).

Due to the growing uncertainties, business continuity management has been introduced as a strategic tool of ensuring that organizations are capable of preserving important operations during the incident and beyond the event of disrupted occurrences. Conventionally, business continuity models tend to cover physical risks to the

business like natural calamities and operations malfunction, but the computerization of the business process has led to the need to revise the approach to include cybersecurity risks. As ISO 22301 (2019) postulated, to have an effective business continuity planning, it is pertinent to adopt the risk management approach that has the cyber threats as its component. Research by Adams and Yusuf (2021); Eze and Chukwu (2023) were of the view that the implementation of cybersecurity risk management into business continuity models strengthens organization resiliency, increases their incident management capabilities and minimizes the period of downtime during cyber-related outages. Such integration is especially necessary in the current digital economy whereby cyber incidents are likely to paralyze business operations in a few days.

However, the efficacy of these cybersecurity practices may largely depend on organizational factors, specifically leadership ICT awareness. Leadership ICT awareness refers to the degree to which business proprietors and top executives comprehend, increase in value, and support the practice of information and communication technologies and cybersecurity strategies within the organization. In most family-owned businesses, decision-making is consolidated around the business owner or executives representing the family whose awareness and perception of ICT risks significantly affect organizational investment in cybersecurity. Leaders with high ICT awareness are more likely to prioritize cybersecurity compliance, invest in digital protection systems, cybersecurity training, and enforce innovation-driven resilience strategies. Although previous studies have examined cybersecurity adoption and business continuity separately (Nwafor & Ijeoma, 2022), limited empirical research has explored how leadership ICT awareness mediates the relationship between cybersecurity management practices and business continuity outcomes among family-owned businesses in Anambra State, Nigeria. This study therefore has developed a conceptual model explaining this relationship.

2. Conceptual Background

2.1 Exposition of Cybersecurity Risk Management Practices

Cybersecurity management practice is defined as a strategic-level capability of an organization to protect their information technology systems, digital processes and information resources within an evolving cyber-threat environment (Rajan *et al.,* 2021). Effective cybersecurity management practice ensures that an organization protects the integrity, confidentiality and availability of its information through legal, administrative, and managerial control (Ye, 2026). It involves developing policies and practices that can ensure the mitigation of risks related to information systems and digital resources (Adam & Yusuf, 2021).

Research on organizational cybersecurity management, described efficient cybersecurity practice to involve employee awareness training, cyber-threat risk assessment process, incident response planning, cyber access control mechanism, continuous monitor of digital systems, and information governance (Rajan *et al.,* 2021). Also, scholars have argued that cybersecurity has moved from just a technical practice to a more strategic responsibility of organization which needs the required managerial support, leadership commitment and organizational support (Nwafor & Ijeoma, 2022; Akinola & Akinyele, 2023; Junior *et al.,* 2023; Ye, 2026). These practices allow organization to be prepared in order to mitigate weakness expose to operational disruption and reputational damage that manifest through cyber-threats and attacks.

2.2 Description of Business Continuity Outcomes Management

Business continuity sometimes referred to as business continuance can be defined as the capacity of an organization to put in place processes and procedures to make sure that critical function can continue during and after disaster at acceptable predefined levels following the disruptive incident (Olubiyi *et al*., 2022). Business continuity management comprises organizational planning, preparedness, crisis response apparatus, disaster-recovery systems, and building resilience tactics designed at sustaining organizational functionality under adverse conditions (Ali *et al*., 2023; Russo *et al*., 2024).

Business continuity outcome management can also be described to encompass adaptive resilience, organizational flexibility, proactive learning, and knowledge preservation (Ali *et al.,* 2023) because it serves as antidote for quick recovery from disruption and long term performance sustainability. In the context of family-owned business, continuity management goes further than operational survival to include generational sustainability, succession continuity, and preservation of family legacy (Olubiyi *et al*., 2022).

2.3 Exposition of Leadership ICT Awareness

Leadership ICT awareness is defined as the degree to which administrative leaders appreciate, comprehend, and strategically apply information and communication technologies (ICTs) for organizational value,

innovativeness, security, and sustainability (Vrhovec & Markeli, 2024). Leadership ICT awareness is progressively accepted as a strategic competence that impacts organizational readiness for cyber-risk management and digital transformation and leaders who possessed this awareness are more probable to sustain investments in innovation systems, cybersecurity infrastructure, employee training, and business continuity planning (Russo et al*,* 2024).

Literature opined that ICT-aware leaders are catalyst that can enhance organizational adaptability and crisis readiness (Russo *et al*., 2024) and they have better capacity to identify digital vulnerabilities, thereby integrate cybersecurity into strategic plan that will promote digital resilience throughout organizational structure (Rajan *et al*., 2021). Within the context of family-owned businesses, leadership ICT awareness is principally imperative because decisions are often determined by family members who might possess different degrees of technological competency (Nwuke & Adeola, 2023) and the nonappearance of ICT awareness by family business leaders can hinder cybersecurity readiness, innovation adoption, and digital transformation (Nwuke & Adeola, 2023; Oriazowanlan & Ekenam, 2024). Conversely, leadership that is technologically informed facilitates healthier risk management process, knowledge transmission, and continuity planning.

2.4 Description of Family-owned Business

Family-owned businesses can be described as business enterprise owned, managed, and organized by the same family members, often with the intent to transfer ownership and management from one generation to another generation. Family-owned businesses make-up a considerable percentage of businesses globally and contribute significantly to wealth creation, economic development, and employment generation (Olubiyi *et al*., 2022). In Nigeria, family-owned businesses dominate the SME sector and play important roles in economic sustainability (Olubiyi *et al*., 2019).

Studies on leadership transition in Nigerian family-owned SMEs reveal that ineffective succession processes, poor mentoring culture, and lack of managerial competence often threaten long-term survival and effective succession planning therefore enhances continuity, stability, and organizational sustainability (Nwuke & Adeola, 2022). Additionally, knowledge management has been identified as a major factor supporting continuity in family businesses (Olubiyi *et al*., 2019). Knowledge sharing, mentoring, and transfer of managerial expertise strengthen organizational resilience and improve survival across generations (Oriazowanlan *et al*., 2024). In recent years, digital transformation has emerged as another important factor influencing family business sustainability and family-owned firms that integrate ICT systems, cybersecurity management practices, and innovation strategies tend to demonstrate greater resilience and competitiveness than those relying solely on traditional operational models (Ali *et al*., 2023).

3. Conceptual Model to Explicate Cyber Resilience Integration Model (CRIM), Cybersecurity Risk Management Integration, Business Continuity Outcomes, and Leadership ICT Awareness

3.1 Cyber Resilience Integration Model (CRIM)

Cyber Resilience Integration Model (CRIM) framework is an outline that was developed to incorporate cybersecurity risk management as a part of business continuity procedures in family-owned businesses. It was conceptualized on the basis of the Nation Institute of Standards and Technology Framework of Cybersecurity and the ISO 22301 International Organization Standards. The CRIM in Fig. 1 was adapted to fit the reality of small medium enterprises and family-owned businesses. The CRIM is comprised of three main elements namely cybersecurity risk identification, business continuity planning and the ability of an organization to respond to it. These aspects combined together guarantee that cyber threats are perceived as essential business risks and are addressed in a systematic way to guarantee business continuity. CRIM also integrates a continuous feedback mechanism to monitor, evaluate and improve cyber resilience processes so that businesses can keep pace with changing cyber threats. It can be progressed into varying degrees Basic, Intermediate and Advanced depending on the technological capability and resources of the organization. Technical, human and managerial conditions such as awareness of all the employees and commitment of the leadership all form the components of CRIM to be used as the holistic approach to resilience which is why it is specifically used to provide the sustainability and overall performance of the family-owned business in the dynamic environments like the Anambra State, Nigeria.

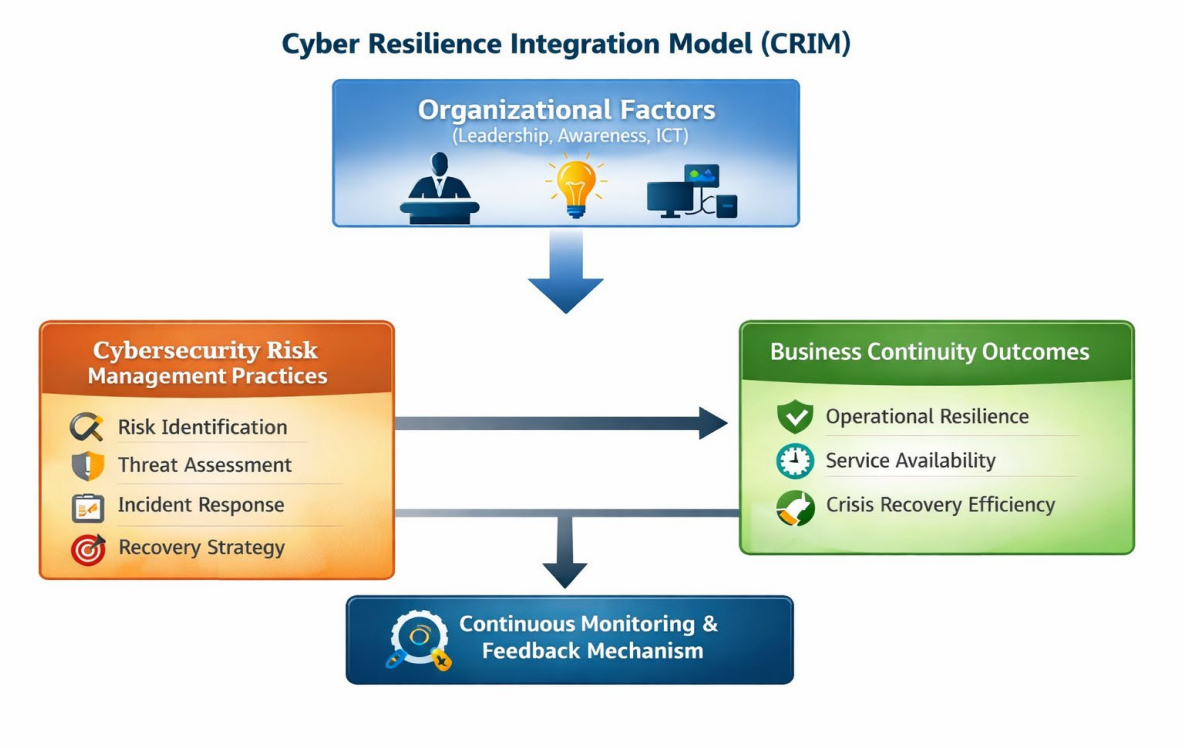


Figure 1: CRIM conceptual model integrating cybersecurity risk management practices, leadership ICT awareness, and business continuity outcomes with a continuous monitoring and feedback mechanism

The cyber resilience integration model (CRIM) in Fig.1 revealed how the practices of cybersecurity risk management play the most dominant role in business continuity outcomes, and organizational factor – leadership ICT awareness is the mediator variable that either makes or breaks the business continuity outcomes. The integrated monitoring and feedback control mechanism keeps the model agile to new cyber threats. This comprehensive CRIM illustrated how technical cybersecurity efforts with organizational preparedness strengthen the resilience, increase access to services and foster effective recovery in family-owned enterprises.

Table 1: Components of the Cyber Resilience Integration Model (CRIM)

Component	Description	Key Elements	Expected Outcome
Cybersecurity risk management practice	Focuses on detecting and evaluating cyber threats affecting business operations	Threat monitoring, vulnerability assessment, risk analysis	Early detection of cyber risks and reduced exposure
Business continuity planning	Integrates cybersecurity into continuity strategies to ensure uninterrupted operations	Disaster recovery plans, data backup, incident response planning	Sustained operations during disruptions
Organizational leadership ICT awareness and response capability	Emphasizes human and managerial readiness in handling cyber incidents	Staff training, leadership commitment, communication systems	Improved crisis response and faster recovery

The Cyber Resilience Integration Model (CRIM), as seen in Table 1, indicates how the framework of business continuity integrates cybersecurity risk management. The model focuses on a rational connection between the identification of cyber risks, disruption planning and the capacity building of the organization to recover successfully. Every element can help improve its operational resilience and the sustainability of the business.

3.2 Cybersecurity Risk Management Integration

The idea of incorporating the concept of cybersecurity risk management (CRM) into the organizational operations has turned out to be a measure to mitigate the threat and securing the digital resources (Adams and Yusuf, 2021). The purpose of this integration is to identify, evaluate, and rank risks in a systematic manner

and put controls in place to mitigate possible effects on operations. In particular, the NIST Cybersecurity Framework, the ISO/IEC 27001, and COBIT frameworks are widely used to help organizations enhance alignment between cybersecurity and business practices (Kraemer et al., 2020; AlHogail, 2021). Research has revealed that the integration of cybersecurity into enterprise governance facilitates proactive identification and management of threats. As an illustration, predictive analytics, and real-time tracking methods are being used as risk assessment tools to identify vulnerabilities and prevent cases of exploitation (Nguyen et al., 2022; Balantrapu, 2024). Also, patterns of network traffic, anomalies flagging, and predicting potential attack vectors have also been analyzed using machine learning models, which has led to an improvement in situational awareness (Patel and Kumar, 2022). These strategies have decreased the use of reactive strategies, and thus organizations have had more effective tools to use to prevent rectificatory actions.

The most significant benefit of integrating cybersecurity is the comprehensive coordination between cybersecurity policies and the business continuity planning as a whole. Integrating cybersecurity risk assessment into continuity frameworks will help organizations to avoid major disruptions brought about by malware, ransomware, or insider threats that can cripple the core functions (Smith et al., 2021; Chen et al., 2023). In addition, integration facilitates security awareness culture among all organizational levels, exposing collaborations among IT, risk management, and the top leadership of the organization. Regardless of these developments several obstacles still exist, such as the scarcity of resources, the ever-changing facet of cyber threats and the challenges of implementing CRM into the existing business processes (AlHogail, 2021; Kraemer et al., 2020). To remain resilient, small and medium enterprises and family owned organizations have to constantly revise their risk management procedures, invest in training of their staff, and use automation technologies. Future studies venture towards adaptive CRM framework that synthesizes AI-monitored predictive and organizational agility to offer scalable real-time security against the emerging cybersecurity threats. Based on the above, the following proposition is suggested:

P1a: Cybersecurity risk identification practices is a positive factor which impacts the business continuity outcomes of family-owned businesses

P1b: Cybersecurity threat assessment practices is a positive factor which impacts the business continuity outcomes of family-owned businesses

P1c: Cybersecurity incident response practices is a positive factor which impacts the business continuity outcomes of family-owned businesses

P1d: Cybersecurity recovery strategy practices is a positive factor which impacts the business continuity outcomes of family-owned businesses

3.3 Organizational Factors - Leadership ICT Awareness

Leadership ICT awareness refers to the extent to which organizational leaders understand, appreciate, and support information and communication technology (ICT) systems, digital innovation, cybersecurity issues, and technology-driven organizational processes. Leadership ICT awareness involves knowledge of emerging technologies; understanding of cybersecurity risks; appreciation of digital transformation; support for ICT investment; technology-driven strategic decision-making; promotion of digital culture within organizations.

Leadership awareness significantly influences organizational technology adoption and cybersecurity readiness. Leaders who possess strong ICT awareness are more likely to allocate resources toward cybersecurity infrastructure, employee digital training, business continuity planning, and innovation. In contrast, leaders with low ICT awareness may underestimate cyber risks, delay technological investments, or fail to establish appropriate cybersecurity governance structures. In family-owned businesses, leadership ICT awareness is especially critical because leadership decisions are often centralized within family members who may rely on traditional management approaches. In many cases, generational differences also influence ICT awareness levels. Younger generations in family businesses may demonstrate greater digital orientation than older founders or owners. Studies suggest that leadership ICT awareness contributes positively to organizational resilience, digital adaptability, and business continuity preparedness. Based on the above, the following proposition is suggested:

P2a: The higher the level of leadership ICT awareness of executives, the more likely family-owned businesses will be more proactive business operational resilience

P2b: The higher the level of leadership ICT awareness of executives, the more likely family-owned businesses will be more proactive business service availability

P2c: The higher the level of leadership ICT awareness of executives, the more likely family-owned businesses will be more proactive business crisis recovery efficiency

4. Limitations

The use of the Cyber Resilience Integration Model (CRIM) in the study is prone to various limitations, especially to family owned businesses in Anambra State. One constraint is associated with the informal nature and low technological capacity of most family-owned businesses. They are not in line with large organizations where cybersecurity infrastructures have been thoroughly built, but these businesses usually do not have any standardized procedures, trained staff, or finances to employ complex cybersecurity and business continuity models. This limitation can have an impact concerning the level of implementation of cybersecurity risk management training like risk threat assessment, incident response planning, and recovery measures, and hence impact the performance of the model in general.

Moreover, integrating the cybersecurity risk management into the business continuity frameworks has practical challenges that are complex. The model presupposes a certain degree of equality between organizational aspects, cybersecurity practices and continuity outcomes which might not be the case in reality. Implementation inconsistency may arise due to variations in the size of business, industry type, and maturity of digital. There are external factors also like regulatory environment, technology infrastructure, and the socio-economic conditions that can also affect effectiveness of the integration, but not completely reflected in the model.

Lastly, there is also an upper limit in quantifying the effect of cybersecurity integration on business continuity outcomes, just as it is in the case of empirical models. Some of these interruptions, especially those that involve complex attacks by the cyber community or other systemic awareness, might be unpreventable irrespective of the degree of readiness. That points at fundamental limitations of the model and the necessity to continuously advance it, better data gathering techniques, and create frameworks that are more context-sensitive when it comes to small and family-owned businesses.

5. Conclusion

In this paper, the Cyber Resilience Integration Model (CRIM) was proposed as a systematic approach to manifesting the management of cybersecurity risk in business continuity regimes among family-owned enterprises in Nigeria, Anambra State. Introducing vital elements like risk identification, threat assessment, planning incident response, and recovery strategies along with organizational elements such as leadership ICT awareness and employee awareness, the model offers an overall approach to boosting operational resilience. This method helped to even further explicate the relationships between cybersecurity management practices and the business continuity, providing useful information about the ways in which integrated strategies could enhance service availability and efficiency of crisis recovery.

The conceptualized postulations highlighted the paramount necessity to integrate cybersecurity factors in business continuity plans, especially among the segments of small and family-owned businesses that are more vulnerable to cyber threats. Even though the model has good potential on enhancing organizational resilience, other challenges identified during the review of the study include limited resources, insufficiency of technical skills and a dynamic cyber threat. Future studies are needed to come up with more adaptive and scalable models, include longitudinal data, and the capacity-building efforts are to be improved. On the whole, the current paper is relevant to the existing literature on cybersecurity management and business continuity as it offers a valuable conceptual model to enhance the stability and competitiveness of family-owned businesses operating in new economies.

Ethics and AI Declaration: This research did not include sensitive data/information that needs approval from any institutional review board (IRB). The authors affirm that AI tool, which include ChatGPT from OpenAI, were only used specifically to edit language and enhance the manuscript clarity of expression. The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Enhancing Cybersecurity Resilience in the Real Estate Industry: Mitigating Phishing and BEC Attacks

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Abstract: As real estate transactions continue to shift toward fully digital workflows, the sector has become an attractive target for phishing and BEC attacks that exploit trust, time pressure, and fragmented communication channels. This paper contributes to cybersecurity research by moving beyond high level discussions of email fraud and focusing directly on the real estate industry as a primary domain of analysis rather than a peripheral use case. The study synthesizes existing academic and industry literature with a structured examination of multiple real-world incidents drawn from residential, commercial, and cross border property transactions. By analysing these cases collectively, the paper identifies recurring patterns in attacker techniques, Organizational weaknesses, and decision-making failures that enable financial loss. Attention is paid to how human behavior, process design, and informal verification practices interact with technical shortcomings to create exploitable conditions. A clearly defined methodology outlines the case selection criteria, temporal scope, and analytic approach, allowing the study to be replicated or extended by future researchers. This methodological transparency strengthens the academic value of the work while grounding the findings in observable evidence rather than assumptions. Based on the cross-case analysis, the paper proposes a practical, sector specific framework that aligns cybersecurity controls with the operational realities of property transactions, including third party coordination, legal timelines, and high value fund transfers. The findings offer practical relevance for cybersecurity professionals, real estate practitioners, and policymakers by translating incident analysis into concrete risk reduction strategies. At the same time, the paper advances scholarly understanding by presenting an industry focused model for addressing cyber enabled financial crime in trust-based transaction environments.

Keywords: BEC, Business email compromise, Phishing, Real estate cybersecurity, Social engineering, Wire fraud

1. Introduction

The real-estate sector has undergone a rapid digital transformation in recent years. Online escrow services, cloud-based e-signatures, and remote closing platforms are replacing paper-based closings and wet-ink signatures (PricewaterhouseCoopers, 2021). As Awofadeju et al. (2024) observe, this rapid digitalization of real estate has led to an industry that is increasingly threatened by cybersecurity challenges, more extensive than conventional ones. Business Email Compromise (BEC) attacks, first identified as an "emerging threat" by the FBI in 2013, have become a global problem due to their increasing sophistication (Bakarich and Baranek, 2020).

BEC continues to grow in threat, with complaints to the Internet Crime Complaint Center (IC3) totalling 19,954 in 2021, with losses up to $2.4 billion (ic3, 2021). The impact of BEC fraud is felt worldwide, with criminals having stolen over $26 billion through BEC scams since 2016 (Saud Al-Musib *et al.*, 2023). The real estate industry houses a trove of invaluable data coveted by cyber criminals, including confidential financial information and personal data. The most significant risk in this sector being the potential for wire fraud following email account compromise. Despite escalating losses, empirical cross-case analysis of BEC within real estate remains limited, and sector-specific resilience frameworks are underdeveloped

1.1 Research Problem, Contribution, and Objectives

The real estate sector's reliance on email for high-value transactions creates a critical vulnerability exploited by BEC attackers who leverage the complexity of the conveyancing process (Comora, 2019). U.S. authorities and FinCEN's 2023 research underscore that the numerous parties involved; buyer, seller, agents, and title/escrow officers and the high volume of document and payment instruction exchanges, particularly large wire transfers, make this industry a prime target. Specifically, sophisticated actors deploy cloned escrow agent emails to

disseminate fraudulent wiring instructions, successfully diverting closing funds to illicit overseas accounts or money mules (Federal Bureau of Investigation, 2022).

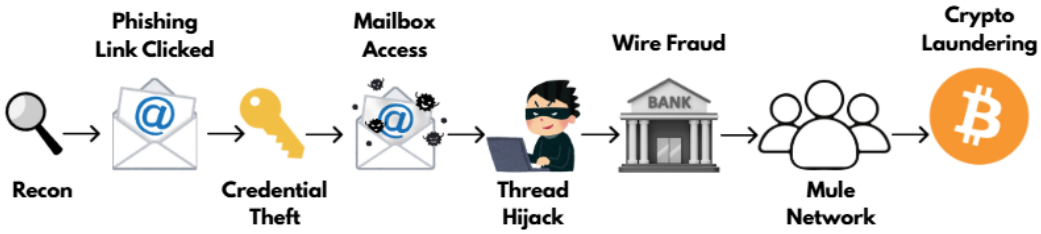


Figure 1: BEC Attack flow in Real Estate

This paper addresses the ensuing cybersecurity imperative: enhancing organizational resilience against phishing and BEC, which cause significant legal, financial, and reputational damage. Our core objectives are to: 1) Investigate BEC in the real estate sector, including criminal motivations; 2) Synthesize BEC attack typologies to inform tailored safeguards for industry stakeholders and policymakers; 3) Analyze the evolving threat landscape, focusing on actor tactics and motivations exploiting transaction vulnerabilities; and 4) Propose a sector-specific cybersecurity resilience framework integrating customized technical controls, governance, and best practices.

2. Research Methodology

2.1 Methodology

This research employs an exploratory multiple case study design to investigate phishing and Business Email Compromise (BEC) incidents within the U.S. real estate sector. This approach is instrumental for exploring phenomena and generating new research avenues (Priya, 2021). Case study research involves the in-depth examination of specific real-world incidents or phenomena in their natural contexts, gathering information over a sustained period using diverse data collection methods (Asenahabi 2019; Priya 2021). An exploratory case study is warranted here because the motivations and triggers of the involved individuals are often unknown (Jain, 2021). Therefore, this qualitative multiple case study is the optimal methodology to examine BEC and investigate the underlying causes of criminal attacks (Helo and Hao 2022). This method excels at answering 'how' and 'why' questions and is particularly suited for cross-case comparisons (Urbinati et al. 2020). Given the limited empirical research on BEC in real estate, this design facilitates a deeper qualitative analysis of real-world incidents, encompassing their technical, organizational, legal, and financial dimensions, thus ensuring a nuanced understanding of attacker techniques and stakeholder responses.

2.2 Data Sources, Case Selection Criteria, Time Horizon, Data Collection, and Limitations

Cybersecurity resilience against phishing and BEC was assessed via evidence triangulation. Aggregate incident data from the FBI Internet Crime Complaint Center (IC3) and Anti-Phishing Working Group (APWG) established macro-level trends. Sector-specific risk profiles and best practices were synthesized from professional bodies such as the American Land Title Association (ALTA) and the National Association of Realtors (NAR). A purposive sampling strategy selected representative BEC incidents (2019-2026), focusing on evolving attacker sophistication, from simple spoofing to targeted campaigns. Selection prioritized critical real estate transaction workflows, specifically closing and wire transfer stages, encompassing residential and commercial deals verified through legal filings or law enforcement. Qualitative thematic analysis was applied to the structured case profiles to identify recurring attacker tactics, techniques, and procedures (TTPs), organizational vulnerabilities, and mitigation patterns. A cross-case comparative approach was used to detect recurring themes across incidents and derive sector-relevant insights that informed the proposed cybersecurity framework. This methodology has inherent limitations: reliance on publicly available data likely results in an understatement of BEC pervasiveness due to underreporting and the qualitative, exploratory nature precludes statistical generalization across the entire sector.

2.3 Search Strategy

A structured literature search was conducted to identify peer-reviewed studies addressing phishing, Business Email Compromise (BEC), financial transaction fraud, and sector-specific mitigation strategies. Scopus was

selected as the primary indexing database due to its broad coverage of cybersecurity, information systems, and interdisciplinary research.

Structured Boolean searches were executed using TITLE-ABS-KEY fields and limited to English-language publications between January 2019 -January 2026. Three focused query groups were developed to capture: (1) phishing and BEC in financial transaction contexts; (2) phishing and wire fraud within real estate transactions; and (3) mitigation and risk management strategies related to phishing-driven financial fraud. Boolean search strings are added below for methodological reproducibility and transparency as shown in table 1.

Table 1: Scopus Searches ((TITLE-ABS-KEY, English, 2019–2026)

Query Focus	Query String	Results	Year
Phishing / BEC in Financial Transactions	TITLE-ABS-KEY ((phishing OR "business email compromise" OR "email fraud" OR "wire fraud") AND ("financial transaction" OR "wire transfer" OR escrow OR "fund transfer")) AND PUBYEAR > 2018 AND (LIMIT-TO (LANGUAGE , "English"))	70	2019 - 2026
Phishing / Wire Fraud in Real Estate	TITLE-ABS-KEY((phishing OR "email fraud" OR "wire fraud") AND ("real estate" OR escrow OR realtor OR "property transaction")) AND PUBYEAR > 2018	9	2019 - 2026
Phishing Mitigation / Risk Management in Financial Context	TITLE-ABS-KEY((phishing OR "business email compromise") AND ("mitigation strategy" OR "risk management") AND ("financial transaction" OR "payment system")) AND PUBYEAR > 2018	11	2019 - 2026
	Total Initial Records	**90**	

After results in Table 1 were obtained, they were then exported and checked to remove duplicates and following duplicate removal, 79 results remained. Title and abstract screening further reduced the dataset to 51 studies directly relevant to phishing, BEC, and financial transaction security. Following full-text review, 46 peer-reviewed articles were included in the final thematic synthesis.

Additional targeted searches were carried out on reputable institutional platforms, such as the FBI Internet Crime Complaint Center (ic3), ENISA, and the National Association of Realtors (NAR), to contextualise industry impact and loss trends between 2019-2026. These reports were not part of the academic thematic coding procedure, but they were utilised for statistical background.

3. Literature Review

This study adopts a structured narrative literature review, using targeted database searches and thematic synthesis to identify key concepts, mitigation strategies, and research gaps related to phishing and BEC in financial transaction environments

3.1 Theoretical Framework

Routine Activity Theory (RAT) provides a systematic framework for understanding crime occurrence by integrating observations and offering structured answers (Connelly, 2014; Evans, Coon and Ume, 2011). Developed initially for US crime rates (Cohen and Felson, 1979), RAT now extends to cybercrime (Krishnakumar and Verma, 2021), positing that crime requires the convergence of three elements: motivated offenders, suitable targets, and the absence of capable guardians (Cohen and Felson, 1979). Financial or non-financial motives, a valuable victim, and inadequate technological, jurisdictional, or legislative guardianship elevate crime likelihood (Leukfeldt and Yar, 2016). Policy professionals utilize RAT for analysis, pattern examination, and generating crime prevention advice due to its analytical clarity (Leukfeldt and Yar, 2016). Motivated offenders, particularly BEC perpetrators, exploit electronic communication vulnerabilities. Applying rational choice theory, these social engineers prioritize the real estate sector for its high-value transactions, assessing risk versus reward

(Cohen and Felson, 1979; Nguyen, 2020). Objectives include diverting real estate funds or stealing Personally Identifiable Information (PII) (Leukfeldt and Yar, 2016). They deploy sophisticated social engineering, Phishing, Smishing, and vishing, often leveraging open-source intelligence to bypass IT security and manipulate recipients (Button et al., 2014; Christopher Hadnagy, 2018; Maimon et al., 2023). Target selection is predicated on potential gains outweighing penalties (Nguyen, 2020; Chen et al., 2023). Suitable targets, determined by the offender's motive, possess value, visibility, and accessibility (Turvey and Freeman, 2014). Prime targets include financial institutions, title companies, individuals in real estate transactions, and document repositories (Hutchings and Hayes, 2009). In phishing and BEC contexts, competent guardianship encompasses security controls, law enforcement (e.g., CERTs), financial institutions, or any entity capable of deterrence, as inadequate supervision increases vulnerability (Hutchings and Hayes, 2009; Nguyen, 2020). Deterring these attacks, which cost the real estate industry billions annually requires a comprehensive cybersecurity guardianship strategy. This necessitates investment in technology, establishing security processes, implementing controls like Multi-Factor Authentication (MFA) and Domain-based Message Authentication, Reporting, and Conformance (DMARC), and crucially, educating and training employees to serve as vigilant, competent guardians (Papathanasiou et al., 2023; Atlam and Oluwatimilehin, 2023).

3.2 Nature and Mechanics of Phishing and BEC

Phishing uses social engineering to criminally obtain sensitive data, often via deceptive electronic communications, such as fraudulent emails, texts, or websites (Bezerra et al. 2024). These attacks exploit user naiveté, frequently using a malicious URL to impersonate legitimate entities (Prasad and Dondeti, 2025). Variants include smishing (SMS), vishing (voice), whaling (targeting executives), and spear-phishing (highly tailored emails) (Birthriya et al. 2025; Prasad Panda, 2025). BEC is a sophisticated form of phishing where threat actors meticulously craft messages, often spoofing sender domains or leveraging compromised accounts, to steal private information or induce fraudulent financial transfers (Papathanasiou et al. 2023). In BEC, attackers impersonate trusted figures, like senior executives or business partners, to manipulate employees into divulging confidential data or wiring funds to fictitious accounts (Saqib et al. 2025). Practically, during real estate transactions, a compromised email account can be monitored by an attacker who then intercedes to request altered payment instructions, redirecting a wire transfer to a fraudulent account (Internet Crime Complaint Center (IC3), 2023).

3.3 Impacts Across Sectors, Existing Frameworks, and Identified Gaps

Phishing and BEC are a critical global financial threat, with FBI's IC3 documenting $2.4 billion in losses in 2021 (Federal Bureau of Investigation, 2021), and phishing as the primary vector for 85% of enterprise breaches (Reuben-Owoh and Haig, 2025). Real estate is acutely exposed, with BEC/EAC accounting for 35% of all recorded dollar losses in 2021 (American Land Title Association, 2022), and real estate-linked losses surging 72% between 2020 and 2022 (FBI Public Service Announcement, 2023; Federal Bureau of Investigation, 2022). While general frameworks like ISO/IEC 27001/27002 are adopted (Bibi et al. 2024; Bernardo et al. 2025; Hossain et al. 2024), their "one-size-fits-all" nature limits their application to specific scenarios (Aljumaiah et al. 2025; Bernardo et al. 2025). This creates a gap, as current standards are not tailored to integrate real estate's unique business practices (e.g., escrow, title transfer) with technical controls. Sector-specific resilience measures are thus essential but remain inadequately articulated in the literature.

4. Case Studies

To examine how phishing and BEC attacks impact real estate transactions, this study analyzes six representative cases drawn primarily from the U.S.. Each case reflects a distinct scenario: law firm system compromise, executive-level residential fraud, cross-border laundering, rapid institutional intervention, minor domain spoofing with limited recovery, and insider-level transaction mirroring. Collectively, these varied contexts enable structured cross-case comparison of technical, procedural, and behavioral vulnerabilities. Together, these cases provide a diverse evidence base for identifying recurring vulnerabilities and mitigation patterns across incidents. Their comparative characteristics are summarized in Table 2.

Case Study 1: Homebuyer loses $600,000 in BEC attack

In August 2024, Richard Bates, a homebuyer in Connecticut, became a victim of wire fraud during his property purchase (Mary K. Jacob, 2024). Hackers breached the email system of his law firm, Hastings, Cohan & Walsh, LLP, and accessed transaction details. Using this information, the attackers sent Bates a fraudulent email, seemingly from his attorney, with fake wire instructions (Mary K. Jacob, 2024).

This case reflects a failure of capable guardianship under RAT. The absence of enforced secondary verification procedures and secure email controls created an exploitable gap in procedural and technical defenses. The lack of mandatory call-back verification represents a process failure rather than purely a technical breakdown.

Case study 2: Silicon Valley executive defrauded of $400,000 in home purchase (USA,2024)

In July 2024, Rana Robillard, became a victim of wire fraud during a high-value residential real estate transaction in California (Bevan Hurley, 2024). This incident exploited a critical vulnerability: the reliance on unencrypted email for sharing sensitive financial instructions. Posing as the mortgage broker, criminals induced the victim to wire a $398,359.58 down payment to a fraudulent JPMorgan Chase account (Son, 2024). Despite rapid FBI intervention to freeze the funds, complex jurisdictional and procedural hurdles significantly delayed restitution (Son, 2024). Although rapid FBI involvement limited damage, the attack succeeded due to the absence of mandatory call-back verification and secure communication channels. It reinforces that organizational process design, rather than victim inexperience, determines susceptibility.

Case Study 3: South Australian Homebuyer Loses $813,000 in BEC Scam (Australia, 2024)

Case 3 exemplifies the sophisticated, cross-jurisdictional nature of BEC fraud targeting real estate conveyancing. In May 2023, a South Australian home purchaser was defrauded of $813,000-the entire property payment via an email impersonation scam (Glover, 2024). The perpetrator employed domain spoofing, utilizing an email address nearly identical to the legitimate conveyancer's, differing by only a single character. While recovery was substantial, the extended restitution timeline highlights the psychological and operational costs of delayed guardianship activation. The capable guardian element under RAT emerged reactively rather than preventively.

Case Study 4: Stamford Homebuyer Email Wire Fraud (USA, 2023)

In March 2023, a Connecticut homebuyer nearly lost $426,000 due to a sophisticated BEC scheme targeting a real estate transaction (Peter Yankowski, 2023). A fraudster interceded in the email exchange between the buyer and their agent, utilizing an email spoofing tactic to redirect the high-value wire transfer to a fraudulent account. While the initial spoofing attack succeeded in redirecting funds, rapid coordination between law enforcement and financial institutions enabled recovery. This suggests that resilience in real estate cybersecurity must incorporate both preventative and responsive guardianship mechanisms. Detection speed significantly influences financial outcome severity.

Case Study 5: Haines City Couple Wire Fraud (USA, 2025)

In Florida, Matthew Brock and his wife experienced a BEC attack while making a down payment on their new home. Cybercriminals intercepted their transaction by impersonating the couple’s title company, changing a single letter in the email address to create a fraudulent account. The altered email allowed the attackers to gain access to the wiring instructions, which they modified by substituting the legitimate bank, routing, and account numbers with their own (Louis Bolden 2025).

This incident shows how minimal technical deception in the form of alteration of a single email character can bypass informal verification habits. The failure occurred primarily at the procedural layer, where no enforced independent confirmation protocol existed prior to fund release.

Case Study 6: Millennial Buyer Wire Fraud (USA, 2024)

In Tennessee, real estate investor, Regina Smith, fell victim to a sophisticated BEC scheme during the acquisition of her fourth property. Preparing a $60,000 down payment for a $280,000 property, Smith received fraudulent wire transfer instructions a day before closing which appeared to originate from the title company. Attackers had achieved system compromise, enabling them to perfectly mirror prior correspondence, including specific transaction variables like the closing date, costs, and personnel names (Pandy, 2024). The success of this attack demonstrates the interaction between technical infiltration and behavioral manipulation as social engineering is combined with contextual transaction knowledge.

Table 2: Summary of Real Estate BEC Case studies

Case	Scenario Type	Attack Vector	Estimated Loss	Key Parties Involved	Outcome
Case 1	Law firm system compromise	Email account compromise / wire instruction manipulation	$726,000	Homebuyer, law firm, bank	$129,000 recovered
Case 2	Executive-level residential fraud	Spoofed email impersonating transaction party	$398,359.58	Buyer, title company	Partial recovery
Case 3	Conveyancer system compromise	Compromised email thread and payment redirection	$813,000	Buyer, bank, international actors	$272,000 recovered. Investigation ongoing
Case 4	Realtor account compromise	Email interception during escrow transfer	$426,000	Buyer, bank, FBI task force	$425,000 recovered
Case 5	Title Email / Domain spoofing attack	Single-character domain spoof of title company	$38,000	Homebuyer, title company, bank	$5,000 recovered
Case 6	Insider-level transaction mirroring	Fraudulent email with detailed transaction data	$60,000	Buyer, title company	$60,000 recovered but property lost

5. Thematic Synthesis and Cross-case Analysis

Thematic synthesis is a technique for finding, examining, and summarising patterns or themes in data. It makes it easier to compare similarities and differences between the events, actions, and procedures that serve as the case study's analytical units (Cruzes et al. 2015). In this body of work, we will combine thematic synthesis with cross-case analysis which systemically evaluates information from individual case studies and identifies patterns across cases (Mynott and Kager 2024). To address recurring vulnerabilities across the six case studies, a structured thematic synthesis was conducted. Each case was coded according to theme / attack vector and control failure. Cross-case comparison was then used to identify patterns that consistently contributed to successful fund diversion.

5.1 Common Attack Vectors and Organizational Vulnerabilities

Cross-case evaluation reveals that email-based impersonation was present in all six incidents and summarized in table 3. Attackers either altered a single character within a legitimate domain, hijacked active email threads, or leveraged compromised accounts to inject fraudulent wiring instructions. This uniform recurrence confirms that email remains the dominant operational attack surface in real estate transactions. A second consistent pattern was the absence of mandatory secondary verification prior to high-value wire transfers. In all six cases, funds were transmitted without independent confirmation through voice call or authenticated secure platform. This procedural deficiency significantly increased transaction suitability under RAT by weakening capable guardianship at the approval stage. Organizational vulnerabilities were further observed in technical control inconsistencies. MFA or secure email configuration deficiencies were identifiable in four of six cases. However, technical weakness alone did not determine loss magnitude. Instead, outcomes were influenced by the presence or absence of structured verification and institutional response coordination. Additionally, limited inter-organizational coordination, particularly between banks and real estate professionals, exacerbates the difficulty in timely detection of suspicious transfers.

Table 3: Thematic patterns identified across all six Cases

Theme	Cases Observed	Primary Failure Type
Email Spoofing / Thread Hijacking	6 / 6	Technical
Absence of Secondary Verification	6 / 6	Procedural
MFA / Email Security Deficiency	4 / 6	Technical
Delayed Detection and Response	3 / 6	Organizational

5.2 Technical vs. Human Factors - Comparative Synthesis Across all Cases

BEC attacks fundamentally succeed by merging technical compromise with sophisticated social engineering (Table 2). While technical vulnerabilities like inadequate identity verification and compromised accounts are contributory factors, human elements are equally significant. Human error, often attributed to insider threats, accounts for a substantial portion of security risks and successful cyberattacks (Alsharif et al. 2021; Rahman et al. 2021). Attackers exploit human factors negligence, lack of awareness, deadline pressure, and routine communication familiarity to influence victims (Kadena and Gupi 2021). Subtle email spoofing is effective even against experienced parties relying on visual cues. The synthesis confirms that BEC attacks, initiated by technical compromise, are ultimately resolved by human decision-making. From a theoretical perspective, motivated offenders target high-value, time-sensitive transactions whose fragmented communication reduces guardianship visibility, exploiting the sector's reliance on large payments and inconsistent security practices. Suitable targets are defined by workflow complexity and coordination gaps, not just financial magnitude. Financial outcome severity is influenced by response speed, with rapid reporting demonstrating partial or substantial recovery, suggesting resilience operates both preventively and reactively. This convergence of technical compromise, procedural gaps, and behavioral susceptibility creates the conditions for successful exploitation, directly informing the layered resilience framework in Section 6.

6. Proposed Framework for Real Estate Cybersecurity Resilience

The cross-case synthesis and findings in Section 5 identified four recurring vulnerabilities: email impersonation as the dominant attack vector, absence of secondary verification, inconsistent technical safeguards, and exploitation of closing-stage urgency. The proposed framework directly responds to these patterns through a structured four-layer model: People, Processes, Technology, and Governance.

The *People* layer is foundational, mandating recurring education from property managers to executives on threats like phishing and social engineering to mitigate human error, a primary attack vector. It targets behavioral susceptibility, particularly urgency exploitation during closing phases. Structured awareness training must emphasize transaction-stage risk, spoof detection, and emotional manipulation tactics. The cases demonstrate that even experienced buyers and professionals are vulnerable when deadline pressure overrides verification discipline. The *Processes* layer formalizes the operational response, establishing clear, sector-specific protocols for risk assessment, business continuity, and disaster recovery, vital for high-value transactions and sensitive tenant data. It mitigates the universal absence *problem* of secondary verification across cases. A non-negotiable, documented call-back verification protocol for all wiring instructions is essential. Wire details must be confirmed through pre-established, independently sourced contact information rather than email correspondence. This procedural control directly addresses the recurrent guardianship gap identified in Section 5. *Technology*, the third pillar, addresses the consistent use of email spoofing and compromised accounts observed in all six cases. Mandatory phish-resistant MFA, enforced DMARC/SPF email authentication, secure client portals for transaction communication, and encrypted document exchange platforms are required to reduce exposure at the primary attack surface. These controls directly mitigate the technical deficiencies identified in Cases 1, 3, and 6. Finally, the *Governance* layer ensures oversight and accountability. Board-level reporting on transaction fraud attempts, periodic audit of wire verification compliance, and integration of cybersecurity risk into fiduciary responsibility frameworks institutionalize capable guardianship. This layer sets in stone the protective and educative role of intermediaries such as law firms, escrow agents, and brokers.

Collectively, this framework operationalizes RAT within the real estate sector by strengthening guardianship mechanisms at technical, procedural, behavioral, and institutional levels. Rather than treating BEC as isolated fraud events, the model addresses systemic transaction design weaknesses. By aligning defensive controls with empirically identified cross-case vulnerabilities, the framework provides a sector-specific roadmap for reducing the probability and impact of BEC attacks in high-value property transactions.

6.1 Next Steps for Empirical Validation

While the People–Process–Technology–Governance framework addresses empirically identified vulnerabilities, its academic contribution can be further strengthened through formal validation. To move beyond the current conceptual model, we propose a large-scale, international survey to validate the framework's effectiveness across different market segments and quantify its real-world utility. Additionally, future research should incorporate the analysis of non-public incident reports to offer a richer, more granular understanding of emerging threats that may be underrepresented in public filings due to reputational concerns. These steps are necessary to transition the framework from a descriptive model to a statistically validated resilience standard.

7. Conclusion

To identify recurrent technological, procedural, and behavioural weaknesses, this study looked at six incidents of phishing and business email compromise on real estate transactions. It was shown through cross-case analysis and thematic synthesis that weakened *guardianship* in time-sensitive transaction procedures is what drives BEC success. Empirical findings are made into practical controls that are suited to the operational reality of real estate using the proposed four-layer framework. The methodology provides an organised way to improve sector-specific resilience by matching defensive actions with patterns of exploitation that have been detected. To conclude, motivated offenders will continue to target the real estate industry for a fast payday, thus, enhancing oversight and resilience in technological, procedural, and institutional areas is critical to reducing the probability of successful BEC attacks.

Ethics Statement: No additional ethical considerations were needed as no experimental subjects were taken.

AI Ethics Statement: AI tools within Grammarly and Google Docs were used for organizing the paper, including grammar and spelling checks.

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Exploring Personalized Personnel Protection within Cybersecurity

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Abstract: Due to their substantial cross-platform exposure, high-profile persons are disproportionately at danger as cyber threats grow across linked digital ecosystems. Most prior research has focused on discrete platform vulnerabilities; however, the ways in which interconnections across services create compound socio-technical hazards have received less attention. By taking a socio-technical systems approach, this study highlights a major flaw in current methods that treat users as a homogeneous population, despite notable differences in exposure and behaviour. The study identifies recurring vulnerability patterns and illustrates how coordinated adversarial activity leverages digital interdependencies to cause financial, reputational, and physical harm through a cross-sector analysis of five high-demand service categories, ranging from remote healthcare to on-demand gig services. It identifies recurring structural vulnerability configurations across sectors, demonstrating that risk stems from shared choices rather than platform specifics. This paper contributes a cross-platform vulnerability map, a socio-technical risk model for high-visibility individuals, and a unified framework linking adversarial behavior to privacy erosion across interconnected services, offering practical insights for developing targeted cybersecurity strategies. Findings show how attackers exploit digital interdependence to achieve blended online compromise, financial loss, reputational harm, and physical danger. The study concludes by proposing a paradigm shift to personalized, privacy-centric, multi-layered cybersecurity capable of safeguarding both high-profile and everyday users emphasizing the importance of adapting security measures to individual user needs while prioritizing the protection of sensitive information. This study employs a socio-technical systems framework, acknowledging that cybersecurity risk arises from the interplay of human behaviour, platform structures, and data flows, rather than from isolated technical vulnerabilities.

Keywords: Account takeover, Coordinated cyber-attacks, Cross-platform risk, High-profile individuals, Socio-technical vulnerabilities

1. Introduction

High-profile individuals represent a critical and differentiated target set within the contemporary digital service economy, increasingly subjected to complex, multi-stage cyberattacks orchestrated by organized criminal networks seeking financial exploitation, reputational compromise, and direct extortion. The defining vulnerability of this demographic stems not merely from reliance on single platforms, but from the necessity of engaging with a vast, interconnected ecosystem of digital services spanning social media, cloud infrastructure, financial technology, and on-demand services which dramatically expands their aggregate, compound attack surface. For targets with high visibility, a breach in one service often serves as the precursor to financial loss, severe reputational damage, or a physical safety risk across another. This systemic exposure is conceptually explored through the lens of Socio-Technical Systems (STS) theory, which asserts that systemic deficiencies originate from the dynamic misalignment between an organization's human and technical components (Walker et al., 2008). Traditional applications of STS in security often treat the human element as a homogeneous unit, thereby failing to account for the dramatic variations in exposure, risk tolerance, and digital conduct among individuals of high public profile. The present study refines the STS perspective by conceptualizing these individuals as differentiated, high-exposure risk nodes, whose unique digital footprint creates distinct vulnerabilities at the intersection of human behavior and platform interdependency (Malatji et al., 2019). The core objective of this study is to qualitatively synthesize existing literature to identify and structurally map the specific vulnerability pathways that emerge across five high-demand service categories. The paper contributes a cross-platform conceptual risk map, articulates a refined STS risk model emphasizing individualized exposure, and presents a framework linking cross-service adversarial exploitation to privacy erosion. Ultimately, this analysis underscores the urgent need for a paradigm shift toward personalized, privacy-centric cybersecurity

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strategies capable of safeguarding differentiated users within an intrinsically interconnected threat environment.

1.1 Methodology and Study Design

This work is an exploratory, qualitative synthesis of the contemporary cyber threat landscape, focusing on high-exposure targets. It is fundamentally a structural exploration, not a systematic review, designed to map converging threat vectors that emerge from digital interdependencies. The overall procedure was structured around five key elements:

(a) Conceptual Framework: We adopted an adapted Socio-Technical Systems (STS) approach, conceptualizing high-profile individuals as differentiated, high-exposure "risk nodes" within a complex ecosystem. The framework's primary function was to guide the structural exploration by identifying vulnerabilities arising from the interplay between user behaviors, platform data flows, and heightened digital exposure.

(b) Sector Selection Criteria: Five service categories - Gig Services, Digital Content, Fintech, E-Learning, and Remote Healthcare were purposefully selected based on their high demand, the volume of sensitive Personally Identifiable Information (PII) and financial data they process, and their critical role in the daily lives of high-visibility users.

(c) Data Collection and Scope: Data was gathered via an unstructured collection and interpretative review of secondary sources published primarily between 2014 and 2024. Sources included academic papers, industry threat reports, and analyses of documented cyber incidents, utilized to construct a foundational map of the contemporary threat landscape.

(d) Analytical Synthesis: The collected sources were subjected to a qualitative, interpretative synthesis focused on identifying and aggregating recurrent vulnerability patterns described in the literature. This process informed the construction of a cross-platform conceptual risk visualization and the development of a socio-technical risk model. No formal coding or systematic protocol was applied to the unstructured data collection.

(e) Case Studies (Constructed Scenarios): Four case studies were developed as constructed, hypothetical scenarios (referred to as "plausible routes"). These scenarios are designed to illustrate the potential financial, reputational, and physical consequences of converging threat vectors, serving as conceptual models rather than real-world empirical demonstrations.

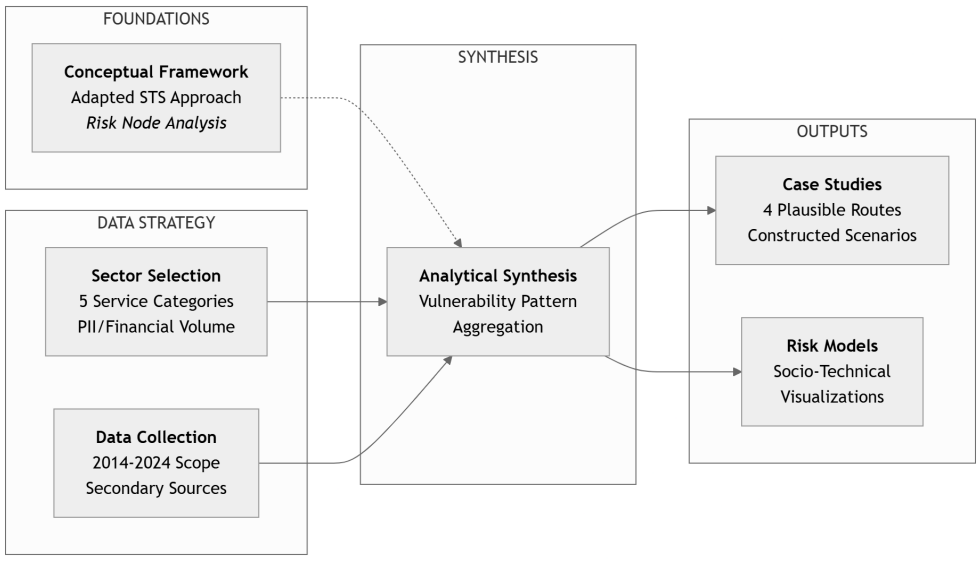


Figure 1: Overview of the study's methodological workflow from conceptual foundations to outputs

2. Analysis of Vulnerabilities Across Service Categories

Table 1: Cross-Sector Cyber Vulnerabilities and Criminal Utility. This matrix maps technical attack vectors to their socio-economic consequences across five domains. It highlights the transition from data-centric losses to cyber-physical threats, illustrating that modern breaches now directly jeopardize financial stability, personal privacy, and human life

Service Category	Primary Attack Vectors	Primary Criminal Utility	Security & Real-World Impact
Digital Content & Subscriptions	Credential Stuffing, Zero Day exploits in legacy servers (FTP)	IP Theft & Account Resale: Authorized publication of media / code, Double extortion ransomware	High financial loss; competitive erosion; reputational damage via leakage
Fintech & Payments	Sim-swapping, Deepfake, Phishing, API exploitation, credential stuffing	Asset Exfiltration: Rapid transfer of funds / crypto; Market manipulation (pump and dump)	Immediate financial devastation for individuals; systemic risk to financial trust
On-Demand Gig Services	Insider threats (Admin access), Database compromise	Physical surveillance: mapping location history, home/work address for stalking	High physical/psychological danger; direct threat to life and personal safety
E-Learning & Skill Acquisition	Poor API security, SQL Injection, Malware via course files	Psychographic profiling: Building identities for "Synthetic fraud" and lateral movement into corporate networks	Long-term identity theft; lateral movement into more sensitive sectors (Gov/Fin)
Remote Healthcare (Telemedicine / OT)	RAAS (Ransomware-as-a-Service), OT malware (Surgical Robots)	Extortion & sabotage: "Shame-based" blackmail of private records; physical interference with surgery	Life-and-death risk; severe psychological trauma; massive HIPAA/legal penalties

2.1 Category 1: On-Demand Gig Services (e.g., Rideshare, Food Delivery, Tasking)

The most widespread attack here is Credential Stuffing, which exploits users' habit of reusing passwords across services by leveraging lists of compromised credentials to perform automated login attempts (Nathan, 2020). Successful stuffing leads to an Account Take Over (ATO) with critical consequences (Wang and Reiter, 2020; El-Taj, Hamedah and Saeed, 2025). ATO grants access to sensitive data, including user behavior, viewing history, and, for B2B software, confidential business plans, representing a direct compromise of corporate or individual privacy (Nathan, 2020). It also enables billing fraud, in which criminals may change subscription tiers, purchase in-app content, or use a legitimate account to test stolen credit cards, resulting in financial loss for the subscriber and reputational damage to the service provider. Furthermore, ATO facilitates intellectual property theft by premium providers, allowing criminals to download source code, proprietary algorithms, unreleased media, or client lists, thereby fuelling sophisticated criminal activities such as corporate espionage and competitive sabotage (Walton, 2023; Meurs et al., 2024).

2.2 Category 2: Criminal Network Utility

The ultimate goal of a cyberattack is the monetization of compromised data or system access, which, for digital content and subscription services, takes several high-impact forms. One method is Ransomware on Intellectual Property (IP), utilizing a "double extortion" tactic where criminals first exfiltrate IP (e.g., source code, unreleased films) and then threaten its publication or sale unless a ransom is paid, leveraging the company's fear of competitive disadvantage and reputational harm (Meurs et al., 2024). A second utility involves blackmail using private content obtained through ATO attacks, where access to deeply personal data in communication channels or cloud storage is weaponized to blackmail high-profile victims, forcing substantial payments to prevent the exposure of embarrassing or confidential information (Al Habsi, Butler and Percy, 2023). Finally, unauthorized publication for financial gain is a straightforward monetization route, including the resale of stolen premium accounts on dark web marketplaces and the theft and unauthorized sale of unreleased IP, directly undercutting the legitimate business model and causing significant lost revenue (Shu et al., 2020; Kramer, Streicher and Niemietz, 2025). The diversity and severity of these criminal utilities underscore the critical need for robust security measures, such as multi-factor authentication (MFA) and continuous monitoring, in the digital content industry.

2.3 Category 3: Fintech (Financial Technology – e.g., Digital Banking, Trading Apps, Payments)

The primary vectors for cyberattacks in the Fintech space blend technical exploits and social engineering, targeting end users or their account credentials. Phishing remains highly effective, evolving into sophisticated spear-phishing that uses deepfake technology to target privileged accounts for login credentials, MFA codes, or cryptocurrency seed phrases (Li et al., 2020; Berrios et al., 2023). Research highlights that psychological manipulation in phishing exploits user trust, a trust that is disproportionately high in mobile-first Fintech environments (Ali, Dida and Sam, 2020). Furthermore, while two-factor authentication (2FA) via SMS is a security boon, the underlying mobile infrastructure is systematically exploited through SIM swapping (or SIM jacking), in which criminals socially engineer a mobile carrier into porting the victim's number (Kim et al., 2022). This provides an effective bypass of SMS-based 2FA and enables rapid account takeover, leveraging the weak link in the telecommunications provider rather than the fintech application itself (Mokhtar et al., 2023). Beyond direct theft, criminals exploit high-frequency trading and consumer investment applications to engage in subtle manipulation, including coordinated "pump-and-dump" schemes. This aligns with broader findings on how organised crime leverages market vulnerabilities to distort financial systems (Mesioye, 2025). and exploiting API security to manipulate trades, unauthorized liquidations, or target opaque instruments like derivatives. The difficulty of detection is compounded by the volume of legitimate algorithmic trades.

2.4 Category 4: E-Learning and Skill Acquisition (e.g., Online Courses, Tutoring)

Since 2020, the E-Learning sector (MOOCs, virtual tutoring, and corporate training) has grown, simultaneously increasing digital security and privacy risks, making these platforms prime targets for criminal networks due to the extensive personal, financial, and behavioral data they hold (Al-Mekhlafi et al., 2020; Waelchli & Walter 2025). Vulnerabilities include user-level compromise, often via credential stuffing exploiting password reuse, platform-level breaches, and pedagogical manipulation with compromised enrollment credentials grant access to academic progress and personal data (Wang and Reiter, 2020; Sahin & Li, 2021). Platform breaches via poor API security or SQL injection expose data, allowing criminals to construct detailed psychographic profiles for successful, personalized social engineering (Oliveira and Fiser, 2024). Internal trust is exploited to distribute malware via seemingly innocuous files (Al-Mekhlafi et al., 2020; Kumar, Sai and Radhika, 2026). The gained data serves multiple high-value objectives: psychographic profiles enable contextualized spear-phishing, and behavioral data is critical for synthetic identity fraud, enabling credible mimicry for schemes like business email compromise (Suthar, 2026). Ultimately, a compromised e-learning account serves as a stepping stone for lateral movement into more critical domains (corporate, government, financial) by exploiting linked primary email addresses to reset passwords (Al-Mekhlafi et al., 2020). The E-Learning sector is a lucrative frontier for criminal networks, transforming educational portals into high-yield targets for multi-stage cyberattacks, underscoring the urgent need for enhanced security and user education (Jawaid, 2023; Waelchli & Walter, 2025).

2.5 Category 5: Remote Healthcare (Telemedicine – e.g., Virtual Visits, Online Therapy, and Robotic Surgery)

Criminal networks highly value remote healthcare vulnerabilities due to data sensitivity and service criticality. Telemedicine data, especially regarding stigmatized conditions, is potent for "shame-based" extortion, targeting high-net-worth individuals for substantial cryptocurrency ransoms (Prasad et al., 2025; Meurs et al., 2024). The RaaS model favors healthcare facilities, where encrypting EHRs and clinical systems compel rapid ransom payment to restore patient care (Anderson et al., 2019). The unique threat posed by robotic surgery enables sophisticated actors to cause physical harm through sabotage or to demand an ultimatum by threatening to interfere with a procedure (e.g., locking the robotic arm) in exchange for an immediate ransom (Amos, 2024; Ludvigsen and Nagaraja, 2022). This transforms utility from mere financial gain to the achievement of significant physical and political objectives.

Table 2: Synthesis of categories showing attack vectors, Assets targeted and Criminal utility plus impact

Service Category	Attack Vectors & Vulnerabilities	Assets Targeted	Criminal Utility & Impact
On-Demand Gig Services	Credential stuffing exploiting password re-use leading to Account Takeover (ATO)	User accounts, payment data, confidential business plans	Billing fraud, card testing, account resale, IP theft; scalable attacks causing financial loss and reputational damage
Criminal Network Utility	Ransomware, data exfiltration, reuse of compromised accounts	Intellectual property, private content, premium accounts	Double extortion (ransom + leak), blackmail, dark web resale; high financial and reputational damage
Fintech	Phishing (incl. deepfake), SIM-swapping, social engineering + telecom weaknesses	Bank accounts, crypto wallets, trading systems	Financial theft, unauthorized trades, market manipulation
E-Learning & Skill Acquisition	Credential stuffing, SQL injection, API flaws, malware via trusted channels; rich behavioural data exposure	Academic data, psychometric profiles, emails	Identity fraud, spear-phishing, lateral movement into other sectors; enables multi-stage attacks
Remote Healthcare (Telemedicine / OT)	Ransomware, system/device exploitation; high sensitivity & critical infrastructure	EHRs, clinical systems, sensitive patient data	Ransomware (RaaS), shame-based extortion, potential physical harm; highest severity including life-threatening consequences

3. The Converging Vectors of Digital Threat: An Analysis of Sophisticated Cyberattack Methodologies Targeting High-Value Individuals

The digital lives of high-value individuals (HVIs) comprise a mosaic of vulnerabilities scattered across multiple platforms. This distributed footprint facilitates brand management but provides sophisticated actors with a broad surface for exploitation. Rather than isolated events, the four vectors analyzed below: cross-platform credential exploitation, advanced social engineering, supply chain attacks, and insider threats, function as interlocking components of modern cyber espionage. These methodologies are underpinned by advancements in data aggregation and artificial intelligence (Prasad et al., 2025).

The following synthesis reveals a dangerous convergence: technical exploits (IT) increasingly impact physical systems (OT) and human safety. While credential stuffing remains the primary "low-effort" entry point, sectors like Gig Services and Healthcare show a "physical pivot", where data breaches serve as precursors to stalking or surgical interference. Ultimately, while some attacks seek data for its own sake, most aim for rapid monetization through ransom, blackmail, or asset theft.

3.1 Cross-Platform Credential Exploitation: The Weakness of Password Reuse

Credential stuffing exploits the systemic habit of password reuse; a breach on an obscure site can unlock a principal's core accounts as botnets automate the testing of stolen login pairs across thousands of unrelated services (Pal et al., 2022; Ali, Dida & Sam, 2020). While Multi-Factor Authentication (MFA) provides a defense, actors increasingly bypass these controls via SIM-swapping or session hijacking, maintaining exploitation as a persistent threat (Kim et al., 2022).

3.2 Advanced Social Engineering: Psychological Manipulation in the AI Era

Modern social engineering has evolved from generic phishing into highly personalized attacks. By aggregating data to build a psychological profile, actors use "whaling" techniques to create urgent, fear-based narratives that bypass judgment (Kumar, M., Sai, D. and Radhika, M., 2026; Gonzaga et al., 2026). Generative AI and deepfake audio, trained on publicly available recordings, allow attackers to impersonate trusted contacts to intercept MFA codes or authorise fund transfers (Malik et al., 2022).

3.3 Supply Chain Attacks: Targeting the Digital Periphery

Supply chain attacks bypass the hardened security of major platforms by targeting the "weakest link": third-party vendors. For HVIs, this includes PR firms, financial advisors, and gig workers who hold legitimate, high-level access to core accounts. Because smaller firms often lack robust cybersecurity budgets, they offer a simpler entry point. This "inherited risk" means that an HVI's security is only as strong as that of their least secure partner (Ilori, Nwosu and Naiho, 2024). The gig economy exacerbates this, as temporary contractors often use personal, unmonitored devices for professional tasks.

3.4 Insider Threats: The Human Element of Breach

Insider threats from employees or associates are uniquely difficult to mitigate because they bypass perimeter defenses using authorized credentials (Whitelaw, Riley and Elmrabit, 2024). In the context of HVIs, this includes platform moderators or customer service agents who may be bribed by organized crime to execute account takeovers or provide real-time location data (Almukheiran and Li, 2020). Mitigation relies on behavioral analytics to detect anomalous access patterns such as a billing clerk accessing private messages - alongside rigorous vetting and psychological screening.

The preceding synthesis of these four primary attack vectors demonstrates a dangerous convergence of technical and human vulnerabilities, confirming that the risk is systemic rather than platform-specific. To illustrate the severe, compounding nature of these threats, the following section presents a series of constructed, hypothetical case studies that translate these systemic weaknesses into tangible financial, reputational, and physical harms. Figure 2 presents the cross-platform vulnerability map derived from the converging attack vectors outlined in this section, illustrating how sector-specific weaknesses accumulate into systemic socio-technical risk.

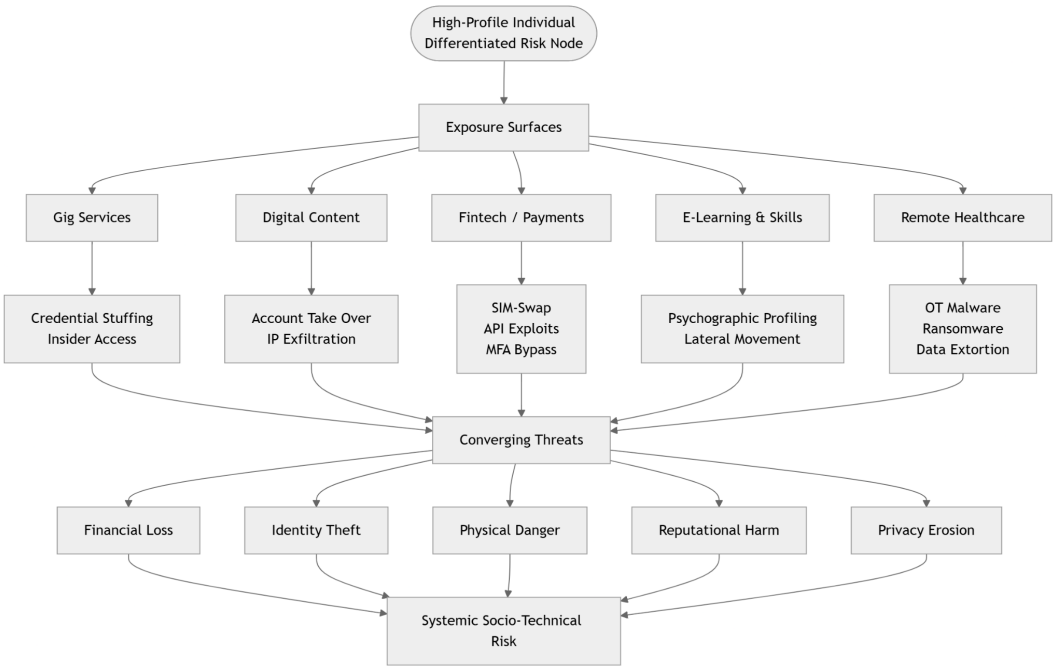


Figure 2: CrossPlatform Vulnerability Map

The cross-platform vulnerability map in Figure 2 shows how distinct weaknesses across gig services, digital content, fintech, elearning, and healthcare converge into shared adversarial pathways. It illustrates that modern cyber risk emerges not from isolated platform failures but from the compounding effects of crossservice interdependencies.

4. Hypothetical Case Studies

All four case studies presented in this section are explicitly constructed, hypothetical scenarios. They are not drawn from specific real-world incidents, nor do they represent anonymised reports of actual events. As disclosed in the methodology (Section 1.1e), these scenarios were developed as "plausible routes" as conceptual models grounded in empirically documented attack patterns and supported by the peer-reviewed

literature cited throughout Sections 2 and 3. Each scenario illustrates the potential financial, reputational, legal, and physical consequences of converging threat vectors, serving as illustrative demonstrations rather than reports of verified incidents. The use of constructed scenarios is a recognised methodological approach in qualitative and exploratory cybersecurity research, where real incident data is frequently unavailable due to non-disclosure agreements, ongoing legal proceedings, or victim anonymity requirements. Their validity as analytical tools rests on the fidelity of the underlying threat intelligence rather than the empirical occurrence of any specific event. Accordingly, the scenarios should be interpreted as conceptual demonstrations that translate the structural vulnerabilities identified in the preceding analysis into tangible, plausible harm pathways. Readers seeking empirical incident data are directed to the primary sources cited within each sub-section.

4.1 Example 1: Ransomware Attack Linked to Digital Content Service Compromise

In a hypothetical scenario, a major Digital Content Service (DCS) falls victim to a sophisticated ransomware attack triggered by a zero-day vulnerability in a third-party vendor's legacy FTP server. In this case, attackers successfully exfiltrate petabytes of sensitive data, including unreleased original content, proprietary algorithms, and extensive subscriber PII such as geographic data and payment details. The subsequent deployment of ransomware paralyzes content delivery, leading to catastrophic financial losses from system rebuilding and subscriber churn. Beyond the technical breach, the company faces global class-action lawsuits for GDPR violations, while the exposure of personal viewing histories creates a long-term risk of personalized spear-phishing against its high-profile users. This scenario illustrates how a single weak link in a complex supply chain can evolve from a simple data leak into a crisis of operational paralysis and competitive erosion.

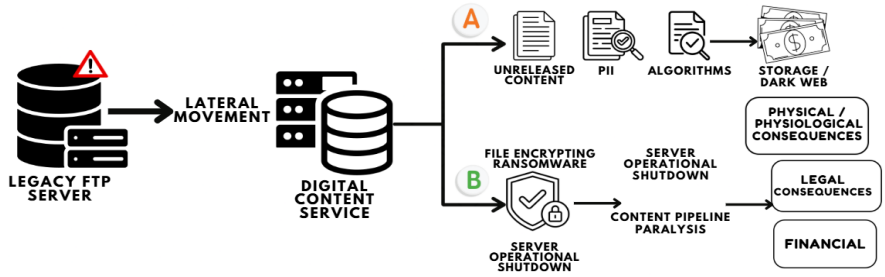


Figure 3: Multi-Vector Impact Model of a Supply Chain Ransomware Attack

4.2 Example 2: Financial Fraud via Fintech Account Takeover and SIM-Swapping

In this hypothetical scenario, attackers socially engineer a carrier representative into porting a victim's phone number, thereby intercepting all SMS-based two-factor authentication (2FA) codes. By pairing these with credentials harvested from a prior third-party breach, the criminals bypass the Fintech app's defenses to execute substantial transfers to untraceable cryptocurrency wallets. This rapid capital flight - depleting the victim's liquid assets in under three hours - demonstrates the "Achilles' heel" of SMS-based 2FA. The resulting financial devastation underscores a systemic vulnerability at the intersection of telecommunications and financial technology, necessitating a shift away from SMS-dependent verification channels.

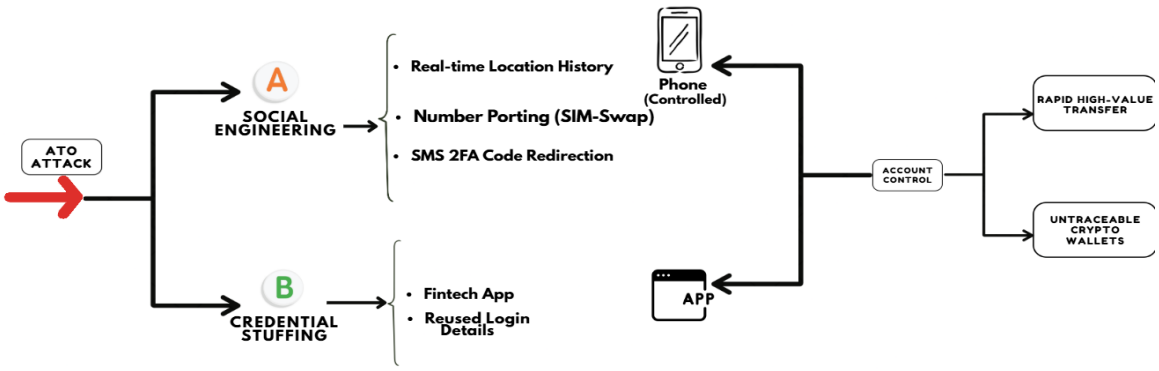


Figure 4: Systemic Vulnerability Matrix in Fintech Account Takeover (ATO)

4.3 Example 3: Stalking/Physical Threat Derived from On-Demand Gig Service Data

In a hypothetical scenario, a high-profile user of a popular on-demand gig service falls victim to a targeted stalking incident facilitated by a significant internal security failure. In this case, a disgruntled former employee leverages retained high-level administrative access to compromise the service's customer and driver database. The perpetrator gains access to highly granular data, including the victim's real-time location history, home and work addresses, and private contact numbers. This intimate data allows the stalker to anticipate the victim's movements, escalating the threat from electronic harassment to direct physical confrontation and creating a sustained environment of fear. This scenario illustrates how a digital breach can transition from abstract data loss directly into the domain of physical safety, necessitating immediate life changes for the victim. For the Gig service provider, the incident results in profound reputational damage and legal challenges arising from a failure of their duty of care, underscoring that location data is often the most dangerous form of compromised information.

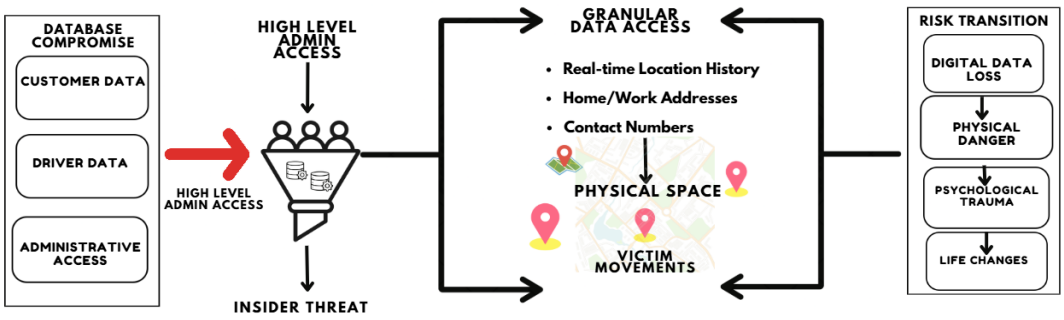


Figure 5: Cyber-Physical Risk Transition Map: Insider Threat and Stalking

4.4 Example 4: Disruption of Robot-Assisted Surgery and Data Leak

In a hypothetical scenario, a politically motivated cyber-attack targets a hospital network during a robot-assisted surgery. In this case, malware is injected into the surgical robot's control system, causing momentary latency and precision failures. Simultaneously, attackers breach the EHR system, stealing the celebrity patient's medical history and genetic data. The incident places the patient in immediate physical danger, highlighting the life-and-death stakes in healthcare OT security. Furthermore, the hospital faces severe legal consequences, including massive HIPAA fines and criminal investigations, following the public data leak. This case illustrates that in connected medical environments, a digital breach is also a physical safety incident, necessitating a paradigm shift toward active risk management of patient safety.

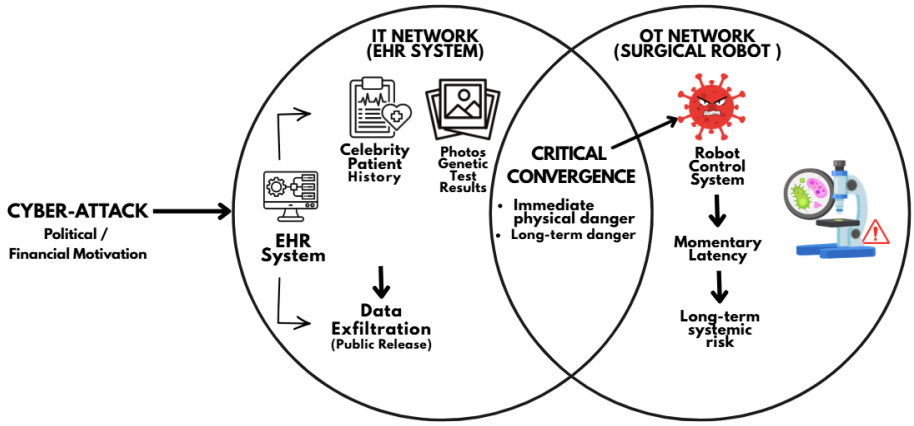


Figure 6: Convergence of IT and OT in Healthcare Cyber-Attacks.

These four examples (Figs. 1-4) collectively illustrate the potential breadth of cyber risk, ranging from financial and corporate liabilities to plausible physical and psychological harm to individuals, further establishing cybersecurity as a core societal and public safety concern.

Together, these four scenarios illustrate how the sector-specific vulnerabilities identified in Section 2 and the converging attack vectors synthesised in Section 3 manifest as real-world financial, reputational, and physical harms. This progression from sector analysis to methodological convergence to applied scenarios sets the foundation for the following discussion of systemic implications and mitigation strategies.

5. Discussion, Mitigation Strategies, and Future Research

This study's qualitative synthesis of the contemporary cyber threat landscape confirms that the risks facing high-profile individuals are fundamentally systemic, stemming from the convergence of cross-platform vulnerabilities and the complex interplay of digital service dependencies. The constructed case studies illustrate that a digital security failure in one domain (e.g., Gig Services or Fintech) acts as a vector that can translate abstract data loss into severe, tangible consequences, including financial ruin, reputational damage, and physical safety threats. This necessitates a strategic shift from generic, perimeter-focused security to a personalized, multi-layered defense posture that addresses the socio-technical vulnerabilities unique to high-exposure risk nodes.

Mitigation strategies must be simultaneously applied across three interdependent domains:

Individual Defense: For high-exposure individuals, fundamental proactive security (von Solms & van Niekerk, 2013) must transition from simple password strength (Berrios et al., 2023; Suthar, 2026) to mandatory, hardware-based two-factor authentication (2FA) (FIDO2/WebAuthn). This measure is paramount for defeating advanced social engineering and mitigating SIM-swapping attacks that bypass weaker SMS-based 2FA (Mokhtar et al., 2023). Furthermore, targeted security training must explicitly focus on the human factors that remain the weakest link, including social engineering and supply chain risk awareness (Indira, 2025; Waelchli and Walter, 2025).

Digital Service Provider (DSP) Measures: DSPs must counter supply chain and insider threats, the principal vectors for high-profile compromise, by implementing stringent organizational controls. Technical measures such as micro-segmentation and strict role-based access controls (RBAC) are essential for limiting the blast radius of any breach and preventing lateral movement into sensitive user data (Kuo et al., 2020). Continuous anomaly monitoring of internal access patterns is also critical for detecting malicious insider activity that exploits legitimate credentials (Jongh et al., 2025; Sharma, 2021).

Regulatory and Legal Frameworks: The transnational nature of organised cybercrime requires a robust legal framework. This includes stricter enforcement of data protection laws like GDPR and HIPAA, coupled with heightened penalties to deter actors in critical sectors (Coupland, 2025). Enhanced international cooperation is required to streamline information sharing, close jurisdictional loopholes, and harmonize standards for evidence collection in transnational cybercrime cases (Cerezo, Lopez and Patel, 2007; Coupland, 2025). In conclusion, this

analysis underscores the critical vulnerabilities inherent in the widespread use of internet-connected services, particularly for high-profile individuals. The findings advocate for a tailored cybersecurity posture that is responsive to individual digital conduct and the cross-platform dependencies that create compound risk.

Future research should operationalize the socio-technical risk model by developing measurable indicators of cross-platform exposure, behavioral vulnerability, and inherited supply-chain risk, and empirically validate the pathways identified in this qualitative synthesis. Studies are also warranted to explore the impact of artificial intelligence and machine learning for both adversarial tools and defense-in-depth solutions. Furthermore, research should examine personalized security interventions for high-visibility users, such as hardware-based authentication and identity compartmentalization, and inform policy frameworks through interdisciplinary research combining cybersecurity, behavioral science, and digital governance.

6. Limitations

This work is subject to several methodological and conceptual limitations that should be acknowledged. First, the data collection process was structured as an unstructured, qualitative synthesis rather than a systematic review; as such, no formal coding protocol or systematic search criteria were applied to the secondary sources. This exploratory approach may lead to the omission of relevant literature outside the selected databases or timeframe. Second, while the Socio-Technical Systems (STS) framework was employed to guide the analysis, it was used conceptually to map vulnerabilities rather than as a tool for empirical operationalization. Consequently, the study's focus on high-profile individuals limits the generalizability of the findings to broader, low-visibility populations. Furthermore, the case studies presented in Section 4 are constructed scenarios intended for conceptual illustration rather than real-world empirical demonstrations and thus represent plausible routes rather than verified incident reports. Finally, the analysis primarily treats service sectors in isolation, with restricted engagement in cross-platform interaction analysis.

7. Conclusion

This study demonstrates that the risks facing high-profile individuals arise from the systemic interaction of human behaviour, platform architectures, and cross-service data flows. By analysing five high-demand service categories and synthesising their shared vulnerabilities into converging adversarial pathways, the paper shows that contemporary cyber threats are inherently cross-platform and socio-technical. The constructed scenarios further illustrate how discrete weaknesses escalate into financial, reputational, and physical harm. These findings highlight the limitations of platform-centric security models and underscore the need for personalised, multi-layered protection strategies tailored to differentiated user profiles. Future research should operationalise the socio-technical risk model introduced here, develop metrics for cross-platform exposure, and evaluate targeted interventions for individuals with elevated visibility. As digital interdependence deepens, cybersecurity must evolve toward proactive, systemic approaches capable of safeguarding both high-profile and everyday users.

Ethics Statement: No experiments were conducted on people or property. An additional ethics statement is not needed.

AI Ethics Statement: This document was organized and spell/grammar checked using AI tools within Google Docs and Grammarly.

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Mapping the Authentication Landscape: A User-Centric View

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Abstract: Authentication is the frontline security control that protects the digitalised society—and paradoxically, it is also the most frequently exploited in breaches. As online services permeate every aspect of life, from banking and healthcare to workplace systems, authentication has become a critical safeguard for citizens and organisations. Yet, the complexity of managing multiple credentials and diverse authentication methods introduces vulnerabilities that attackers routinely exploit. Despite this, research has often examined authentication in isolation—focusing on single methods or user behaviours—without considering the broader ecosystem users navigate daily. This paper reframes authentication as an authentication landscape, a multidimensional environment encompassing all features and experiences users encounter when accessing digital systems. Through a systematic literature review of 43 peer-reviewed articles from leading Information Systems, Cybersecurity, and Human-Computer Interaction journals, we identify ten key features shaping this landscape: (1) services and systems, (2) diversity of methods, (3) guidance and restrictions, (4) devices, (5) security products, (6) use context, (7) culture and relationships, (8) user responsibilities, (9) accessibility, and (10) threat outlook. Our analysis reveals that authentication complexity—driven by proliferating accounts, evolving technologies, and inconsistent policies—creates fertile ground for security lapses. Different aspects of the landscape may lead users to trade security for convenience, adopt risky coping strategies, or struggle with contradictory guidance, amplifying systemic vulnerabilities. The implications are urgent: strengthening authentication cannot rely on piecemeal improvements to individual methods when advances in technology demand a comprehensive readjustment. Designers, policymakers, and security professionals must address the authentication landscape holistically to reduce attack surfaces and enhance resilience. Future research can operationalise the identified features to study users' landscape perception. For practice, this perspective informs the design of authentication systems and awareness programs that align with users' lived realities. By recognising authentication as a complex, interconnected landscape, we advance the discourse toward strategies that safeguard not just individual accounts but the integrity of the digital society itself.

Keywords: Authentication, User, Literature review

1. Introduction

Authenticating with online services and devices is a task most people do daily in a digitalised society. As employees they use multiple systems for work and their personal lives are managed through online systems for banking, shopping, and even identification documents (Cheswick, 2013; Kruzikova *et al.*, 2022). Both the productivity at workplaces as well as people's welfare are now dependent on authentication that permits access to these systems and restricts unwanted tampering.

Passwords are widely provided as an authentication mechanism because they are easy for users to adopt and for system developers to implement (Bonneau *et al.*, 2015; Furnell, 2022). Each user may have dozens of password-authenticated accounts across their private and work systems (Dhamija and Dusseault, 2008; Helkala and Bakås, 2014). However, the authentication market is changing rapidly through new innovations, standards, and legislation. We have come to a situation where the increasing number of digital services provides people with more options, and they may choose another service if they dislike some features, such as the authentication method (Kruzikova *et al.*, 2022; Taherdoost, 2017). On the other hand, corporate policies may contribute to the increased amount of credentials when they require work and personal accounts to be separate (Dhamija and Dusseault, 2008). All this leads to users spending a considerable amount of their time logging into different systems (Bhana and Flowerday, 2020).

Research literature largely focuses on user interactions with authentication methods but does not consider how this might be affected when the user operates in the landscape of authentication. The landscape metaphor is used here to draw attention to the fact that each user views a plethora of authentication-related features from their own vantage point while another user may view the same things from another perspective. Literature has primarily focused on improving the design of authentication methods or the security behaviour of the users. Here we shift the focus from the single user, single authentication mechanism and zoom out to the entire authentication landscape with the aim of conceptualizing this level of analysis. There are very few studies that have explored users' perceptions of authentication as a daily activity spanning all walks of life. One exception is

a diary study that was carried out to see how people cope with passwords in their daily lives (Grawemeyer and Johnson, 2011).

There are several forces influencing the authentication landscape that have been discussed in research literature. Our aim is to understand *what kind of features users perceive in the authentication landscape*. We will answer this question by reviewing research literature on user aspects of authentication. We will first present our review method and then present the authentication features we recognized. Lastly, we discuss the implications and offer conclusions.

2. Survey Method

The literature for this review was selected using a modified systematic review method (Okoli, 2015). The search was limited to 25 prominent journals in fields of information systems, cybersecurity and human-computer interaction to avoid including substandard, non-peer reviewed papers. We used Elsevier Scopus as the search database. The search term included selected journals and a word search of *authentication OR password* AND user* in article title, abstract and keywords. The search resulted in a list of 647 articles which were first evaluated by title and then by abstract. This resulted in a list of 155 articles for full text evaluation and 43 were included for having themes relating to authentication landscape. We excluded papers not related to the research question, published before 2000, and without user point-of-view. The sample was analysed using interpretive thematic clustering.

3. User Authentication

Authentication methods are often divided into three categories: knowledge-based, token, and biometric (Bhana and Flowerday, 2020). Passwords are the most used authentication method (Furnell, 2022) and the best-known knowledge-based method. PIN numbers or longer passphrases may use a similar interface but different rules for forming the secret (Bhana and Flowerday, 2022). Another category of knowledge-based authentication methods is the graphical password, and probably the best-known type is the Android pattern-lock that uses a three-by-three grid where a pattern is drawn (Cho *et al.*, 2020). Biometrics have also gained popularity over the years as sensor technologies have been added to personal devices, such as smartphones. The fingerprint is the most popular biometric, even when face recognition or iris scan would be an option (Cho *et al.*, 2020). Smartphones are often also used in token-based authentication as a trusted device (Constantinides *et al.*, 2023). These authentication methods can be used as combinations in multi-factor authentication to increase security if one factor is compromised and tokens are commonly used as the additional factor (Weir *et al.*, 2010).

Authentication methods cannot be examined in isolation as each user may have several user accounts in both their personal and professional lives. This creates a problem for knowledge-based passwords, which people tend to reuse to reduce the number of secrets but, at the same time, create opportunities for malicious actors to enter several systems with one leaked password (Campbell *et al.*, 2011; Woods and Siponen, 2024). Similarly, dedicated tokens may create the issue of needing to match the token with the correct account (Weir *et al.*, 2010). There are solutions that users can use to mitigate the problems created by multiple credentials, such as password managers (Bonneau *et al.*, 2015). Federated authentication allows login with third-party credentials such as the “Login with Facebook” provided in many consumer services. Some users may avoid this option due to privacy concerns. (Bonneau *et al.*, 2015; Satchell *et al.*, 2011.)

3.1 Authentication Landscape

When we consider the authentication landscape, we focus on a combination of features that the user perceives when interacting with the digital world. This point-of-view differs from studies that focus on qualities of individuals such as self-efficacy (Dodel and Mesch, 2019; Mattson *et al.*, 2023), anxiety (Woods and Siponen, 2024) or IT security diligence (Datta and Krancher, 2024). It also extends the view from studying single types of authentication instances such as passwords or devices. In the following sections we discuss the authentication landscape features we identified in the 42 articles in our literature sample by interpretive thematic clustering.

3.1.1 Services and systems

The security of the digital world can appear very differently to people depending on what type and how many systems or online services they use. People in IT related jobs have even reported having “hundreds” of accounts which can lead to using less secure coping strategies (Wolf et al., 2018). People may use stronger authentication methods or unique passwords for systems with sensitive information (Crossler and Posey, 2017; Grawemeyer and Johnson, 2011). For example, stronger passwords are used for online banking due to the clear personal loss

that could result from a security breach while convenience is valued more in services like email, where the repercussions are less obvious (Tam et al., 2010).

3.1.2 Diversity of methods

The diversity of systems comes with the diversity of authentication methods. The password may be seen as being problematic if there are too many and they change too often (Hadzidedic *et al.*, 2022). There may be alternatives to passwords depending on the service or device. Performance of the methods such as perceived time spent and success rate influence users' preferences (Ibrahim *et al.*, 2019; Kruzikova *et al.*, 2024). Familiarity with methods such as biometrics affects how users perceive their security and convenience (Breward *et al.*, 2017). A single site can offer several alternative authentication methods such as SSO logins, but their usefulness depends on the service provider and if other sites provide the same option (Morkonda *et al.*, 2024). Furthermore, when MFA is used it may use a combination of various types of authenticators, such as security apps or dedicated devices (Sinigaglia et al. 2020).

3.1.3 Guidance and restrictions

The correct use of authentication methods affects their security, which is why users are subjected to different types of guidance and restrictions when authenticating. Users may be gently nudged in the right direction to make better decisions while creating passwords (Kaleta *et al.*, 2019). In organisations the password creation policies may be more compelling and require more secure passwords (Florêncio *et al.*, 2016). Password composition policies may also be technically implemented (Bargas-Avila *et al.*, 2011). However, users may find it confusing when different online services have different requirements for password composition (Cheswick, 2013; Furnell, 2024).

3.1.4 Devices

The devices that people use also play a role in how people perceive authentication. The different hardware and software features across devices affect what types of authentication options are available (Botha *et al.*, 2009). Then again, a single device like the smartphone can offer several different authentication options that can be activated and used interchangeably (Cho *et al.*, 2020). The use experience of authentication methods may vary across devices since their input systems are different (Forget *et al.*, 2015). The novelty of the device and user's skills in using it also affect the authentication experience (Kruzikova *et al.*, 2022).

3.1.5 Security products

Security-related services may affect the authentication mechanisms and how they are used. These include password managers, SSO/identity management, physical authentication devices, and security software which may be free to use or paid services. It has been found that less than half of people are willing to pay for federated identity management, even though the free versions (e.g., login with Facebook or Google) have been deemed questionable in protecting the users' privacy (Roßnagel *et al.*, 2014). Also, the cost of switching to such systems may not only be monetary but require substantial effort (Renaud *et al.*, 2019).

The features of security tools affect the perception people have of them such as authentication devices' physical attributes and functionalities (Nanda *et al.*, 2024). In software it can be the quality of tips provided to make security decisions (Furnell and Clarke, 2012; Ortlieb, 2014). Unfortunately, the positive experience that these services provide can also be detrimental if people engage in risky behaviour due to over-reliance on the technology's ability to protect (the Pelzman Effect) (Datta and Krancher, 2024). Then again people may also not believe that service providers are able to limit unauthorized access to their data (Crossler and Posey, 2017; Hadzidedic *et al.*, 2022).

3.1.6 Use context

Authentication is needed while acting in different roles and places. People's preferences vary depending on their surroundings such as home, office or public area (Crossler and Posey, 2017). The work environment differs from private use in many ways. At work there may be other clearer demands like production deadlines that distract people from the more ambiguous authentication security demands (Grawemeyer and Johnson, 2011). The type of work, or the workplace, can also affect authentication. Entrepreneurs tend to choose stronger passwords as they have the responsibility of the business on their shoulders (Helkala and Bakås, 2014). Then again people in state government organisations have been found to adhere better to password policies due to more training, guidance and enforcement (Fitri *et al.*, 2025).

3.1.7 Culture and relationships

The authentication landscape is also affected by users' culture and social relationships. The use of textual passwords is affected by the user's language and culture. A study on a leaked user database revealed that the most common passwords have different patterns of character use across different nationalities. (AlSabah et al., 2018.) Differences have also been found between countries on how much users tend to follow rules on password security which may be attributed to differing uncertainty avoidance across cultures (Hadzidedic et al., 2022).

Social relationships also have effects on their perception of authentication. People may worry about their shoulder surfing family members and roommates, affecting the selection of authentication methods (Ortlieb, 2014). On the other hand, social influence has a significant positive effect on trust of password managers which affects their adoption (Tian, 2024).

3.1.8 User responsibilities

Users have varying perceptions of how much their own choices influence the authentication landscape. People adapt their security behaviour according to their personal risk assessment of the digital environment (Wolf *et al.*, 2018). They may weigh risks and benefits when choosing their password management techniques (Merdenyan and Petrie, 2022). On the other hand, many have lacking and erroneous knowledge of the secure use of systems (Grawemeyer and Johnson, 2011). People need to learn the functionalities of security technologies to correctly operate them on personal devices (Furnell and Clarke, 2012). Furthermore, one time learning is not enough since technology changes over time and managing the increasing amount of credentials requires creating and adapting routines (Renaud *et al.*, 2019).

3.1.9 Accessibility

People's perceptions of the authentication landscape are also affected by their ability to operate technology. Digital divide between users means that there are notable disparities in access to digital world, such as internet use timespan and frequency, and digital safety skills (Dodel and Mesch, 2019). People may also have cognitive, sensory and physical restrictions in using authentication methods (Furnell *et al.*, 2022). Authentication often requires error-free entry and perfect recall, good memory, hearing, attention, dexterity, vision or learning (Renaud and Ramsay, 2007). New authentication innovations may need to consider user physical characteristics such as the effect of body composition on smart watch vibration detection (Lee *et al.*, 2023). Physical characteristics may also change over time which poses a challenge for biometric authentication such as facial recognition (Ibrahim *et al.*, 2019).

3.1.10 Threat outlook

A core feature of the authentication landscape is the threat outlook meaning the users' perception of threats toward the information, systems and devices that should be protected from unauthorised access. When choosing an authentication method, people weigh the perceived probability of attacks toward different methods (Kruzikova *et al.*, 2022). As technology advances new threats can emerge that could compromise for example the biometric data that is used for authentication, making it useless for future authentication (Zhang *et al.*, 2024). Centralised systems such as password managers may cause widespread problems if users' all accounts are compromised in one leak (Nehme *et al.*, 2024).

Fear against threats and the perceived ability to face them may affect authentication method use (Mattson *et al.*, 2023). Differences have been detected between regular IT users and security experts in perception of risk and using password workarounds (Rooney *et al.*, 2024). People may not comprehend how authentication protects them and understanding varies on the consequences of being victimised (Dodel and Mesch, 2019). Fear appeals may evoke the willingness to take better protective measures, but their effect deteriorates over time (Mwagwabi *et al.*, 2018).

4. Discussion

The aim of this review was to understand what kind of features users perceive in the authentication landscape. The research literature on user authentication discusses multiple features which we grouped into ten categories. Authentication is often studied from the point-of-view of a single user and a single authentication method which was prevalent in this review. We find this approach does not account for the interplay between the user's other experiences with authentication.

Many of the identified key issues span across several feature categories. These underlying themes include increasing complexity, changes over time, learning, and quality of information (and misinformation). Complexity can be detected in the increasing number of systems and authentication methods users need to adopt. When a user is presented with another authentication task, it may not matter how simple it is if it adds to the complexity of the landscape. Complexity is also one of the things that changes over time. When people create more accounts for more services over time, they increase their authentication load by creating passwords or connecting new accounts to password managers or SSO services. The authentication load gets worse as we get older and at the same time our ability to create new safer habits gets worse (Renaud and Ramsay, 2007). Our capabilities and opportunities to learn about new threats and innovations vary depending on where we work (Fitri *et al.*, 2025) and how we age. Furthermore, our perceptions of the authentication landscape are affected by the quality of the information we get from online services, security tools, social connections and employers. Acknowledging the interplay of the landscape features is important for reducing attack surfaces and increasing resilience for authentication.

Future research can utilise the identified features of authentication landscape in both qualitative and quantitative studies. A qualitative study could add understanding of the underlying themes that are still quite sparsely discussed in research literature. A quantitative study could turn the ten features into a measuring instrument that could be used for clustering users into groups that perceive the landscape in a similar way. This approach could be useful in conjunction with the choices people make, such as choosing usability over security or one method over another. When combined with observed ratings of usability and security of methods (Zimmermann *et al.*, 2019), the perceived features of authentication landscape may shed light on how the overlapping effects of features can affect decisions compared to objective ratings.

This review also comes with some limitations. Due to the overwhelming number of authentication papers and the wide scope of our research question, we could not include more than 25 journals. The analysis method used here was very free form, but future research could also attempt a more robust meta-analysis. This may be challenging as the literature on user authentication is very heterogeneous and includes a limited number of comparable variables.

5. Conclusion

This review advances the understanding of the user perspective of the authentication landscape in a digitalised society. We analysed 43 research articles on user authentication and categorised the identified issues into ten categories: services and systems, diversity of methods, guidance and restrictions, devices, security products, use context, culture and relationships, user responsibilities, accessibility, and threat outlook. These features offer a more organised look into the user perception of authentication for researchers, policymakers, designers and security professionals. They lay the groundwork for studies that aim to understand user authentication choices in relation to users' overall authentication experiences. Furthermore, system developers may consider these features when designing the authentication experience of their service.

Acknowledgements

This research was funded by Business Finland (1610/31/2022).

Ethics Declaration: Ethics clearance was not needed.

AI Declaration: DeepL was used for grammar checks.

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Predicting Sabotaged Open-source Libraries

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Abstract: Open-source software provides free and publicly available software maintained by the open-source community. The variety of contributors creates an environment conducive to the intentional and unintentional introduction of software bugs by participating organizations. Enemy nation-states and independent hackers can exploit these attack vectors to gain access to industry and government systems. Repositories of known vulnerabilities and tools to check vulnerable versions and analyze code exist, but realistically, reviewers can miss issues within many repositories due to constant updates and technological advances. Hence, this research investigates an alternative, non-code-based method for identifying high-risk repositories using repository metadata and commit history, which, when coupled with machine learning, enables us to identify at-risk repositories at rates above 60%. This was achieved using a dataset composed of 41,710 repositories. The contribution of this research is twofold. First, it presents an empirical evaluation of the viability of a non-code-based analysis approach to detecting high-risk, i.e., potentially compromised code repositories. Second, it provides foundational research for non-code-based filtering of open-source repositories, potentially accelerating software investigations and reducing resource requirements.

Keywords: Vulnerabilities, Supply chain attack, Open source, Machine learning, Malicious code

1. Introduction

Open-source software encourages collaboration and innovation for enterprise-level software development on a global scale SolutionsHub (2023). Mercedes-Benz claims that Free and Open Source Software (FOSS) "has become the foundation of just about every application across the industry" (Mercedes-Benz, 2021). According to a GitHub report, 90% of companies use open-source software (GitHub, 2023). Companies pursue open-source software to enhance their development capabilities and to reduce financial dependencies on licensed software (Millidge, 2018). These enhanced capabilities translate into reduced core code development timelines and an increased ability to focus on custom products and features (Barabakh and Meir, 2023). However, like all software, open-source code can suffer from bugs and glitches. Some software defects lead to holes in security that allow attackers to exploit the software to gain access to a system or network for malicious purposes (Clark, Doran, and Glisson, 2018); (Fitzgerald et al., 2023); (Glisson et al., 2015). A report from the Synopsys Cybersecurity Research Center states that of the 1,703 code bases examined, 96% contained open-source code, and 84% contained at least one vulnerability (Synopsys, 2023).

According to the FBI's Internet Crime Complaint Center (IC3) 2022 Internet Crime Report, cybercrime cost the United States more than $10 billion in losses, where $34 million was from ransomware and $9 million from malware (Federal Bureau of Investigations, 2022). Attempting to detect problems at an early stage is a standard countermeasure in the cybersecurity arena (Ceballos Delgado et al., 2021); (Luckett et al., 2018); (McDonald et al., 2017); (Nguyen et al., 2020). In fact, it has been noted that there are tools that the community uses to identify vulnerable open-source libraries (Koussa, 2021). However, several of these tools use a combination of known vulnerabilities from the NIST Vulnerability Database and library versions to identify known vulnerable code.

In addition, commercial solutions can potentially require a database of reported and discovered vulnerabilities to identify security issues. The reliance on discovered vulnerabilities makes them ineffective against zero days (Ohm et al., 2020). It has been noted that open-source software is susceptible to these supply chain attacks and poisoning (Xu et al., 2022). The escalating cost of cybercrime, as well as the accelerating accessibility and growing adoption of open-source software in corporate and government development projects, suggest that organizations should be able to identify high-risk repositories. Open-source repositories can track changes through commits, which researchers could use to detect and identify poisoning. To investigate this idea, this research investigates the hypothesis that it is possible to identify a high-risk poisoned library from the commit history and library metadata. The hypothesis raises the following questions:

- What information from commits and library metadata contributes to the likelihood of a library being at risk?

- Can enough data be gathered to predict risk accurately?
- Can ML be used to predict if a library is at risk?

The contribution of this research is twofold. First, it presents an empirical evaluation of the viability of a non-code-based analysis approach to detecting high-risk, i.e., potentially compromised code repositories. Second, it provides foundational research for non-code-based filtering of open-source repositories, potentially accelerating software investigations and reducing resource requirements.

The paper is organized as follows; section two provides a background of relevant research. Section three addresses methodology and data acquisition. Section four presents research results and analysis. Section five contains the conclusion and offers future work on this topic.

2. Relevant Work

Malicious actors are increasingly exploiting open-source libraries for software supply chain attacks. Ohm et al. (2020) focus on the programming languages JavaScript, Python, Ruby, and Java. The malicious actors use typo squatting, trojan horses, and infecting upstream libraries to compromise their targets. The study identified 469 malicious packages designed to damage computer systems. By avoiding automated data collection, Ohm attempts to ensure that they did not miss a package due to negligence. Looking at package history shows that malicious packages are available for an average of 209 days before removal. Currently, there is no effective method for quickly identifying these malicious libraries. Security experts use machine learning to identify known, recurring vulnerabilities in code. Xu et al. (2022) use a plethora of open-source repositories to train machine learning on real-world samples. Xu's data is from GitHub and focuses on code analysis. Overall, the model trained from GitHub code had a precision of 84.1% and an accuracy of 86.1%, demonstrating the value of GitHub repositories.

Chan and Chandy (2022) analyze Common Vulnerabilities and Exposure (CVE) databases and GitHub commits to studying how often CVEs document the fixes for corresponding vulnerabilities. Using the CVE database patch records and checking the GitHub repository commits to find the number of CVEs with patches.

Ponta, Plate, and Sabetta. (2018) use a combination of static and dynamic analysis to identify vulnerable applications in open-source software, as results indicated the combination furthers vulnerability detection. Their approach is a code-centric method that combines static and dynamic analysis. After detecting a vulnerable library through abstract syntax trees, the goal is to investigate an attack's ability to reach the vulnerable portion of the library. The problem they highlight is the need for a comprehensive knowledge base for vulnerabilities that security experts can reference alongside specialized detection tools.

Bhandari, Naseer, and Moonen (2021) created a tool to create a vulnerability dataset from the CVE records in the National Vulnerability Database (NVD) by collecting vulnerable code and proposed fixes from CVE records. Using the knowledge base, their tool would also provide helpful information on vulnerabilities such as programming language, security metrics, and patches. This enabled quick identification of vulnerable code and the corresponding patch to fix it, potentially leading to an automated patching tool for known vulnerabilities.

Russell et al. (2018) used open-source libraries to create data for machine learning algorithms using a combination of static analysis, dynamic analysis, and commit-message/bug-report tagging. They used neural network classification combined with an ensemble classifier, random forest, to create their model. Their results showed that their machine learning methods outperformed traditional static analysis tools because they are faster and can be tuned to achieve a desired level of precision.

Chakraborty et al. (2022) discuss whether the advances in Deep Learning improved automated vulnerability detection. They find that Deep Learning detection is less than half as effective as other methods. The team attributes the performance drop to the quality of the training data and model choices. They propose a more systematic and principled way to gather training data, and models showed a 33.57% boost in precision and a 128.38% boost in recall. They highlight the potential of Deep Learning-based vulnerability detection when done correctly.

Research exists that uses static and dynamic code analysis to detect vulnerabilities. While some of the methods utilize GitHub to obtain a richer/more diverse training set, minimal research investigates repository information other than code or patches to identify potentially vulnerable repositories.

3. Method

This section provides the approach used to identify potentially vulnerable repositories. This includes the data gathered from repositories, such as user actions, configurations, and summary statistics; the code is explicitly not utilized. The data cleaning, the labeling of the repositories, and Machine Learning (ML) methods utilized are provided in this section. The software employed in this research is presented in Table 1.

Table 1: Hardware and Software

Software	Version
RapidMiner Studio	10.1.002
RapidMiner XGBoost	0.1.3
RapidMiner Python Scripting	10.0.1
RapidMiner Operator Toolbox	2.16.0
Golang	1.20.5
Python	3.10.6
Python imbalanced-learn	0.11.0

3.1 Data Acquisition

This study focuses on popular GitHub repositories for analysis. Believing that frequently used repositories are more likely to incur vulnerabilities, this research gathers information from actively used repositories. The number of GitHub stars is used as an overall indicator to evaluate a repository's rank. To reduce the dataset size, only repositories with 1,500 or more stars were considered, yielding 41,710 repositories.

The project focuses on data from user actions, configurations, and summary statistics. Any user information gathered from the repositories is saved for future work. Commit history is limited to the last four years to save space and time. The method used to determine if a repository ever contained a vulnerability consisted of two parts. The reported issues from each repository are used to mark any repository with an issue that has keywords indicating security patches or vulnerabilities in the title or body, using regular expressions.

For the second part, the results are combined with the results of MITRE's CVE keyword search. Using MITRE's Application Program Interface (API) for CVEs, a repository is marked when any repository's user and name combination returned results. The list of all positive results from both was labeled as repositories with possible vulnerabilities and given a positive mark in the label category "posvuln"; otherwise, it was given a negative mark (no problem). The split between positive and negative results for this label was 13,732 positive and 27,977 negative.

3.2 Feature Selection and Data Discovery

RapidMiner Studio 10.1.002 was used for all the analysis, cleaning of data, feature selection, and testing of the Machine Learning methods. The feature selection begins with removing useless attributes and correlated attributes operators from the complete set of attributes in Table 2. The first operation removes id-like attributes and the second removes attributes that have a correlation value above 0.95. Ensuring consistent results required setting a seed for all RapidMiner modules that rely on a random seed. The seed used, 123456789, was chosen arbitrarily and was set within every applicable module. The set seed ensured that results were repeatable across runs and that direct comparisons among methods could be made. Feature selection continues with the implementation of forward selection and backward elimination. Each RapidMiner module uses one ML Algorithm, of the tried algorithms, internally to perform the feature selection. The backwards elimination and forward selection allowed for a reduction from the already reduced initial 60 features to fit to the separate ML algorithms. When using the Synthetic Minority Oversampling Technique (SMOTE) or Tomek-link reduction methods in a test, they are applied after the use of reduction techniques and before the machine learning algorithms. The SMOTE up-sampling and Tomek reduction methods are used after feature selection to balance and define the feature areas within the data. They balance the number of positive and negative data points and reduce overlap between the two groups to aid the algorithms' learning by providing more well-defined boundaries. The lack of Tomek-Link reduction in RapidMiner requires the python module with the imblearn v0.11.0 library. When required, the data is normalized using Z-transformation and piped to the following ML algorithms for evaluation: Decision Trees, Random Forest, k-NN with k=5, 11, and

15, SVM with analysis of variance (ANOVA), Generalized Linear model, and XGBoost 0.1.3 using logistic regression and regression with squared loss.

4. Results and Analysis

After removing useless and correlated attributes, 44 attributes remained from the original 60. Initial performance in some of the models was imbalanced. Across all models, recall rates were low for positive classification and extremely high for negative classification, except for k-NN, SVM, and XGBoost. Among the models, the lowest positive recall was 2.52%, and the highest negative recall was 99.66%. Unfortunately, all the models had an inverse relationship between recall and precision.

The better models with more even splits, such as XGBoost, had combined recall of 67.04% with splits of 63.29% for positive and 70.79% for negative but had imbalanced precision of 31.03% for positive and 90.28% for negative. Continued testing showed better performance and balance when using a training set of only 2,000 evenly split observations compared to 20,000 observations also evenly split. An example of the imbalance is the k-NN (k=11) model. The same k-NN (k=11) model went from 28.03% positive classification precision to 46.79% when switching from a training set of 20,000 to 2,000. This showed imbalances in the gathered dataset.

Tables 3 and 4 are the results of the decision tree and random forest methods, split between the forward selection (FS) and backward elimination (BE) selection methods. Even though they show precision at 60%-70% and a high level of learning from the models, they have low positive recall. A bias toward negative can result in the model not detecting a true vulnerbility and is not ideal for an early warning system. Random Forest performs better than the lone decision tree in predicting more true positives, but is slightly inferior in precision by including more false positives. Further analysis showed that the models suffer from data imbalance, as they perform worse rather than better with more training data.

Table 3: Decision Tree

Selection Method	Training Size	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	67.53%	70.36%	13.45%	96.95%
Forward Selection	20000	56.53%	83.76%	7.77%	98.76%
Backwards Elimination	2000	69.29%	69.97%	11.22%	97.65%
Backwards Elimination	20000	56.07%	83.76%	7.80%	98.73%

Table 4: Random Forest

Selection Method	Training Size	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	59.25%	74.24%	34.78%	88.71%
Forward Selection	20000	54.05%	83.84%	8.57%	98.49%
Backwards Elimination	2000	60.02%	72.63%	26.92%	91.54%
Backwards Elimination	20000	51.52%	83.83%	8.65%	98.31%

Table 5 contains all the results of the k-NN iterations of 5, 11, and 15. The results from the model have the best performance so far in positive recall classification, but they suffer with positive precision. The higher recall with k-NN and not with the other classification methods, shows that the data's separation is not well defined.

Table 5: k-NN

Selection Method	Training Size	K	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	5	44.27%	76.95%	58.62%	65.17%
Forward Selection	20000	5	25.87%	88.48%	59.46%	64.92%
Backwards Elimination	2000	5	45.04%	76.51%	55.87%	67.82%
Backwards Elimination	20000	5	26.34%	88.70%	60.02%	65.16%
Forward Selection	2000	11	46.76%	76.85%	55.06%	70.41%

Selection Method	Training Size	K	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	20000	11	27.67%	88.99%	59.73%	67.59%
Backwards Elimination	2000	11	46.79%	77.49%	57.41%	69.18%
Backwards Elimination	20000	11	28.03%	88.97%	59.06%	68.53%
Forward Selection	2000	15	47.47%	76.99%	54.81%	71.37%
Forward Selection	20000	15	27.76%	89.19%	60.77%	67.17%
Backwards Elimination	2000	15	46.77%	76.60%	54.07%	70.95%
Backwards Elimination	20000	15	28.53%	89.06%	59.00%	69.32%

Tables 6 and 7 display the performance of the Generalized Linear Model and SVM. The drops in recall with the larger training sizes further highlight an issue with poorly defined data separation.

Table 6: Generalized Linear Model

Selection Method	Training Size	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	58.07%	73.83%	33.44%	88.60%
Forward Selection	20000	43.61%	83.14%	3.11%	99.17%
Backwards Elimination	2000	54.24%	76.13%	45.63%	81.83%
Backwards Elimination	20000	34.90%	87.72%	44.08%	82.93%

Table 8 contains the results of the XGBoost model. The ensemble method, XGBoost, performs the best results of all the preliminary tests. The recall is split 61.27% to 68.55%, demonstrating that is better than guessing. The precision is lower than others at 47.90% positive precision which shows a lower learning of the data.

Table 7: SVM

Selection Method	Training Size	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	57.20%	72.93%	29.55%	89.57%
Forward Selection	20000	-	-	-	-
Backwards Elimination	2000	50.80%	77.46%	53.38%	75.61%
Backwards Elimination	20000	37.99%	84.83%	19.59%	93.36%

Table 8: XGBoost

Selection Method	Training Size	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	2000	57.23%	71.43%	21.77%	92.32%
Forward Selection	20000	0.00%	82.81%	0.00%	100.00%
Backwards Elimination	2000	47.90%	78.95%	61.27%	68.55%
Backwards Elimination	20000	31.03%	90.28%	63.29%	70.79%

To mitigate the separation issues in the data, we implemented the use of SMOTE upsampling with a 30-70 training-testing split to add new data points for the minority class to improve results. A lack of indication in the open-source libraries of vulnerability patches and discrepancies between CVE reports and these libraries likely led to data imbalance and overlap. Rapid miner does not include SMOTE in the base application, but by installing the operator toolbox extension 2.16 SMOTE becomes an available operator. Comparing results after SMOTE upsampling, there was an overall drop in recall but an increase in precision. The test was set up to perform two separate test each with half of the of the models to reduce overall run time. However, the tests excluded XGBoost because of errors during testing with SMOTE.

Table 9 shows the SMOTE results from the tree models. The Decision Tree model's recall decreased with SMOTE but had a major increase in precision meaning the model learned better with the upsampling. This

shows there is an overlap from the up sampling. The Random Forest model had an increase in positive recall, but a decrease in precision showing an overlap within the data.

Table 9: SMOTE first batch testing results

Selection Method	Model Type	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	Decision tree	71.72%	68.98%	10.22%	98.02%
Backwards Elimination	Decision tree	80.85%	67.44%	1.84%	99.79%
Forward Selection	Random Forest	49.82%	76.95%	55.83%	72.39%
Backwards Elimination	Random Forest	55.13%	74.95%	43.86%	82.47%

Table 10 shows how the k-NN model increased its positive recall and improved with more neighbors, higher k, instead of decreased. SVM shows an improvement in precision and recall for the backwards elimination method with a 12% increase in positive precision and only a 7% decrease in negative precision and a more balanced recall of 58.71% positive and 71.81% negative compared to 19.59% positive and 93.36% negative.

Table 10: SMOTE second batch testing results

Selection Method	Model Type	Precision Positive	Precision Negative	Recall Positive	Recall Negative
Forward Selection	k-NN (k=5)	43.72%	75.17%	59.89%	64.05%
Backwards Elimination	k-NN (k=5)	44.28%	75.72%	58.13%	64.09%
Forward Selection	k-NN (k=11)	44.21%	75.48%	57.33%	64.48%
Backwards Elimination	k-NN (k=11)	45.46%	77.06%	61.24%	63.93%
Forward Selection	k-NN (k=15)	45.71%	77.13%	61.12%	64.36%
Backwards Elimination	k-NN (k=15)	46.05%	77.17%	60.80%	65.03%
Forward Selection	Generalized Linear Model	57.64%	72.91%	33.42%	87.94%
Backwards Elimination	Generalized Linear Model	54.39%	75.36%	46.02%	81.06%
Forward Selection	SVM	32.92%	65.00%	99.83%	0.15%
Backwards Elimination	SVM	50.55%	77.99%	58.71%	71.81%

The other models share a similar trend of favoring backwards selection with an overall increase in positive recall but a decrease in precision. To normalize all feature across the models, further tests used features gathered by combining SMOTE upsampling with the forward selection and backwards elimination methods and choosing the top five recall models.

The five chosen ML models were: k-NN (k=11) using SMOTE and the backwards elimination method with a 61% positive and 63% negative recall, k-NN (k=15) using SMOTE and the forwards selection method with a 61% positive and 64% negative recall, Random Forest using SMOTE and the forward selection method with a 55% positive and 72% negative recall, k-NN (k=5) using the forward selection method with a 58% positive and 65% negative recall, and XGBoost using the backwards elimination method with a 61% positive and 68% negative recall.

These five models had positive and negative recall classifications that was 55% and above while maintaining a reasonably balanced precision. To reduce the total number of evaluated attributes, attributes found in at least three of the top five models were included in the final feature set. The included features were: has downloads, lower quartile removed, has wiki, Fork, total pulls, upper quartile commit inserts, total branches, lower quartile added, avg commit files, total contributors, and median commit files.

The resulting feature set includes attributes corresponding to repository activity levels, indicating a link between user engagement and risk for a repository to have a vulnerability. The last tests achieve the best results when testing the best performing models with the new feature set by adding Tomek-link under-sampling. The tests use Tomek-link under-sampling to separate the data into more defined groups and combine it with the SMOTE upsampling used previously. Using the same data cleaning and normalization to

test SMOTE Tomek-link performance, tests used cross-validation on random forest, k-NN (k=15), XGBoost, SVM (ANOVA), and Generalized Linear Models.

Table 11 contains the results of three models that are split by model into four groups: no SMOTE or Tomek-Link, SMOTE, Tomek-link, and both SMOTE with Tomek-link. All three models had a decrease in precision from the upsampling and under-sampling. The limited feature selection caused lower positive recall rates for the models before SMOTE and Tomek-link, but all models improved in recall with SMOTE upsampling.

Table 12 contains the same test with two other models. The Generalized Linear Model follows the pattern of a decrease in precision after SMOTE and Tomek, but SVM increases in both recall and precision, achieving the most balanced result.

Table 11: SMOTE-Tomek result comparison

Sampling Method	Model Type	Precision Positive	Precision Negative	Recall Positive	Recall Negative
None	Random Forest	71.37%	70.12%	15.90%	96.87%
SMOTE	Random Forest	41.68%	80.29%	76.14%	47.70%
Tomek	Random Forest	64.34%	72.00%	26.46%	92.80%
S&T	Random Forest	48.03%	77.55%	59.73%	68.28%
None	k-NN (k=15)	54.79%	72.87%	34.87%	85.87%
SMOTE	k-NN (k=15)	45.16%	77.01%	61.49%	63.37%
Tomek	k-NN (k=15)	51.53%	74.51%	44.66%	79.38%
S&T	k-NN (k=15)	43.01%	77.22%	65.49%	57.40%
None	XGBoost	62.92%	73.50%	33.72%	90.25%
SMOTE	XGBoost	57.03%	75.23%	43.77%	83.82%
Tomek	XGBoost	58.01%	75.41%	43.93%	84.39%
S&T	XGBoost	54.72%	76.44%	49.94%	79.71%

The results show that the Tomek-link under-sampling method increases precision but decreases recall. However, when balanced with SMOTE's recall increase and precision decrease, the test results get a 'balance' of recall and precision. Models that benefit from better defined data separation, k-NN and SVM, see the most benefits and reach recalls and precisions of 60%.

Table 12: SMOTE-Tomek result comparison

Sampling Method	Model Type	Precision Positive	Precision Negative	Recall Positive	Recall Negative
None	SVM (ANOVA)	42.85%	71.22%	38.31%	74.92%
SMOTE	SVM (ANOVA)	50.84%	77.44%	56.60%	73.14%
Tomek	SVM (ANOVA)	48.06%	71.91%	35.31%	81.27%
S&T	SVM (ANOVA)	46.22%	79.68%	68.32%	60.98%
None	Generalized Linear Model	65.69%	70.93%	20.97%	94.62%
SMOTE	Generalized Linear Model	51.11%	76.31%	52.29%	75.44%
Tomek	Generalized Linear Model	62.08%	72.38%	29.03%	91.30%
S&T	Generalized Linear Model	47.94%	77.50%	59.66%	68.20%

Although the results are not perfect for detecting high-risk libraries, they do show a clear, predictable pattern. The data from testing provides evidence that this pattern is consistent and can identify potential vulnerabilities in software systems.

5. Conclusions and Future Work

The results of the research indicate a link between public GitHub repo data and vulnerability risk indicators. With a recall and precision of around 60%, the models demonstrate that the collected data can predict high-

risk repositories. Moreover, the highest-performing models, SVM and k-NN, reveal that the data contains defined groups and is suited to classification via distance analysis and linear separation. Hence, this investigation provides a foundation for subsequent research into repository analysis, serving as an early-warning or vetting process that can bolster code-analysis solutions.

These findings highlight potentially malicious accounts for additional investigation and initial screenings on code repository platforms such as GitHub. However, there is also a risk that malicious actors could misuse the method to identify vulnerable repositories. Using this method could enhance current vulnerability-search methods by reducing the pool of potentially vulnerable code libraries before an actor feeds code into more computationally expensive skill-based language models to build exploits. Alternatively, repository maintainers or security researchers can pre-screen code flagged using the same method to patch identified vulnerabilities.

Future work will investigate alternative machine learning methods, including neural networks and deep learning, as well as further analysis with distance-specific techniques such as subspace analysis. In addition, research will expand to include data from less frequently used and less popular repositories to compare results across different levels of user activity. Another consideration stems from the timeframe of the data collection. Research will need to account for significant changes in potential results due to the advent of artificially generated code, and it will be closely monitored as a variable in future iterations.

A deeper investigation into analyzing active repository contributors as indicators for compromise could enable the identification of accounts that intentionally commit vulnerable code. Research would begin with using user data to construct maps of all users associated with compromised libraries and associated activities. Furthermore, additional analysis would use commit history patterns, code preference, and repository commit history as the initial feature set for prediction. The end goal is to profile user accounts by commit history and account indicators to identify malicious actor accounts.

Ethics and AI Declaration: No ethical clearance was required, and no Generative AI was used in process of this paper.

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Privacy Under Pressure: Assessing Online Commercial Surveillance Countermeasures and Gaps

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Abstract: Ubiquitous technical surveillance is reshaping the modern information environment. Commercial web-tracking technologies have evolved into a pervasive technical surveillance infrastructure, enabling the large-scale collection of data from everyday activities as people participate in modern society. With sufficient analysis, this data can reveal sensitive information - posing risks to individuals, organizations, and national security. Several software packages exist to limit the exposure of personal information collected online. In recent years, laws and regulations, such as the GDPR and CCPA, have been implemented to help users protect their personal information, with varying degrees of success. This paper examines the recent scholarly literature on web tracking and commercial surveillance techniques. We then synthesize these studies to outline the methods that enable large-scale commercial surveillance on the Internet. Then, we analyze countermeasures designed to limit commercial data exposure, specifically assessing their effectiveness, technical constraints, and operational challenges. Our analysis reveals gaps in existing countermeasures and identifies opportunities for both technical and policy-based improvements to mitigate vulnerabilities introduced by commercially available information. These findings clarify the limitations of current web browser defenses and provide researchers and policymakers with directions on where further effort and investment are most needed.

Keywords: Commercial digital surveillance, Countermeasures, Data collection, Web tracking

1. Introduction

Digital Force Protection (DFP) has emerged as a critical component of operations security (OPSEC) for military personnel in an increasingly data-driven, global information environment (Shipp, 2026). Ubiquitous Technical Surveillance (UTS)[1] is a phenomenon in which data is continually collected about everyone. Data is derived from smartphone usage, purchases at retail locations, security cameras, Internet web browsing, and many other touchpoints of daily life in modern society. These data are often collected for the purpose of serving targeted advertising to consumers and increasing corporate profits. The data itself has become marketable; commercial data brokers buy, aggregate, and sell personally identifiable information (PII) about people without their consent or knowledge (Sherman, 2021). Researchers have shown how commercially available information (CAI), such as the data provided by data brokers, can be exploited with the potential for economic, psychological, and even physical harm to those targeted (GAO, 2025; Fox, 2024; Dawson & Matthew, 2024). CAI poses threats to force protection and OPSEC, as it can enable adversaries to identify, profile, and target service members and their families without requiring resources that were formerly held only by nation-state intelligence services.

The risks of aggregated CAI are not theoretical: for as little as $0.12 per record, foreign adversaries can acquire detailed personal information of active-duty U.S. service members from commercial data brokers with minimal verification or scrutiny (Sherman et al., 2023). This statement is based on a study conducted at Duke University, where the researchers purchased data sets containing information about 30,000 active-duty military members, including names, residential addresses, email addresses, health conditions, financial information, and religious affiliations, from three U.S. data brokers with little or no identity verification. A companion report by the Army Cyber Institute (ACI) examines the processes by which data enters the commercial ecosystem. The report found that data acquisition can involve tracking pixels on military-affiliated websites, identity verification tools such as ID.me (which offer discounts to military members), and third-party cookies that monitor users' online activity (Fox et al., 2023). An example case study was the ACI's examination of shopmyexchange.com, the online retail store operated by the Army and Air Force Exchange Service. There, the researchers found 22 ad trackers, 14 third-party cookies, keystroke loggers, and browser fingerprinting tools, which collectively transmit users' personal data to the commercial sector. If online services that cater directly to military members and their families have this amount of advertising technology (AdTech) embedded in their services, even service members

[1]The U.S. Federal Bureau of Investigation (FBI) defines UTS as the widespread collection of data and application of analytic methodologies for the purpose of connecting people to things, events, or locations (FBI, 2025).

who attempt to maintain small digital profiles and practice appropriate OPSEC in their personal lives will risk exposure through CAI.

The Duke data broker study demonstrates how consumer data can be easily extracted, packaged, and sold online (Fox et al., 2023). Although the tools threat actors use to gather data are unknown, a correlation between advertising techniques and clusters of PII can be identified. Even when utilizing privacy-preserving technologies, such as a virtual private network (VPN), browser data can be exploited if the victim irresponsibly enters their PII or fails to understand the digital surveillance environment.

The focus of this paper is on browser-based collection mechanisms, which are the front end of the data pipeline, and on the effectiveness of countermeasures, if any, against commercial digital surveillance. We offer a synthesis of recent literature on commercial web tracking to identify the browser-based mechanisms most likely to contribute to the data broker pipeline. We also assess the countermeasures publicly available to an average user, such as browsers, extensions, privacy settings, and DNS-based filtering, for their effectiveness against surveillance threats. Some of the findings highlight potential gaps, including the lack of countermeasures against server-side tracking, cross-site identity linking, and behavioral inference from metadata. Some countermeasures have usability challenges and cause browser anomalies, which, counterintuitively, increase users' identifiability. These findings have significant implications for service members and users operating in high-risk environments, especially regarding the information accessible to online malign actors. This paper is a structured narrative synthesis of recent literature rather than a systematic review; its aim is to identify practical gaps and generate hypotheses for future empirical work.

2. Background

Extensive data collection online has been ongoing for several years, primarily for targeted advertising. Specifically, these “Web tracking systems…automatically record data and behaviors of Internet users,” and are crucial for “marketing and advertising strategies;” however, they “pose a threat to individual privacy rights” as “users often lack awareness” of the extent to which their data is collected (Tasoulas, Gazis, and Tsohou, 2025). The lack of user awareness poses concerns for everyday users, especially when combined with the vast array of digital surveillance technologies currently in use. This threat applies particularly to service members, whose PII can be exploited if acquired by malign actors. For example, “commercial data brokerage services expose[d] location data of service members and use[d] it to follow them from their residences to sensitive facilities, such as intelligence organizations or nuclear sites around Europe” (Master et al., 2025). Data gathered online contributed to this exposure, but it stems from an issue on the Internet that every user experiences: a lack of transparency about how their data is collected and what can be done to limit this process.

2.1 Related Work

From our literature analysis, several patterns emerge in research on commercial internet surveillance. The taxonomy of internet surveillance techniques by Gazis, Tasoulas, and Tsohou (2025) divides the subject into four primary categories: HTTP Tracking, API Tracking, User Identification, and Complex Tracking.

The first category, HTTP Tracking, involves collecting personal data from internet users via the HTTP protocol, including cookies, web beacons, and email tracking. In the literature, cookies have been shown to be effective for large-scale, passive tracking of internet users, often without their knowledge, for clustering identities and profiling them over the long term (Englehardt et al., 2015). Although first-party cookies have been proven to be helpful in the provision of Internet services, third-party cookies and the use of tracking pixels have been identified as a major privacy concern to the Internet and its users (Ourrahte, El-Yahyaoui, and Ziani, 2025). Despite web browsers broadly moving to block third-party cookies,[2] server-side and scriptless methods, such as those using tracking pixels, can still be used for session and configuration inference (El Hajj Chehade, Stock, and Troncoso, 2025).

API and storage-based internet tracking techniques have been found to be effective in the collection of the personal data of internet users, including the use of Flash cookies, HTML5 local and session storage, and the so-called “evercookies” that have the ability to regenerate their IDs even after being deleted by the internet users (Tasoulas, Gazis, and Tsohou, 2025).

[2] Google Chrome is a notable exception; see (Chavez, 2024) and (Leith, 2021). While Alphabet originally intended to block third-party cookies in Chrome, the company abandoned the effort in 2024.

Another avenue that enhances tracking persistence is the use of user identification techniques. These techniques involve creating fingerprints from system-level attributes. Techniques such as canvas fingerprinting and cookie synchronization enable unique identification of individuals without the need for traditional cookies (Ourrahte, El-Yahyaoui, and Ziani, 2025). The literature has highlighted the challenges users face in identifying and mitigating fingerprinting techniques, given that these techniques provide minimal evidence of tracking (Kaur et al., 2017). Recent studies in the field suggest that fingerprinting techniques can also exploit interactions users have with countermeasures; for example, Solomos et al. (2022) demonstrated the ability to fingerprint browsers using extensions, thereby undermining the effectiveness of many countermeasures.

Other sophisticated tracking methods often include integrating HTTP tracking, storage-based identifiers, fingerprinting, and behavioral tracking. These tracking methods are often associated with robust data infrastructures and the use of machine learning capabilities. These tracking methods are often used for in-depth analytics, cross-site user linkage, and behavioral analysis (Tasoulas, Gazis, and Tsohou, 2025). Behavioral tracking methods, such as keystroke tracking, have been used to extend tracking capabilities to include sensitive user information in malware-related tracking (Baek et al., 2012). Recent studies have indicated the extension of tracking to cellular networks and mobile devices. In this case, fingerprinting tracking methods have been used to track application usage, geolocation, and inter-user relationships within the same network cell (Baek, 2023). This can be detrimental to OPSEC because users often access the Internet using personal devices rather than enterprise equipment with network or browser-based mitigations in place.

3. Methodology

Focusing specifically on the data types revealed by service members in the Duke paper, our research question becomes: “How do commercially available data sources enable the aggregation of service members’ personally identifiable information, and what gaps in existing countermeasures allow this exposure to persist?” Research has been completed on several surveillance countermeasures and their effectiveness (such as the work completed by Bujlow et al.; Ourrahte, El-Yahyaoui, and Ziani; Englehardt et al.; and Luangmaneerote, Zaluska, and Carr). However, the application to service members is underexplored. First, we survey the literature for studies of commercial digital surveillance technologies. Papers were sourced from OpenAlex, Semantic Scholar, and Scopus, with a supplementary Google Scholar search for existing systematic reviews. Two parallel search streams covered tracking mechanisms (2015–2026) and countermeasures (1995–2026), excluding physical surveillance, non-English publications, and non-peer-reviewed sources. Of 3,060 initial records, 262 duplicates were removed, and the remaining 2,798 were screened by title and abstract; 39 candidates advanced to full-text review, yielding a final corpus of 15 studies. Additional sources were identified through citation chasing, reflecting the fragmented publication landscape of web-tracking defense research across security conferences, journals, and government reports.

Then, we synthesize the effectiveness of various countermeasures, highlighting gaps that threaten service members and OPSEC. Additionally, the overall impacts of a lack of information regarding digital surveillance (along with the current countermeasures) are analyzed.

The synthesis was also intended to explore the extent to which data have already been collected about service members. As seen in Fox et al.’s report (2023), several datasets of active-duty personnel were collected from data brokers at “at low cost, by domestic or foreign entities” (including information such as “[n]ame, home address, email,” and other information on around 5,000 personnel). This vast data collection, when combined with the primary methods of digital surveillance and the leading countermeasures, will provide the foundation for recommendations on future policy and further research.

We first classify the primary digital surveillance technologies (namely, cookies, tracking pixels, fingerprinting, behavioral methods, and cross-device methods). Then, we analyze the gaps that remain to offer recommendations for further research and development of countermeasures.

4. Survey

4.1 Cookies

Cookies themselves act as an “identifier” within a website’s database and will “store user data, such as passwords” with the overall goal of convenience (Tasoulas, Gazis, and Tsohou, 2025). Websites typically use first-party cookies to improve overall functionality, with the user’s experience in mind. These cookies are not primarily a privacy concern, as they are tied to the specific website the user intended to visit; the responsibility

falls on both the user and the website owner to ensure that both parties understand the services being provided. However, the issue becomes apparent with the introduction of third-party cookies.

4.1.1 Third-party cookies

The "presence of multiple unrelated third-party cookies on most web pages, albeit pseudonymous, can tie together most of a user's web traffic without having to rely on IP addresses" or other surveillance techniques (Englehardt et al., 2015). This issue extends beyond the third-party as well, as "many web pages reveal an already logged-in user's identity in plaintext. Thus, an adversary that can wiretap the network can not only cluster together the web pages visited by a user but can then attach real-world identities to those clusters" (Englehardt et al., 2015). This is especially threatening to OPSEC. Adversaries—in order "[t]o link users across different networks and over time"—will "utilize…third-party unique cookies assigned to browser instances by websites" that allows adversaries to "accumulate browsing statistics through many different websites" (Englehardt et al., 2015; Bujlow et al., 2017). PII is within reach of any threat actor, making third-party cookies a worrying threat to privacy.

4.1.2 Persistent cookies

In conjunction with third-party cookies, persistent cookies are more difficult for users to delete. They "track users over a long period," "remain[ing] on the device even if you close the browser" which makes them especially dangerous (Ourrahte, El-Yahyaoui, and Ziani, 2025). In the purpose of this paper, this section will also include other versions of advanced cookies—including zombie cookies and evercookies, which are "highly advanced tracking techniques…to leave tracking in place, even if a user tries to delete them"—as they all are more dangerous than basic third-party cookies (Ourrahte, El-Yahyaoui, and Ziani, 2025). While third-party cookies primarily track users for advertising purposes, other forms of cookies are more effective at tracking users for harmful intent. Additionally, these persistent cookies can be "controlled by scripts," allowing a threat actor with a clear target to passively attack anyone (Tasoulas, Gazis, and Tsohou, 2025).

4.2 Tracking Pixels

Another prevalent tool used for both advertising and surveillance is a tracking pixel.[3] These are "small pieces of embedded code that transmit user data to external vendors," and these propose a high risk to personal information as they "collect, transmit, and potentially expose sensitive…information to external entities" (Atasoy, McDonough, and Zhang, 2025). Although these can be protected against with browsers, they "operate server-side, making them harder to detect and block" while also "becom[ing] a dominant tracking tool for measuring user engagement" (Atasoy, McDonough, and Zhang, 2025). These three researchers found "a critical regulatory gap in healthcare privacy, as tracking pixels operate outside the traditional scope of Health Insurance Portability and Accountability Act protections" (2025). This gap is explained within an article from Huo, Bland, and Levchenko, in which they "discovered that 14% of 465 [medical] systems…leak[ed] some form of protected health information to third-party services…including laboratory test results, phone numbers, patient names, emails," and more (2022). This is directly comparable to the threats proposed in this paper, as the disclosure of service member's PII by threat actors through tracking pixels offers an avenue to secretly record information.

4.3 Fingerprinting

Fingerprinting describes the "technique used to create a unique string that identifies internet users" which "is stored in a cookie or browser storage, allowing websites to request it and identify visitors" (Tasoulas, Gazis, and Tsohou, 2025). However, it does not necessarily need cookies; it is also able to "rel[y] on information obtained from the user's browser and device," making them extremely difficult to avoid (Ourrahte, El-Yahyaoui, and Ziani, 2025). This goes beyond cookies, as threat actors develop profiles that—in the best case—"provide personalized services," while—in the worst case—collect vast amounts of PII about someone through "the unique pattern of information visible whenever a computer visits a website" (Tasoulas, Gazis, and Tsohou, 2025; Kaur et al., 2017). Examples include "Canvas, Browser, HTTP Headers, Battery, IP Address," and others; all of these rely on characteristics unique to the user accessing the internet and range from digital components (i.e. browser settings) to physical components (battery type).

These are especially concerning because they can allow threat actors to map users across websites, as persistent cookies do. Additionally, knowledge of a user's component version can lead to the exploitation of vulnerabilities

[3]Tracking pixels are sometimes also referred to as web beacons.

specific to that version. In the context of OPSEC, as outlined in the cookies section, threat actors can build profiles of service members by leveraging data service members use to access the Internet without their awareness.

4.4 Behavioral Methods

Other methods focus on analyzing specific user behaviors. For example, spyware— "software programs installed on a computer to monitor activity or cause harm"—will "often collaborate with other software or techniques, such as Adware or keystroke loggers" (which can "capture sensitive information like passwords") (Tasoulas, Gazis, and Tsohou, 2025). Unlike the methods described previously, surveillance technologies analyze user behavior and actions to monitor trends and gather data. This includes a plethora of various techniques, but for the purpose of this paper, we will broadly generalize the human element. This is fully shown in Bella et al.'s "A Socio-Technical Methodology for the Security and Privacy Analysis of Services," which breaks surveillance technologies into "layers" and introduces the human element as an important level for future research to understand the human impact on digital surveillance (2014). Additionally, the paper argues that "an extended view of a security protocol is needed to include human users, social protocols, and behaviors; that is, see the system as a much more complex socio-technical system" (Bella et al., 2014).

This argument posits that humans are the most vulnerable aspect of digital security, with PII gathered to target users based on their specific behavior. This can include data gathered from other digital surveillance techniques (cookies, fingerprints, etc.), but they can also include behavioral surveillance techniques such as keystroke logging, "bidding history," "shopping preferences," "[m]ouse click and movement analysis," or other PII "in context-aware phishing" (Bella et al., 2014; Ourrahte, El-Yahyaoui, and Ziani, 2025). Logging information while analyzing the human element emphasizes the need for education on proper internet usage, especially for service members. Behavioral surveillance techniques only increase the opportunities for threat actors to gather PII, posing a risk to users and servicemembers alike.

4.5 Cross-device Methods

Cross-device methods address a real threat that has become increasingly prevalent with cellular devices. The possibility of threat actors targeting users through the victim's phone is another category of digital surveillance techniques. Within Baek et al.'s "Targeted Privacy Attacks by Fingerprinting Mobile Apps in LTE Radio Layer," the researchers "demonstrate[d] that the physical channel of LTE alone is sufficient to carry out previously-proposed privacy attacks to identify which mobile applications are in use on a device," which "can be carried out through self-deployed sniffers directly on the exact traffic transmitted in the air…to…detect communication links between targeted users" (2023). Although this technique uses fingerprinting (and is worrisome because it employs "undetectable techniques"), it warrants a specific classification because it represents the development of adversarial techniques used by threat actors against users' cellular devices (Baek et al., 2023). As more people continue to purchase and use smartphones, this presents a new opportunity for an adversary to exploit vulnerabilities in their wireless capabilities.

This surveillance technique also has implications for service members. Digital phones could disclose PII if a threat actor detected communication links or connected to the LTE channel the victim was on. Of course, this does not argue for service members to refrain from cell phone usage. Instead, it ties directly to a future research recommendation in "Tracking the Trackers: Commercial Surveillance Occurring on U.S. Army Networks," where the authors stated that "[d]evices such as smartphones utilize commercial cellular providers to connect to Internet resources, and do not benefit from DoDIN security;" therefore, methods should be imposed to protect service members digital devices to ensure threat actors do not take advantage of them (2025).

5. Synthesis

We now outline the different categories of countermeasures to digital surveillance technologies currently available, along with their effects and capabilities. Additionally, the limitations and gaps are analyzed to determine the drawbacks of each and their overall effectiveness. The findings are summarized in Table 1, which is used to graphically represent the synthesis. Additionally, the categories will be modeled after the research conducted in Ourrahte, El-Yahyaoui, and Ziani's "Exploring Techniques and Countermeasures Against Browser Tracking: A Comprehensive Survey" (2025) to group similar technologies and aggregate data.

Table 1: Synthesis of Countermeasures to Digital Surveillance Technologies

Category	Examples	Usage (against)	Gaps	Sources
Browsers	Tor Browser, Mullvad Browser, Brave Browser, Mozilla Firefox, Apple Safari	Cookies, tracking pixels, fingerprinting, cross-device identification	Reduced functionality of some websites, burden to users	Ourrahte, El-Yahyaoui, and Ziani, 2025; Luangmaneerote, Zaluska, and Carr, 2016
Browser extensions/plugins	Ghostery, uBlockOrigin, AdBlock Plus, NordVPN Extension	Cookies, tracking pixels, fingerprinting, advertisements	Blocks some content, increases processing time, added burden to users	Englehardt et al., 2015; Ourrahte, El-Yahyaoui, and Ziani, 2025
Domain Name System (DNS)	pfBlockerNG, NextDNS, PiHole	Tracker domain endpoints	Domains and IP addresses are often ephemeral	Master et al., 2025; Lin et al., 2022
Education	Organization-wide, Individual training	Behavioral	Requires user commitment and cognitive load	Fox et al., 2023
Policy/Regulatory	General Data Protection Regulation (GDPR), California Consumer Privacy Act (CCPA)	Data collection, data sharing, data deletion	Varies by jurisdiction of regulated entities and which citizens are entitled to protections	Miller et al., 2024; Papadogiannakis et al., 2021

5.1 Browsers

A basic (but effective) way to protect against digital surveillance online is to use specific browsers. For example, Microsoft Edge allows users "to block trackers designed to monitor user behavior," "prevents tracking by blocking trackers from sites the user has not visited," and "can…block all tracking by activating [an] option;" however, it is not as robust as alternative browsers designed specifically with privacy implementations (Ourrahte, El-Yahyaoui, and Ziani, 2025). Other browsers, like Mozilla Firefox and Brave, have built-in mitigations for cross-site tracking, third-party cookies, and resistance to browser fingerprinting (Ourrahte, El-Yahyaoui, and Ziani, 2025). Additionally, there exist "[p]rivacy-focused search engines" that include DuckDuckGo, which "use some techniques to prevent forwarding the search results to the linked website" (typically through obfuscation) (Bujlow, 2017). Firefox also, by default, "is known for forbidding reading cookies by third parties" and offers several plugins/addons to enhance protection, such as RequestPolicy (which "blocks all the cross-site requests") and Lightbeam (which "enables the user to see the requests made to the first- and third-party sites") (Bujlow, 2017).

Another major browser committed to keeping the user secure is Tor. While investigating the effectiveness of countermeasures to fingerprinting, Luangmaneerote, Zaluska, and Carr (2016) found that Tor was very effective at preventing fingerprinting (2016). However, this came with some gaps that offered adverse effects to users. This included problems with "display, functionality, usage, and login problems," making it "appear to generate more user dissatisfaction than other techniques," as well as slower connection speeds. So, while certain protective browsers might be more effective at protecting user information, they may come at the cost of usability, potentially limiting their widespread adoption due to user frustration.

5.2 Browser Extensions/Plugins

Another primary countermeasure to digital surveillance technologies is the usage of browser extensions/plugins. These allow users to provide additional protection for their browser of choice, ensuring their data is further protected against threats. One example is "Ghostery…a popular list-based browser extension for blocking third-party requests to domains considered to be trackers" (Englehardt et al., 2015). This countermeasure was effective in a study by the authors of "Cookies That Give You Away: The Surveillance Implications of Web Tracking," which showed a statistically significant decrease in clustering via cookies (2015). Another similar plugin is uBlock Origin, which "[b]locks tracking scripts, ads, and intrusive domains" that is "[l]ightweight, open-

source, and highly configurable" (Ourrahte, El-Yahyaoui, and Ziani, 2025). However, despite these tools' effectiveness, users sometimes remain vulnerable, which can also cause user experience degradation on some websites. These extensions attempt to block data collection, but rely on data feeds of known third-party endpoint domains to function. As new tracker domains are introduced (or large advertising firms change their tracker domains to avoid blocking tools), users experience gaps in coverage.

This solution still does "offer tools for blocking trackers, encrypting data, or masking IP addresses and other information" to protect user data online (Ourrahte, El-Yahyaoui, and Ziani, 2025). However, user experience degradation may prevent adoption of such tools. Ad blocking extensions may "slow down browsing," cause extra effort to use (from users), "block some useful content," "slow down your connection," and be incompatible with certain websites (Ourrahte, El-Yahyaoui, and Ziani, 2025). Although these add extra burdens to users, they can still reduce the likelihood of a PII breach. Additionally, both browsers and browser extensions/plugins can be installed on cellular devices, further protecting phones and user data.

5.3 Domain Name System (DNS)

From the user standpoint, it is possible to block the advertising servers that deliver content directly to devices and web browsers. DNS-based ad-blocking tools such as Pi-hole (Pi-hole LLC, 2024), pfBlockerNG (Nguyen, 2024), and NextDNS (NextDNS, 2024) operate as DNS sinkholes, intercepting DNS queries for known tracker and advertising domains before a connection is established and returning a non-routable address in place of the tracker endpoint (Master et al., 2025). Because blocking occurs at the network layer before any data exchange, these tools can protect all devices on a network, regardless of operating system or browser, including smart TVs, mobile devices, and IoT devices that cannot run browser-level extensions (Pi-hole LLC, 2024). While DNS-based ad blocking is very effective, it requires users or organizations to create access lists that block specific domains. The IP addresses and domain names of ad and tracker servers may change over time, requiring configuration adjustments.

The effectiveness of DNS-based blocking depends on the currency and coverage of upstream blocklists, which aggregate known advertising and tracking domains from community-maintained sources such as EasyList and EasyPrivacy. Lin et al. (2022) demonstrate this requirement as a structural vulnerability rather than a routine maintenance burden. After conducting a crawl of 50,000 websites, Lin et al. (2022) show that advertisers systematically register replica ad domains that evade filter lists. Many users remained exposed for over two years despite having DNS-based blocking enabled.

5.4 Education

Another countermeasure exists beyond software or even applications. This section primarily focuses on preventing digital surveillance by raising users' awareness through simple education to counter the "socio-technical" surveillance described in behavioral methods for digital surveillance. As many of these surveillance techniques are passive and rely on unaware users, proper training on these topics will help users develop the online skills necessary to use the Internet safely.

ACI has also emphasized this need for education, especially among military service members. For example, while analyzing the commercial surveillance occurring within U.S. Army Networks, recommendations were proposed to "[e]ducate service members and civilian employees about the risks posed by commercial tracking, CAI (commercially available information), and data brokers" (Master et al., 2025). This directly ties into the data brokers mentioned within Sherman et al., 2023, where it is recommended that "[t]he Army should provide awareness training and best practices surrounding commercial data collection" at the institutional level (as, although individual training is helpful, it is not always fully enforced as it relies upon the responsibility of the individual much more heavily).

6. Discussion and Conclusion

The literature reveals that the primary design goal of surveillance architectures is to externalize the processes of data collection and identity resolution, effectively limiting the visibility of the aggregation of session data, metadata, and behavioral data post-transmission. While countermeasures implemented on the client-side may effectively limit the visibility of tracking signals, they do not limit session aggregation, probabilistic identity resolution, or long-term profile construction on the server-side. Thus, the effectiveness of countermeasures is inherently limited, regardless of proper implementation.

The above findings are particularly relevant to OPSEC. The findings of the Duke study reveal that the information present in the commercially available datasets is already sufficiently rich to enable the identification, clustering,

and profiling of service members without access to classified systems or government networks. The findings of the above studies, in combination with the literature on tracking pixels, fingerprinting, and behavioral inference, reveal that the issue of exposure is not simply the result of the presence of unique identifiers, but rather the result of the aggregation of impermanent signals that, in combination, can be indicative of an individual's activities. The inability to view the aggregation mechanisms effectively limits the user's ability to properly assess risk, thereby making the risk mitigation process more complex.

Several studies suggest that the use of privacy-enhancing tools may have unintended effects. Configuration-based defenses, such as customized ad blockers or extension-rich browsers, may decrease population-level anonymity by making users more distinctive. This is important to service members who operate in high-risk environments. Efforts to minimize surveillance exposure may facilitate identity resolution when combined with server-side analytics, underscoring that individual-level countermeasures alone are not sufficient to achieve OPSEC-relevant risk reductions.

The overall body of evidence indicates that current countermeasures place the onus on the end user while ignoring the most significant means of digital surveillance. While education and awareness are important for reducing risk-taking behaviors, they are not enough to address the passive, opaque data flows associated with commercial infrastructures. This will require further research into server-side tracking behaviors and methods to reduce data collection, retention, and resale at the source.

Prevalent digital surveillance technologies and gaps in existing countermeasures underscore the need for expanded policy measures to protect users. Examples of existing policy include the General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA). The GDPR "obliges websites to seek users' consent before collecting their personal data," and "users must be informed if their data is stolen, and companies must protect their customers' data" (Ourrahte, El-Yahyaoui, and Ziani, 2025). This provides some protection to users in Europe. Current legal frameworks in the U.S. provide few avenues to limit or restrict data collection and are only at the individual state level rather than applied nationally. The CCPA is a law that governs the protection of online users' privacy and the processing of their data by companies, which allows users to "opt out" of the sale of their data (Ourrahte, El-Yahyaoui, and Ziani, 2025). This does not provide recourse after data has been collected, shared, or sold, and the exposure of PII through CAI persists despite California's efforts – and protections are only afforded to California residents. Policymakers should consider widely implementing "opt-in only" requirements when proposing consumer privacy legislation, to extend proactive protection to at-risk populations such as service members and their families. Users should be fully aware when first-party or third-party entities are collecting their sensitive personal information, and have the agency to reject such requests if they desire or must do so due to the sensitivity of their employment. Given that commercial entities can aggregate service members' PII, sell it to others, and profit from it – some of those customers potentially being malicious online actors – poses significant challenges for military members and government officials working in a national security context.

Acknowledgements

We would like to express our gratitude to the Army Cyber Institute for their financial support. We also thank our anonymous peer reviewers for their detailed and helpful feedback, which improved this manuscript's quality.

The analysis presented in this paper is attributable exclusively to the authors. It does not represent the views of the United States Military Academy nor imply or constitute endorsement by the U.S. Army or U.S. Government.

Ethics declaration: No IRB approval was required for this study.

AI declaration: We used Grammarly to correct spelling mistakes, identify grammar errors, and adjust awkward phrasing. We also used Semantic Scholar to find sources. Our use of artificial intelligence tools helped to refine our scope and focus of tracking technologies toward OPSEC and its application to service members; all conceptual content, analytical framing, and interpretation reflect the intellectual contribution and responsibility of the authors.

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From Evidence to Decisions: Interview-based Study of Reporting Practices in Defensive Cyber Operations

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Abstract: Defensive cyber operations (DCO) missions demand rapid decision-making under active digital threats. Established doctrine and industry standards provide technical procedures for handling incidents. However, they offer little guidance on how reporting artifacts, such as data analytics, visualization, and briefs, are produced, adapted, and communicated for decision-making. To address this gap, we conducted an empirical investigation of reporting practices in DCO through semi-structured interviews with 15 cybersecurity practitioners (managers, analysts, infrastructure technicians, and developers) engaged in incident response and threat hunting. We derived a three-dimensional model of the reporting lifecycle structured around reporting roles, purpose, and operational timeline that characterizes how network data and analytic outputs are represented in reporting artifacts such as templates, risk matrices, and briefs under time pressure and organizational constraints. Our findings highlight how reporting is shaped by trust, audience language, and the balance of standardized and flexible templates. We point to the need for traceability-linked modules, audience-aware data analytics and visualization tools, and playbooks that incorporate reporting artifacts with flexible guidance in DCO.

Keywords: Incident response, Defensive cyber operation, Stakeholder, Human-dimension, Analytics, Reporting

1. Introduction

Defensive cyber operations (DCO), including incident response and threat hunting missions, place practitioners in environments where decisions must be made at speed, often under active adversary threat and incomplete information. Established doctrine and industry standards, such as NIST SP 800-61, MITRE ATT&CK framework, and Department of Defense (DoD) cyber operations guidance (2023), provide detailed technical procedures for detecting, analyzing, containing, and recovering from incidents. However, they offer comparatively limited direction on how reporting artifacts such as templates, briefs, and risk/impact visuals are produced, adapted, and communicated as decision products that leadership can trust and act upon, or how organizational structures and human factors shape the credibility and consumption of those reports. The challenge lies in understanding how technical evidence is translated into decision-ready reporting, and how human-factors, audience alignment, and time pressure influence that translation. Prior work leaves key aspects of reporting practice unexplored. Questions remain about how credibility is maintained or lost when evidence is transformed into reporting products.

To address this gap, we conducted an empirical study of reporting practices in DCO. We carried out semi-structured interviews with 15 cybersecurity practitioners, including managers, analysts, infrastructure technicians, and developers engaged in incident response and hunt missions to examine how reporting practices are shaped by technical, human, and organizational factors. We analyze how reporting and analytics are produced, adapted, and communicated in operational settings. From these interviews, we derived a three-dimensional model of the reporting lifecycle linking practitioner roles, goals, and operational timelines to contextualize practitioners' insights. *Figure 1* summarizes this three-dimensional model by mapping the reporting goals *(Section 3.2)* described in our interviews to phases of operation and primary work-role associations. The model explains how analytical and reporting practices unfold in context and surfaces the conditions under which reporting products are accepted or dismissed. These conditions span human dimensions and the translation of technical evidence into decision-focused artifacts.

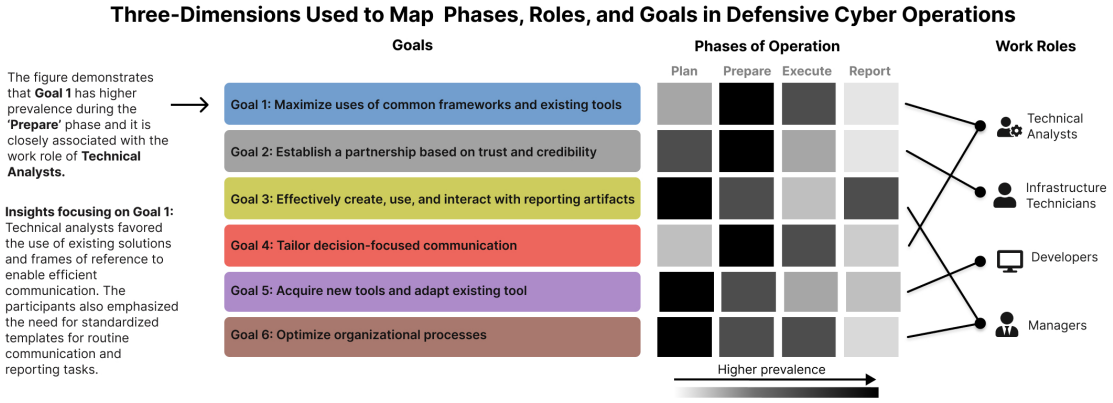


Figure 1: Three-dimensional model illustrating how practitioner goals align with operational phases and DCO work roles. Shading indicates prevalence across phases; connecting lines show primary role associations. Example insights (left) highlight how Goal 1 emerges during the 'Prepare' phase and is emphasized by technical analysts

In addition to the framework, we also offer reflections and practices for improving reporting credibility and effectiveness, emphasizing conditions such as trust and acceptance that determine whether reports succeed in practice. We emphasize the importance of reporting technologies, such as traceability-linked modules, that connect data to decision artifacts and make their sources transparent. We also highlight the value of audience-aware analytics and visualization tools that allow tailoring and scoping to different stakeholders. Finally, we call for updates to playbooks and doctrine that provide flexible guidance on producing and adapting reporting artifacts in DCO.

2. Related Work

We consider three main areas of prior work: input and tool credibility, playbook requirements, and decision-making during analysis. Our interest lies in how DCO experts create and use reporting artifacts, examining how reports are adapted and communicated across operational phases. We also consider how reporting practices are shaped by organizational hierarchies and complex analytical workflows.

Kassim et al.'s study of national CSIRTs, which examined how teams evaluate tools and data for incident response, argued for systematic evaluation, but no shared procedure exists (Kassim et al., 2023). They proposed candidate criteria for assessing tools (usability, maintainability, security) and data (credibility, timeliness, structure), but their work remains at the input level. Like doctrines such as NIST SP 800-61 and ISO/IEC 27035, Kassim et al.'s work does not examine how credibility carries into reporting. This focus on inputs is also reflected in adjacent studies of analysts' practices. D'Amico et al.'s cognitive task analyses show that analysts under time pressure often rely on heuristics and struggle to judge the reliability of feeds and tools (D'Amico et al., 2005). Parsons similarly observes that evaluation practices are typically ad hoc rather than systematic (Parsons 2022). Gutzwiller et al., extend this point in the situational awareness literature, noting that analysts' ability to act depends heavily on whether inputs are trusted, and in later work, they identified differences in cyber operator roles and called on the research community to further develop situational awareness from the perspective of end-users (Gutzwiller et al., 2016, Gutzwiller et al., 2020). Together, these works underscore the role of input credibility in analysis and decision-making, while leaving open questions about its role in the reporting artifacts used across organizations.

Works on structured playbooks and doctrines extend beyond inputs to formalize incident handling steps, including reporting. Doctrine and standards such as NIST SP 800-61 (Nelson et al., 2024) and ISO/IEC 27035 define phases of incident response and prescribe procedures for detection, analysis, containment, and recovery. Similarly, DoD doctrine (Staff 2018) codifies cyber operations at the organizational level. Frameworks such as MITRE ATT&CK (MITRE 2025) provide taxonomies of adversary tactics that can be embedded into playbooks. These sources emphasize structure, standardization, and technical coverage, but often treat reporting as compliance documentation or post-incident summaries. They offer little guidance on how reporting artifacts should be produced, adapted for different audiences, or evaluated for credibility in practice. Recent work on playbooks reflects the same limitation, identifying reporting as a feature but not addressing how it is enacted in real-world settings. Akbari et al. identified sixteen requirements for playbook-assisted incident response,

including reporting ability, adaptability, and confidentiality (Gurabi et al., 2024). They proposed a framework and prototype tool that support established process-modeling and machine-readable playbook standards, enabling interoperability and reuse across platforms. Gurabi et al. (2024) fill part of the standards gap by formalizing playbook requirements and creating a specification that includes reporting. We build on their framework by using their categories to structure our coding related to reporting tasks and extending it with evidence of reporting practice in DCO.

Other research illustrates why these requirements are difficult to realize in practice. Nyre-Yu et al. describe the conflicting priorities of mission, policy, and organizational processes within incident response teams, showing how a lack of contextual understanding can bias operations (Nyre-Yu et al., 2019). In our study, we view these findings through the lens of decision-making and reporting in operational environments, where such biases can shape how reporting artifacts are created and used. Gao highlights how cyber defense is constrained by organizational policies and the limits of monitoring technologies, reinforcing the tension between formalized procedures and practice in ways that can also shape how reporting artifacts are produced and how decisions are made under operational pressure (Gao et al., 2021). Mathews et al. propose collaborative approaches for integrating cyber threat data from traditional and non-traditional sources, highlighting the challenges of structuring and interpreting heterogeneous information across organizations (Mathews et al., 2012). We see similar challenges in how reporting artifacts are adapted and understood across organizational boundaries.

Spring and Illari review how analysts make decisions during incident analysis, highlighting three persistent challenges: how to prioritize tasks and tactics, when to generalize from incomplete evidence, and how to craft persuasive reports that others trust (Spring and Illari 2021). These challenges underscore the human dimension of incident response, showing that decision-making is not only technical but also social and communicative. We used this contribution in how we approached findings of our own study, interpreting participants' accounts of prioritization, uncertainty, and persuasion through this lens. In doing so, we extend Spring and Illari's framing with empirical evidence of how these challenges unfold under operational tempo and organizational constraints.

Prior work in this area highlights the importance of these challenges. D'Amico et al. describe how analysts escalate evidence under time pressure and struggle to communicate uncertainty with credibility (D'Amico et al., 2016). Dimara et al. emphasize that visualization and communication in cyber defense are shaped by human-centered constraints in time-sensitive contexts (Dimara et al., 2022). Gutzwiller et al. extend this perspective by showing how situational awareness depends on how inputs are trusted, and later call for research that attends more directly to operator roles and perspectives (Gutzwiller et al., 2016; Gutzwiller et al., 2020). Classic situational awareness frameworks, such as Endsley's three-level model (Endsley 1995), and subsequent elaborations (e.g., Coufalíková et al., 2021; Malviya et al.,2011), also stress that analysts' ability to act depends on how information is represented and interpreted.

Prior work converges on the importance of credibility, structure, and communication in incident response, but the practices of reporting remain insufficiently understood.

3. Methodology

To contextualize practitioner perspectives on the topic of DCO reporting and communication to decision makers, we conducted a qualitative study using semi-structured interviews. The goal of this study is to understand how practitioners in DCO create, use, and communicate data and artifacts while working under operational constraints. We aimed to capture how reporting practices unfold in real settings and what factors influence whether reporting artifacts are trusted and acted upon.

Participants: We interviewed 15 cybersecurity practitioners across three government organizations who play key roles in DCO reporting and decision-making, including managers, technical analysts, infrastructure technicians, and developers (Table 1). We identified participants through professional networks across organizations. From an initial group of 24 qualified candidates, we selected participants to ensure a mix of roles and experience levels. We did not provide monetary compensation.

Data Collection: We conducted interviews either virtually or in person, depending on participant availability. Each session lasted about an hour. Given the sensitive nature of the domain, we maintained strict confidentiality and avoided collecting any identifying operational details. We stored audio recordings locally for analysis and then removed them. This approach builds on prior interview-based studies that examine data work and communication practices in context (Tory et al., 2023; Liu et al., 2020; Erete et al., 2016).

Data Analysis: We analyzed the interview data using an iterative qualitative coding approach informed by grounded theory (Strauss and Corbin, 1997; Glaser and Strauss, 2017). We focused on identifying recurring practices and conditions that shape how practitioners use reporting and visualization across roles and operational phases. Two researchers reviewed and coded the data together and resolved differences through discussion until reaching agreement. We then grouped the codes into higher-level themes, which informed the three-dimensional framework below and contextualized practitioner insights.

Framework: How practitioners create, use, and communicate data varies based on work role, operational phase, and immediate goals, influencing how artifacts are adapted, trusted, and acted upon.

Table 1: Participant demographics and work roles, with reported uses of data artifacts

Participants	Job titles held	No. of years (Experience)	Education	Workrole	Use of Data Artifacts
P1	Element Lead, Capability Manager, Network Engineer	5	Bachelor's	Managers	Aggregate; Tailor to audience; Seek decision and support; Disseminate information
P4	Element Lead, Operations Officer	10	Master's		
P7	Element Lead	6	Master's		
P14	Operations Officer, Executie Officer	5	Bachelor's		
P3	Network Analyst, Host Analyst, Hardware Engineer	8	Bachelor's	Technical Analysts	Gain situational understanding; Communicate scheme of maneuver; Support decision making
P5	Analyst, Instructor	15	Bachelor's		
P10	Host Analyst, Cyber Planner, Technical Advisor	11	Master's		
P13	Network Analyst, Host Analyst, Technical Advisor	5	Master's		
P2	Network Analyst, Cyber Planner, Hardware Engineer	8	Master's	Infrastructure Technicians	Gain situational understanding,; Understand network infrastructure, and highlight hardware, connection and operational capability
P6	Network Analyst	6	Master's		
P8	Network Analyst, Host Analyst, Data Engineer	11	Master's		
P11	Network Analyst, Host Analyst	6	Bachelor's		
P9	Software Developer	8	Master's	Developers	Understand requirements; Delegate tasks; Demonstrate capability
P12	Software Developer, Traninee Advisor	10	Master's		
P15	Software Developer	6	Master's		

Based on our interviews, we developed a three-dimensional framework to contextualize practitioner insights focusing on work roles, phases of operation, and practitioner goals. The framework explains how reporting and communication artifacts evolve as work progresses, and information is translated for different audiences.

3.1 Phases of Defensive Cyber Operations

Our analysis showed that reporting in DCO is organized around recurring operational phases that practitioners use to orient themselves. These phases shape when information is collected, how it is refined, and when it is communicated, even when real operations involve iteration, overlap, or exceptions. Prior work has similarly examined how data and cybersecurity practitioners rely on phases and processes to structure their work (Muller et al., 2019; Muckin and Fitch, 2014).

Across interviews, we observed that reporting artifacts changes based on who owned the work, how mature the evidence was, and what the reporting output needed to achieve, rather than movement through a rigid procedure. Naming the phases let us track how reporting artifacts evolve over time, from early alignment and readiness to real-time operational updates, and finally to decision-focused products.

We identified four phases that consistently emerged across interviews:

Plan: The team works with stakeholders and technical experts to clarify mission scope and requirements, define responsibilities, identify gaps, and establish initial communication with the customer organization.

Prepare: The team turns the plan into operational readiness by securing support and authority, validating personnel and tools, establishing access and connectivity, and rehearsing key procedures before mobilization.

Execute: The team carries out the defensive task while adapting to new findings, maintaining access to the customer environment, and providing periodic updates to sustain shared understanding and situational awareness.

Report: The team consolidates findings into a formal report that explains impacts and provides recommendations for mitigating identified vulnerabilities and threats.

3.2 Work Roles

In large hierarchical organizations, roles shape what information people see, what they are responsible for, and what they need from data and visualizations (Rajan et al., 2021). This is consistent with prior observations that

job titles vary across organizations while underlying duties and separation of work remain similar (D'Amico, Whitley, et al., 2005), and that role boundaries create real handoff and coordination challenges when analytic and visualization work is distributed across teams (Walny et al., 2020, Crisan et al., 2021). We also ground our role grouping in common cybersecurity functions noted in prior research (Sabillon et al., 2017).

We grouped interview participants into four work roles based on function, since job titles alone were not reliable indicators of responsibilities:

Managers: Oversee the operation and translate technical findings into updates and products that enable decisions and shared understanding across stakeholders.

Technical Analysts: Work directly with mission data to identify and investigate malicious activity, then communicate technical assessments that shape what gets reported and how evidence is framed.

Infrastructure Technicians: Establish and sustain the access and connectivity needed for the team to operate in the customer environment, often relying on infrastructure views (for example network diagrams) to communicate dependencies and operational constraints.

Developers: Build or adapt scripts, analytics, and applications to close technical gaps, then demonstrate and explain tool capabilities to audiences with mixed technical backgrounds.

Table 2: Key tasks involving interactions with data artifacts, with specific examples of data and visualization products within different phases of operations

Phases	Data	Reporting Arctifacts	Key tasks per phase
Plan	• Task orders • Network logs and data • Threat intelligence	• Organizational chart and hierarchy map • Network map (initial ingest)	• Identify needs, gaps, and requirements • Pair tools and techniques • Establish hardware requirement • Establish development requirement
Prepare	• Authority • Credentials and access • Additional network logs and data • Additional threat intelligence	• Decision template • Infrastructure and topology related visualization products • Scheme of maneuver	• Build relationships • Conduct on-site visits • Establish lines of communication • Communicate for decision and support
Execute	• Collect • Network data • Updated threat intelligence	• Reporting template • In-progress reports	• Communicate with decision makers and stake holders • Provide in-progress and periodic reports • Ensure shared understanding
Report	• Technical notes	• Updated reports	• Report findings to stake holders

3.3 Practitioner Goals

Practitioner goals were grouped and summarized from our interviews. We analyzed interview transcripts using a grounded theory-informed, multi-pass coding approach using open, axial, and selective coding. Two researchers reviewed and coded the data together and resolved differences through discussion until reaching agreement. We then grouped recurring codes into higher-level themes and consolidated those themes into a small set of practitioner goals and sub-goals that capture what participants were trying to achieve through reporting and communication across roles and operational phases. These goals give us a practical way to link reporting artifacts to intent and success criteria, and by showing how priorities shift across roles and phases.

Common Framework *Goal 1: Maximize use of common frameworks and existing tools:* Use shared language, templates, and standard products to coordinate work, while adapting them when context demands it. Participants emphasized using common language for effective communication and relying on standardized tools. This often meant a shared lexicon and *"common frame of reference"* that helps teams establish and maintain communication across customer and home organizations and translate evidence into brief-ready outputs. Templates and standard products supported routine reporting, but practitioners emphasized the need to adapt details and framing to the case context and the audience.

Trust *Goal 2: Establish partnerships based on trust and credibility:* Build working relationships that make findings believable and actionable, especially early in an operation. Participants described trust and credibility as a condition that develops between the customer and the enabling entities supporting the mission. They emphasized that early interactions shape whether later reporting is accepted, including "dos and don'ts" that influence credibility during initial engagement and coordination.

Visualization *Goal 3: Effectively create, use, and interact with visualization:* Use visual representations to build shared understanding, communicate updates, and make technical work legible to different audiences. In this paper, visualization includes common reporting visuals and artifacts used in DCO products, such as risk or impact visuals and brief-ready representations that help translate technical evidence into decision-focused reporting. This goal emphasizes visualization as part of the reporting workflow, supporting coordination and communication across roles under time pressure.

Communicate *Goal 4: Tailor decision-focused communication:* Produce outputs designed to drive a decision, with careful framing of impact, urgency, and what to do next. Practitioners emphasized that reporting must be shaped around the stakeholder who will act on it, since communication often moves *"up the chain"* to audiences with different technical backgrounds. They described tailoring as translating technical evidence into decision-ready language and levels of detail that support timely action and acceptance.

Acquire and Adapt *Goal 5: Acquire new tools and adapt existing tools:* Identify capability gaps and integrate new methods (including automation) into existing environments and constraints. Participants described the need for decision-support capabilities such as automation and AI/ML, while also emphasizing the practical work of adapting current tools to fit operational needs. They specifically pointed to emerging requirements like automating parts of the workflow, piping data into reporting systems, and improving interoperability across tools to support faster reporting and coordination.

Process *Goal 6: Optimize organizational processes:* Reduce friction from coordination, handoffs, and knowledge management across a multi-tier organization. Participants emphasized that reporting success depends not only on analysis quality, but also on how work is coordinated across roles and organizational tiers. They described recurring process challenges such as collaboration overhead, role handoffs, and knowledge management gaps that slow reporting and reduce consistency in decision-focused outputs.

We overlay our three framework dimensions into a single representation to connect roles, phases, and goals in one view. Building on our qualitative coding, we identified key tasks and events described across interviews and mapped each to the goals above. We then placed these tasks within the phases and roles where participants most often described them occurring, and color-coded them by goal to show how practitioner intent aligns with operational work. *Figure 2* shows this mapping; for readability, it highlights the most prominent tasks that relate to reporting and communication artifacts, including the subset involving interactions with data artifacts that we expand in *Table 2*. Although we label phases for clarity, participants described time-critical operations where phases often overlap or compress. Here, "customer/home" indicates defended vs supporting organizations; "teams" are functional sub-teams; "rehearsals" are brief pre-execution checks; and "threat intelligence integration" applies external indicators to interpret current evidence.

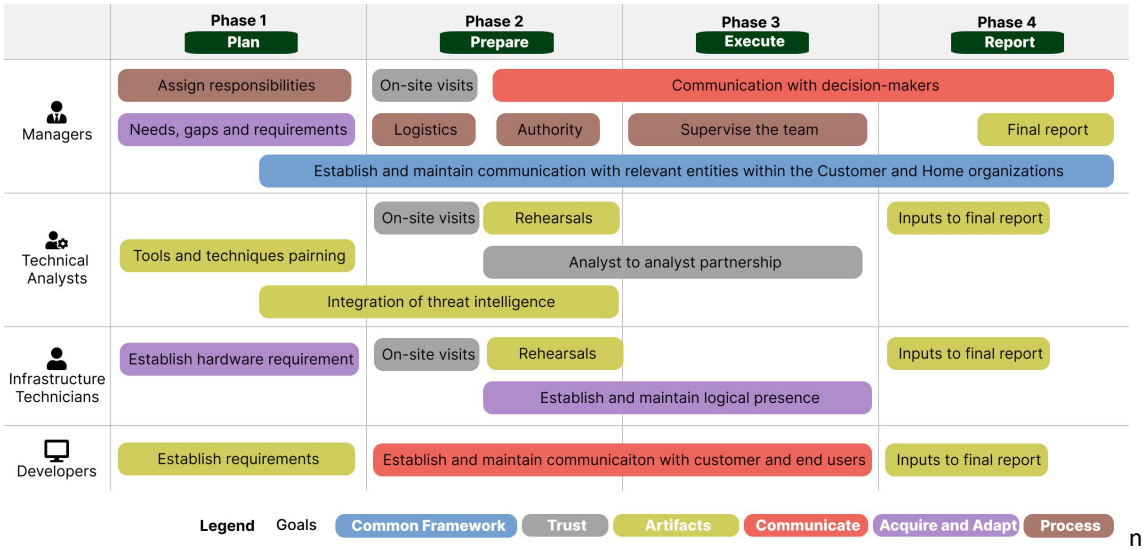


Figure 2: This figure combines all three DCO framework dimensions, overlaying key tasks and events for each work role. The key tasks are nested within various phases of operation and coded based on their associated goals. We expand the identified key tasks that apply to interactions with data artifacts in Table 2

4. Insights

In this section, we share the key insights we garnered from our participants listed in *Table 1* and using our framework in Section 3 for context.

4.1 Socio-technical: Early Coordination and Trust Groundwork

When a mission begins, participants describe early work as heavily shaped by coordination, relationship-building, role clarification, and resolving access and integration issues. Multiple participants emphasized that people and process dynamics can be more challenging than the technical work itself. P8 noted that "The biggest obstacle is not the technical, it is the personnel in that network space" (P8). P11 explained that supporting personnel are often balancing their own responsibilities while also helping the incoming team, making the work "very people heavy" and "very relationship driven" (P11). Participants also pointed to the value of identifying the right people early to build situational awareness and reduce avoidable breakdowns in communication (P12).

Early-phase progress is often shaped by socio-technical work, especially building trust and coordinating across organizations. Participants emphasized the need to clarify who to engage, who owns which actions, what information is missing, and which access or integration steps are blocking progress.

4.2 Standardization: Templates with Room to Adapt

Participants were very direct about how much time routine communication and reporting during operation takes, especially when teams have to recreate products and visuals from scratch. P6 described this as "reinventing the wheel" (P6). P4 emphasized that expectations shift across units and leaders, noting, "You have to make a new standard every time you do something, and every unit and every leader has a different standard. Makes it very tough" (P4). At the same time, participants described the value of modularity. P13 argued for "modular standardized products" that facilitate adjustments when mission conditions change, articulating an idea of "plug and play" (P13).

Participants also cautioned that standardization can become harmful when it turns into a checklist. P6 noted, "I think it definitely kind of kills creativity," and warned that analysts may stop looking for issues that are not captured by the template, even if something important occurred earlier (P6). Participants also described the burden of constantly tailoring products to different audiences. P13 pointed out that different leaders expect different standardized products, which can result in reporting the same information multiple ways, calling this "not great" (P13). P3 similarly observed that "sometimes the format becomes more important than the information you're trying to convey" (P3). Finally, P14 raised the challenge of handling non-standard details, asking how teams can "ingest that properly and make that viewable by analysts in a meaningful way" and then communicate it back to the larger organization (P14).

Standardization helps when it speeds recurring operational updates, but participants cautioned that rigid checklist-style templates can narrow attention and make it harder to surface non-standard details, motivating modular products that balance consistency with adaptation.

4.3 Communication: Audience-aware Translation and Decision-focused Reporting

Participants emphasized knowing their audience and tailoring how information is presented because the same evidence must be translated into different levels of detail, terminology, and impact framing depending on who is making the decision and what authority they hold. P7 stated, "[...] You have to know your audience" (P7), and P4 noted, "The key difference is how the commander perceives information and how we tailor it to them" (P4). Participants also highlighted credibility-building through language. P4 stated, "So, the biggest thing that helped us build credibility was knowing the right terms to use and incorporating that into our products" (P4), and P7 emphasized communicating intent and reassurance ("I'm here to help") when engagement becomes combative (P7).

Participants described using common frames of reference to support communication across organizations. P3 discussed using the MITRE framework (Xiong et al., 2022) and noted, "We have a common understanding in terms of down to the level of the MITRE techniques [...]" (P3). P6 described using MITRE as a common lexicon and presenting non-MITRE techniques in the same tactic-technique-procedure style so they are understood in a familiar way (P6). Participants also described using analogies to communicate technical details to non-technical leadership (P5, P12). Participants emphasized that decision-makers want clear risk and impact analysis, and that communication becomes less technical as it moves up a chain of command (P12, P15).

These themes highlight the need to support audience-specific lexicon, bridge technical and non-technical communication, and convey risk and impact while preserving confidence in the reporting.

4.4 Adoption: Tool fit, Automation Limits, and how Reporting Lands in Practice

Participants cautioned that automated solutions and new tools are not always trusted or helpful in practice. P13 described analysts getting overwhelmed by "big data" and questioned whether automation can be trusted "if there's no standardization," noting that "the human element is messing it up at the ground level" (P13). P10 similarly stated that tools can hinder productivity when analysts spend time following what a tool tells them rather than doing the work, and when the tool requires everyone to use it, "consuming their bandwidth" (P10). This illustrates that simply replacing a process with a tool does not necessarily fix problems, and aligns with the need to design tools that "meet them where they are" (Tory et al., 2023).

5. Reflection

Reporting and communication in DCO are shaped by more than technical work. Audience, organizational context, and trust affect what gets reported and how it is received. Across interviews, we observed that reporting artifacts changed as they moved across roles and phases. Participants described how the same evidence gets explicitly tailored to the audience to support a decision. This sheds light on why teams use standard formats yet still adapt them, and why language, trust, and credibility emerge as practical constraints.

We also note growing pressure on evidence-to-decision translation as threats become more automated and operational timelines compress, making it harder to turn evolving evidence into decision-ready reporting fast enough. This issue motivates bounded uses of automation and AI in decision-support tools to speed up evidence-to-artifact translation and support analysis in the workflow, while preserving traceability so outputs from AI-infused workflows remain auditable and accountable.

Conducting and sharing research in security-sensitive settings also raised practical challenges. Designing the interviews was especially challenging because we were most interested in real personal stories that would provide rich insights, rather than generalizations and hypotheticals. We also iterated on question phrasing and categories to reduce the risk that small details could combine into something more sensitive.

We recognize limitations in our study. Our interview sample is small and may not fully represent the broader DCO community; participant selection also affects generalizability. In addition, given the sensitive nature of DCO, participants may not have been able to expand on their responses as much as they would have liked.

Finally, many participant recommendations emphasized visualization and reporting for *communicating* findings to decision-makers, not only for *understanding* the technical picture. Future work can validate these findings with additional teams and settings, and examine how the reporting lifecycle varies across organizations.

6. Conclusion

In this study, we present a descriptive framework that organizes reporting and visualization practices in DCO along three dimensions: work roles, operational phases, and practitioner goals. We use this framework to contextualize themes from our interviews and show how human and organizational factors, including trust, audience expectations, and communication practices, shape how data and visualization artifacts are created, adapted, and used in practice. The DCO study highlights how evaluation, feedback, and design decisions are intertwined in practice, often in ways that existing frameworks leave implicit. While these dynamics are not unique to cyber operations, they become especially visible in settings where decisions are time-sensitive and accountability matters.

Acknowledgements

Justin Raynor and Bijesh Shrestha are co-first authors and contributed equally to this work. We thank the interview participants for sharing their time, experiences, and perspectives.

Ethics Declaration: This study involved semi-structured interviews with human participants. Worcester Polytechnic Institute's IRB reviewed the study and granted an exemption.

AI Declaration: We used generative AI tools to assist with grammar and rephrasing.

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Cybersecurity Entry Points to the Energy Sector and Their Time-To-Compromise

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Abstract: Digitalisation has increased the cybersecurity vulnerability of critical sectors. It is essential to improve and gain knowledge of these sectors to minimise the risk of successful cyber-attacks. The energy sector is a vital part of society since infrastructures, such as healthcare and transportation, rely on it. Cyber warfare targeting the energy sector can cause severe consequences. The energy system consists of many, and distributed, parts for generation, transmission, distribution and consumption of electricity. A digital energy system also consists of Advanced Metering Infrastructures (AMIs), Electric Vehicle Charging Systems (EVCSs) and other smart grid components. This makes it difficult to gain an overview of where the energy system is the most vulnerable and where cybersecurity defence measures should be prioritised. In this paper we outline the most vulnerable cybersecurity entry points to the energy systems by analysing the known vulnerabilities. We compile a dataset of vulnerabilities within the energy systems domain based on Common Vulnerabilities and Exposures (CVEs) of the Industrial Control System (ICS) advisories from the Cybersecurity and Infrastructure Security Agency (CISA) for the energy sector. Thereafter, we focus on the 2717 vulnerabilities with the attack or access vector "Network", which indicates vulnerabilities that are exploitable via cyber-attacks. The dataset is categorised based on the type of vulnerability and the Smart energy Grid Architecture Model (SGAM) domain that it belongs to. With the dataset we are able to estimate the Time-To-Compromise (TTC) for different types of vulnerabilities and domains of the energy system. The dataset also allows for other conclusions, for instance that the most commonly found type of vulnerabilities are due to web-based weaknesses. Furthermore, the SGAM domain in which most vulnerabilities are found is the Customer Premises. TTC values are used to assess the cybersecurity of systems to make more informative decisions of where to prioritise defence measures. The values can be added to risk assessments, such as threat modelling frameworks and attack graphs to estimate which entry point an attacker is most likely to target.

Keywords: Cybersecurity, Energy systems, Cyber warfare, Vulnerability dataset, Time-to-compromise

1. Introduction

As a society, we are dependent on electricity to function. It is evident that this dependability is exploited in cyber warfare by attacks on the energy system. Two examples of this are attacks in Ukraine and Iran. A Ukrainian electricity distribution company was attacked in 2015, which resulted in around 225 000 people being without electricity for several hours in the winter (E-ISAC, 2016). The Iranian nuclear program is understood as having been attacked by the first malware targeting Industrial Control Systems (ICS), Stuxnet, in 2010 (Shakarian, 2011). It is a difficult task to protect the energy system against cyber-attacks considering that the system is large and complex. With digitalisation and new technologies, the cybersecurity attack surface of power systems is increasing (Krause et al., 2021). This translates to a need for more information regarding the possible vulnerabilities that exists in the energy system, so that the correct prioritisations can be made when protecting it.

One contribution of this paper is the dataset of vulnerabilities that exists specifically for the energy sector and the categorisation of these vulnerabilities in terms of domain and type of vulnerability. The second contribution is the estimations of Time-To-Compromise (TTC) for attacking these vulnerabilities. Being able to compare different attacks with a metric, such as TTC or probability for successful attack, is a key concept in threat modelling and attack graph generation. Threat modelling is an established method of assessing the cybersecurity of a system and attack graph analysis is a method of estimating the possible paths that an attacker could take.

By using the contributions of this paper, the dataset and the TTC estimations, this paper is able to estimate where the energy sector is most vulnerable to a cyber-attack. The energy sector is a broad term that enables the security analysis and risk assessment across all energy infrastructures. We are, however, able to draw conclusions of vulnerabilities per domain, due to the categorisation according to the domains defined in the Smart energy Grid Architecture Model (SGAM).

2. Related Work

There are similar efforts to aid in the assessment of cybersecurity for critical infrastructures. There is, however, a research gap in terms of categorised vulnerability datasets specifically for the energy sector, which is one of the main contributions of this paper. In terms of datasets, Thomas and Chothia (2020) compiled and categorised a dataset with vulnerabilities for ICS. The dataset is similar to the one created for this paper, as we categorised the vulnerabilities inspired by them into eight categories based on the detection method. However, the dataset is not energy specific and has not been updated since its first publication. Another dataset that focuses on vulnerabilities for ICS is ICS-LTU2022 (Alanazi, Mahmood and Chowdhury, 2025). The authors are able to categorise the vulnerabilities based on, for example, the energy sector by using keywords, but only compiles vulnerabilities for eight years. In addition, there is related work that deals with categorising vulnerabilities. Biebel et al. (2025) analysed the difference between power grid attacks discussed in literature and published vulnerabilities, while also applying the attacks to MITRE ATT&CK. MITRE ATT&CK is a knowledgebase that includes tactics and techniques of malicious actors. Biebel et al. found that the research community is discussing Man-in-the-Middle (MitM) attacks, but CVEs show that initial access and lateral movement attacks are more prevalent.

Gathering information on vulnerabilities and assessing where a system is most vulnerable is a common research topic in cybersecurity. Instead of producing datasets of vulnerabilities, categorising and analysing these, related work also performs literature reviews. In the work by Kreso (2025), the most critical vulnerabilities are mapped to the potential cyberattacks. In this paper, a quantitative assessment is made based on known vulnerabilities whereas in the work by Kreso, this assessment is made by finding the potential threats and critical vulnerabilities mentioned in research. They argue that the most critical vulnerabilities of the energy sector are those that are most commonly mentioned in research. In this paper, we estimate the most critical vulnerability by estimating the Time-To-Compromise (TTC).

3. Background

The digital energy system includes everything from sensors and management platforms to IP cameras. In addition, new technologies are introduced to the energy system, such as Electric Vehicles (EVs) and solar panels. This leads to an increased attack surface and difficulty to prioritise where the most imminent cybersecurity threat lies. One method of assessing where to prioritise defending the energy system is to use the metric Time-To-Compromise (TTC). TTC was first introduced by McQueen et al. (2006) and an updated TTC for the ICS domain was introduced by Rencelj Ling and Ekstedt (2022). In this paper, we apply the already existing TTC for the ICS domain (TTC_{ICS}) for the estimations and refer to the original TTC papers for further description and justification of the estimation method. TTC estimates the time that it would take for an attacker to complete three different processes based on several variables and the probability for the attacker to be in the three different processes. The first process is when there is at least one known vulnerability and at least one known exploit. The second process assumes that there is at least one known vulnerability, but that there are no readily available exploits. The final process is considered to run in parallel to the first two since it is the attacker's continuous process to find new vulnerabilities and develop new exploits.

To estimate the TTC_{ICS}, several variables are required. Firstly, the dataset of vulnerabilities must be categorised based on the type of product, domain or any other category that is being analysed. Secondly, the dataset must be categorised on the type of vulnerability. In addition, the dataset must include the Common Vulnerability Scoring System (CVSS) (FIRST, 2025) value for each vulnerability. CVSS is a numerical assessment of how critical a vulnerability is. All CVSS versions include a base score, and the CVSS version 3.x also includes an exploitability CVSS value. The exploitability score estimates how easily the vulnerability can be exploited. The estimate also considers the Mean Time Between Vulnerabilities (MTBV), which is the average number of days in between the vulnerability publication dates. Lastly, the number of available exploits for the type of vulnerability is used to estimate the TTC and this number is retrieved from the exploit tool Metasploit's exploit database (Metasploit 2025). The Common Enumeration Platform (CPE) (Manion et al. 2025) is a naming system to identify the type of product or software that the vulnerability applies to. The CPE is available for some of the vulnerabilities and have in these cases been used in this paper to assess which domain the vulnerability can be found in. Another common term for vulnerability categorisation is Common Weakness Enumeration (CWE) (MITRE 2024). CWE is a list of software and hardware weaknesses that may lead to the existence of a vulnerability.

4. Method

To assess the cybersecurity entry points of the energy system, we first compiled a vulnerability dataset. The vulnerability dataset includes vulnerabilities specific to the energy sector and is categorised by both domain and the type of vulnerability. Thereafter, the Time-To-Compromise (TTC) values were estimated.

4.1 Energy Sector Vulnerability Dataset

The steps summarised in Figure 1 were taken to create the dataset. The vulnerability dataset was created by using information found in the America's Cyber Defense Agency's Cybersecurity Alerts & Advisories (CISA) (CISA, 2025). The information was gathered in September 2025 and the number of advisories has increased since then. The advisories that belonged to the energy sector were filtered out and the Common Vulnerabilities and Exposures (CVEs) mentioned per CISA were added to the dataset. In this process we used the Comma Separated Value (CSV) list of advisories as provided by the ICS Advisory Project (ICS Advisory Project, 2025). Once a list of CVEs that according to CISA belong to the energy sector was created, the duplicate CVEs were removed and 3656 CVEs remained. Thereafter, the list was extended to include details regarding each CVE. These details were added from the National Institute of Standard (NIST) National Vulnerability Database (NVD) (NIST, 2025).

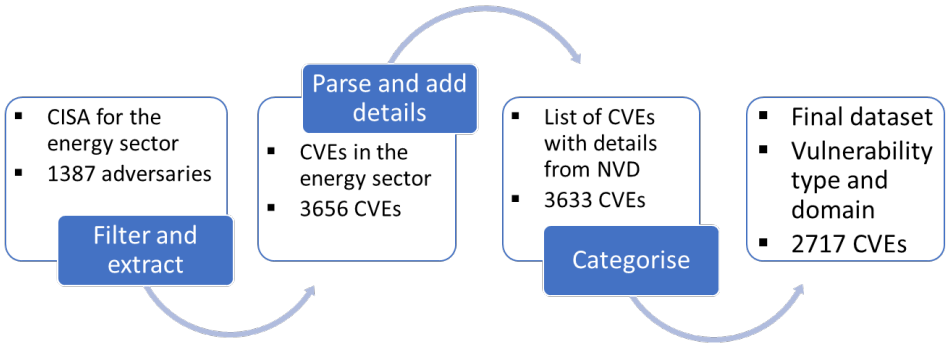


Figure 1: A summary of the process of creating the energy sector vulnerability dataset

Since the CVE information stored in the NVD is in JavaScript Object Notation (JSON) format, we were able to build a parser in Python that extracts the relevant information from the list of CVEs and exports it to an Excel .csv file. The information that is extracted in the parser is the CVE ID, CVE description, access vector or attack vector, CVSS base and exploitability scores, as well as, the CPE. If the CVE includes multiple versions of CVSS (2, 3, 3.1 and 4) we use the latest value. The information extracted from the NVD showed that some of the CVEs were rejected or duplicate and these were therefore removed from the list. We also remove three CVEs that were published before the year of 2010 since they were not part of the ICS Advisory Project. In the end, 3633 unique CVEs for the energy sector were included in the final dataset (Energy Sector CVEs, 2025). To further enhance the dataset and to make it useable for TTC estimations, each CVE were categorised. We only assign type of vulnerability and domain for the 2717 vulnerabilities with attack or access vector of network, since we in this paper are focusing on cyber-attacks.

The first step to categorise the CVEs into domain and type of vulnerability is to decide what the categories should be. We use the sane eight categories of vulnerabilities as in the Learning from Vulnerabilities Dataset (Thomas and Chothia, 2020). They defined the categories to aid in the detecting of vulnerabilities by categorising them by the method to detect them. The "Other" category does not fit into the other categories and are, for example, design flaws or programming issues. Below is a list of the categories with a short description and an example of a CWE.

- Access Control Privilege Escalation & Authentication Weaknesses, shortened as *Web*, are, for example, SQL injections (CWE-89).
- *Default Credentials*, in the case that default passwords have not been changed (CWE-1392).
- Denial of Service & Resource Exhaustion, shortened as *Denial of Service*, can occur by flooding the network with requests (CWE-410).
- Exposed Sensitive Data, shortened as *Information Leakage*, caused by, for example, not encrypting documents (CWE-200).

- Weak & Broken Cryptography, shortened as *Cryptography*, can be lack of sufficient character length for passwords (CWE-521).
- Memory & Buffer Management, shortened as *Memory*, for example, buffer overflows (CWE-122).
- Permissions & Resource Access Control, shortened as *Access Control,* can be when a too large group is mistakenly given access (CWE-1220).
- Privilege Escalation and Authentication Weaknesses, shortened as *Authentication*, can be cases where the identity of the user is not verified (CWE-1390).

We found an overlap of 1467 vulnerabilities with the ICS Dataset by Thomas and Chothia (2020) and therefore did not have to categories these again. For the other vulnerabilities, we manually categorise them based on the CWE ID and CVE description. There are some vulnerabilities where one vulnerability leads to another one. For example, a DoS vulnerability exists due to weak authentication. In these cases, we categorise the vulnerability by the first type of attack, since we analyse entry points to the energy system in this paper.

The dataset is also categorised based on where the vulnerability exists in the energy system. This gives an indication of where the entry point is on a higher abstraction. To enable applications in other contexts beyond this paper, we choose to use the already defined domains of the Smart energy Grid Architecture Model (SGAM) (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012). These domains are bulk generation, transmission, distribution, DER and customer premises. For the purpose of this paper, we combine the domains of transmission and distribution since they often have similar products and architectures in terms of cybersecurity. One main difference between the two domains is that transmission of electricity is over long distances and the distribution focus on supplying electricity to consumers. To categorise the vulnerabilities based on the domain, we analysed the CVE description and, if they have been defined, the CPE values. Many vulnerabilities are found in multiple different domains and some vulnerabilities can be found in all of them. Examples of vulnerabilities that are found in all the domains of the energy system are those that are found in devices for network connectivity or physical security.

4.2 Estimating the Time-To-Compromise

When estimating the TTC values, we use the categorised dataset (Energy Sector CVEs, 2025) and filter the vulnerabilities based on the type of vulnerability and domain that we want to analyse. There are also some fixed values that are used to estimate the TTC. The value *k* is 2717 since it is the total number of vulnerabilities of the dataset. The exploits are ranked based on how reliable they are and we use this ranking to determine the type of attacker that it could be used by. We assume that an attacker of any skill level could use the easier exploits and the more difficult it is to achieve a successful outcome of the exploit, the more skilled the attacker must be. The value *m* is defined by the number of exploits found in the Metasploit (2025). Table 1 summarises the value *m* based on the type of vulnerability and the attacker skill level. The value *v* is the number of vulnerabilities for the use case that the TTC is estimated for. These values are used to estimate the probability that an attacker is in the first process (P_1).

$$P_1 = 1 - e^{-vm/k} = 1\text{-}P_2$$

where v is the number of vulnerabilities for the type of vulnerability and domain that is investigated, m is the number of exploits available to the hacker based on skill level as seen in Table 1 and k is the total number of vulnerabilities of the dataset, 2717.

The time taken for an attacker to complete process 1 (t_1) is dependent on the CVSS values.

$$t_1 = 1 * ((10/c2 + 3, 9/c3)2) \text{ days}$$

where c2 is the average version 2 or 4 base CVSS score for the vulnerabilities and c3 is the version 3.x average exploitability CVSS for the vulnerabilities.

Another fixed value is the fraction of vulnerabilities that are considered exploitable based on the attacker skill level (*f*), as seen in Table 2. To calculate this value, the vulnerabilities that include a CVSS version 3.x exploitability score are counted and the assumption is made that a less skilled attacker would have a lower exploitability score. This value is used to estimate the time taken for an attacker to complete process 3.

$$t_3 = (f' - 0.5) * b + t_2 \text{ days}$$

where t_2 is the time taken to develop a new exploit, f' is the inverse of the fraction of vulnerabilities that are exploitable based on skill level and b is the Mean-Time-Between-Vulnerabilities (MTBV) in days based on the CVE publication date.

Table 1: The number of exploits from the Metasploit (2025) database available to the different skill level of an attacker, per type of vulnerability

Type of Vulnerability	Novice attacker	Beginner attacker	Intermediate attacker	Expert attacker
Access Control	69	73	101	106
Authentication	481	517	568	573
Cryptography	21	21	22	22
Default Logins	51	53	65	66
Denial of Service	10	13	13	13
Information Leakage	10	10	45	45
Memory	127	195	374	402
Web	708	792	1007	1068

Table 2: The number of exploitable vulnerabilities and the fraction of vulnerabilities that are exploitable per skill level of the attacker, based on the CVSS version 3.x exploitability score

Attacker skill level	Number of exploitable vulnerabilities	Fraction of exploitable vulnerabilities (*f*)
Expert	1951	1
Intermediate	759	0,39
Beginner	181	0,09
Novice	107	0,06

The complete TTC is estimated by combining the probability for the attacker to be in processes 1 or 2 and the time taken to complete the processes.

$$T = t_1 * P_1 + t_2 * (1 - P_1) * (1 - u) + t_3 * u * (1 - P_1)$$

where T is the estimated time-to-compromise in days, $u = (1-f)^v$, which is the probability that Process 2 is unsuccessful where v is the number of vulnerabilities and f is fraction of vulnerabilities that are exploitable for a specific skill level. Also, u=1 if v=0.

5. Results

In Table 3, we can see that the most common types of vulnerabilities are memory and web. In terms of domains, as seen in Table 4, customer premises appear to have the most vulnerabilities. We found that 1037 of the vulnerabilities can be found in all of the domains.

Table 3: Vulnerability metrics per category of vulnerability, rounded to one decimal point

Category of Vulnerability	Number of Vulnerabilities	Average Base CVSS	Average Exploitability if CVSS v3.x	Mean time between vulnerabilities (MTBV)
Access Control	304	7,8	3,3	18,4
Authentication	270	8,1	3,3	19,2
Cryptography	78	6,9	3,2	62,3
Default Logins	55	8,7	3,7	92,4
Denial of Service	313	7,1	3,7	15,9
Information Leakage	191	6,8	3,4	26,7
Memory	651	8,2	3,4	8,3
Web	788	7,4	2,9	7,1
Other	67	7,9	3,5	79,1

Table 4: Vulnerability metrics per SGAM domain, where a vulnerability may exist in multiple sectors

SGAM Domain	Number of Vulnerabilities	Average Base CVSS	Average Exploitability if CVSS v3.x	Mean time between vulnerabilities (MTBV)
Bulk Generation	1310	7,6	3,2	4,2
Customer Premises	2280	7,7	3,3	2,5
DER	1669	7,6	3,3	3,3
Transmission & Distribution	1595	7,6	3,2	3,5

We plot the trends of number of vulnerabilities through the years in Figures 2 and 3. The majority of the type of vulnerabilities in the different domains appears to follow a similar trend. Even though the year 2025 does not have complete data, it is visible that the number of vulnerabilities for web, and access control vulnerabilities, appears to increase.

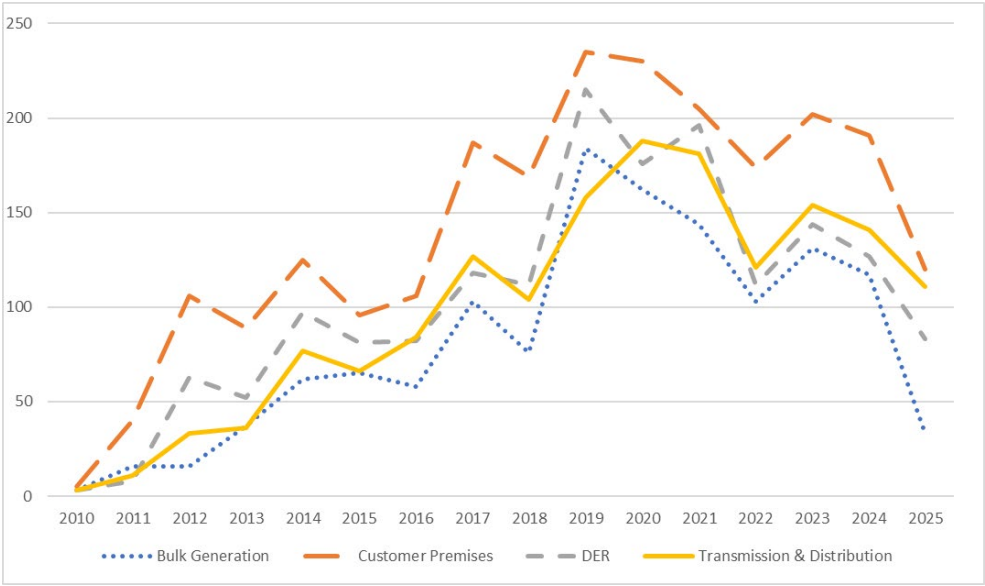


Figure 2: The number of vulnerabilities per domain over years

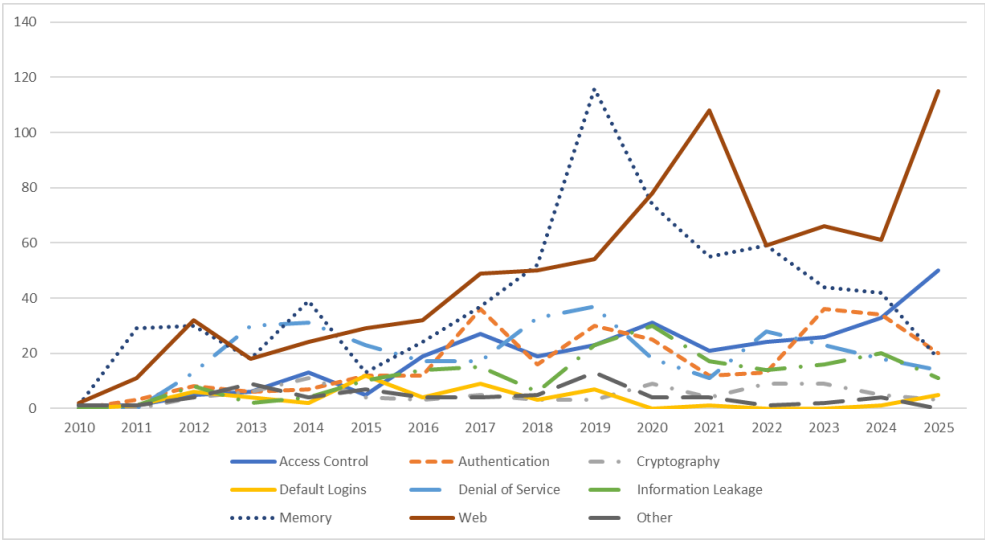


Figure 3: The number of vulnerabilities per type of vulnerability over years

Cryptography and default logins have the longest TTC values and could be considered as less critical types of vulnerabilities, as visualised in Figure 4. For access control, authentication, memory and web the TTC values are close to 1 day for all skill level.

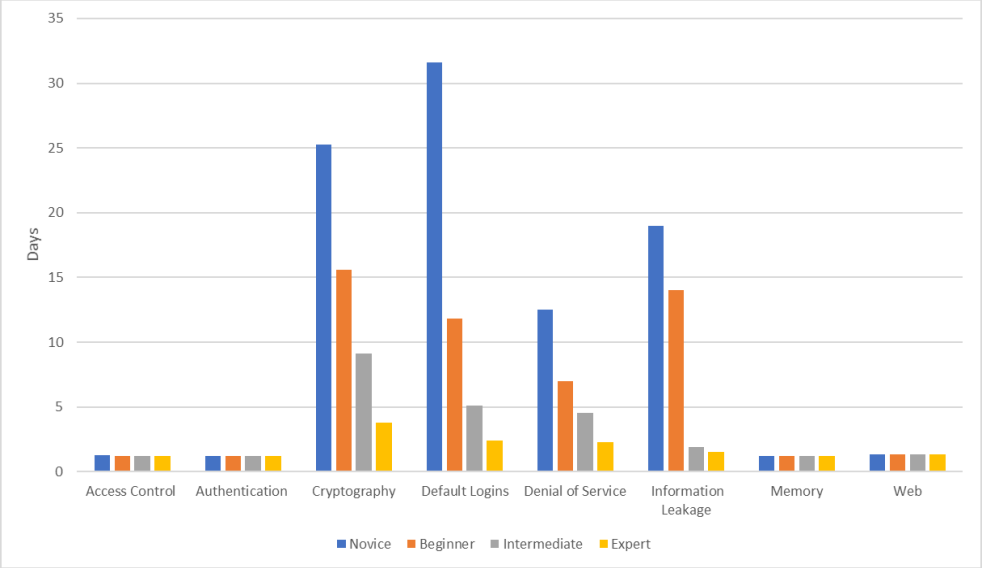


Figure 4: The estimated TTC for the different vulnerability types per attacker skill level

When the TTC for all types of vulnerabilities are estimated for the four different SGAM domains, the result shows that for all skill level and domains, the number is 1,2 or 1,3 days. This indicates that it would only take an attacker on average just over 1 day to successfully compromise any domain of the energy system.

In Figure 5, we illustrate the TTC values of web and access control for the different SGAM domains. These specific types of vulnerabilities were chosen to illustrate due to the upward trend shown in Figure 3. According to the results, the most time-consuming attack to succeed with would be to compromise an access control type vulnerability for a novice in the Bulk Generation domain. The lowest TTC values can be found for the expert attacker for access control vulnerabilities in the Customer Premises domain.

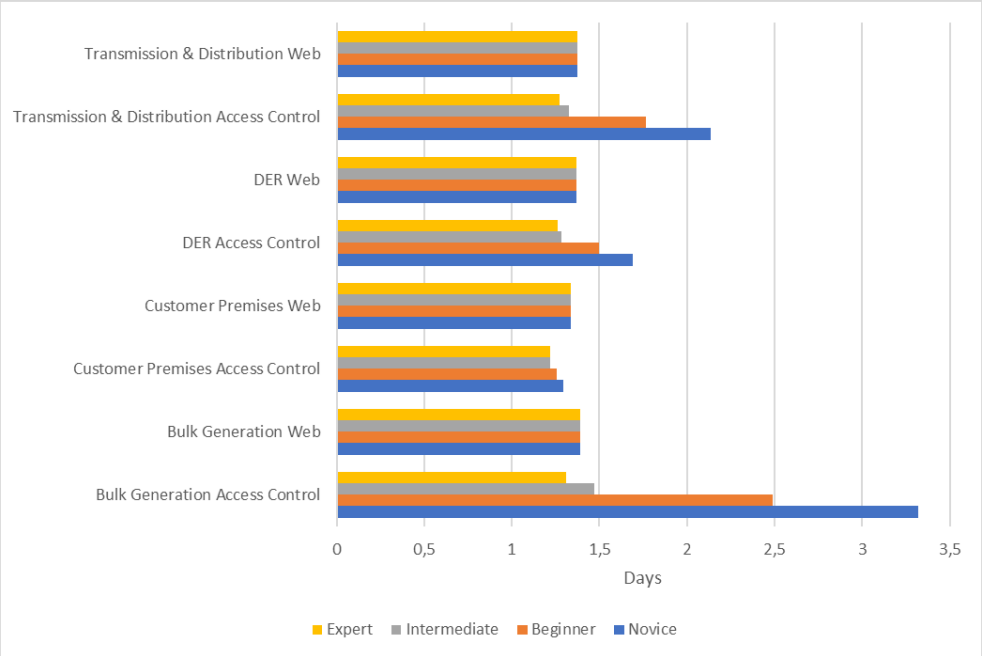


Figure 5: The TTC for Access Control and Web type of vulnerabilities for the different SGAM domains and attacker skill levels

6. Discussion

The results of the TTC estimations are highly dependent on the dataset, its categorisation and the source of the variables. The TTC values are estimated on quantifiable numbers, such as the number of vulnerabilities and their severity scores. Due to this, the estimations can be considered objective, even though the manual

categorisation and other manual tasks may introduce bias. These is also the assumption made that the general analysis for the different types of vulnerabilities and domains can be applied to more specific cases. In risk assessment, there is sometimes lack of information and generalisations are made, but should be made clear. The contributions and results presented in this paper will enable researchers in the topic of threat modelling and attack graph generation to strengthen the trustworthiness of their analysis. It is a challenge to evaluate security assessments due to the lack of data describing real attacks to compare the assessments with. This limitation also applies to this paper. There is no data that represent the truth in regards to which entry point is the most vulnerable and the TTC for this entry point, even though we estimate it.

We acknowledge that there may be vulnerabilities with incorrect data (Dragos, 2025) and that there is work that has found some inconsistencies (Tomas et al. 2020). Some evaluation of the categorisation of the type of vulnerabilities have been evaluated previously by Thomas and Chothia (2020). A limitation of the results is that there can be several products that are affected by one CVE. In this case we have used the first mentioned product. We, however, see that these different products are similar and we assume that they are found in the same domain when we perform the categorisation.

Around one day for an attacker to successfully compromise a domain in the energy sector may appear low, but there exist many vulnerable products with readily available exploits. In a paper by Wang et al. (2017), it was found that around 50% of the internet-exposed ICS devices, investigated by them, were patched within 60 days of a vulnerability being known. This would, according to our results, give the attacker enough time to successfully compromise the vulnerability. The result shows a low fraction of exploitability for novice and beginner attackers. This indicates that an attacker must typically be at least intermediate in order to be able to exploit the energy system. Considering that the communication system of the energy sector is often more complex than that of a typical IT system, we could expect this result. The dataset presented in this paper only includes known vulnerabilities, however, unknown vulnerabilities are considered in the third process when estimating the TTC value. The third process is the continuously ongoing attempts to find unknown vulnerabilities and develop new exploits.

7. Conclusions and Future Work Directions

It is clear that our society is dependent on electricity supplied by the energy system. The critical infrastructure is at stake because of the threat of cyber warfare targeting the energy system. In this paper, we have contributed with a categorised vulnerability dataset for the energy sector. We have also estimated the Time-To-Compromise (TTC) for exploiting different types of vulnerabilities in the four different Smart energy Grid Architecture Model (SGAM) domains. We have analysed the access control and web vulnerabilities specifically for the bulk generation, customer premises, distribution & transmission and Distributed Energy Resources (DER) domains. The majority of the vulnerabilities can be exploited in between one to two days, regardless of the attacker skill level. This emphasises how imminent the threat is and the importance of securing the energy system against such attacks, as well as, where to focus the future cybersecurity research.

Directions for future works includes categorising the vulnerabilities per type of asset, in contrast to the existing broader domains. This would be a step towards solving the issue with generalising the vulnerabilities across an entire domain of the energy system. Future work directions also include expanding the dataset with CVEs that are not mentioned in CISA advisories. Lastly, the evaluation of the results presented in this paper is another future research direction and especially finding or creating information sources to enable the evaluation.

Acknowledgements

This work has been funded by Svenska kraftnät (Swedish national grid, the power transmission system operator).

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: AI tools were not used in the development of this paper.

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Digital State Erasure: Data as Both a Target and a Vector of Political and Military Influence

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Abstract: Modern states increasingly rely on digital infrastructures and critical data for continuity, governance, and societal resilience. As national functions become more and more digitalized, the accumulation of sensitive data increases data-related risks, including hostile interference and exploitation. This paper introduces the concept of digital state erasure as an analytical framework, defined as the deliberate destruction, manipulation, or strategic exploitation of a nation's critical data in ways that undermine its ability to govern, provide services, authenticate its population, or defend itself. Unlike conventional cyberattacks, digital state erasure targets datasets whose compromise can dissolve a state's operational capacity and institutional coherence. Drawing on critical data studies, this paper conceptualizes critical national data as three interlinked categories and demonstrates how disruptions in either the target or vector dimension can cascade across national systems. This paper further argues that control over critical data constitutes the foundation of state authority and continuity in cyberspace. Losing that control risks digitally erasing a state, even in the absence of conventional military conflict.

Keywords: Digital state erasure, Critical national data, Sovereignty in cyberspace, Resilience, National security

1. Introduction

Digital technologies have fundamentally reshaped how modern states function. Governance, public administration, welfare provision, infrastructure management, and national defence as examples of vital functions of the state are all increasingly dependent on digital platforms, automated decision-making systems, and large-scale data repositories. Population registries, taxation systems, electoral processes, healthcare services, and crisis response mechanisms are now inseparable from data-driven infrastructures.

This transformation has significantly altered the foundations of state power and vulnerability. Where state continuity was once anchored primarily in physical territory, institutions, and personnel, it now depends increasingly on the state's capacity to exercise effective control over its critical national data, in addition to ensuring its confidentiality, integrity and availability (the CIA triad). In this context, considerations of data veracity – relating to the reliability and accuracy of data used for analysis and decision-making – can be understood as closely linked to the integrity dimension (cf. Ardagna et al. 2021). As a result, disruptions to data confidentiality, integrity and availability can have consequences that extend well beyond technical inconvenience, affecting political legitimacy, social trust, and the state's ability to act. Critical national data should be defined and regarded as a strategic resource, since loss of control over such data would undermine state authority and continuity. Without reliable control over critical data, a state's ability to govern, provide services, and maintain institutional continuity may be fundamentally undermined, making data protection a core national security concern (Rossbach 2024). This paper examines whether a state's operational capacity and institutional coherence can be comprehensively undermined – or effectively erased – through an attack directed solely at its critical national data.

The growing strategic significance of data has been more and more recognized in both academic and policy discussions. Research on cyber power and data-driven security highlights how control over data infrastructures and datasets has become an important dimension of contemporary power and influence (e.g., Shandler & Gomez 2023). At the policy level, defence organizations have likewise emphasized the transition toward data-centric architectures in which data is treated as a strategic resource that enables decision-making, operational effectiveness, and institutional resilience (cf. U.S. Department of Defense 2020; Finnish Defence Forces 2025). These developments reflect the broader recognition that modern governmental and military systems are deeply dependent on the confidentiality, integrity and availability of digital data. However, much of this literature focuses primarily on data as an operational or technical resource supporting governance and military effectiveness. Less attention has been paid to how the systematic loss of control over critical national data could undermine the state's ability to function as a governing entity.

From a national security perspective, data must therefore be understood not merely as an operational resource but as a strategic asset. Data occupies a dual role. On the one hand, data constitutes a target: its confidentiality, integrity and availability can be compromised by destroying, corrupting, encrypting, or rendering inaccessible in

order to both undermine and disrupt core state functions. On the other hand, data functions as a vector of influence: through its manipulation, selective disclosure, or strategic withholding, adversaries can shape decision-making, undermine confidence, and create dependency without direct confrontation.

This paper examines how operations on critical national data can challenge state authority and continuity even in the absence of large-scale kinetic force. It introduces the concept of digital state erasure to describe a condition in which the compromise of essential datasets erodes a state's practical ability to govern, authenticate its population, provide services, or recover from crises. In this paper, state authority and continuity refer to the state's ability to exercise legitimate governance, maintain essential functions, and independently recover during crises. The central argument is that, under conditions of deep digital dependency, the loss of control over critical data can be strategically equivalent to the loss or occupation of physical territory.

2. Digital State Erasure as a Concept and a Strategic Dimension

Digital state erasure refers to a strategic process in which a state's operational capacity and institutional coherence are undermined through the deliberate targeting or exploitation of its critical data. The concept does not imply the formal disappearance of the state, but rather the erosion of its effective governmental agency: the state may continue to exist legally, yet lose the ability to function in practice.

This form of erosion differs from conventional cyber operations in both intent and effect. Traditional cyberattacks are typically motivated by extortion, espionage or sub-threshold coercion. Digital state erasure differs from these phenomena in that it focuses specifically on the strategic compromise of critical datasets, rather than infrastructure disruption alone. Digital state erasure, by contrast, targets foundational datasets that underpin governance, legitimacy, recovery and continuity. The objective is not temporary inconvenience but systemic destabilization. Thus, digital state erasure should be distinguished from conventional cyber operations, hybrid pressure, or isolated critical infrastructure disruptions. Not all cyber operations against government systems constitute digital state erasure, even when their immediate effects are severe. The concept applies specifically to operations and dependencies that directly undermine state authority, continuity, and recoverability through data.

Strategically, digital state erasure aligns with operations conducted below the conventional threshold of armed conflict and can be employed across the spectrum of peacetime competition, crisis, and the transition to conflict and war. Shaping activities may be undertaken during periods of peacetime competition and heightened crisis, while execution can support coercive escalation or pre-conflict activities short of open hostilities. It enables adversaries to impose significant costs, constrain policy choices, and undermine societal resilience without necessarily triggering immediate military escalation. As such, it integrates seamlessly into broader strategies of hybrid activities, where technical, legal, economic, informational, and political instruments are employed in a coordinated manner.

In this paper, digital state erasure is not conceptualized as a discrete event or a formally observable outcome, but as an analytical construct that captures the cumulative strategic effects of control over critical national data under conditions of deep digital dependency. It serves as an analytical instrument rather than a predictive model, highlighting how incremental disruptions, dependencies, and external control can undermine effective state governance over time. Although this paper develops a conceptual framework, real-world incidents such as large-scale ransomware attacks on government registries or the destruction of national data infrastructure during armed conflict illustrate the potential relevance of the problem.

3. What is Critical National Data?

Drawing on critical data studies, which conceptualize data as a socio-technical construct embedded in relations of power, governance, and control (Dalton et al. 2016; Iliadis & Russo 2016; Kitchin 2014), critical national data in this paper refers to datasets whose confidentiality, integrity and availability, and, most importantly, controllability are essential to the state's authority and societal functioning. This includes data that enables the identification of individuals, the operation of essential services, the exercise of jurisdiction, and the recovery of systems following disruption. Furthermore, in this paper, data is distinguished from information (cf. e.g., Zins 2007). Data refers to the underlying digital records, registries, and system-level inputs that enable state authority, governance, and operational control, whereas information denotes data that has been processed or interpreted to convey meaning. Crucially, while information primarily shapes perception, data structures the condition under which governance, influence, and coercion become possible.

Despite its importance, critical data is rarely treated as a coherent analytical category within national security research. While prior research has examined data governance, data sovereignty, and data-centric security architectures (e.g., Shandler & Gomez 2023; Rossbach 2024), these approaches typically focus on data protection, cyber resilience, or technological infrastructures. They rarely conceptualize critical national data specifically in terms of its role in maintaining state authority, continuity, and recoverability. Existing approaches tend to favour the protection of physical critical infrastructure sectors (e.g., energy, transport, ICT) and view cybersecurity primarily through a technical lens focused on networks and systems rather than on data as a strategic asset and source of vulnerability (cf. Weber et al. 2023; Mussington 2021). As a result, data is treated as a by-product of technical systems rather than as a strategic asset in its own right.

This conceptual gap has practical consequences. Without a clear understanding of which datasets are critical under all conditions, states struggle to prioritize protection, allocate responsibility, and assess risk. In practice, identifying such datasets requires mapping dependencies between administrative systems, legal authorities, and digital infrastructures. Data that is essential for sovereignty may be outsourced, replicated across jurisdictions, or placed under contractual arrangements that limit state control. The problem is compounded by the tendency to view data governance as an administrative or economic issue rather than a security concern. Decisions driven by efficiency, cost savings, or innovation can gradually shift control over critical data away from the state, creating dependencies that are difficult to reverse. In a crisis, these dependencies may translate into strategic vulnerability.

4. Data as a Target and a Vector of Influence

The confidentiality, integrity and availability of critical national data can be targeted through various technical means, ranging from various malware and denial-of-service operations to the manipulation of backups, access controls, and authentication systems (cf. e.g., ENISA 2025). However, non-technical mechanisms are equally important. These include legal jurisdiction, infrastructure dependency, contractual constraints, and geopolitical pressure exerted to service providers, all of which can imperceptibly affect the controllability of data.

As a vector of influence, data can be manipulated to distort situational awareness, undermine trust, and shape political outcomes. Data-driven political communication, micro-targeting and misinformation have demonstrated the capacity to influence electoral behaviour and public perception of democratic legitimacy (Bradshaw & Howard 2019; Dad & Khan 2023; Jungherr 2023; Mont'Alverne et al. 2024). Furthermore, reliance on external digital infrastructure – such as cloud-hosted electoral systems or outsourced data management – can create strategic dependencies that can be exploited indirectly without direct cyberattacks (Farell & Newman 2019; Kwet 2019).

In a recent case, a democratic state planned to migrate its core electoral data – including voter registries, candidate databases, and vote-counting systems – to a foreign-owned cloud service with data centres located outside national territory. This decision was justified primarily on cost-efficiency grounds, but it entailed a significant transfer of control over critical democratic infrastructure (Hakahuhta 2025). Nevertheless, hosting electoral systems in foreign cloud environments introduces structural risks. Access control is no longer exclusively national; data recovery during crises depends on external actors; and the data becomes subject to foreign legal regimes and extraterritorial legislation. Electoral data is foundational to democratic legitimacy, and its integrity and availability must be demonstrable beyond doubt. Importantly, undermining elections does not require vote manipulation. Creating uncertainty about the reliability of voter registries or result calculation may be sufficient to erode public trust. Foreign-hosted electoral infrastructure thus constitutes a strategic vulnerability: electoral data functions simultaneously as a target of disruption and as a vector of influence through which legitimacy, trust, and political stability can be challenged.

In another case, a state indicated the migration of highly sensitive health, welfare, and social security data to cloud services operated by multinational providers, with data potentially stored outside the state's legal jurisdiction. The precise location of the data was not publicly disclosed, and recovery capabilities depended on external infrastructure and contractual arrangements (Koponen 2025). This configuration creates vulnerabilities without requiring technical intrusion. Interface may occur through the compromise of data integrity, restricting availability, or exerting control through legal, regulatory, or geopolitical pressure on service providers. Even limited inconsistencies in medical or welfare records can produce systemic effects, rapidly undermining trust in public services. Disruption to data availability – whether intentional or incidental – translates directly into delayed healthcare, interrupted benefits, and weakened crisis response. If control over who can access critical national data and when systems can be restored shifts to external actors, the state's ability to effectively manage

its own welfare and health systems is significantly reduced. In such conditions, a state's capacity to exercise authority can be constrained without overt or attributable influence.

Consequently, the dual role of data as both target and vector mean that vulnerabilities are not confined to cybersecurity failures. What a state does not fully control can be transformed into leverage against it. In the following, the aim is to demonstrate how critical national data could be systematically categorized from a national security point of view and how each category functions both as an object of attack or larger set of operations and as a mechanism through which political and strategic influence could be exercised.

5. Three Categories of Critical National Data

Data classification is widely recognised as a systematic process for categorising data based on sensitivity, value, and potential impact in the event of compromise. For example, NIST (2023) defines data classification as the process of assigning labels to data sets in order to ensure confidentiality, integrity, and availability requirements. Common classification schemes organise data into public, internal, confidential, and higher sensitivity categories, enabling prioritised protection and governance of critical data assets. Such frameworks are foundational in both organisational and information security contexts, providing a basis for risk management and compliance (cf. e.g., ITU 2025).

This paper conceptualizes critical national data as three interlinked categories: 1) Identity and Authentication Data; 2) Operational and Functional Data; 3) Authority, Control, and Recovery Data. These categories are analytically distinct but mutually reinforcing, and disruption in one category can cascade across the others (cf. Shivayogi 2025; Nguyen, H–N. & Cuong 2025; Ofili et al. 2024). While analytically distinct, these three categories are not equal in strategic significance. Authority, control, and recovery data constitute the uppermost layer, as loss of control at this level constrains the state's ability to restore, validate, or govern the other two categories.

5.1 Identity and Authentication Data: Who the State Recognizes and Protects

The first category of critical national data consists of datasets that identify and authenticate individuals, organizations, and other legal entities. These include population registries, citizenship and residency records, personal identity numbers, tax identifiers, company registries, land ownership records, and other administrative datasets that establish legal personality and status. Together, they define who belongs to the political community, who is entitled to protection and services, and who is subject to obligations and enforcement.

From the perspective of state authority, identity data forms the basis of trust between the state and society. Public administration, welfare provision, law enforcement, and democratic participation all rely on the assumption that identity data is accurate, consistent, and authoritative. Even minor inconsistencies can generate legal uncertainty, while systemic corruption can undermine confidence in the state's ability to govern fairly and predictably.

As a target, identity and authentication data can be corrupted, deleted, or rendered unreliable in ways that erode institutional trust, and during a conflict, when combined with other instruments of influence, these effects can become paralyzing. If records of citizenship, residency, or legal status are compromised, the state may be unable to determine who is eligible for services, who may exercise political rights, or who falls under its jurisdiction. Restoring such data is not merely a technical task but a political one, as decisions about validity and correction inevitably involve questions of legitimacy.

As a vector of influence, identity and authentication data can be manipulated to enable impersonation, administrative paralysis, or selective exclusion. Control over authentication mechanisms can allow external actors to disrupt governance indirectly by creating uncertainty, contestation, or bureaucratic overload. In extreme cases, the inability to reliably authenticate individuals can paralyze core state functions, as every decision becomes potentially disputable.

Because identity and authentication data underpin all other categories of critical data, its compromise tends to cascade across governance systems. Service delivery, taxation, voting, and law enforcement all depend on reliable identification, making this layer particularly sensitive to both deliberate attack and structural dependency.

5.2 Operational Data: How the State Functions

The second category of critical national data consists of operational data that enables the day-to-day functioning of the state. This includes data used in public administration, emergency management, healthcare, energy

systems, transportation, financial oversight, and military logistics. Such data supports planning, coordination, and real-time decision-making across sectors.

Operational data is often distributed across complex digital ecosystems involving public authorities, private providers, and international service platforms. While this distribution can enhance efficiency and resilience under normal conditions, it also increases systemic complexity and interdependence. Decisions made in one domain may have immediate consequences in others, amplifying the effects of disruption.

As a target, operational data can be destroyed, delayed, or distorted to halt essential processes. Disruption does not need to be total to be effective; selective interference with key datasets or decision-support systems can degrade performance sufficiently to overwhelm administrative capacity. During crises, even temporary loss of operational data can have disproportionate effects on public safety and trust, and when coordinated with other tools of influence, the resulting synergistic effect can be greater than the sum of its individual components.

As a vector of influence, operational data can be manipulated to shape outcomes without overt disruption. Altered datasets, biased inputs, or delayed information flows can distort situational awareness and lead decision-makers toward suboptimal or harmful choices. This form of influence is particularly difficult to detect, as decisions may appear procedurally correct while being substantively flawed.

The strategic significance of operational data lies in its role as the unifying factor of governance. When control over this data is weakened, the state may retain formal authority while losing practical capacity, creating a gap between legal responsibility and operational control.

5.3 Authority, Control, and Recovery Data: Who Controls the Digital Backbone

The third category of critical national data concerns authority, jurisdiction, and recovery capability. This category includes system logs, backup repositories, cryptographic keys, root certificates, domain name control, and other data that determine who can validate outcomes, restore systems, and assert ultimate control over digital infrastructures.

Control over this category is essential for sovereignty in cyberspace. Even if operational systems are disrupted, a state that retains authority over recovery mechanisms can re-establish functionality and trust. Conversely, if recovery data or control mechanisms are compromised or placed under external jurisdiction, the state's autonomy is directly challenged.

As a target, attacks on authority and recovery data can prevent restoration, prolong disruption, and magnify the effects of failures in other layers. Destruction or corruption of backups, for example, can transform manageable incidents into existential crises for governance systems.

As a vector of influence, external control over recovery mechanisms can be used to exert pressure, enforce dependency, or constrain political choices. States that rely on foreign-controlled cloud platforms, certification authorities, or system administrators may find that their ability to recover or verify outcomes is contingent on the cooperation of external actors.

This category thus represents the deepest point of vulnerability in digital governance. When authority over the digital backbone is lost, the state may continue to exist formally, but its capacity to act independently and recover from disruption is fundamentally weakened.

6. Discussion: What if a state Loses Control Over its Critical Data?

While earlier research has recognized the strategic importance of data in cyber security and defence policy, the concept of digital state erasure highlights the cumulative governance-level consequences that may arise if a state loses control over critical national data. From an analytical perspective, early indicators of digital state erasure may include persistent external dependency over identity, authentication, or recovery mechanisms; legal or contractual constraints limiting sovereign access to critical datasets; uncertainty regarding data integrity that delays decision-making; and the inability to independently restore systems under crisis conditions.

The preceding categorisation demonstrates that digital state erasure should be understood not as an isolated act or a singular catastrophic event, but as a cumulative and potentially gradual process. Because the three categories of critical national data are deeply interlinked, disruptions in one category can propagate across governance systems, producing cascading effects that far exceed the initial point of failure. Identity data, operational data, and authority- and recovery-related data reinforce one another in ways that make modern states simultaneously efficient and structurally fragile.

A central strategic implication is that the loss of control over critical data undermines state continuity even when formal institutions remain intact. A state may continue to possess territory, armed forces, and legal authority, yet struggle to exercise effective governance if it cannot reliably authenticate its population, trust its administrative data, or restore essential systems after disruption. In such conditions, the state's existence becomes increasingly symbolic rather than operational. Authority is asserted in principle, but not consistently enacted in practice.

These dynamic challenges and traditional security assumptions that equate national survival primarily with physical defence and territorial integrity. Digital state erasure, while often conducted below the threshold of armed conflict and without clear attribution, can intensify as tensions escalate, becoming an increasingly significant component of coercive measures. Strategic vulnerability emerges not from a single decisive blow, but from persistent uncertainty regarding data confidentiality, integrity, availability, and, moreover, control. Over time, this uncertainty erodes institutional confidence, public trust, and the credibility of decision-making.

The discussion also highlights the risks associated with efficiency-driven digitalization. Cost savings, scalability, and rapid deployment have motivated states to outsource critical data storage, processing, and system management to transnational cloud providers and complex vendor ecosystems. While these arrangements may improve performance under normal conditions, they frequently introduce dependencies that weaken sovereign control. Jurisdictional ambiguity, contractual limitations, and reliance on external recovery mechanisms can constrain a state's ability to act autonomously in times of crisis.

From a resilience perspective, contested control over data is often more destabilizing than an outright loss. When authorities cannot be certain whether data has been manipulated, selectively altered, or rendered incomplete, decision-making becomes hesitant and reactive. Officials may delay action to avoid errors, while citizens may lose confidence in the fairness and reliability of public institutions. This erosion of trust can itself become a strategic outcome, even if no single system has fully collapsed.

Digital state erasure therefore aligns closely with broader patterns of hybrid operations and grey-zone competition. Rather than seeking immediate collapse, an adversary may aim to degrade governance capacity incrementally, exploiting legal, technical, and institutional seams. The ambiguity surrounding data control complicates attribution and response, reducing the likelihood of decisive countermeasures and enabling sustained pressure over time.

Importantly, the discussion underscores that technical cybersecurity measures alone are crucial but alone insufficient to address these challenges. Encryption, redundancy, and intrusion detection are necessary components of protection, but they do not resolve questions of authority, jurisdiction, and recovery. Strategic resilience requires explicit recognition of which datasets are existential for the state, where they are located, under which legal regimes they operate, and how they can be restored independently under extreme conditions. Without such clarity, states may inadvertently accept structural vulnerabilities that only become visible during crises.

7. Conclusions: Data, Sovereignty, and the Future of State Security

This paper argued that modern state authority and continuity are increasingly inseparable from control over critical national data. As governance, security, and societal resilience become data-dependent, the confidentiality, integrity, availability, and controllability of key datasets emerge as foundational elements of sovereignty. The concept of digital state erasure captures this transformation by showing how the deliberate destruction, manipulation, or strategic exploitation of critical data can undermine a state's ability to function without the use of kinetic force.

By conceptualizing critical national data as three interlinked categories, this paper provided a framework for understanding why certain datasets are strategically irreplaceable. Identity and authentication data define who the state governs and protects; operational data enables the delivery of services and the exercise of authority; and authority- and recovery-related data determines who ultimately controls the state's digital backbone. Vulnerabilities in any one layer can cascade into the others, producing systemic effects that compromise institutional coherence, legitimacy, and continuity.

A key conclusion is that a state cannot be fully sovereign if it lacks control over the data upon which governance, legitimacy, and recovery depend. Control over critical data constitutes the digital foundation of sovereignty in cyberspace. Losing that control risks digitally erasing a state from the map, even in the absence of conventional military conflict. Therefore, sovereignty in cyberspace should not be fragmented into subcategories, like 'data

sovereignty', but rather highlights how control over data is central to exercising sovereignty itself in the contemporary security environment. The growing reliance on foreign-owned infrastructure, cloud platforms, and transnational service providers therefore represents not only a technical or economic choice, but a strategic trade-off with long-term implications for national autonomy.

Preventing digital state erasure requires a shift in how states conceptualize security and resilience. Critical national data must be identified, prioritized, and governed explicitly as a part of national security planning. This includes ensuring sovereign control over the most sensitive datasets, maintaining independent recovery capabilities, and aligning legal, institutional, and technical frameworks to support continuity under crisis conditions. Such measures are not aimed at technological isolation, but at preserving the state's ability to act independently when it matters most.

Ultimately, the strategic value of data lies not only in its content, but in the authority it enables. A state that loses the ability to authenticate its population, conduct legitimate elections, provide essential services, or restore its systems after disruption risks losing more than operational capacity – it risks losing its political existence as a self-governing entity. In this sense, critical data constitutes the digital foundation of state authority and continuity. Its protection is therefore not merely a matter of cybersecurity or administrative efficiency, but a core obligation of sovereign governance in the digital age.

Ethics declaration: Ethical approval was not required for the research described in this paper.

AI declaration: AI tools were used to support language editing; the conceptual framework, analysis, and conclusions are the responsibility of the authors.

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A Framework for Privacy-Preserving Data Analytics Using Differential Privacy

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Abstract: This paper presents a comprehensive privacy-preserving analytics framework that embeds differential privacy principles across the entire data lifecycle, from collection and preprocessing to analysis, interaction, and output generation. Unlike approaches that simply apply existing differential privacy libraries, the proposed platform emphasizes end-to-end integration, ensuring that privacy guarantees are continuously maintained throughout the analytical process. An adaptive privacy management layer dynamically regulates privacy budgets and mechanisms based on data sensitivity, analytical objectives, and real-time system conditions, enabling a balanced trade-off between privacy protection and analytical utility. The framework also supports real-time privacy-preserving analytics, demonstrating that strong confidentiality measures can coexist with responsive and practical data-driven decision-making. A proof-of-concept prototype demonstrates the architecture's feasibility and illustrates its applicability to high-sensitivity domains that require rigorous privacy assurances.

Keywords: Differential privacy, Privacy-preserving, Healthcare data

1. Introduction

The exponential growth of data in today's digital age has revolutionized various fields, driving innovation and enabling data-driven decision-making. However, this rapid data proliferation raises significant privacy concerns, particularly when handling sensitive information such as healthcare and financial data. The protection of individual privacy in the face of extensive data collection and analysis is a critical challenge that requires robust, reliable mechanisms to preserve privacy.

Differential privacy has emerged as a leading solution to address these privacy concerns. Introduced by Dwork et al., differential privacy provides a mathematical framework that ensures the privacy of individuals in a dataset by adding calibrated noise to query results. The core principle of differential privacy is to maintain a balance between data utility and privacy, ensuring meaningful insights can be derived from data without compromising individual privacy.

Despite the theoretical robustness of differential privacy, its practical implementation across the data lifecycle—spanning collection, preprocessing, analysis, and dissemination—poses significant challenges. Many existing solutions focus on specific stages of the data lifecycle but lack a holistic approach that integrates differential privacy throughout the entire lifecycle. This paper presents a comprehensive framework for privacy-preserving data analytics that seamlessly integrates differential privacy techniques throughout the data lifecycle. By leveraging state-of-the-art tools such as Google's PyDP and IBM's diffprivlib, the framework aims to provide a scalable and generalizable solution that ensures robust privacy protection while maintaining data utility. Using state-of-the-art tools such as Google's PyDP and IBM's diffprivlib, the framework aims to provide a scalable, generalizable solution that ensures robust privacy protections while maintaining data utility.

To this end, the rest of this paper is organized as follows. Section 2 reviews related work in privacy-preserving data analytics. Section 3 presents the proposed framework and its architectural components. Section 4 discusses the data flow. Differential Privacy Techniques and Quantitative Evaluation are presented in Sections 5 and 6, respectively. Section 7 explores potential use cases for the framework. Finally, Section 8 concludes the paper and offers ideas for future work.

1.1 Research Contribution

The contributions of this research are:

- This paper proposes a comprehensive and holistic privacy-preserving analytics framework that embeds differential privacy principles across the entire data lifecycle (collection, preprocessing, analysis, interaction, output).

- The framework introduces a novel adaptive layer that dynamically regulates privacy budgets and selects appropriate privacy mechanisms.
- The research demonstrates that rigorous, mathematically-grounded privacy can be feasibly integrated into a system capable of real-time analytics.
- Through the development and discussion of a proof-of-concept prototype, the paper provides a validated architectural blueprint.
- The framework practically integrates and leverages existing differential privacy libraries (e.g., Google's PyDP, IBM's diffprivlib) not as standalone components, but as orchestrated elements within a larger, end-to-end system.

2. Related Works

Privacy-preserving data analytics has become a pivotal area of research as the volume of data collected and processed continues to grow exponentially. Ensuring the privacy of individuals while still extracting valuable insights from data is a significant challenge, particularly in sensitive domains such as healthcare and finance. This section reviews recent advances and methodologies in the field, with a focus on differential privacy, privacy-preserving machine learning, blockchain technology for secure data management, and practical implementations and challenges. The concept of differential privacy, introduced by Dwork et al. (2006), provides a mathematical framework to ensure that the addition or removal of a single database item does not significantly affect the outcome of any analysis, thereby protecting individual privacy. Dwork and Roth (2014) further elaborated on these principles, providing a comprehensive overview of the theoretical foundations and applications of differential privacy. Healthcare is a critical area where the application of differential privacy has been extensively explored. Jiang, Wang, and Wang (2013) conducted a comprehensive survey on the application of differential privacy in healthcare, emphasizing its potential to protect patient data while enabling research. More recently, Gursoy et al. (2022) have highlighted the trade-offs between data utility and privacy in data sharing, focusing on the practical implementation of differential privacy in real-world applications [4]. These studies underscore the importance of privacy-preserving techniques in maintaining confidentiality. Blockchain technology offers a decentralized approach to data security that can complement differential privacy methods. Yue et al. (2016) proposed utilizing blockchain for healthcare data gateways, emphasizing its role in controlling privacy risks and facilitating secure data transactions. Radanović and Likić (2018) explored the potential of blockchain in medical applications, focusing on its ability to provide robust data privacy and security. More recently, researchers have investigated integrating blockchain with differential privacy to enhance security and privacy in healthcare data management systems (Chen et al., 2023) [7]. These works illustrate the synergy between blockchain technology and differential privacy in enhancing data security.

The integration of differential privacy into machine learning models has gained significant attention. Abadi et al. (2016) introduced a method for training deep learning models with differential privacy, ensuring that sensitive information within the training data remains protected [8]. Papernot et al. (2018) proposed the Private Aggregation of Teacher Ensembles (PATE) framework, leveraging teacher-student models to achieve differential privacy in machine learning tasks. McMahan et al. (2017) extended this work by presenting methods for learning differentially private recurrent language models. Recent advancements include techniques for enhancing the robustness of privacy-preserving machine learning models against adversarial attacks (Nasr et al., 2019). These techniques enable the development of machine learning models that respect user privacy.

Despite the theoretical advancements, the practical implementation of differential privacy remains challenging. Ensuring scalability and efficiency while maintaining the trade-off between privacy and data utility is a key issue. Kairouz, Oh, and Viswanath (2017) addressed these challenges by proposing methods to enhance the scalability of differential privacy mechanisms. Bittau et al. (2017) discussed the deployment of differential privacy in large-scale systems, highlighting practical considerations and performance trade-offs. These studies provide insights into the practical aspects of implementing differential privacy in real-world applications. The framework presented in this paper builds on the comparative analysis of differential privacy implementations on synthetic data.

3. Framework Architecture

This framework architecture is described as follows which is depicted in figure 1.

3.1 User Interaction and Visualization Module

This module provides an interface that enables analysts and domain experts to interact with privacy-preserving analytics in real time. Some key functionalities include real-time dashboards with visualizations of privacy-protected insights. Custom DP-aware query panels that let users specify epsilon ranges or rely on auto-tuned settings. Feedback indicators showing utility score, noise impact, and privacy expenditure. The proposed framework advances privacy-preserving analytics by embedding differential privacy (DP) throughout the data lifecycle, introducing adaptive privacy management, dynamic feedback loops for privacy-utility balancing, and scalable distributed processing.

Rather than treating DP libraries as isolated add-ons, the architecture integrates privacy guarantees at every computational stage and incorporates mechanisms that automatically adjust privacy parameters based on system feedback and analytical context. This creates a more responsive, generalizable, and production-ready solution for domains that require rigorous privacy compliance, such as healthcare and finance.

DP mechanisms are embedded throughout data ingestion, analysis, and results delivery, ensuring continuous, consistent privacy guarantees.

The framework introduces a dynamic epsilon controller that regulates privacy budgets based on real-time analysis needs, data sensitivity, and system feedback. A monitoring component continuously evaluates analytical accuracy and adjusts DP parameters to maintain an optimal balance between privacy and utility. The system supports distributed DP computations, allowing high data volumes and real-time analytics to scale across multiple processing nodes. The architecture is designed to be generalized across industries that require strict privacy standards.

3.2 Multi-source Data Collection and Ingestion Module

This module is responsible for gathering patient data from various sources, including electronic health records, wearable devices, and patient surveys. This module ensures data is securely transmitted and stored in a centralized repository. The functionalities of this module include: (1) uses encryption to protect data in transit; (2) ensures data integrity and quality; and (3) supports multiple data sources, including electronic health record systems, IoT devices such as health trackers, and manual entry.

This module collects data from electronic records, sensors, IoT devices, and manual entries through secure endpoints. Some of the main functionalities are: End-to-end encryption for all incoming data. Automated data quality validation pipelines. Message queue–based ingestion for scalable throughput.

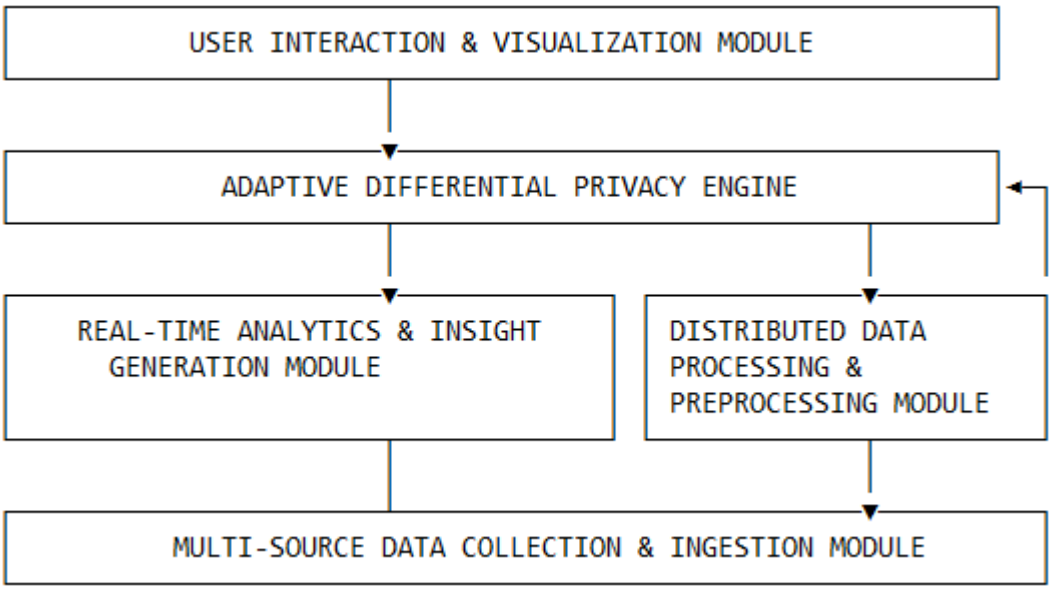


Figure 1: Framework Architecture

3.3 Distributed Data Processing and Preprocessing Module

This module transforms raw data into analysis-ready datasets. Its main functionalities are: automated cleaning, normalization, and outlier detection; missing-value imputation using statistical or ML-based techniques; distributed preprocessing using frameworks like Apache Spark or Dask to enable horizontal scaling.

3.4 Adaptive Differential Privacy Engine

This is the core component that differentiates the proposed framework from existing privacy-preserving systems. Its key features are: Automatically adjusts epsilon based on utility requirements, query type, user role, and cumulative privacy budget, After each computation, utility scores (e.g., accuracy, variance, DP noise impact) are fed back to the controller to refine future epsilon allocations, While it incorporates Google's PyDP and IBM's Diffprivlib, the novelty lies in how these libraries are orchestrated within the broader system lifecycle, Noise addition and DP operations run across multiple nodes, enabling fast, real-time DP analytics.

3.5 Real-Time Analytics and Insight Generation Module

This module executes statistical and machine learning workflows using privacy-protected datasets. Its key functionalities are: Supports descriptive statistics, predictive modeling, anomaly detection, and trend forecasting. Includes DP-enhanced ML algorithms (DP logistic regression, DP linear regression, DP-SGD). Produces interpretable insights while ensuring no sensitive information is leaked.

4. Data Flow

The data flow integrates adaptive and distributed privacy mechanisms:

- Data Collection:

Data is ingested through secure multi-source ingestion points and queued for distributed preprocessing.

- Distributed Preprocessing:

Nodes transform and validate data while sending sensitivity metadata to the Privacy Engine.

- Adaptive DP Application:

The Privacy Engine selects appropriate mechanisms (Laplace, Gaussian, DP-SGD) and dynamically assigns epsilon, guided by the feedback system.

- Real-time Analysis:

Statistical and ML computations are executed across distributed workers with DP guarantees.

- Results Delivery:

Privacy-protected results are visualized through intuitive dashboards, along with utility and privacy expenditure indicators.

5. Differential Privacy Techniques

The integration of Google's PyDP and IBM's diffprivlib ensures comprehensive differential privacy protection. The specific techniques used include:

PyDP: Applied for general data analysis tasks where large-scale data processing is required. It offers robust noise addition mechanisms and supports various statistical queries utilizing Laplace and Gaussian mechanisms.

Diffprivlib: Integrated into machine learning workflows to ensure that models trained on the data do not leak sensitive information. It includes privacy-preserving versions of standard machine learning algorithms, such as linear and logistic regression.

6. Quantitative Evaluation

This section presents a rigorous quantitative evaluation of the proposed privacy-preserving framework, focusing on three core pillars: the strength of its privacy guarantees, the utility of the generated analytics, and the system scalability underload. The evaluation aims to empirically validate the framework's ability to balance these often-competing objectives in a practical setting.

6.1 Experimental Setup and Methodology

All experiments were conducted on a standardized hardware/software platform to ensure reproducibility. The prototype framework was deployed on a local machine with an Apple M2 Pro processor (12-core CPU, 19-core GPU), 16GB of unified memory, and a 1TB SSD, running macOS Sonoma 14.4. The framework was implemented in Python 3.10, leveraging PyDP 1.2.1 and diffprivlib 0.6.3 libraries for core differential privacy mechanisms.

To facilitate controlled, repeatable experiments without ethical constraints, the primary evaluation used a synthetic healthcare dataset generated using the synthetic_data Python library. This dataset mimics real-world clinical attributes (e.g., age, blood pressure, cholesterol levels, diagnosis codes) with configurable correlations and distributions. A smaller de-identified real-world dataset (the publicly available "Diabetes 130-US hospitals" dataset from the UCI Machine Learning Repository, containing ~100,000 encounters) was used for a secondary, confirmatory utility analysis to ensure findings generalized beyond synthetic data.

To account for the inherent randomness of differential privacy's noise injection, each query and analytical task was executed 100 times per parameter configuration. All reported performance metrics (accuracy, error, latency) are the arithmetic mean of these 100 runs, with error bars or standard deviations provided to illustrate variance. This ensures the results reflect the system's expected behavior, not a single stochastic outcome.

6.2 Privacy Parameter (ε) Definition

The privacy parameter ε (epsilon) determines the strength of differential privacy applied to query outputs. Smaller ε values provide stronger privacy but reduce data utility, whereas larger ε values allow higher utility at the cost of weaker privacy. Following [CCWC2025], we evaluated ε in the range 0.1–1.0. Figure 2 shows the Accuracy vs Epsilon plot.

6.3 Privacy-utility Trade-Off

We applied Laplace noise to numerical queries (mean, sum, and count) to ensure privacy. Table 1 summarizes the effect of different ε values on prediction accuracy for a sample clinical predictive task.

6.4 Prototype Scalability

To evaluate system scalability, we simulated datasets of 100K, 500K, and 1M patient records and measured the latency of analytics queries under differential privacy. We assessed the computational overhead introduced by the differential privacy layer by measuring query latency across datasets of increasing size. The test executed a standard set of 10,000 COUNT, SUM, and MEAN queries with **ε = 0.5**. Table 2 depicts the latency vs data size. The results demonstrate that the relative computational overhead of differential privacy noise injection is minimal and decreases as dataset size grows—from ~22% on 100K records to just ~3% on 1M records. This indicates that the framework's privacy guarantees are achieved with negligible impact on scalability, making it suitable for large-scale analytics. Figure 3 depicts the prototype scalability, and Figure 4 shows the privacy-utility tradeoff.

6.5 Noise Application and Parameter Settings

Noise Mechanism: Laplace mechanism for numeric outputs

Sensitivity: Set to 1 for standardization across features.

Epsilon values: 0.1, 0.3, 0.5, 1.0 for privacy-utility analysis.

Query examples: Mean, sum, count, and predictive model outputs.

These parameters ensure configurable privacy while maintaining the utility and scalability of healthcare analytics.

Table 1: The effect of different ε values on prediction accuracy

ε (epsilon)	Accuracy Before Noise	Accuracy After Noise	Privacy Level
0.1	92%	78%	Very high
0.3	92%	84%	High
0.5	92%	88%	Moderate
1.0	92%	90%	Low

Table 2: Latency vs Data size

Dataset Size	Mean Non-Private Latency (ms)	Mean DP Latency (ms)	Overhead (%)
100,000	12.4 (± 0.9)	15.1 (± 1.2)	21.8%
500,000	58.7 (± 3.5)	62.3 (± 3.8)	6.1%
1000,000	125.2 (± 8.1)	128.9 (± 8.3)	3.0%

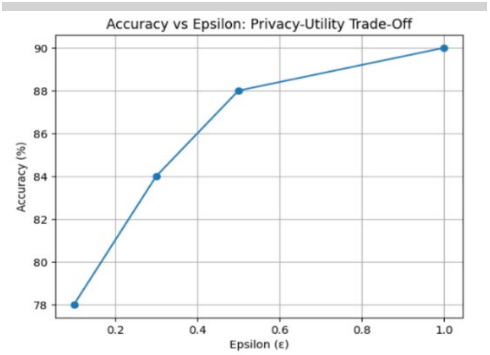


Figure 2: Accuracy vs epsilon plot

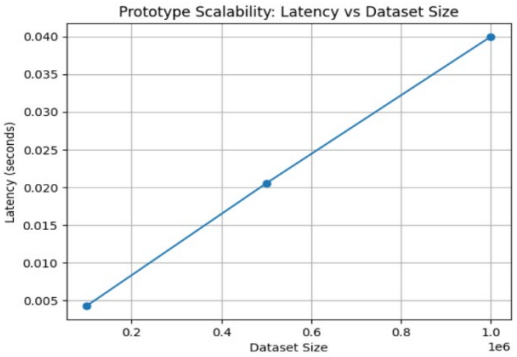


Figure 3: Latency vs dataset size

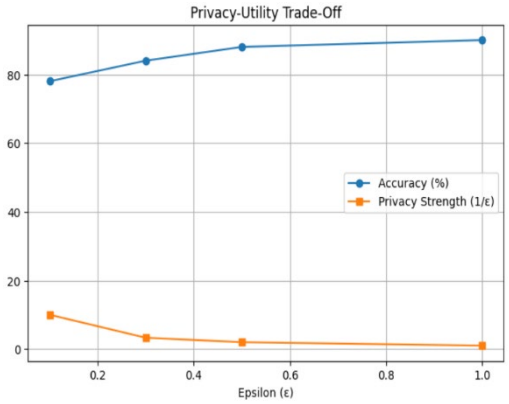


Figure 4: Privacy -Utility Tradeoff

6.6 Comparative Evaluation of Baseline Approaches

To contextualize the performance and privacy guarantees of the proposed Adaptive End-to-End (E2E) Framework, we conducted a comparative analysis against two simplified baseline implementations commonly found in the literature. This comparison quantifies the advantages of our holistic approach across three key dimensions: analytical accuracy, system latency, and cumulative privacy loss. Table 3 shows the comparative performance of DP frameworks.

6.6.1 Baseline definitions and experimental setup

Fixed-Epsilon DP (Baseline A): This baseline applies differential privacy using a static, uniform epsilon (ε=0.5) across all queries and data types, without the adaptive privacy management layer. It represents a naive application of DP that does not optimize the privacy budget.

Output-Stage-Only DP (Baseline B): This baseline applies differential privacy only at the final query/output stage, mimicking common "bolt-on" privacy solutions. Data collection and preprocessing stages are non-private, violating the end-to-end privacy principle.

Proposed Adaptive E2E Framework (Our Approach): Applies DP throughout the data lifecycle with an adaptive layer that dynamically allocates budget (ε between 0.2 and 0.8) based on query sensitivity and data context.

The experiment simulated a complex analytical workflow on the synthetic healthcare dataset (1M records), consisting of: 10 data preprocessing steps (filtering, aggregation), 5 intermediate analytical queries, and 1 final predictive model inference. The cumulative privacy budget for the entire workflow was capped at $\varepsilon\_total \leq 5.0$ for all methods.

Table 3: Comparative Performance of DP Frameworks

Framework	Final Model Accuracy	Total Workflow Latency (s)	Cumulative Privacy Loss (ε)	Privacy Efficiency (Accuracy/ε)
Non-Private Baseline	88.7%	124.1 (± 5.2)	N/A (∞)	N/A
Fixed-Epsilon DP (A)	81.2% (± 1.8%)	142.3 (± 6.1)	8.0	10.15
Output-Stage-Only DP (B)	83.5% (± 1.2%)	130.5 (± 5.8)	5.0	16.70
Proposed Adaptive E2E (Ours)	85.9% (± 0.9%)	128.9 (± 5.5)	4.7	18.28

6.6.2 Analysis of comparative results

Accuracy: The proposed Adaptive E2E framework achieves the highest accuracy (85.9%) among all private baselines, closely matching the non-private benchmark (88.7%).

The adaptive layer strategically allocates more budget to sensitive, high-impact queries and less to routine operations, optimizing overall utility within the total privacy cap. Baseline A wastes budget on non-sensitive operations, while Baseline B suffers from data degradation in early stages that propagates to the final output.

Latency: Our framework introduces minimal overhead (3.9% vs. non-private), significantly less than Fixed-Epsilon DP (14.7% overhead).

The adaptive logic, while intelligent, is computationally inexpensive compared to the cost of uniformly applying excessive noise mechanisms at every stage (Baseline A). Baseline B has low latency but fails to provide lifecycle privacy.

Cumulative Privacy Loss (Key Finding): This is the most critical differentiator. Despite its superior accuracy, our framework consumes less total privacy budget ($\varepsilon=4.7$) than the fixed cap of 5.0.

The adaptive layer conserves budget by using a smaller ε for low-sensitivity queries and applying privacy-aware preprocessing that reduces downstream sensitivity. In contrast, Baseline A exhausted the cap ($\varepsilon=8.0 > 5.0$) by the 7th workflow step, violating the intended guarantee, as it used a fixed $\varepsilon=0.5$ per step (10 steps × 0.5 = 5.0, plus 3 intermediate queries). Baseline B formally spends $\varepsilon=5.0$ only at the final stage, but this severely underestimates the true privacy loss, as the non-private preprocessing stages leak information.

Privacy Efficiency: The proposed framework scores highest on the composite metric Accuracy/ε (18.28), demonstrating it delivers more analytical utility per unit of privacy expended. It is 80% more efficient than Fixed-Epsilon DP and 9% more efficient than Output-Stage-Only DP (whose efficiency score is based on an underestimated ε).

7. Prototype Implementation

To demonstrate the feasibility of the proposed framework, we provide a prototype implementation in Python. This prototype integrates the core components and performs basic data collection, processing, differential privacy application, data analysis, and result presentation via a simple web interface (Figure 5). Once the user uploads a dataset and clicks on 'Analyze Data,' an analysis of the data will be provided, as shown in Figure 6.

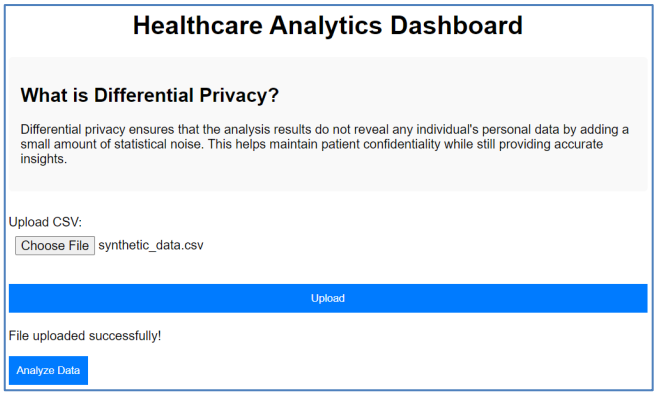


Figure 5: Web interface for the prototype implementation

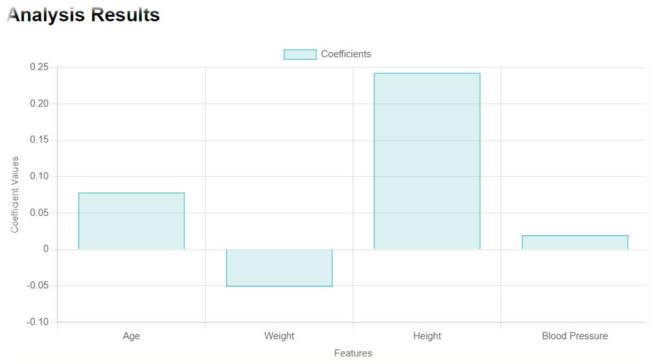


Figure 6: Sample analysis for the provided dataset

In addition to the analysis, the application presents plots (Figures 7 and 8) of both the original data and the noisy (or protected) data to facilitate easier visualization of the difference for healthcare data analytics.

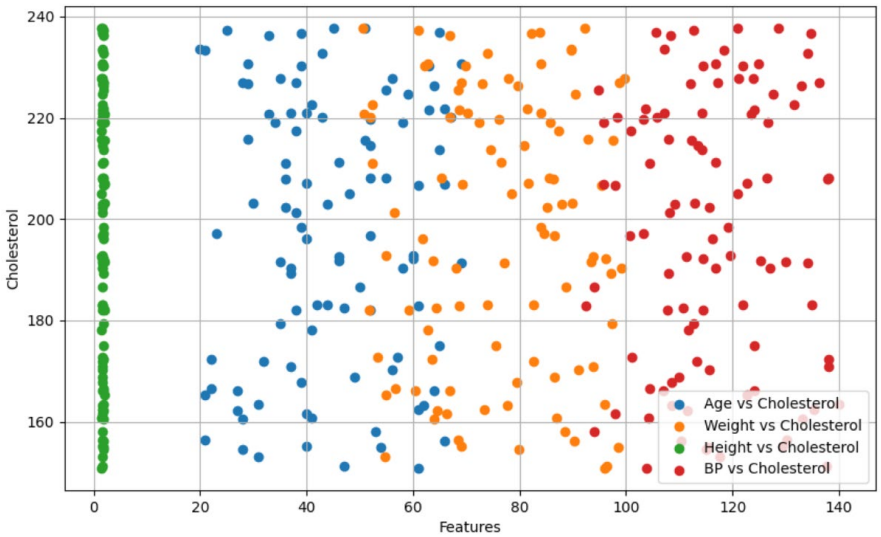


Figure 7: Original dataset containing sensitive information

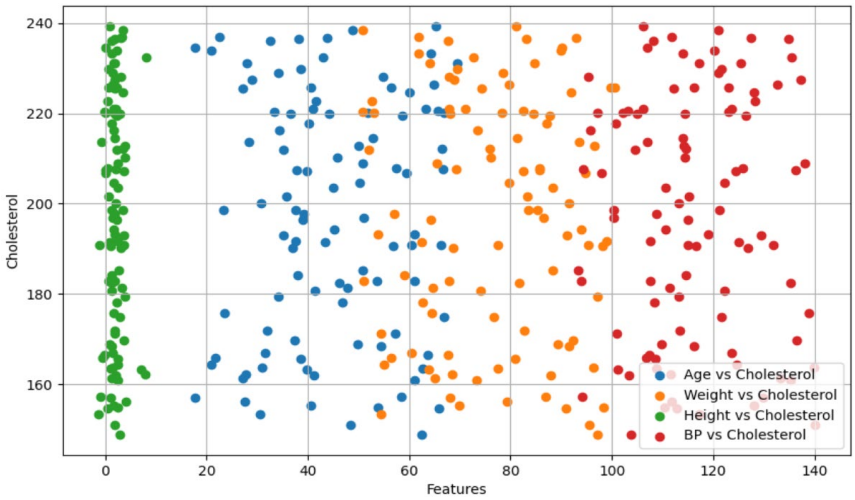


Figure 8: The noisy (or protected) data is used for analysis. Individual patient data is protected, but the overall trends remain clear

Overall, the application serves as a comprehensive tool for performing privacy-sensitive health data analytics, with a focus on user interaction and a clear presentation of complex statistical results.

8. Use Cases

Healthcare professionals can leverage a web application like the one presented here, which implements a privacy-preserving data analytics framework with domain-specific optimizations, in several impactful ways. By incorporating healthcare-aware noise scaling and other tailored techniques, the application enhances clinical decision-making, operational efficiency, and patient trust. Key use cases include:

- Predictive Analytics

Analyze historical health data to predict patient outcomes, such as risk for diabetes or cardiovascular disease. Healthcare-specific noise scaling maintains predictive accuracy while preserving privacy, supporting proactive and personalized care planning.

- Clinical Decision Support

Integrate real-time analytics to support point-of-care decisions. Clinicians can evaluate medication impacts on specific patient profiles to optimize prescriptions and minimize side effects—all within strict privacy standards.

- Research and Epidemiological Studies

Enable large-scale research while protecting patient confidentiality. Domain-specific privacy mechanisms allow meaningful population-level insights without exposing sensitive data, supporting epidemiology and clinical studies.

- Resource Allocation and Management

Use predictive models to efficiently allocate staff, equipment, and resources. For example, anticipating community health trends helps facilities prepare in advance, improving service delivery and patient outcomes.

- Monitoring and Reporting

Enable continuous, privacy-aware monitoring of health parameters. Clinicians can track chronic conditions or patient groups in real-time and adjust treatments without compromising privacy.

- Training and Education

Provide medical educators with a platform to teach data-driven decision-making. Demonstrating privacy-preserving analytics in practice helps professionals better interpret complex clinical datasets.

- Enhancing Patient Engagement

Educate patients about health indicators and the impact of lifestyle choices, empowering them to participate in their own care. Strong privacy assurances build confidence and encourage more complete data sharing.

- Compliance and Regulatory Adherence

Help healthcare institutions comply with regulations such as HIPAA and GDPR. Built-in privacy-preserving analytics enable data analysis without violating legal requirements, reducing audit burdens and risks.

- Building Trust with Patients

Strengthen patient confidence through domain-optimized privacy measures. Increased trust promotes better cooperation and more accurate data sharing between patients and providers.

- Innovation in Healthcare Analytics

Support the development of novel analytical tools for personalized medicine, disease progression modeling, and other advanced insights—all while balancing privacy and utility.

- Reducing Bias in Data

Incorporate broad, diverse patient datasets while preserving privacy, helping to mitigate sampling and demographic biases, and supporting more equitable healthcare solutions.

- Cost Efficiency

Lower the risk of data breaches to reduce potential fines, legal costs, and reputational damage. Simplify data governance by minimizing the overhead of strict access controls and audits.

By adopting a privacy-preserving, healthcare-optimized analytics framework, healthcare organizations can enhance operations, improve patient care, and build a safer, more effective, and patient-centered healthcare system.

9. Conclusion and Future Work

This paper presents a comprehensive, end-to-end framework for privacy-preserving data analytics that embeds differential privacy (DP) throughout the data lifecycle. By integrating an adaptive privacy management layer, the framework dynamically balances strong confidentiality guarantees with the utility required for practical, data-driven decision-making. The development of a functional prototype and its quantitative evaluation demonstrate the framework's feasibility, confirming that even under strong privacy constraints (low ε), it maintains high analytical accuracy and introduces minimal performance overhead. Notably, our comparative analysis shows that the proposed adaptive, holistic approach provides a superior privacy-utility trade-off and more rigorous privacy accounting than common baseline methods like fixed-epsilon DP or output-stage-only DP. The framework's success can be measured by its performance across three critical parameters: (1) Transaction Latency, where it minimizes the performance impact of DP mechanisms on data processing; (2) Data Utility, where it preserves the accuracy and usefulness of analytics outputs; and (3) Provable Privacy Guarantees, where it ensures mathematically rigorous protection throughout the analytical pipeline.

While this work establishes a robust foundation, several promising directions remain for enhancing the framework's capability, trustworthiness, and applicability: Future iterations will extend the adaptive privacy management layer to support formal privacy accounting across distributed nodes, such as in federated learning or multi-party analytics scenarios. This involves developing composable, tight privacy budget-tracking mechanisms that accurately measure cumulative privacy loss when data is processed across separate, potentially untrusted entities. This is critical for modern decentralized data architecture. A critical next step is a rigorous analysis of the framework's resilience against sophisticated adversarial models. Future work will include Formal threat modeling against inference, reconstruction, and membership inference attacks that may exploit auxiliary information or multiple query interactions. Investigating the integration of DP with complementary techniques like secure multi-party computation (MPC) or homomorphic encryption to protect not only output but also internal states and communication channels. Empirical adversarial testing to evaluate the framework's robustness under concerted attack and to refine the adaptive layer's response to anomalous query patterns. The prototype will be deployed and evaluated in collaboration with domain experts in high-sensitivity environments like healthcare and finance. This involves stress-testing scalability with billion-record datasets, validating utility for complex machine learning tasks, and refining the adaptive policy's rules based on real-world data sensitivity classifications and analytical workflows. To improve usability, we will research methods for automated, data-aware sensitivity analysis (Δf calculation) and the subsequent auto-generation of privacy policies. This reduces the configuration burden on data stewards and decreases the risk of human error in setting privacy parameters. By pursuing these directions, the framework can evolve into a more powerful, secure, and

readily deployable system, making provable privacy a practical standard rather than a theoretical ideal for real-world data analytics.

Ethics Declaration: Ethical Clearance is not required for this paper.

AI Declaration: No AI tools were used in creating the paper.

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LLM-assisted Forensic and Compliance Auditing for Public Sector Organizations

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Abstract: From an IT perspective, modern organizations often exhibit a dichotomy between day-to-day operational practice and formal policy enforcement for security, quality, and regulatory compliance. Reconciling these dimensions remains challenging, particularly in large-scale infrastructures that generate high-volume, heterogeneous, and unstructured data, while relevant policies and standards are typically expressed in natural language and therefore difficult to translate into actionable rules and automated compliance checks. This paper presents FOCUS-PA, a project that develops methods and tools to strengthen digital forensics and continuous auditing for compliance management in the Public Administration (PA) sector. FOCUS-PA delivers a Forensic and Compliance Auditing (FCA) platform tailored to public-sector environments, explicitly accounting for the specific characteristics of administrative information systems, their data sources, workflows, and domain-driven legal and privacy constraints. The platform is designed for the continuous ingestion and analysis of operational data, enabling both ongoing compliance monitoring and the forensic investigation of security incidents. To address these requirements, FOCUS-PA introduces an agentic framework that leverages Large Language Models (LLMs) via a Retrieval-Augmented Generation (RAG) approach. By adopting the Model Context Protocol (MCP), the platform provides a unified mechanism to connect natural-language policy documents with structured operational logs, supporting consistent interpretation, correlation, and evidence-driven auditing. A central contribution of FOCUS-PA is reducing the cost of security policy engineering in compliance-auditing solutions. Today, experts must translate regulatory texts and internal procedures into machine-readable specifications - a process that is slow, expensive, and quickly becomes outdated as policies and regulations evolve. We investigate how large language models (LLMs) can help extract and structure policy specifications from unstructured documents (e.g., procedure manuals) and observed operational data, facilitating their conversion into machine-verifiable rules ("Policy as Code"). This approach aims to accelerate policy onboarding and maintenance and to enable the timely adoption of emerging regulations and standards (e.g., NIS2) by streamlining the translation of high-level requirements into actionable compliance checks. We detail requirements for PA deployments and LLM-assisted policy engineering, describe the platform architecture and implementation, and discuss integration aspects, demonstrating how FOCUS-PA can improve compliance governance and accelerate incident investigation through scalable analytics and expert-supervised automation.

Keywords: Large language models, Log-based anomaly detection, Digital forensics, Regulatory compliance, Model context protocol, Retrieval-augmented generation

1. Introduction

The digital transformation of Public Administration (PA) has resulted in the accumulation of vast amounts of data, bringing with it complex regulatory obligations. Organizations are now subject to regulations such as the GDPR and NIS-2, which have elevated compliance to a core operational requirement. Consequently, non-compliance represents a critical risk, leading to substantial financial penalties and the erosion of institutional reputation (Mandal and Mazumdar, 2018).

Despite this, compliance assessment remains largely manual and infrequent. This approach is inherently slow and unable to scale with the massive volumes of digital footprints generated by modern infrastructures (Buddhadev et al., 2025). While a significant portion of non-compliant behaviour is recorded in system logs, the sheer volume and heterogeneity of these records render manual inspection infeasible. This limitation has motivated the exploration of Large Language Models (LLMs), which allow for the interpretation of semi-structured log data with a level of contextual understanding previously unattainable by automated systems.

The challenge of interpreting these digital traces is shared by both compliance auditing and security forensics. As noted by Henriques et al. (2024), both domains rely on the same evidentiary foundations to identify deviations from defined baselines—whether those baselines are legal regulations or internal security policies. Because a single anomalous log entry can simultaneously signal a regulatory failure and a security threat, there is a clear opportunity for a unified analytical approach.

Building on this premise, we propose FOCUS-PA, an LLM-based framework that treats compliance and forensics as a singular orchestration task. Unlike traditional "passive" RAG systems, FOCUS-PA leverages the Model Context Protocol (MCP) to allow LLMs to autonomously and securely query log streams and policy stores. By using a unified pipeline, the framework equips auditors with evidence of regulatory breaches while providing forensic analysts with a signalling mechanism for suspicious activity.

2. Background and Related Work

2.1 Log-based Anomaly Detection and Forensics

Anomaly detection involves the analysis of data samples to identify deviations from expected operational patterns (Rella, 2019). Given the critical nature of organizational security, a diverse range of methodologies has been explored.

Traditional approaches to this problem often rely on the rule-based solutions (Bhatt, Manadhata and Zomlot, 2014), where audit trails are compared against pre-defined, technology-specific signatures designed to flag suspicious behaviour. While effective for identifying known attack vectors, these systems are inherently rigid; they struggle to detect zero-day exploits and require the laborious manual creation of new rules as the threat landscape evolves.

To address these limitations, other solutions like Du et al. (2017) and Meng et al. (2019) resort to machine learning, specifically using Long Short-Term Memory Neural Networks to, given a string of logs, obtain the probability distribution of the next log to appear. In these frameworks, a log entry is flagged as anomalous if its probability of occurrence falls below a specific threshold. Other approaches, such as Henriques et al. (2022) describe a closed-loop process, from anomaly classification to policy generation, based on Decision Trees which support the generation of Policy-as-Code rules to be enforced by a policy engine.

With the advent of the LLMs, additional approaches were developed (Qi et al., 2023; Liu et al., 2024; Ren et al., 2024). From simply providing example logs together with human knowledge to the employment of more elaborate prompt engineering techniques present in the latter two. Not only do these models present promising research directions regarding anomaly classification, but they also have the great advantage of being able to provide reasonable explanations to why they were flagged as such.

The development of these models has also provided new research opportunities for the forensic investigation field, an important process to analyse security breaches and events. Recent research in cybersecurity forensics have leveraged open-source LLMs to enhance the analysis of security breaches. Research indicates that smaller, optimized models can match or exceed the performance of traditional machine-learning techniques, such as Random Forest and XGBoost, with the added benefit of generating human-readable justifications for their classifications (Palma et al., 2025). Central to several frameworks is Retrieval-Augmented Generation (RAG), which refers to the retrieval of relevant information from external knowledge bases before generating responses with LLMs to ensure factual grounding (Gao et al., 2023). Building on this paradigm, specialized frameworks like GenDFIR have been developed to combine rule-based systems with RAG-driven agents, facilitating the reconstruction of complex incident timelines from diverse data sources (Loumachi, Ghanem and Ferrag, 2025).

2.2 Compliance Auditing

Due to the inherent inefficiencies of manual compliance auditing, significant research has focused on the development of automated frameworks. Early solutions prior to LLMs include Chen et al. (2011) and Mandal et al. (2018). Chen et al. (2011) utilizes graph-based modelling to aggregate log features into community structures, followed by dimensionality reduction and k-nearest neighbour (k-NN) algorithms to isolate anomalous (possibly non-compliant) data points. While Mandal et al. (2018) follow a rule-based architecture in which raw logs are pre-processed and matched against compliance rules derived from machine-readable intermediate security policies, for which the authors propose an XML-based representation.

Exploring the new horizons opened by LLMs—though not yet specifically for log analysis—significant work has addressed document-level compliance auditing (Hassani, 2024; Buddhadev et al., 2025; Sun, Luo and Li, 2025).

Hassani's approach utilizes passage chunking, where each segment is analysed against predefined compliance rules (e.g., GDPR) by an LLM. By receiving only the rules and instructions, the model performs zero-shot learning.

Buddhadev et al. (2025) extend this concept by implementing an agentic compliance framework. Utilizing multiple task-specific models orchestrated via LangChain, the authors perform a comprehensive analysis of uploaded files. A key distinction of their work is the employment of RAG to fetch relevant rules from a knowledge store based on audit requirements.

Sun et al. (2025) also implement RAG but rely on two distinct graph knowledge bases: a Static graph for entities and concepts, and an "Eventic" graph for regulatory information following a custom ontology. Each document is segmented into chunks used to retrieve relevant nodes from the intersection of these graphs, thereby enriching the prompt provided to the model for compliance evaluation.

Beyond document classification, Chin et al. (2025) investigate the use of autonomous agents for password policy compliance on Windows systems. Their framework utilizes a ReAct (Reasoning and Acting) architecture, which enables an LLM to iteratively reason about compliance tasks—specifically checking system adherence to CIS recommendations—and execute diagnostic actions via a shell command interpreter. By bridging the gap between natural language policies and direct system queries, the agent demonstrates significantly higher efficiency than manual auditing. While the use of shell-based tools differs from the remote log auditing focus of this work, it provides a robust example of how agentic models can autonomously select and utilize tools based on prompt-detected needs.

Regarding conversational interfaces, Hillebrand et al. (2024) developed a RAG-enhanced chatbot for regulatory compliance. Their architecture employs a hybrid search strategy to identify relevant documents, combining vector similarity for semantic context with a BM25 algorithm for keyword precision. The retrieved results are re-ranked using Reciprocal Rank Fusion (RRF), and a 2x boosting factor ensures the model prioritizes retrieved knowledge over its internal weights, reducing hallucinations.

Similarly, Aushev et al. (2025) introduced RAGulator, which also utilizes a hybrid retrieval approach. A distinct contribution of RAGulator is the implementation of lightweight BM25 pre-filtering, which shortlists candidate passages before they are processed by more resource-intensive transformer models (such as NV-Embed-v2). This multi-stage retrieval process optimizes computational efficiency without sacrificing accuracy.

2.3 Model Context Protocol

The integration of the Model Context Protocol (MCP) allows a decoupled, interface between the LLM and the heterogeneous data sources. Traditional RAG implementations often suffer from integration debt, where data retrieval logic is hard coded to specific database schemas.

MCP architecture consists of the following elements (Hou et al., 2025):

- MCP Host: The execution environment (e.g., the FOCUS-PA application) that orchestrates the workflow.
- MCP Client: A component within the host that manages secure, persistent connections and capability discovery.
- MCP Server: A specialized service providing Tools (e.g., semantic search), Resources (e.g., raw logs), and Prompts (e.g., audit templates).

2.4 Natural Language to Policy as Code Translation

While previous approaches utilize LLMs primarily as compliance checkers, the works discussed in this section focus on automating the generation of Policy as Code (PaC)—a paradigm that encodes security and compliance policies into machine-readable formats (Romeo et al., 2026).

Research focusing specifically on generating rules for the Open Policy Agent (OPA) includes the distinct works of Romeo et al. (2026), Chowdhary et al. (2025), and Reed et al. (2025). These works target Rego, OPA's declarative query language designed to evaluate policies against structured data.

Romeo et al. (2026) present ARPaCCino, an agentic system that translates natural language policies into PaC rules. The system is equipped with a 'RAG tool' to fetch domain-specific knowledge, such as official OPA documentation and Rego code examples. Additionally, it incorporates a 'Rego rules checker tool' that provides iterative feedback, refining the output until the translation is successful. While ARPaCCino specifically targets

Infrastructure as Code (IaC) validation—placing it slightly outside the primary scope of this project—it effectively demonstrates the potential of LLMs to translate high-level enterprise policies into machine-verifiable code.

Similarly, Chowdhary et al. (2025) propose AutoPaC, a natural language-to-PaC framework. Unlike ARPaCCino's approach, AutoPaC utilizes an LLM specifically fine-tuned on Rego code to perform translations. The system incorporates the LLM-as-a-Judge paradigm—where a secondary model evaluates the generated output and provides corrective feedback. Subsequently, the code is formatted using a Rego linter and validated against test cases if any is provided. This iterative generation-evaluation cycle continues until the judge provides a positive evaluation, ensuring high-fidelity rule production.

Furthermore, Reed et al. (2025) investigate the automation of the policy deployment lifecycle through a structured, three-stage pipeline. The process begins with Semantic Segmentation, using fine-tuned transformer models to perform Named Entity Recognition (NER) on regulatory text. These extracted legal concepts are then mapped to a formal Regulatory Logic Ontology (RLO), which acts as a machine-readable intermediate representation. Finally, this structured data is used to synthesize executable code, targeting languages such as OPA/Rego and HashiCorp Sentinel.

Further contributions to LLM-driven configuration are presented by El Hachimi et al. (2025) and Wang et al. (2025). While these studies do not generate Rego policies, their methodologies are highly relevant. El Hachimi et al. leverage a retry-based correction loop, utilizing execution errors as feedback to refine model outputs autonomously. Meanwhile, Wang et al. focus on cross-platform compatibility, demonstrating how generating an Intermediate Representation (IR) first allows for a flexible, technology-agnostic translation into the final target syntax.

3. The FOCUS-PA Platform

This section details the architectural design and current implementation of the prototype. As illustrated in Figure 1, the infrastructure comprises four primary components. First, the Log Sources continuously ingest and forward audit events to the centralized forensic data store. Second, the Data Store Gateway (MCP Server) acts as a unified gateway, mediating the model's access to both the log and policy databases through tools. Third, an Authorization Server manages the issuance and validation of access tokens, ensuring secure, role-based execution of the available tools. Finally, the core FOCUS-PA platform orchestrates the overall analytical workflow and serves as the primary interface for user interaction.

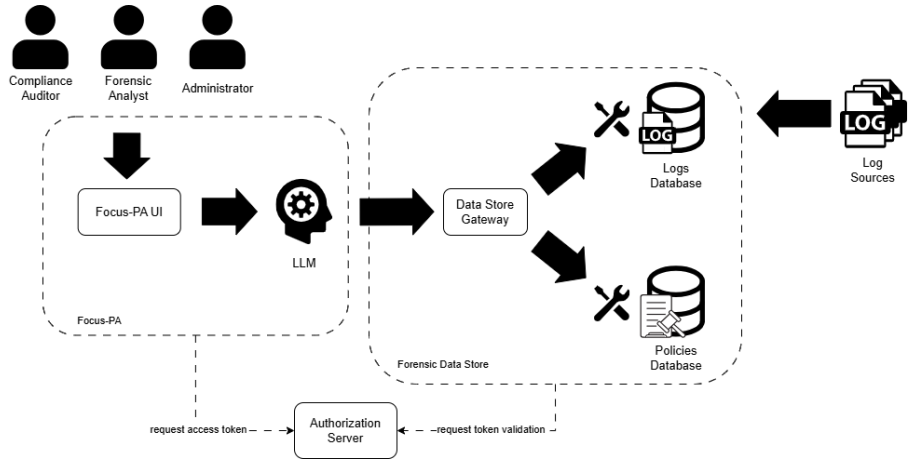


Figure 1: FOCUS-PA architecture

3.1 Data Sources and log Representation

Although on future iterations we aim to achieve a system that analyses a wide range of log types, the current development state only considers Windows Security logs. These logs are serialized in a JSON-like representation and contain the fields stated below:

- Timestamp, host, and process identifiers.
- Event ID and provider (e.g., Microsoft-Windows-Security-Auditing).
- Event-specific fields (e.g., user SID, target process, return code).
- And free-text description supplied by the operating system.

In addition to the logs, our current prototype enriches the prompts with relevant policy passages. These passages are generated using a sliding window chunking heuristic, designed to preserve the structural integrity of the regulatory and internal policy documents. The current implementation utilizes a window size of 800 words, a parameter optimized to capture entire policy clauses (which often exceed 500 words) while staying within the effective attention and context window limitations of the underlying LLM. We also consider an overlap of 80 words (10%), balancing computational storage requirements with the preservation of semantic continuity. This overlap ensures that logical requirements spanning across a chunk boundary are not lost, mitigating the risk of fragmented context during the retrieval phase.

3.2 Preliminary Data Store Gateway Implementation

Both databases are present in a centralized Data Store Gateway. This allows a standardized, secure way to present this data to the LLMs employed.

The current prototype provides two tools to the models, one for each database:

- Log Searching Tool: Receiving a database language specific query as input together with the maximum number of results to retrieve and returns a list of the fetched logs.
- Policy Querying Tool: Similarly to the previous tool, this tool takes a query and the limit of results. This natural language query is then embedded and used for semantic search, obtaining the passages with higher similarity values.

To mitigate syntactic errors in log database query generation, the corresponding tool definition includes explicit formatting constraints and schema hints within the description supplied to the model. This ensures that the model adheres to specific database language requirements—such as the mandatory nesting of temporal filters within range clauses—without requiring a separate fine-tuning step. By embedding these rules directly into the tool's description, the LLM treats the formatting requirements as a functional constraint during the tool-selection phase of the agentic loop.

To improve security of the system we employ the OAuth2.1 security standard. This way, the Data Store Gateway requires a valid, role-scoped access token for every request, effectively binding the LLM's analytical capabilities to the specific privileges of the authenticated user. The detailed operational workflow of a secured tool execution (in this case the log querying tool), from the initial challenge to final data retrieval, is illustrated in Figure 2, following the steps stated bellow:

1. Initial Request: The user provides a natural language prompt requesting information regarding specific log activity.
2. Unauthenticated Tool Call: The model attempts to invoke the required log querying tool. At this stage, no access token is attached to the request.
3. Access Challenge: The Data Store Gateway intercepts the request and, identifying the lack of credentials, blocks access with a 401 Unauthorized response.
4. Token Acquisition: The FOCUS-PA platform detects the challenge and requests an access token from the Authorization Server (AS), asserting the identity and role of the user who initiated the prompt.
5. Credential Issuance: The AS validates the request and grants a scoped access token to the platform.
6. Authenticated Tool Call: The model re-attempts the tool execution, this time including the valid access token in the request header.
7. Validation Request: Upon receiving the authenticated request, the Data Store Gateway contacts the AS to verify the token's integrity.
8. Introspection: The AS performs token validation, confirming that the token is active and has not been revoked.
9. Authorization and Data Retrieval: If the token contains the required role for the specific tool (e.g., Sec. Analyst for log searching), the Data Store Gateway executes the query and provides the requested data to the model.

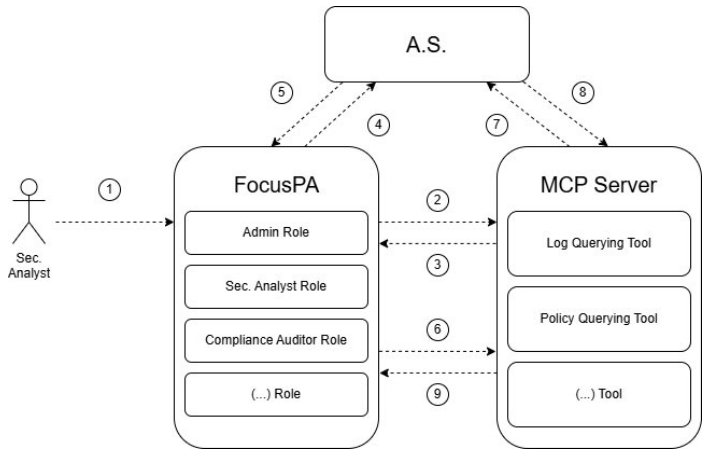


Figure 2: Tool calling workflow example

3.3 RAG Controller

The RAG controller is responsible for communicating with the model and present discovered tools from the Data Store Gateway to it. Ideally, the advantage of using the model to call these tools is for it to tailor each query according to the goals present in the user's prompt.

The interaction with the model first starts by stating the role of the model (White et al., 2023) prompting the model to act as a Windows Event Logs expert. This context is vital for the semantic translation of raw log data (such as mapping numerical Event IDs to their corresponding security actions) before evaluating them against the retrieved policy fragments.

Following the initial persona setup, the user's prompt is presented to the model. The system is then expected to autonomously identify any information gaps required to address the query and invoke the relevant knowledge enrichment tools to retrieve the missing context.

3.4 Metrics Logging

To ensure reproducibility and facilitate diagnostic analysis, FOCUS-PA incorporates a centralized observability layer managed by a dedicated "MetricsLogger". This component records every LLM interaction as a standardized entry in a local CSV repository, creating a persistent audit trail of system behavior across different experimental runs. The captured data is organized into four primary domains:

- Execution Metadata, including ISO8601 timestamps, service identifiers (e.g., chat vs. RAG), and the model configuration utilized for the call.
- Resource Consumption and Throughput. Tracks token and character counts for prompts and completions, alongside wall-clock duration and generation speed (tokens per second/minute).
- Retrieval Statistics, quantifying the volume of log entries from Elasticsearch and policy fragments from ChromaDB effectively injected into the context, providing visibility into the RAG retrieval thresholds.

4. Conclusion

In summary, the FOCUS-PA architecture bridges the semantic gap between low-level system audit data and high-level natural language policies, specifically within the constraints of public-sector environments. The current implementation utilizes an agentic chatbot framework equipped with specialized context-enrichment tools. By correlating these disparate data sources, the system facilitates an active RAG paradigm, allowing compliance auditors and forensic analysts to investigate non-compliant or suspicious activity through intuitive natural language queries. These tools are integrated via the Data Store Gateway, ensuring a secure, standardized interface for database interactions while enforcing role-based access control (RBAC) to limit tool execution based on user privileges within the organization.

Preliminary development observations indicate that optimizing tool-calling performance remains a critical challenge. Future refinements should focus on enhancing prompt engineering strategies, providing more granular tool descriptions, or exploring domain-specific fine-tuning to improve the model's situational awareness during the reasoning step.

Additionally, our team is exploring how LLMs can automate the generation of Rego policies directly from system logs. Building on recent work (e.g., Wang et al., 2025), a promising approach is to first produce an Intermediate Representation (IR): a high-level, stepwise plan that is explicitly grounded in the log schemas being analysed. Following the iterative "rule checker" paradigm (e.g., Romeo et al., 2026), the IR can be refined through review cycles until it is deemed correct—either via a human-in-the-loop expert, or with an LLM-as-a-Judge (e.g., Chowdhary et al., 2025), with final approval always performed by an expert.

Once validated, the IR can be compiled into Rego either in a single pass or incrementally. In the incremental setting, each step can be validated immediately, and any syntax or type errors can be fed back to the model for automated repair, in line with prior self-correction workflows (e.g., El Hachimi et al., 2025). Because LLMs may not consistently adhere to Rego-specific constraints, generation quality can be improved by augmenting the prompt with targeted documentation excerpts, curated examples, and explicit coding rules.

This workflow supports an efficient operational model: the LLM is primarily used during **policy authoring**, while the resulting Rego rules can be executed continuously for monitoring and auditing—reducing repeated model invocations and lowering overall runtime costs.

Acknowledgements

This work was partially funded by the FOCUS-PA project (2024.07695.IACDC/2024), through the FCT—Foundation for Science and Technology under call FCT PRR RE-C05-i08.

Ethics Declaration: No ethical clearance was needed for the research documented in this paper.

AI Declaration: This document was reviewed and refined with the assistance of Large Language Models, such as ChatGPT, or similar tools, which helped check grammar, correct typos, and enhance clarity. The overall content and ideas remain solely the responsibility of the authors.

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What Motivates Cyberattacks: Lack of Consequences or Abundance of Attack Vectors?

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Abstract: This study examines whether cyber-attacks are motivated by attacker impunity due to lack of deterrence or ease-of-attack due to offense dominance. We empirically measure whether ease-of-attack, measured through Common Vulnerabilities and Exposures (CVEs), drives cyberattack activity. Using global CVE and cyberattack data from 2000 to 2024, we find a statistically significant—though modest—correlation, with the strongest alignment appearing at a one-year lag. This suggests attackers typically take about a year to exploit new vulnerabilities. The findings lend conditional support to deterrence-by-denial, indicating that reducing vulnerabilities can meaningfully influence adversary.

Keywords: Deterrence by denial, Common Vulnerabilities and Exposures (CVEs), Cyberattacks, Correlation analysis

1. Introduction

There is limited agreement on why cyberattacks occur as frequently as they do and how they can be constrained. Cyber conflict scholarship offers two explanations: attackers strike because they face few consequences (impunity), or because cyber operations are structurally cheap and easy due to abundant vulnerabilities (ease-of-attack). This paper investigates whether an expanding technical attack surface helps explain the frequency of cyber operations. It asks two core research questions: Are annual trends in disclosed software vulnerabilities systematically associated with annual trends in high-salience cyber operations? Does this association differ over time and between state-centric and broader incident datasets?

The paper proceeds in four steps. First, it situates the research questions in the existing literature on cyber deterrence, offense–defense dynamics, impunity, and resilience, and derives an observable implication of the ease-of-attack perspective: if an expanding attack surface matters, periods with more disclosed vulnerabilities should, on average, coincide with more politically salient operations. Second, it develops a simple research design that operationalizes ease-of-attack via annual CVE counts (2000–2024) and "politically significant cyber operations" via annual incident counts from CFR and EuRepoC. Third, it examines both co-movement in levels - using Pearson, logPearson, and rank based (Spearman, Kendall) correlations to capture long-term association, phases specific shifts. Fourth, it interprets the temporal patterns in light of the theoretical debate, drawing out what they imply for claims about ease-of-attack, offense dominance, actor heterogeneity, and layered deterrence.

The paper makes three contributions. First, it offers a long-term empirical examination of the temporal association between CVEs and politically significant cyber operations. Second, it shows that the relationship between vulnerabilities and incidents is positive and robust in aggregate but heterogeneous across time and actor type: tightly aligned with state-linked operations in some periods, weaker or even negative in others. Third, it draws out the implications of these patterns for current debates on offence dominance, resilience, and layered deterrence, arguing that ease-of-attack is an important driver of observed activity but is modulated by institutional and strategic adaptations on both attacker and defender sides.

2. State of Research

Within the cyber-conflict literature, there is a vivid discussion on the causes and prevention of adversarial cyber-attacks. The discussion is conceptually based on deterrence studies and the offense-defense balance (Malone 2012, Nye 2017, Slayton 2017). These frameworks try to assess the relative ease, costs, and benefits of initiating an attack versus defending against it (Jervis 1978, van Evera 1998, Gafinkel Dafoe 2019).

The offense-defense balance in cyberspace remains contested because offensive and defensive cyber capabilities are hard to distinguish because they rely on similar tools and are hard to quantify (Valeriano 2022). Many argue that offense dominates due to abundant vulnerabilities, automation, and imperfect defenses (Saltzman 2013; Slayton 2017; Huntley & Shives 2024). Others note that defenders' system knowledge and network control offer advantages given sufficient investments (Campell & Donahoo 2024). Our focus, however, lies on why cyberattacks occur in the first place.

There are two competing explanations. The first argues that cyber-attackers are motivated because of attacker impunity, i.e., they must fear no consequences. Attacker impunity is facilitated by several factors. Cyber-operations can provide a degree of anonymity, and attackers can obfuscate their identities and hide their traces, making attribution of cyber-attacks to perpetrators slow and complicated (Kello 2017, Brantly 2018, Libicki 2009. If cyberattacks can be conducted with impunity, the attacker has little reason to stop. Because attribution is time-consuming and not always feasible and law enforcement and apprehension of cyber-operators is relatively weak, some scholars make the case for deterrence by punishment: Deterrence by punishment is a strategy aimed at discouraging an adversary from initiating or escalating a conflict by convincing them that the costs of such actions will outweigh any anticipated benefits. Aggressors must be convinced psychologically, through communication and credibility, that they will be identified and punished. Cyber-deterrence by punishment can occur through *in-kind* retaliation using offensive capabilities (Healey 2019) to raise the costs of attacks (Borghard & Lonergan 2023) or *cross-domain* measures such as sanctions, legal actions, public attribution, or limited conventional strikes (Libicki 2009; Van de Velde 2023). Yet, effectiveness is disputed: technical limits and delayed attribution undermine credibility (Borghard & Lonergan 2017; Brantly 2018; Soesanto 2022). Consequently, research finds cyber deterrence by punishment largely impractical.

The other school of thought argues that cyberattacks are driven by the ease of attacking, due to offense dominance (Borgard Lonergan 2023). First, cyberattacks are comparatively cheap and easy to execute (compared to conventional attacks or covert operations) and thus have a low barrier for entry (Libicki 2011, Bendiek & Metzger 2015, Lonergan and Montgomery 2021). Second, due to architectural vulnerabilities of the global internet, there is an abundance of software and hardware vulnerabilities, in addition to human weaknesses, that can be exploited for cyberattacks (Slayton 2017, Taddeo 2018).

The anticipated strategic gains of many cyberattacks, whether they are financially motivated cyber-crime (ransomware & fraud) or intelligence-driven cyberespionage operations, often outweigh the assumed costs (including punishment) in the calculus of the attacker (Fischerkeller, Goldman & Harknett 2022, 37). Research from other disciplines stresses reward structures as well, whether it is profit, psychological thrill, fame, power and status as primary motivators for cyberattacks (Aldasoro et al. 2022, Lim & Thing 2022). In other words, it is lucrative to attack, and having more to gain than to lose is a powerful motivator for attackers.

These dynamics encourage adversaries to exploit vulnerabilities and launch cyber operations. If ease-of-attack is the root cause, defenders have two goals: strengthening defenses to hinder intrusions and discouraging attacks by convincing adversaries that success is unlikely (Nye 2017). Deterrence by denial thus seeks to prevent attacks externally by changing the attackers calculus and psychology, while defense focuses inward on damage reduction. Defense is generally more feasible as it depends on resource investment rather than influencing attacker psychology (Fischer 2019).

Fischerkeller and Harknett argue that there is little evidence for successful deterrence by denial. i.e., demotivating advanced persistent adversaries from attacking, given the prevalence of continuous cyberattacks against systems (Fischerkeller & Harknett 2017). In addition, nowadays defenders must “assume breach”, that networks already have been compromised. Therefore, many experts and scholars argue for cyber-resilience: the ability to rapidly recover from successful attacks, in case both defense and deterrence by denial fail (Fischer 2019, Valeriano et al. 2022). However, there is no empirical research that tests these assumptions.

3. Methodology

This study examines whether the ease-of-attack argument is systematically and empirically related to politically significant cyber operations over time. The empirical strategy focuses on one observable implication of the ease-of-attack perspective rather than on attacker psychology. Ease-of-attack is determined by available software vulnerabilities (IV). These represent technical weaknesses that can be exploited by malicious actors to compromise systems. In principle, a larger stock of unpatched vulnerabilities increases the attack surface and expands the set of feasible operations for capable attackers. Under this logic, more publicly known vulnerabilities should be associated with more opportunities for exploitation and, ultimately, with higher recorded activity in incident datasets that track politically relevant cyber operations (DV).

Formally, the main hypothesis and its null counterpart are:

> *H1: Annual counts of publicly disclosed vulnerabilities are positively associated with annual counts of politically significant cyber operations.*

H0: If attack surface is not a key driver, vulnerability counts and operation counts will be largely uncorrelated once general time trends are taken into account.

These hypotheses concern temporal association, not causation. The analysis therefore focuses on whether vulnerability and incident series move together in systematic ways, rather than on estimating causal effects or modeling attacker decision-making directly.

3.1 Data

The primary data source documenting the annual number of publicly disclosed software vulnerabilities is the Common Vulnerabilities and Exposures (CVE). The CVE system provides a standardized dictionary of unique identifiers for publicly disclosed software vulnerabilities, enabling consistent tracking and communication across security tools, vendors, and researchers. Launched in 1999 and originally maintained by MITRE Corporation under the U.S. Department of Homeland Security, funded via CISA, it relies on CVE Numbering Authorities (CNAs)—such as vendors, researchers, and organizations like Microsoft—to validate reports from stakeholders, assign IDs, and publish entries to a central list enriched by data publishers. For our purpose, annual CVE counts are aggregated by the year of disclosure. We analyze the 2000–2024 period.

CVE entries underpin both defensive and offensive cybersecurity practices, supporting patch management, penetration testing, and red-teaming. Public vulnerabilities feed into exploit kits (Metasploit) and automated scanning tools, making CVEs operationally significant for state and non-state actors alike. Yet CVE volumes also reflect defensive activity—the extent of research, discovery, and disclosure within the security community.

This dual nature complicates interpretation: CVE counts measure research intensity as much as exploitability. Expanding disclosure practices, vendor compliance with reporting norms, and regulatory pressures have increased the likelihood of CVE assignment, inflating counts without necessarily reflecting greater code weakness. Likewise, bug bounty programs, crowdsourced testing, and advances in automated scanning have accelerated vulnerability discovery, driving CVE growth independent of shifts in actual attack surface.

The analysis therefore treats CVEs as an imperfect but informative proxy for the evolving attack surface. The ease-of-attack perspective expects that, despite these measurement dynamics, an expanding and catalogued vulnerability landscape should, on average, be associated with more opportunities for politically significant cyber operations.

Politically significant cyber operations (DV) are measured using two complementary datasets: 1) The Council on Foreign Relations Cyber Operations Tracker records publicly known, state-linked cyber operations with foreign policy relevance since 2005, focusing on incidents attributed to governments or industry (Council on Foreign Relations n.d.). 2) The European Repository of Cyber Incidents (EuRepoC) documents cyber incidents with political dimensions and critical-infrastructure impact since 2000, being initiated by both state and non-state actors and a broader range of targets (Zettl-Schabath et al. 2025). It captures 3400 incidents, 60 coded variables based on a daily collection of 220 news sources.

For each dataset, annual incident counts are measured over the period 2000–2024 (EuRepoC) and 2005–2024 (CFR). CFR emphasizes state-sponsored, foreign policy-driven operations, whereas EuRepoC also includes incidents by non-state actors such as hacktivists and criminals. Divergent patterns across the two series can therefore shed light on whether any association with vulnerabilities is specific to particular actor types or incident profiles. From an ease-of-attack perspective, one might expect that an expanding vulnerability landscape affects both types of actors, but possibly with different timing and intensity. For instance, non-state actors may exploit widely known vulnerabilities opportunistically and quickly, while state actors may selectively use both known and undisclosed vulnerabilities for more targeted campaigns. The analysis therefore treats divergence between CVE–CFR and CVE–EuRepoC correlations across periods as substantively meaningful, not merely as noise.

Both datasets are subject to selection and reporting biases. They cover only publicly known incidents, rely on media and open sources, and are shaped by evolving coding practices and geopolitical attention. The analysis thus treats their counts not as comprehensive measures of global cyber activity but as indicators of the temporal dynamics of high-salience, politically relevant operations.

All variables are aggregated to the annual level. This choice reflects both data availability and the study's focus on long-term trends rather than short-lived spikes, recognizing that reporting practices can vary within years and that many politically significant operations unfold over weeks or months. Yearly aggregation smooths some of this volatility and makes broad temporal patterns more visible.

3.2 Measurement

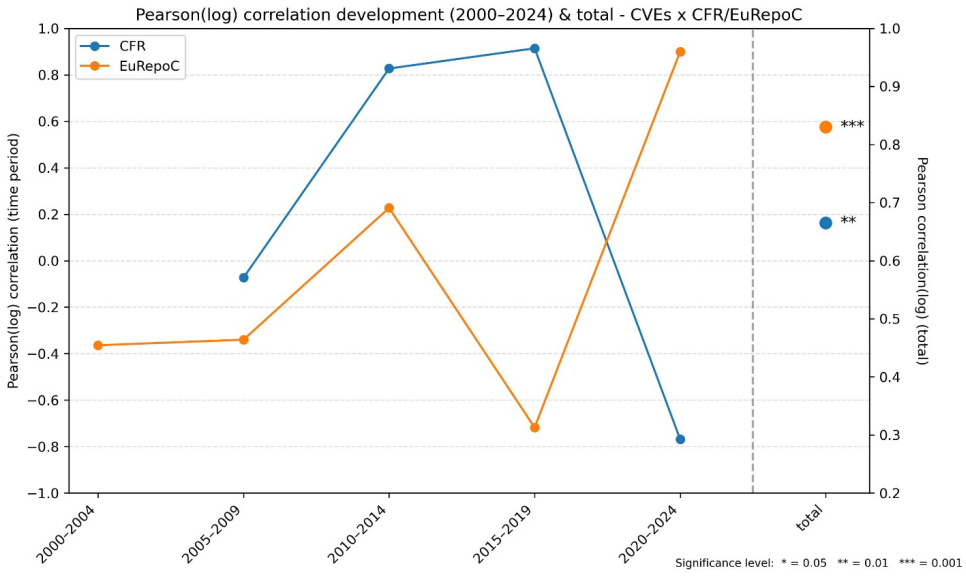
The core quantitative strategy is correlation analysis between annual CVE counts and annual incident counts. To address skewed distributions and long-run growth, and concerns about spurious correlation from common trends. The analysis proceeds in four steps:

1. Pearson correlations between raw annual counts of CVEs and incidents are computed to capture linear association over the full period and within 5-year windows.
2. Pearson correlations on log-transformed values are calculated to attenuate the influence of extreme values, especially the sharp rise in CVE counts in later years, and to reflect proportional rather than absolute changes. The goal is to account for possible skewed distributions, which is very often the case within cyber data and better captures underlying log-linear relationships.
3. Rank-based correlations - Spearman's rho and Kendall's tau - are computed for both the full period and five-year windows to assess whether monotonic relationships exist even when functional forms are non-linear or affected by outliers. All three measures range between −1 and 1, indicating direction and strength of association, where values close to ±1 indicate strong relationships and values near 0 indicate weak or no relationships, and conventional significance levels are reported for the full-period correlations. For the five-year windows, coefficients are interpreted descriptively, as the small sample size precludes strong inferential claims.
4. The analysis considers concordance in growth rates to address residual concerns about shared trends and to approximate dynamic responsiveness to changes in the vulnerability landscape. For each series, year-on-year changes (first differences) are computed, and concordance scores between 0 and 1 are used to summarize the share of years in which CVEs and incidents move in the same direction and jointly accelerate or decelerate. A value of 1 indicates perfect alignment; 0 indicates perfectly opposing movement, and 0.5 indicates no systematic association. Because attackers may respond to newly disclosed vulnerabilities with a delay, concordance is calculated for three scenarios: no lag, a one-year lag, and a two- year lag of incident changes behind CVE changes.

This combined strategy offers a transparent, data-driven assessment of whether and when publicly disclosed vulnerabilities and politically significant cyber operations exhibit systematic temporal alignment and how this alignment differs across state-focused and broader incident datasets. Within the constraints of annual data, common upward trends can mechanically generate strong associations and relatively short time series. The results are interpreted as evidence of co-movement consistent with the ease-of-attack perspective, not as proof of a causal effect of CVEs on cyber operations.

4. Empirical Findings

The empirical analysis reveals pronounced temporal and actor-specific shifts in the relationship between CVEs and politically significant cyber operations. Over the full period, both CFR and EuRepoC show strong positive associations with CVE counts, but the strength and sign of these relationships vary across subperiods and between state and non-state actors.



Long-run correlations

Over the full observation period, correlations between CVEs and both CFR and EuRepoC are positive, relatively large, and statistically significant across all correlation measures. Total Pearson correlations between CVEs and CFR incidents (0.624), and between CVEs and EuRepoC incidents (0.854), are strong and change slightly when log transforms are used, indicating that the association is not driven solely by a few extreme years. Non-parametric rank correlations (Spearman and Kendall) yield similarly robust positive coefficients in aggregate, suggesting that the positive relationship holds for monotonic co-movement as well.

These long-run patterns clearly reject a strict null hypothesis of "no relationship", in which vulnerability counts and operation counts would be largely uncorrelated once general time trends are considered. At this coarse temporal level, more disclosed vulnerabilities coincide with more recorded cyber-operations, which is consistent with the notion that an expanding attack surface is associated with more politically relevant cyber activity.

Temporal phases and actor heterogeneity

The five-year correlations highlight substantial temporal heterogeneity. In the early years (2000–2009), correlations between vulnerabilities and cyberattacks are very weak (Pearson(log): -0.073) for CFR (2005–2009) and weakly negative (Pearson(log): -0.364 2000-2004 and –0.340 2005-2009) for EuRepoC, indicating little synchrony between vulnerability disclosures and the rate or visibility of documented cyber-operations. During this phase, CVE volumes rise, but incident reporting - especially for geopolitically cyber-operations - remains sparse, plausibly reflecting underreporting, lower global awareness, and immature tracking infrastructures.

From 2010 to 2014, correlations between CVEs and CFR increase sharply, reaching values close to 0.9 for both Pearson and log-Pearson measures, while correlations with EuRepoC remain very weak to weak (Pearson: 0.083 and Pearson(log):0.227) In the 2015–2019 period, these high CVE–CFR correlations persist (Pearson(log):0.914) , indicating sustained alignment between the volume of disclosed vulnerabilities and recorded state-sponsored activity, as both CVE counts and CFR incidents grow markedly. This pattern suggests a phase in which expanding attack surfaces and state-linked operations move in close temporal step, at least in the observable record.

By contrast, the relationship between CVEs and EuRepoC turns strongly negative (Pearson(log): -0.718) in 2015–2019, even as CVE x CFR correlations remain strongly positive (Pearson(log): 0.914). Possible explanations include a tactical shift among non-state and mixed-motivation actors towards attack vectors less directly tied to known software vulnerabilities, as well as a denominator effect: annual CVE counts increase steeply while EuRepoC incident counts grow slowly and partly plateau, which can mechanically generate negative correlations despite an underlying positive link.

In the most recent period (2020–2024), a clear divergence emerges: correlations for CVE × EuRepoC become strongly positive (Pearson(log): 0.900), whereas those for CVE × CFR turn sharply negative, particularly for the Pearson coefficients (Pearson(log): -0.769). This pattern is consistent with a saturation effect in vulnerability reporting, in which rapidly growing CVE counts no longer translate into higher rates of recorded state-linked operations, while broader, non-state and mixed-motivation activity captured by EuRepoC remains more closely aligned with disclosed weaknesses. Taken together, the temporal phases point to an association that is positive and robust in aggregate but heterogeneous across time and actor type.

Concordance of growth rates

The concordance analysis of year-on-year changes provides a complementary view focused on dynamic alignment rather than levels. Across all three datasets, a one-year lag consistently yields the highest concordance between changes in CVE counts and changes in incident counts, with EuRepoC non-state and others reaching a concordance score of 0.619. This implies that in roughly 62% of years, CVEs and non-state incidents move in the same direction and jointly accelerate or decelerate when non-state incidents are allowed to respond with a one-year delay to changes in vulnerabilities. For EuRepoC total and CFR, lag-1 concordance also exceeds the contemporaneous values, but remains only modestly above the 0.5 baseline that would indicate no systematic association.

	CVEs		
	lag 0 concordance	lag 1 concordance	lag 2 concordance
EuRepoC	.348 (n=23)	.565 (n=23)	.522 (n=23)
EuRepoC (non-state and others)	.238 (n=21)	.619 (n=21)	.476 (n=21)
CFR	.474 (n=19)	.579 (n=19)	.368 (n=19)

These values point to moderate, not tight, dynamic alignment. They suggest that changes in the vulnerability landscape and changes in recorded cyber incidents move together more often than would be expected by chance, especially for non-state actors, but far from perfectly. In other words, the concordance patterns are compatible with a view in which some actors adjust activity with a delay to shifts in the vulnerability environment, yet they do not show strong or systematic responsiveness across all actors and periods.

The graphical comparison of annual changes further highlights differences in temporal alignment across datasets.. For CFR (state-affiliated and state-sponsored attacks), similarity in growth rates is largely confined to a narrow window around 2015–2019, with little sustained correspondence outside this interval. For total EuRepoC incidents, synchrony is most between roughly 2012 and 2020 but is less consistent beyond that. A similar pattern holds for EuRepoC non-state incidents in which both CVEs and non-state incidents rise, flatten, or decline in broadly similar fashion.

Overall, the concordance analysis reinforces the aggregate correlation findings by showing modest dynamic co-movement, particularly for non-state actors and when a one-year lag is allowed, but it also underscores the limits of the association and cautions against strong claims about tight intertemporal coupling.

5. Discussion

Over the full period, strong positive correlations between CVEs and both CFR and EuRepoC reject the null hypothesis of no relationship. In the long run, more disclosed vulnerabilities align with increased high-salience cyber operations, supporting the view that a growing attack surface drives politically significant activity.

However, the temporal patterning complicates any simple reading that more CVEs automatically mean more attacks. The early 2000s with weak or negative correlations suggest that, when vulnerability disclosure and offensive cyber-postures were still in development, increases in CVEs did not immediately translate into a higher visible rate of cyber-operations. Only once both vulnerability ecosystems and offensive cyber-capabilities matured—roughly from 2010 onward—do CVE and incident series move in closer synchrony, particularly state-linked operations in CFR. Note for example, that many countries created their first cyber-command structures, able to launch offensive operations, around the year 2010.

This staged pattern fits an ease-of-attack story that is mediated by institutional capacity: vulnerabilities may expand opportunity structures, but they only show up in the observable record of political cyber operations especially once they became a tool of international statecraft around 2010, represented by high profile operations such as (Stuxnet 2010, Operation Aurora 2010, Shamoon 2013 and others).

The late-period divergence—where CVE–EuRepoC correlations become strongly positive while CVE–CFR correlations turn negative— is puzzling. One explanation could be that the EuRepoC dataset is more reactive than the CFR dataset. CFR only lists cases with clear state-attribution. EuRepoC also lists unattributed incidents, which is especially the relevant since the Russian invasion of Ukraine in 2022, which coincided with a splurge in hacktivist cyber-operations. Future research should evaluate whether this due to the delay in attribution activity or represents a change in attack patterns. It is also possible that changes in political signalling, attribution capabilities, and the credibility of punishment selectively affect state behaviour, while a large pool of non-state actors continues to exploit readily available vulnerabilities, but these mechanisms cannot be identified directly from the present design.

The temporal dynamics connects to the offense–defense and deterrence literature. The strong positive correlations during 2010–2019 between CVEs and CFR incidents align with arguments that offense enjoys structural advantages in cyberspace as long as vulnerabilities are abundant and patching is imperfect. In those years, the data resemble a world in which expanding attack surfaces and growing offensive programmes move

in lockstep, strengthening the intuitive link between exposed weaknesses and the volume of state-sponsored operations.

The later divergence, however, suggests that defensive investments, changes in patching practices, and evolving norms might reshape this relationship, as vulnerability counts continue to grow rapidly while state-linked operations do not keep pace and in some windows even move in the opposite direction —this is consistent with at least four possibilities highlighted by the literature:

- Improved denial and resilience: Investments in cyber capacity, incident response, and resilience may make it harder or less attractive for states to rely on widespread exploitation of known vulnerabilities, even as those vulnerabilities continue to be discovered and catalogued.
- Strategic substitution: State actors may increasingly rely on 0days, Denial of Service attacks, social engineering, password spraying or living-off-the-land techniques without the use of software vulnerabilities to achieve political objectives, decoupling their activity from the public CVE stream. Another explanation could be that China decoupled from the global CVE system and built its own vulnerability ecosystem. Since 2021 Chinese security researchers do no longer report CVE's to the US-led system but have to report them to Chinese vulnerability databases and ministries (Cary & Del Rosso 2023).
- Selective enforcement and signalling: Stronger attribution regimes, such as the EU Cyber-Diplomacy Toolbox (since 2017) and more or offensive-denial strategies such as through US persistent engagement (since 2018) could deter some forms of state behaviour without changing the underlying technical attack surface.

The concordance analysis refines this picture by focusing on dynamic alignment. The modestly elevated concordance with a one-year lag, particularly for non-state actors in EuRepoC, is compatible with a view in which at least some attackers adjust activity with delay to changes in the vulnerability landscape, which is a necessary condition for deterrence-by-denial mechanisms to operate. At the same time, concordance values clustered only slightly above 0.5 underline that dynamic alignment is moderate, not strong, and that the short effective sample size cautions against firm claims about the presence or effectiveness of denial strategies. The analysis can therefore indicate compatibility with such mechanisms but cannot demonstrate that denial measures have actually reduced attack frequency.

The differences between CFR and EuRepoC correlations and concordance scores underscore the importance of actor heterogeneity. EuRepoC's broader coverage of nonstate and mixed-motivation incidents appears more tightly coupled to CVE volumes in the most recent period, while the state-focused CFR series decouples both in levels and growth rates. This pattern fits a view in which: Nonstate actors and opportunistic groups continue to benefit directly from a growing pool of known vulnerabilities, especially when they can rapidly integrate published CVEs into their tools off-the-shelf tools (such as the Metasploit Framework). State actors may be constrained by strategic, legal, or normative considerations that make reliance on easily attributable, widely known vulnerabilities less attractive over time. For instance, Chinese operations often favour stealth and hidden long-term access, often based on 0-days. In contrast, Russian operations are relatively noisy and also utilize known CVEs (Steiger 2022).

In theoretical terms, the ease-of-attack logic may apply most straightforwardly to actors for whom marginal cost and tool availability are primary constraints, whereas more sophisticated state actors operate under a more complex mix of constraints and incentives such as long-term planning, or techniques that are less directly tied to vulnerabilities. The results therefore suggest that offense dominance may be segmented: strong and persistent for certain classes of actors, attenuated or reshaped for other.

6. Conclusion

Overall, the findings support a nuanced version of the main hypothesis: publicly disclosed vulnerabilities and politically significant cyber operations generally move together over the long run, but this relationship is contingent on time, actor type, and institutional context. However, correlations cannot establish causality or uncover attacker motivations. Future work should move beyond correlation by explicitly modelling time trends, unit roots, and lag structures. Simple models that correlate incidents with lagged CVEs (and vice versa), or that correlate detrended residuals rather than raw levels, would help distinguish shared growth from more substantive temporal linkages. With richer data, vector autoregression or panel timeseries designs could test whether changes in vulnerability exposure systematically precede changes in incident rates. This study focuses on publicly disclosed vulnerabilities. Incorporating information on 0days, exploit markets, and stockpiling

practices—where available—would help clarify when state behaviour decouples from public CVE streams and relies instead on private vulnerability arsenals. This would speak directly to debates about strategic substitution and the limits of attacksurface measures based solely on disclosed vulnerabilities.

Ethics Declaration: Ethical approval was not required for this research.

AI Declaration: Perplexity AI was used to assist in streamlining drafts of the manuscript. The final text was streamlined by the authors.

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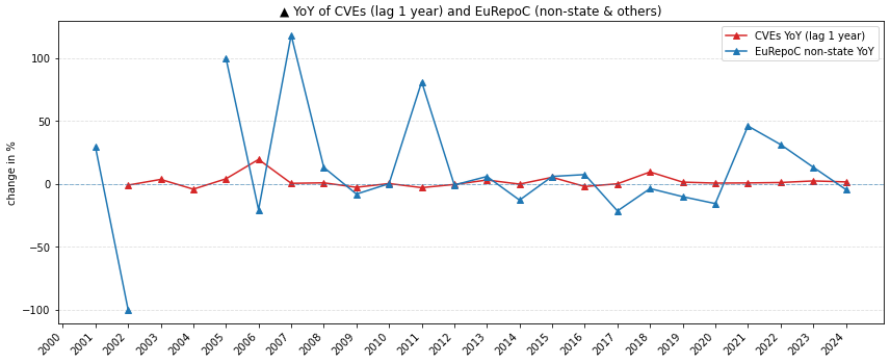
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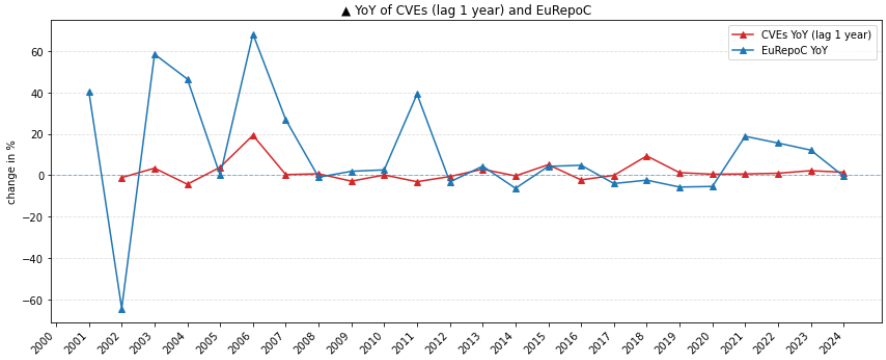
Appendix 1

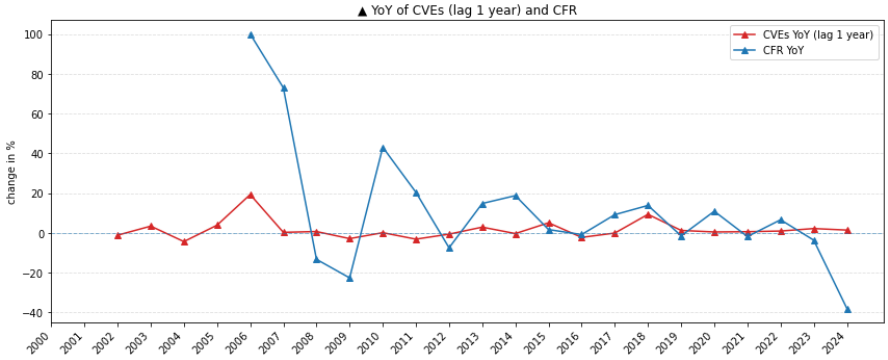
	2000 to 2004	2005 to 2009	2010 to 2014	2015 to 2019	2020 to 2024	total [b]
Pearson						
CVEs x CFR	-	0.157	0.910	0.899	-0.770	0.624** (n=20)
CVEs x EuRepoC	-0.321	-0.370	0.083	-0.757	0.878	0.854*** (n=25)
Pearson(log)						
CVEs x CFR	-	-0.073	0.827	0.914	-0.769	0.665** (n=20)
CVEs x EuRepoC	-0.364	-0.340	0.227	-0.718	0.900	0.830*** (n=25)
Spearman's						
CVEs x CFR	-	0.100	0.500	0.900	-0.200	0.677** (n=20)
CVEs x EuRepoC	-0.300	-0.100	-0.200	-0.900	0.900	0.664*** (n=25)
Kendall's tau						
CVEs x CFR	-	0.000	0.400	0.800	-0.200	0.495** (n=20)
CVEs x EuRepoC	-0.200	0.000	-0.200	-0.800	0.800	0.491*** (n=25)
CVEs	7,287	32,320	26,897	61,416	132,633	260,553
CFR	0	25	86	266	520	897
EuRepoC	16	108	547	643	2,008	3,322

[b] significance only given for total values
significance level: * = 0.05 ** = 0.01 *** = 0.001

Year-on-year (YoY) values are log-transformed:






▲ YoY of CVEs (lag 1 year) and CFR
CVEs YoY (lag 1 year)
CFR YoY
change in %
100
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Testing ML-KEM Implementations for Side-channel Vulnerability: The Airtight Framework

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Abstract: As quantum computing advances toward operational capability, traditional public-key communication schemes are becoming obsolete. Algorithms like Rivest-Shamir-Adleman and Elliptic Curve Cryptography cryptosystems, foundational to current secure communications, are vulnerable to Shor's algorithm, which can efficiently factor and compute discrete logarithms once large-scale quantum systems emerge. In anticipation of this threat, the National Institute of Standards and Technology (NIST) has standardized the Module-Lattice Key Encapsulation Mechanism (ML-KEM), derived from the Crystals KYBER family, as a post-quantum cryptographic (PQC) solution designed to secure communications against both classical and quantum attackers. However, while ML-KEM's lattice-based cryptographic system provides provable resistance to cryptanalytic attacks, its real-world implementations are susceptible to side-channel attacks (SCA). These attacks, which exploit timing variations, power consumption, or electromagnetic emissions, bypass the algorithm's theoretical security by extracting secret keys from physical leakage. Even as cryptographic design moves beyond quantum threats, physical-layer vulnerabilities reintroduce risk at the hardware level. These physical-layer security vulnerabilities are a looming threat to future PQC security. Given the dangers posed by correlation power analysis, cryptographic programs must be implemented to mitigate these vulnerabilities, or else the increased security provided by PQC methods will be in vain. In this paper, we assert that the secure adoption of PQC in defense communication systems demands accelerated implementation of ML-KEM within secure communication protocols to ensure post-quantum readiness and rigorous evaluation of its side-channel resilience through experimental validation and countermeasure integration. We survey recent research into ML-KEM side-channel resistance, identify existing countermeasure frameworks (masking, constant-time operations, noise injection), and propose Airtight: a framework for standardized testing of secure communication methods.

Keywords: Post-quantum cryptography, Module-Lattice-Based Key-Encapsulation Mechanism (ML-KEM), Side-Channel Attacks (SCA), Power analysis, Secure implementations, Defense communications

1. Introduction

Quantum computing poses an evolving and rapidly growing threat to current cryptographic methods. A quantum computer implementing Shor's algorithm can break RSA, one of the most commonly deployed cryptographic schemes, once a high enough number of logical qubits is achieved (Nehal, Farhan and Sunad, 2020). In response to the growing capabilities of quantum computers, NIST standardized ML-KEM as a post-quantum key encapsulation mechanism (KEM).

As current systems grow increasingly vulnerable to quantum attacks, the transition to post-quantum cryptography must be prioritized. However, implementing ML-KEM poses significant challenges, particularly in ensuring its security against side-channel attacks. These attacks exploit information leaked through various channels, such as power consumption, timing, and electromagnetic emissions.

Some organizations have attempted to delay quantum risk by transitioning to larger RSA key sizes (U.S. Department of Defense, 2023), but this is a temporary solution to a longer-term problem. A new scheme, one secure against quantum computing, is required. ML-KEM, as a standardized post-quantum KEM, is a promising candidate. Nevertheless, its security relies heavily on proper implementation, which can be compromised by side-channel attacks.

Before ML-KEM can be widely adopted, it must be tested thoroughly against side-channel attacks. This paper partially addresses the need for comprehensive testing by proposing a testing framework, called Airtight, which focuses on identifying and mitigating side-channel vulnerabilities in ML-KEM implementations.

The rest of this paper is organized as follows: Sections 2 and 3 discuss the ML-KEM scheme and attacks on the communication system, specifically in relation to side-channel attacks. Section 4 explores common countermeasures against side-channel attacks and how attackers may try to circumvent these defensive strategies. Finally, Section 5 presents Airtight, a general framework for testing the side-channel attack security of ML-KEM for implementation in secure systems.

2. The ML-KEM Scheme and Security

ML-KEM relies on lattice-based cryptography to provide key encapsulation for asymmetric communication. NIST standardized ML-KEM in 2024 because of its theoretical security against quantum computing (NIST, 2024).

ML-KEM derives its computational hardness from the Module Learning with Errors (MLWE) problem (Marmebro and Stenbom, 2024; NIST, 2024). MLWE is a generalization of the Learning with Errors Problem (LWE). In LWE, attackers analyze a set of "noisy" linear equations after perturbation through introduction of error values (NIST, 2024). This perturbation makes solving for the set of linear equations computationally infeasible for attackers.

In the context of lattice-based cryptography, LWE is computationally difficult because of a set of lattice problems, including the Shortest Independent Vectors Problem (SIVP) and Closest Vector Problem (CVP). These problems relate to determining the closest vector on a lattice to a point in space, and depend on the basis vectors used to traverse the lattice. When using orthogonal bases, lattice traversal, and by extension, these problems, are comparatively easy. When bad bases are used, finding solutions to these problems within a lattice becomes computationally infeasible. Importantly, Regev (2009) proved that an average-case implementation of a public-key cryptosystem using these problems for its security can be reduced to a worst-case problem for attackers, keeping the system more secure.

The ML-KEM scheme, like all KEM schemes, includes three main steps: KeyGen, Encaps, and Decaps. The following is a short discussion of the functions:

2.1 ML-KEM.KeyGen

In KeyGen, randomness is generated internally to create the encapsulation and decapsulation keys. The encapsulation key, commonly known as the public key, is created from a set of random noisy linear equations in the Number Theoretic Transform domain:

$\hat{t} \leftarrow \hat{A} \circ \hat{s} + \hat{e}$

The decapsulation key is generated from the same randomness used above, and is the byte-encoded $\hat{\mathbf{s}}$ vector.

2.2 ML-KEM.Encaps

Encaps uses internally-generated randomness to generate a message *m*, then encrypts *m*, outputting (*K*, *c*). The encryption function also uses the mathematical security of LWE, generating a vector and a value from the set of noisy linear equations which are concatenated and sent to the receiver as the ciphertext.

$u \leftarrow NTT^{-1}(\hat{A}^{T} \circ \hat{y}) + e_1$

$v \leftarrow NTT^{-1}(\hat{t}^{T} \circ \hat{y}) + e_2 + \mu$

The shared secret key *K* and ciphertext *c* are then sent for decapsulation.

2.3 ML-KEM.Decaps

The Decaps function uses the decapsulation key to decrypt the ciphertext, recovering the message *m′*.

$w \leftarrow v' - NTT^{-1}(\hat{s}^{T} \circ NTT(u'))$

After message recovery, a hash function is used to generate a shared secret key *K′*. Decaps also re-uses the encryption function to calculate *c′* using *m′* to compare with the given ciphertext. If *c=c′*, then *K′* is the correct shared secret key and symmetric encrypted communication can begin.

Notably, decryption occurs whether or not $c \neq c'$, which exposes ML-KEM to possible side-channel attacks at the decryption step. Next, this paper discusses side-channel attacks on ML-KEM, including an in-depth discussion of Correlation Power Analysis (CPA) attacks.

3. Side-channel Attacks on ML-KEM

Although ML-KEM resists quantum cryptanalysis, attackers can still successfully exploit side-channel leakage in its implementations. Specifically, CPA attacks on implementations of ML-KEM pose a looming threat (Primas, Pessl and Mangard, 2017; Kennaway et al., 2025). Side-channel attacks introduce multiple attack vectors for consideration when creating cryptosystems, as seen in Fig. 1.

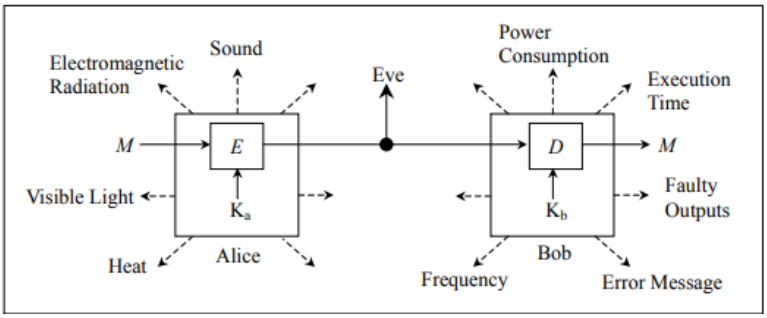


Figure 1: Attack vectors added by side-channel attacks (Zhou and Feng, 2005)

3.1 Timing Attacks

Timing attacks involve measuring the amount of time taken for a function to complete. The differences in expected versus actual function execution times give attackers information about the system's internal state. Timing attacks may be defended against comparatively easily by introducing constant-time algorithms (Arriaga, Barbosa and Jarecki, 2025).

3.2 Power Analysis Attacks

The two power analysis attacks discussed here are correlation power analysis (CPA) attacks and differential power analysis (DPA) attacks. Both attempt to discover secret information by determining points of interest in schema execution, then analyzing the power differential after a function is completed on data. Attackers usually determine sensitive information by calculating the Hamming weight and Hamming distance of intermediate values. Fig. 2 shows trace values during point of interest discovery for a power analysis attack.

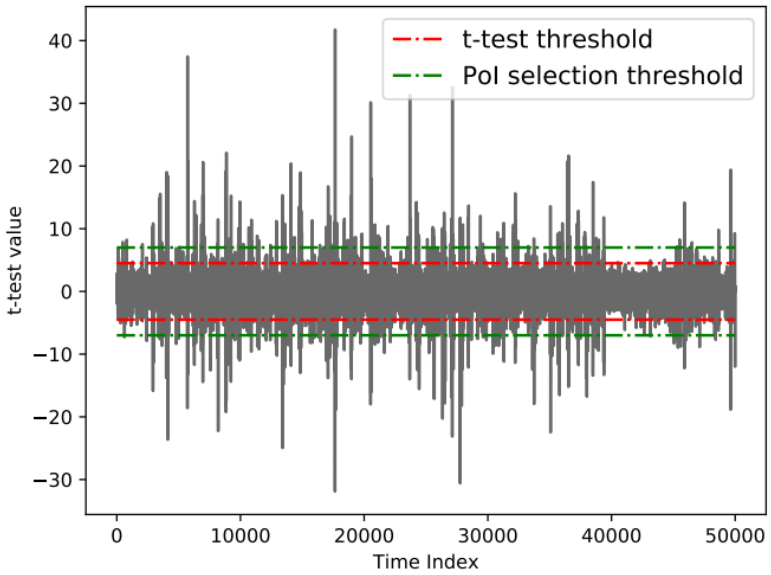


Figure 2: Point of interest discovery for power analysis attack on KYBER (Ravi et al., 2020)

3.2.1 Differential power analysis attacks

Differential power analysis (DPA) attacks typically use the difference of mean calculation to determine sensitive information in power consumption during task execution.

3.2.2 Correlation power analysis attacks

CPA attacks are another subset of power analysis attacks and typically use the Pearson correlation coefficient to calculate the correlation between power difference and sensitive data.

Side-channel attacks on cryptosystems are greatly strengthened by profiling the communication system used. A profiled attack occurs when an attacker has an identical copy of the communication system being used, creating a larger attack surface. The vast majority of non-profiling attacks on ML-KEM target the polynomial multiplication step, but in profiled attacks, many different functions are targeted (Kennaway et al., 2025).

When designing a security testing framework, researchers must assume that attackers can mount profiled side-channel attacks.

In addition to profiling capabilities, deep-learning has enhanced SCA capabilities due to its usefulness in cluster recognition and pattern analysis (Kennaway et al., 2025). Because of the possible increased use of deep-learning in future side-channel attacks, a framework for securing cryptosystems against these attacks must address the security vulnerability created by deep-learning power analysis attacks.

Although ML-KEM is secure enough to use in PQC communications, it, along with other lattice-based cryptosystems, remains vulnerable to side-channel attacks (Primas, Pessl and Mangard, 2017). Some countermeasures have proven effective against these threats, but the increased sophistication of possible attacks due to deep-learning, along with research in single-trace power analysis attacks, continues to pose a threat. In the next section, this paper discusses countermeasures against side-channel attacks, specifically for ML-KEM and other lattice-based cryptosystems.

4. Countermeasures Against Side-channel Attacks

Although side-channel attacks (SCAs) expose vulnerabilities at the physical and implementation layers, a variety of countermeasures have been developed to mitigate these risks. For ML-KEM and other lattice-based cryptographic systems, these defenses attempt to ensure that operations remain secure even under direct power, timing, or electromagnetic analysis (Eldib and Wang, 2014). Effective countermeasure designs must protect against key leakage without imposing excessive computational or hardware overhead. This section reviews the common types of SCA countermeasures, evaluates their effectiveness as described in the recent literature, and highlights the continuing challenges in standardizing protections for post-quantum cryptographic implementations.

Table 1 clarifies the strengths and weaknesses of different side-channel attack countermeasures to be discussed in the following paragraphs. These trade-offs must be considered when developing a framework for testing ML-KEM and other lattice-based KEM implementations in the future to reduce the attack surface on the new communication scheme.

Table 1: Countermeasure categories for ML-KEM implementations

Type	Strength	Weakness
Constant-Time Execution	Strong against timing side channels	Still leaks power/EM traces
Masking	Protects against first-order CPA	Breakable by higher-order attacks; high overhead in NTT ops
Noise Injection	Resists basic DPA and CPA	Machine learning overcomes noise
Hardware Defenses	Best long-term physical security	High cost; not practical for legacy systems

4.1 Countermeasures Against Timing Attacks

Developers counter timing attacks by designing functions that execute in constant time regardless of secret data (Arriaga, Barbosa and Jarecki, 2025). This can be implemented in multiple ways. One common method is to rework encoding and transform functions with rejection sampling to maintain the uses of core functions while eliminating time variation due to rejections (Eldib and Wang, 2014). This can be accomplished by encoding public keys as byte strings. A trade-off of this method is larger public key sizes, leading to slower computation times.

4.2 Countermeasures Against Power Analysis Attacks

The two major countermeasures against power analysis attacks are masking and noise injection. Masking techniques statistically decouple intermediate computations from secret key values, leading to perfect masking of one function (Eldib and Wang, 2014). This defeats first-order CPA and DPA attacks; however, higher-order CPA and DPA techniques can still defeat perfectly masked implementations, especially when profiling or deep-learning assistance is available (Ravi et al., 2020; Kennaway et al., 2025). Masking also imposes significant computational and memory overhead, as each masked operation requires additional randomness and duplicated computation paths. These resource demands make masking particularly difficult to deploy in lightweight or embedded environments where power, latency, and hardware area are tightly constrained (Ravi et al., 2024b). Noise injection is another technique for countering CPA and DPA attacks.

Noise injection makes finding points of interest difficult by introducing randomness into power emittance during function execution. Nonetheless, noise injection can also be defeated with deep-learning classifiers capable of filtering or reconstructing signal leakage.

4.3 Common Methods for detecting Chosen-ciphertext Attacks

Two common methods exist for detecting and countering chosen-ciphertext attacks, as described in Ravi et al. (2024a). The first involves checking ciphertext values and ignoring any ciphertext sent for decapsulation if it does not meet an entropy threshold. This check allows for pre-decryption rejection of suspicious ciphertexts, but in practice, the method remains vulnerable to masked chosen-ciphertext attacks because adversaries can craft ciphertexts that pass entropy validation while still leaking key material. The second method detects failure during decapsulation, typically resulting from a chosen-ciphertext attack (Ravi et al., 2024a). ML-KEM implements this approach by re-encrypting the decrypted message and ensuring $c = c'$ (NIST, 2024). This failure check remains widely adopted because most chosen-ciphertext attacks require multiple malicious ciphertexts before a key can be recovered. Nonetheless, attackers can still defeat this defense by exploiting valid ciphertexts and leveraging statistical leakage, as demonstrated in Ravi et al. (2024a).

4.4 Secure Hardware Implementations

Implementing cryptosystems on secure hardware can also help prevent attacks, specifically CPA and DPA attacks (Ravi et al., 2024b). For example, using shielded hardware to emit less power during execution or using algorithmically noisy devices that have a low signal-to-noise ratio can also deter attacks (Ravi et al., 2024b). Secure hardware implementations can be effective countermeasures to side-channel attacks because they offer longer-term physical security. Implementations of ML-KEM must use secure hardware from the first implementation because transitioning from legacy systems to secure hardware implementations takes time and is expensive. Additionally, with increasing adoption of cloud and virtualized computing environments, security professionals must ensure that real-time power consumption and performance telemetry are not exposed through cloud monitoring channels, as remote leakage of power traces may enable CPA or DPA attacks without requiring physical device access.

4.5 Black-box Implementations

Black-box implementations of cryptosystems are often considered more secure because an attacker may only analyze input and output. However, SCA attacks mean that black-box implementations of any cryptosystem are practically impossible to achieve. These schemes can be hardened to include as many countermeasures to side-channel attacks as possible, but Ravi et al. (2020), Ravi et al. (2024a), and Kennaway et al. (2025) show that almost any countermeasure against SCA attacks can be defeated. Attacks that defeat these countermeasures must be considered when developing a testing framework for PQC cryptosystems.

5. The Airtight Framework

Airtight is a proposed testing and validation structure designed to evaluate the side-channel resilience of ML-KEM implementations before they are fielded in secure communication systems. While the cryptographic design of ML-KEM provides worst-case to average-case hardness guarantees against quantum and classical adversaries (Regev, 2009; NIST, 2024), its real-world implementations may still leak sensitive information through timing, power, or electromagnetic emissions (Primas, Pessl and Mangard, 2017; Kennaway et al., 2025). The Airtight framework bridges the gap between theoretical security and real-world assurance by providing standardized testing, evaluation, and integration strategies for ML-KEM within defense communication systems.

5.1 Framework Overview

Airtight consists of three modular phases aligned with DoD cryptographic agility goals and the PQC transition requirements for future secure networks (U.S. Department of Defense, 2023):

- Leakage Detection in Controlled Environments
- Validated Countermeasure Integration
- Operational Deployment and Certification

Each phase produces quantifiable metrics that evaluators use to certify whether an ML-KEM implementation meets mission security requirements.

5.2 Phase 1: Leakage Detection and Profiling

The first phase focuses on establishing a controlled test environment equipped with power, timing, and electromagnetic measurement instruments. Implementations are profiled using industry-standard techniques such as Test Vector Leakage Assessment (TVLA) and correlation power analysis (CPA), alongside timing analysis methods designed to detect variable-latency execution. The framework defines standard parameters such as:

- minimum of 50k–100k trace captures for TVLA evaluation (Unger et al., 2022)
- t-value thresholds of $|t| > 4.5$ to indicate statistically significant leakage
- targeting NTT multiplication, rejection sampling, and decapsulation comparison logic as primary points of interest (Kennaway et al., 2025)
- timing jitter and execution-path variance measurements to detect deviation from constant-time behaviour

Profiling in Phase I identifies vulnerable execution windows before any defensive measures are applied, ensuring that countermeasures are evaluated from a data-driven baseline and that both power-based and timing-based leakage are characterized early in the evaluation process.

5.3 Phase 2: Countermeasure Testing and Metrics

The second phase integrates SCA countermeasures such as masking, constant-time arithmetic, and noise injection. Airtight evaluates both the reduction of side-channel leakage and the operational cost of the countermeasure. This dual assessment allows security effectiveness to be weighed against performance and resource demands, including the mitigation of timing leakage:

- Leakage Reduction: percentage decrease in correlation or variance relative to unprotected traces.
- Performance Overhead: increase in cycle count, power draw, or memory size
- Break Resistance: resistance to profiling-based CPA, higher-order DPA, and deep-learning–enhanced SCA (Kennaway et al., 2025). Scored 0-3, dependent on if the system is resistant to first-order, higher-order, and deep-learning enhanced CPA and DPA attacks, with the score incrementing for each type of attack the implementation is resistant against.
- Timing Leakage Mitigation: reduction in execution-path variance, jitter, and branch-dependent latency relative to baseline; verification of constant-time implementations through repeated statistical timing analysis

This scoring system enables consistent comparison across hardware platforms, microarchitectures, or compiler configurations while capturing both power/EM and timing-based leakage characteristics.

5.4 Phase 3: Operational Deployment and Certification

The last phase aligns tested implementations with ML-KEM deployment guidelines from FIPS 203/204 (Marmebro and Stenbom, 2024; NIST, 2024). Implementations that pass Phase II testing are packaged with mandatory metadata including leakage profiles, required hardware constraints, and recommended compiler settings. Airtight proposes that DoD-approved implementations be given a Side-Channel Security Certification Level (SCSL) score derived from Phase II metrics, enabling predictable reuse and procurement contracting.

Finally, because the framework treats leakage detection and countermeasure scoring as algorithm-agnostic, Airtight can be reused to test future PQC schemes such as ML-DSA or BIKE, enabling a larger DoD cryptographic assurance pipeline (U.S. Department of Defense, 2023). This modularity enables repeatable validation and reduces algorithm-transition costs over the next decade of PQC standardization.

Because of Airtight's modularity and capability to be used in myriad organizations, no single scoring system can be proposed. Each organization should develop its own method of validating security with a scoring system tailored to its needs. For example, an organization that values confidentiality may give less weight to performance overhead penalties, while an organization that requires lightweight communications systems may value that metric more. An opportunity for future work in this area would be to further develop scoring frameworks for stereotypical organizations in different fields, using data-driven cost-benefit analysis to determine which sectors of ML-KEM's security must be guaranteed.

5.5 Example Scoring Systems

Although no single scoring system can be recommended, the following are two general scoring systems for organizations that favor confidentiality and availability or performance, respectively.

Variables in Example Scoring Systems:

ΔL: Leakage reduction (0 = none, 1 = fully reduced)

O_P: Performance overhead (fractional increase in cycles/memory/power consumption)

R_B: Break resistance (0 = fully breakable, 3 = unbreakable by first-order, higher-order, and deep-learning enhanced CPA and DPA attacks)

ΔT_L: Timing leakage mitigation (0 = fully mitigated, 1 = not mitigated)

A_S: Airtight Score (higher is better)

For meaningful assessment, each instance must be compared to a baseline defined by the organization, commonly an implementation of the scheme on a deliberately leaky board.

5.5.1 Example scoring system for high-confidentiality prioritization

Organizations that prioritize confidentiality will weigh break resistance and leakage mitigation higher than performance overhead to ensure security. Because of this, performance overhead will be weighted comparatively much lower. The following is a scoring system that takes these constraints into account:

$$A_S = (3 \times \Delta L) - (0.1 \times O_P) + (2 \times R_B^2) - (10 \times \Delta T_L)$$

This scoring system reflects a high-confidentiality prioritization by emphasizing leakage reduction and break resistance while minimizing the impact of performance overhead. The positive weight on ΔL rewards implementations that effectively reduce side-channel leakage, while the quadratic weight for R_B^2 further favors very strong break resistance. The small negative weight on O_P ensures performance penalties are considered but do not dominate the score. Finally, the negative weight on ΔT_L penalizes any residual timing leakage, aligning the score with security-critical requirements.

5.5.2 Example scoring system for high-availability prioritization

When Airtight is applied to implementations that focus on availability, performance overhead will be weighed heavily. Especially in lightweight applications, some countermeasures may be too computationally expensive to be feasible to implement. The following is a scoring system that prioritizes performance overhead as a metric without forfeiting security:

$$A_S = (3 \times \Delta L) - (2 \times O_P) + (2 \times R_B) - (7 \times \Delta T_L)$$

This equation reflects a high-availability prioritization by placing a stronger penalty on performance overhead (O_P), ensuring that computationally expensive countermeasures reduce the overall score. Leakage reduction (ΔL) remains positively weighted to maintain baseline security, while timing leakage mitigation (ΔT_L) is still penalized to discourage implementations with exploitable timing behavior. This balance allows lightweight or performance-sensitive applications to remain secure without sacrificing availability. The next section will discuss a strengths, weaknesses, opportunities, and threats (SWOT) analysis of Airtight.

5.5.3 Case study for an application of Airtight

To illustrate the applicability of Airtight, both scoring systems will be applied to a theoretical organizational improvement on the benchmark set in Chhetri (2026). Given Airtight's use case of evaluating organizational improvements in implementation, a baseline insecure implementation of ML-KEM is used as the baseline against which to compare a more secure implementation. Three methods will be used to increase the security of the implementation: decapsulation failure checks, constant-time algorithms, and changing to low-leakage hardware. Jati et al. (2024) state that decapsulation failure checking introduces approximately 5% overhead and Kolosick et al. (2025) state that constant-time execution adds another 5% overhead, on average. Combined, these security additions add 10.25% overhead by multiplying the two overhead costs together. Additionally, Ravi et al. (2024a) state that decapsulation failure checking can be defeated with higher-order CPA attacks, so implementing this protocol will increase R_B from 0 to 1. The implementation of constant-time algorithms will increase ΔT_L from 1 to 0. Finally, using low-leakage hardware will increase leakage detection to 0.9. These changes yield values of: $\Delta L = 0.9$, $O_P = 0.1025$, $R_B = 1$, and $\Delta T_L = 0$.

With these changes from the baseline to the more secure implementation, an organization may use Airtight to score the new implementation of ML-KEM. If the organization favors confidentiality, the new implementation's Airtight score will be 4.68975. If the organization prioritizes availability, the Airtight score

will be 4.495. The organizational leaders must then weigh the cost of changing to the new implementation against the Airtight score and determine whether to change or not. This scoring process enables reproducible and consistent scoring for ML-KEM implementations across varied organizational priorities.

5.6 SWOT Analysis

A systematic SWOT analysis enables organizations to assess how the Airtight framework aligns with their operational requirements and risk tolerance, particularly when deploying ML-KEM in environments vulnerable to side-channel attacks. By weighing strengths and opportunities against potential weaknesses and external threats, security professionals can better evaluate whether Airtight provides sufficient leakage resilience, resource feasibility, and long-term adaptability. The following SWOT analysis illustrates key internal and external factors that influence Airtight's effectiveness and may be tailored to reflect the mission constraints and security priorities of individual organizations.

5.6.1 Strengths

Airtight provides standardized and repeatable leakage detection methodologies that can be applied consistently across different hardware and implementation environments (Unger et al., 2022). Its modular phase structure allows evaluators to isolate leakage sources, integrate countermeasures incrementally, and compare mitigation effectiveness using quantifiable metrics. Furthermore, the framework's algorithm-agnostic design enables compatibility with multiple PQC schemes beyond ML-KEM, benefiting from worst-case to average-case security reductions established in lattice-based cryptography (Regev, 2009; Langlois and Stehlé, 2014). This supports long-term cryptographic agility and reuse within evolving DoD systems (U.S. Department of Defense, 2023).

5.6.2 Weaknesses

Airtight introduces overhead in the form of increased testing time, and specialized instrumentation, particularly for CPA and TVLA measurement environments (Eldib and Wang, 2014; Unger et al., 2022). Analyzing deep-learning–enhanced SCA traces may exceed the capabilities of organizations with limited technical resources, especially as recent attacks target ML-KEM's decapsulation and NTT operations (Primas, Pessl and Mangard, 2017; Kennaway et al., 2025). Additionally, the framework does not inherently eliminate leakage; instead, it depends on successful countermeasure integration, which may vary in effectiveness based on hardware and compiler constraints. Lastly, with an increased reliance on cloud computing, remote CPA attacks may be facilitated when side-channel data can be collected or inferred from shared hardware resources (Ravi et al., 2024b).

5.6.3 Opportunities

Airtight aligns with ongoing DoD efforts to transition to PQC and supports agency requirements for cryptographic agility and secure acquisition pathways (U.S. Department of Defense, 2023; Marmebro and Stenbom, 2024; NIST, 2024). By establishing consistent scoring criteria and certification levels, the framework could streamline procurement, reduce redundant testing, and enable shared evaluation baselines across services and contractors. Further opportunities arise in academia–DoD collaboration, where the framework could serve as a testbed for evaluating new SCA countermeasures or integrating secure hardware accelerators (Eldib and Wang, 2014; Ravi et al., 2024b).

5.6.4 Threats

Threats originate primarily from the rapid evolution of side-channel attack methodologies, particularly profiling attacks and deep-learning classifiers capable of bypassing masking or noise injection (Ravi et al., 2020; Kennaway et al., 2025). Attackers with access to advanced hardware or pre-characterized device models may reduce the effectiveness of standardized testing assumptions (Primas, Pessl and Mangard, 2017). Additionally, the pace of PQC research and potential revisions to ML-KEM parameters may outdate existing metrics or require framework adaptation, posing risks to long-term sustainability (NIST, 2024).

6. Conclusion

Organizations must prevent store-now, break-later attacks by transitioning to post-quantum cryptography early. The sooner a PQC scheme is standardized, the more secure communications will be. Ensuring cryptographic agility, resilience, and readiness is of paramount importance, and implementing ML-KEM represents a critical step toward this goal.

Before quantum computers achieve a high enough number of qubits to decrypt our current common encryption algorithms, PQC standards must be implemented. By implementing lattice-based cryptography, organizations can ensure their systems are more secure and resilient against quantum attacks. In tandem with PQC cryptography, comprehensive testing must be created and employed to strengthen security against side-channel attacks. By combining the use of secure cryptography with thorough testing, organizations can significantly enhance their security posture in an increasingly insecure environment. The Airtight framework represents a standardized, repeatable, and tailorable method for organizations to evaluate ML-KEM implementations, enabling confident, validated deployment in future secure ML-KEM communications.

Ethics declaration: Ethical clearance was not required for this research.

AI declaration: AI was used for this paper to convert between formatting styles and for spelling, punctuation, and grammar checking.

Disclaimer: The views expressed are those of the author and do not reflect the official policy or position of the US Air Force, Department of Defense or the US Government.

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Satellite Cyber Security Assurance Framework: Assured Unified SPARTA-COSMOS2 Assessment Notation (AUSCAN)

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Abstract: Satellite systems present unique cyber security challenges that distinguish them from conventional IT infrastructure. Once deployed, physical intervention is virtually impossible, leaving operators unable to patch, repair, or replace compromised hardware in orbit. These systems operate under severe constraints in power, processing capability, and bandwidth, limiting the complexity of onboard security measures. Furthermore, the growing integration of commercial off-the-shelf components and IP-based networking has significantly expanded the attack surface, while the increasing dependence of critical sectors on space-based assets has elevated the consequences of a successful attack. Despite these unique risk characteristics, current assessment approaches often treat space systems as standard IT networks, failing to account for the architectural context in which threats occur. Existing cyber security frameworks address either threat identification or architectural classification, but not both simultaneously. SPARTA provides a comprehensive taxonomy of space-specific Tactics, Techniques, and Procedures (TTPs), while COSMOS2 defines the architectural segments of space missions. However, no standardised method currently exists to quantify risk at the intersection of these two frameworks. To address this gap, this paper proposes AUSCAN (Assured Unified SPARTA-COSMOS2 Assessment Notation), a quantitative, segment-aware risk assessment framework. AUSCAN synthesises SPARTA's threat intelligence with COSMOS2's architectural segmentation and applies NIST FIPS 199 impact standards to assign criticality weights to each mission segment. The resulting risk scores are aligned with NASA NPR 8000.4C governance directives to enable actionable decision-making. A hypothetical Ground Segment command injection scenario is used to validate the framework. The results demonstrate that AUSCAN effectively quantifies the impact of security control maturity on risk, reducing the score from 38.4 (Medium/Yellow) to 9.6 (Low/Green) when verified mitigations are applied. This research makes three contributions to space cyber security. First, it establishes a quantitative methodology that integrates SPARTA threat intelligence with COSMOS2 architectural segmentation, grounded in NIST FIPS 199 impact standards. Second, it introduces segment-aware risk scoring, ensuring that identical threats are assessed differently depending on whether they target a recoverable ground station or an irrecoverable satellite. Third, through the inclusion of dynamic vulnerability factors, the framework is adaptable to missions with varying criticality profiles and risk appetites.

Keywords: AUSCAN, SPARTA, COSMOS2, Satellite cyber security, Space risk assessment, Mission assurance

1. Introduction

Space systems provide critical communications, scientific, and national security services globally, with industries spanning banking, logistics, defence, agriculture, and communications now heavily dependent on space-based assets (Akande et al., 2023, Kang et al., 2018). As of 2024, over 11,000 satellites were operating in orbit, driven by the affordability of launch and increased private sector engagement in satellite manufacturing and commercialisation (Jones et al., 2025). This growing dependence makes space a contested environment, where the convergence of space and cyber domains creates attack vectors capable of denying and disrupting critical services including Intelligence, Surveillance and Reconnaissance (ISR) and Position, Navigation and Timing (PNT) (Harrison et al., 2020).

The cyber threat to space systems is growing and evolving, as demonstrated by the 2022 cyberattack on Viasat's KA-SAT network (Boschetti et al., 2022). Nation states are developing jamming, cyberspace capabilities, directed energy weapons, and ground-based anti-satellite capabilities (Defense Intelligence Agency, 2019). Cyber-attacks can target the entire end-to-end space system, ranging from space vehicles and communication links to ground stations and integrated terrestrial networks (Pavur and Martinovic, 2020). The increasing use of Commercial-Off-The-Shelf (COTS) hardware and IP-based networking on Low Earth Orbit (LEO) satellites has significantly expanded this attack surface (Budroweit and Patscheider, 2021). The growth of LEO constellations introduces both inherent resilience and new vulnerabilities that adversaries can exploit at scale (BryceTech, 2025).

Satellite systems present unique challenges that distinguish them from conventional IT infrastructure. Once deployed, physical intervention is virtually impossible, leaving operators unable to patch or replace compromised hardware in orbit (Plotnek and Slay, 2022a). Satellites operate under severe constraints in power, processing capability, and bandwidth, limiting onboard security measures (Falco, 2018). Encryption is

generally only employed between the ground station and the satellite, leaving onboard authentication and data integrity minimal (Banu, 2007, Yue et al., 2023). Existing security approaches in the space domain tend to be isolated, lacking a layered defence-in-depth philosophy (Shahzad et al., 2024, Botezatu, 2024).

Since 2022, the Australian government has recognised these risks by listing space systems as critical infrastructure under the Security of Critical Infrastructure (SOCI) Act (Plotnek and Slay, 2022a). However, despite these unique risk characteristics, current assessment methodologies often treat space systems as standard IT networks, failing to account for architectural segmentation and potentially misidentifying threat severity based on location (Shahzad et al., 2024, Khan et al., 2024, Peled et al., 2023).

Two existing frameworks address aspects of this challenge. The Space Attack Research and Tactic Analysis (SPARTA) framework, modelled after MITRE ATT&CK, provides a comprehensive taxonomy of Tactics, Techniques, and Procedures (TTPs) specific to the space domain (Aerospace Corporation, 2026, Ear et al., 2024). The Compound Space Security (COSMOS2) framework defines five architectural segments, namely Governance, Human, Ground, Space, and Communications, Control and Computing (C3). These segments enable precise asset mapping for security evaluation (Plotnek and Slay, 2022b). However, while SPARTA details what threats exist and COSMOS2 defines what needs protecting, no standardised method currently exists to quantify risk at their intersection.

To address this gap, this paper proposes the Assured Unified SPARTA-COSMOS2 Assessment Notation (AUSCAN), a quantitative, segment-aware risk assessment framework for space cyber security. The research objectives are:

- To develop a quantitative risk assessment methodology that integrates SPARTA's threat intelligence with COSMOS2's architectural segmentation, supported with NIST FIPS 199 impact standards.
- To demonstrate that AUSCAN can differentiate risk severity based on the mission segment, ensuring that identical threats are assessed contextually.
- To validate the framework through a hypothetical case study and align the results with NASA NPR 8000.4C for actionable decisions.

The remainder of this paper is structured as follows. Section 2 reviews background and related work. Section 3 presents the AUSCAN methodology. Section 4 provides a case study and evaluation. Section 5 concludes with contributions and future research directions.

2. Background and Related Work

Historically, space missions relied on physical isolation and limited public knowledge of system architectures as de facto security measures (Abbasi et al., 2025). However, the paradigm has shifted due to the convergence of space technologies with COTS hardware and IP-based networking (Budroweit and Patscheider, 2021, Janicik and Heberle, 2005). These convergences have expanded the cyber-attack surface significantly (Remy and Xu, 2025), with recent studies demonstrating vulnerabilities across multiple segments of the space ecosystem (Plotnek and Slay, 2022b). As space assets become critical to national security and the global economy, standardising cyber security frameworks has moved from theoretical discussion to operational necessity.

Several frameworks have emerged to address this need, each with distinct strengths and limitations.

The SPARTA framework from the Aerospace Corporation addresses the industry-wide lack of space-specific cyber threat intelligence. Modelled after the MITRE ATT&CK framework, SPARTA provides a comprehensive taxonomy of TTPs specific to the space domain (Ear et al., 2024). Its primary strength is the depth and specificity of its threat catalogue, which enables defenders to identify and characterise attack vectors across the space mission lifecycle. However, SPARTA has a notable limitation: it provides detailed information from an attacker's perspective but does not inherently prioritise threats based on the specific architecture of the victim system. A technique is catalogued the same way regardless of whether it targets a ground station or a satellite.

To address architectural ambiguity, the COSMOS2 framework moves beyond the traditional dichotomy of "space vs. ground" segments (Plotnek and Slay, 2022a). Its strength lies in standardising the description of space system architectures by defining five distinct segments: Governance, Human, Ground, Space, and Link (C3), enabling precise asset mapping for risk assessment. However, while COSMOS2 effectively defines what needs to be protected, it does not provide a mechanism to measure how severely a specific threat impacts those segments. It is a descriptive ontology rather than a risk quantification tool.

The integration of threat taxonomies with risk quantification is an emerging field. A notable contribution is the work of Seo and Kim (2025), who proposed a multi-tiered Threat Analysis and Risk Assessment (TARA) framework. Their work demonstrates that SPARTA TTPs can be adapted for quantitative metrics, successfully integrating them to quantify supply chain and infrastructure risks. This represents an important advance in bridging the gap between threat identification and risk measurement. However, their approach focuses primarily on supply chain and defence-in-depth layers and does not explicitly address the architectural segmentation of space missions. Risk is calculated based on the technique (e.g., "How dangerous is malware?") rather than the target segmentation (e.g., "How dangerous is malware on the satellite versus the ground station?").

A clear pattern emerges from this review. SPARTA provides the threat intelligence but lacks architectural context. COSMOS2 provides the architectural context but lacks risk quantification. Seo and Kim's TARA demonstrate quantification is feasible but does not incorporate architectural segmentation. There is currently no standardised metric that weights SPARTA threats according to the COSMOS2 segment they impact. This paper addresses this specific gap by proposing AUSCAN, which applies NIST impact weighting to the COSMOS2 ontology to derive a segment-aware risk assessment score in conjunction with the SPARTA framework.

3. Methodology

AUSCAN is a quantitative assessment notation designed to assess cyber risk in space missions. Unlike traditional risk assessment which usually focus and origin from TTPs, AUSCAN looks from the architecture of the overall space mission. This allow AUSCAN to dynamically adjust the severity of a threat based on the specific segment it targets.

The assessment notation operates by synthesising three variables: Threat Severity (S_{NRS}), Asset Criticality (W_{FIPS}), and Vulnerability Factor (V_f) into the mathematical way to calculate risk at the intersection SPARTA and COSMOS2.

3.1 Threat Severity

Threat Severity quantifies the inherent danger of the attack vector. Utilising SPARTA matrix for TTP identification and adopt the Notional Risk Scores (NRS) methodology proposed by Aerospace Corporation (Seo & Kim 2025). NRS is a tool within SPARTA that helps to provide a baseline for risk assessment for space assets. As there is an overwhelming number of TTP collections in SPARTA, using NRS will reduce the workforce burden by identifying the most mission critical risks (Ear, Bailey & Xu 2024). NRS assign a base risk level to specific techniques based on likelihood and technical impact which is the S_{NRS} variable.

The NRS assigns a base score (0-100) to each SPARTA TTP based on its technical complexity and potential impact. For the purposes of AUSCAN, raw NRS value is utilised. Example: On a high criticality system, a "Flooding" attack to disrupt communications (SPARTA ID EX-0013) has a score of 25; whereas a "Eavesdropping: Active Scanning (RF/Optical)" interference with link by actively transmitting packets to activate the transmitter has a score of 9.

3.2 Asset Criticality

This component quantifies the value or the target asset using COSMOS2 and NIST FIPS 199 (Standards for Security Categorization of Federal Information and Information Systems). COSMOS2 is an ontology which presents segments of space systems in the context of security. The segments are Governance Segment, Human Segment, Ground Segment, Space Segment, Communications, Control & Computing (C3) Segment (Plotnek & Slay 2022b). COSMOS2 when combined with NIST FIPS 199 (Radack 2002), it allows "Critical Value" to be assigned to each segment. FIPS 199 defines three impact levels: Low, Moderate, High which maps to numbers (e.g. 1, 2, 3) to derive an Asset Criticality Weight - W_{FIPS}. See table below.

Table 1: Asset Criticality Weight

COSMOS2 Segment	FIPS 199 Impact Level	Weight	Rationale
Governance	Low	1	Administrative. Attacks here involve policy violations or compliance issues. Possible long-term risk, but no immediate mission failure.
Human	Low	1	Limited range/personnel. Attacks here usually affect data confidentiality (spying) rather than mission critical. Satellite remains safe.

COSMOS2 Segment	FIPS 199 Impact Level	Weight	Rationale
Ground	Moderate	2	Recoverable. Critical for operations but often has redundancy (backup sites) and allows for physical recovery intervention (re-imaging servers).
Space	High	3	Irrecoverable. Impossible physical access to repair. A successful attack here (e.g., de-orbiting) results in total mission loss.
C3	High	3	Critical Path. If the C3 is jammed or compromised, there will be loss of control over satellite, results in total mission loss

The Asset Criticality Weight is assigned to the architecture segment that contain the vulnerability but not necessarily the segment suffering the ultimate consequence. Example will be discussed in the case study section.

3.3 Vulnerability Factor

The third component represent the effectiveness of existing defences. Even a high-severity threat targeting a critical segment poses low risk if sufficient security controls are in place. This is calculated using the "Likelihood of Occurrence" criteria from NIST SP 800-30 Rev. 1 (Appendix G). The "Likelihood of Occurrence" in NIST's guide is the probability that a threat will attempt and successfully exploit a vulnerability, based on threat capability, system exposure, vulnerabilities, and the strength of existing security controls (Fikri et al. 2019). The factor in AUSCAN context represent the probability of a SPARTA TTP bypassing existing controls in COSMOS2 segment. See table below for the quantification of Vulnerability Factor (V_f):

Table 2: Quantification of Vulnerability Factor

NIST Rating	Description (Adapted from SP 800-30 Rev 1)	Vulnerability Factor (V_f)
Very High	No control exists; or controls are incompetent. Attack is almost certain to succeed.	1.0
High	Controls exist but are insufficient or not integrated.	0.8
Moderate	Controls are in place but have known gaps.	0.5
Low	Controls are verified.	0.2
Very Low	Multiple layers of strict controls; exploit is theoretically possible but practically difficult.	0.1

Using Vulnerability Factor is critical as it allows risk assessor to simulate different security controls. It is a coefficient ranging from 0.1 (Secure) to 1.0 (Vulnerable), presenting as multiplication or division depending on the control in place. For example, when encryption is added, V_f drops from 1.0 to 0.2, reducing the total risk score.

3.4 AUSCAN

The final risk score $(Risk_{Total})$ is calculated by the product of the three variables. This multiplicative model present risk is "High" when a dangerous threat targets a critical asset with weak controls. The proposed equation as follows:

$$Risk_{Total} = \sum (S_{NRS} \times W_{FIPS}) \times V_f$$

Where:

S_{NRS} = SPARTA Notional Risk Score of the specific technique used. Range from 1 to 25.

W_{FIPS} = COSMOS2 Weight of the segment being attacked derived from NIST FIPS 199. Range from 1.0 to 3.0.

V_f = Vulnerability Factor is the likelihood of an attack. Range from 0.1 to 1.0.

This formula produces a maximum theoretical risk score of 75 and a minimum of 0.1. To assist in decision-making, the numerical output is aligned with the NASA Risk Management Matrix defined in NASA NPR 8000.4C.

Unlike enterprise IT standards that prioritise data confidentiality, NPR 8000.4C focuses on Safety and Mission Success. This aligns with AUSCAN's targeted assessment domain, which is space asset that has always prioritise safety and mission success. NPR 8000.4C codified the vision of managing risk that threatens space mission and

objectives (Dezfuli et al. 2024). Space agencies and operators utilise the Red-Yellow-Green matrix defined in the NASA Risk Management Handbook, by mapping AUSCAN score to these established tiers, AUSCAN can be directly integrated into existing Continuous Risk Management (CRM) and Risk-Informed Decision Making (RIDM). NPR 8000.4C classified risk based on risk tolerance levels, which is inspired the following tier alignment:

Table 3: AUSCAN Risk Tier

Tier / Colour	AUSCAN Score Range	Risk Definition	Governance Action
High (Red)	51 – 75	Unacceptable	Stop and Fix (T-0 Mitigation). Operations should not procced without immediate mitigation. Acceptance of this risk requires a formal waiver signed by the Program Manager or Control Board.
Medium (Yellow)	25 – 50	Marginal	Plan and monitor. Mitigation resources should be allocated. If immediate mitigation is not possible, risk must be entered into CRM database for tracking and monitor.
Low (Green)	0.1 - 25	Acceptable	Standard Maintenance. Risk is accepted within the standard operational baseline. Standard maintenance and best practices apply.

In NASA context, a "Red" risk represents a threat to Mission Success or Safety of Flight. By setting the threshold for the "High (Red)" at 51, this classification is reserved for scenarios involving high-severity risks against critical space asset, thereby aligning with NASA's comprehensive Safety and Mission Assurance (SMA) processes (Dezfuli et al. 2024). By aligning the quantitative scores with the "Red-Yellow-Green" reporting format used in NPR 8000.4C, AUSCAN provide governance action. Therefore, a score above 51 is not merely a number but serves as a governance action trigger, which should initiate a requirement for Program-level or board-level review. This prevents critical cyber risks from buried in technical logs but a call for actions.

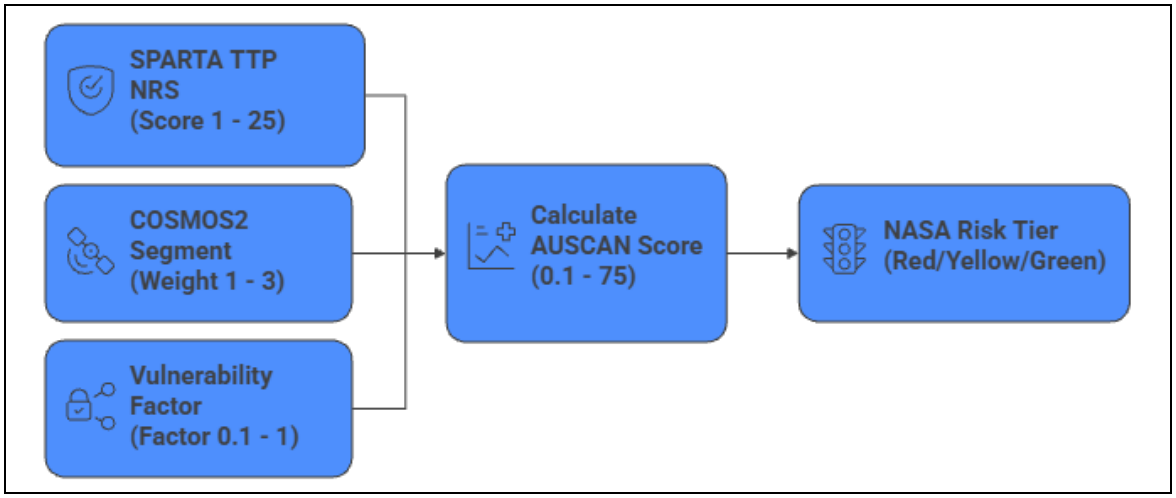


Figure 1: The AUSCAN Process Workflow. This assessment notation synthesised SPARTA and COSMOS2 to derive a quantitative risk score that triggers governance actions

4. Case Study and Evaluation

To validate AUSCAN, this section applies the framework to a hypothetical command injection scenario, demonstrates its sensitivity to architectural context, compares it against technique-only assessment, and discusses limitations.

4.1 Scenario Description

A Low Earth Orbit (LEO) mission architecture consists of a CubeSat constellation control by a ground station. The threat is an external attacker gains unauthorised access to ground station's Command and Control (C2) server and attempts to send a malicious "shutdown" command to the satellite. The mapping with both framework is:

- SPARTA Technique: Modify On-Board Values: Attitude Determination and Control Subsystem. (ID: EX0012.08).

- COSMOS2 Segment: Ground Segment (Attack entry point).

4.2 Variable Assignment

Using the methodology defined in previous section, the following values are assigned to the scenario variables:

1. Risk Severity (S_{NRS}): The attacker is attempting to shut down the satellite.

- Value: 24 (High Severity)
- Rationale: This SPARTA TTP is a direct manipulation of satellite's physical state. NRS of near-maximum score has been assigned by SPARTA.

2. Asset Weight (W_{FIPS}) : The compromised asset is the C2 server in the ground station that communicates with the satellite in space.

- Value: 2.0 (Moderate Impact, per Table 1).
- Rationale: While critical, ground station is physically accessible and can be restored. It is important to note that ground station is where the vulnerability exists and where the mitigation needs to be applied. AUSCAN focus on to bringing out the root cause of the risk where governance action should be taken. Satellite is not weighted as it is not vulnerable in this scenario; it is simply obeying a command. The vulnerability component is the ground station's lack of validation.

3. Vulnerability Factor (V_f) : In this scenario, two states are compared:

- State A (Vulnerable): The C2 server only has single-factor authentication and lack of command signing. Value: 0.8 (Controls exist but are insufficient or not integrated.)
- State B (Mitigated): The C2 server implemented Multi-Factor Authentication (MFA) and cryptographic command validation. Value: 0.2 (Controls are verified.)

4.3 Risk Calculation Results

Applying AUSCAN to both State A and B and the results are as follows:

Table 4: Example Case Study using AUSCAN calculation

State	S_{NRS}	W_{FIPS}	V_f	$Risk_{Total}$	Risk Tier
State A (Vulnerable)	24	2	0.8	38.4	Medium
State B (Mitigated)	24	2	0.2	9.6	Low

The 75% reduction from 38.4 to 9.6 is driven entirely by improved security controls, with threat severity and asset criticality held constant. This demonstrates that AUSCAN can quantify the measurable impact of specific defensive investments.

4.4 Sensitivity Analysis: Segment-Aware Scoring

To validate AUSCAN's architectural sensitivity, the same technique (EX0012.08, S_{NRS}= 24) is applied across all five COSMOS2 segments under identical vulnerability conditions (V_f= 0.8, representing insufficient controls).

Table 5: Sensitivity analysis – same threat across different COSMOS2 segments

COSMOS2 Segment	S_{NRS}	W_{FIPS}	V_f	$Risk_{Total}$	Risk Tier
Governance	24	1	0.8	19.2	Low
Human	24	1	0.8	19.2	Low
Ground	24	2	0.8	38.4	Medium
Space	24	3	0.8	57.6	High
C3	24	3	0.8	57.6	High

A traditional technique-only assessment would assign a single score regardless of target. AUSCAN produces scores ranging from 19.2 to 57.6, which spans across all three risk tiers. This confirms that the framework captures the operational distinction between a recoverable ground station and an irrecoverable space asset.

4.5 Comparative Analysis: AUSCAN vs. Technique-Only Assessment

Table 6: Comparative analysis – technique-only vs. AUSCAN assessment

Approach	Risk Score	Risk Tier	Governance Action
SPARTA NRS only	24	N/A (no tier mapping)	No defined action
AUSCAN — Ground (State A)	38.4	Medium	Plan and monitor
AUSCAN — Space (State A)	57.6	High	Stop and fix

Without AUSCAN, a score of 24 provides no architectural context, no vulnerability adjustment, and no governance action mapping. AUSCAN resolves this by producing contextualised scores linked to NASA NPR 8000.4C response tiers (Dezfuli et al., 2024).

4.6 Limitations

Two key limitations must be acknowledged. First, the case study is hypothetical. Although variable assignments are grounded in established standards, the framework has not yet been validated against operational data from a real-world mission. Second, AUSCAN currently evaluates threats individually. In practice, space missions face compound threats where multiple TTPs may be executed simultaneously, and the current formula does not model cascading risks (Remy and Xu, 2025).

5. Conclusion and Future Work

5.1 Summary

As space systems transition from isolated legacy architectures to networked ecosystems, the need for cyber security frameworks that account for both threat intelligence and mission architecture has become urgent. This paper addressed the gap between threat-focused frameworks such as SPARTA and architecture-focused ontologies such as COSMOS2 by proposing AUSCAN (Assured Unified SPARTA-COSMOS2 Assessment Notation), a quantitative, segment-aware risk assessment framework for space cyber security.

The AUSCAN methodology synthesises three variables – Threat Severity derived from SPARTA's Notional Risk Scores, Asset Criticality derived from COSMOS2 segments weighted using NIST FIPS 199, and a Vulnerability Factor adapted from NIST SP 800-30 – into a single risk score mapped to NASA NPR 8000.4C governance tiers.

5.2 Key Findings

The framework was validated through a hypothetical Ground Segment command injection scenario. Three key findings emerged from the evaluation:

First, AUSCAN demonstrated sensitivity to security control maturity. The implementation of verified controls (MFA and cryptographic command validation) reduced the risk score from 38.4 (Medium/Yellow) to 9.6 (Low/Green), representing a 75% reduction. This confirms that the framework can quantify the measurable impact of specific defensive investments.

Second, the sensitivity analysis confirmed that AUSCAN produces architecturally meaningful distinctions. The same SPARTA technique applied across all five COSMOS2 segments generated scores ranging from 19.2 (Low) to 57.6 (High), spanning all three risk tiers. This validates the core claim that identical threats should be assessed differently depending on where in the mission architecture they occur.

Third, the comparative analysis demonstrated that without segment-aware scoring, a technique-only assessment provides no architectural context, no vulnerability adjustment, and no mapping to governance actions. This would have left mission directors without a standardised basis for decision-making.

5.3 Contributions

This research makes three contributions to the field of space cyber security:

- Methodological Integration: AUSCAN establishes, to the authors' knowledge, the first quantitative methodology that integrates SPARTA threat intelligence with COSMOS2 architectural segmentation. By grounding the framework in established standards (NIST FIPS 199 and NASA NPR 8000.4C), it ensures compatibility with existing governance processes including Continuous Risk Management (CRM) and Risk-Informed Decision Making (RIDM).

- Architectural Context: The use of COSMOS2 segmentation ensures that risk scores reflect the operational reality of space missions. The sensitivity analysis confirmed that a vulnerability in a recoverable ground station (score: 38.4) is assessed differently from the same vulnerability in an irrecoverable space asset (score: 57.6), directly addressing the limitation of technique-only approaches identified in prior work (Shahzad et al., 2024, Seo and Kim, 2025).
- Mission Adaptability: Through the inclusion of dynamic vulnerability factors, AUSCAN can be tailored to missions with varying criticality profiles and risk appetites. The framework's variables are modular, allowing mission-specific customisation of segment weights and vulnerability assessments without altering the underlying methodology.

5.4 Implications for Practice

The practical significance of AUSCAN extends beyond academic contribution. For mission directors and space system operators, AUSCAN provides a structured mechanism to translate technical cyber threats into governance actions. The alignment with NASA's Red-Yellow-Green reporting format means that AUSCAN outputs can be integrated directly into existing risk reporting workflows without requiring new governance infrastructure. For the Australian context specifically, where space systems are now classified as critical infrastructure under the SOCI Act, AUSCAN offers a potential pathway for standardising cyber security risk assessment across the growing Australian space industry.

5.5 Future Work

Several concrete avenues for future research have been identified:

- Real-World Validation: The immediate priority is to apply AUSCAN to operational data from a real-world CubeSat mission, working with industry partners to validate the framework against actual threat scenarios, security architectures, and operational risk tolerances. This will test whether the fixed FIPS 199 segment weights hold across different mission types or require mission-specific calibration.
- Software Prototype and Automation: A software tool that ingests live data feeds from C2 systems and vulnerability scanners to calculate AUSCAN scores in real-time would transform the framework from a manual assessment tool into a live cyber-risk dashboard for Mission Control. This prototype should include automated alert triggering based on risk tier thresholds.
- Digital Twin Integration: Connecting the AUSCAN software prototype to a digital twin of a satellite mission would enable predictive risk forecasting, allowing operators to simulate the impact of emerging threats or proposed security control changes before they are implemented in the operational environment.

5.6 Closing Remarks

As the global reliance on space-based services continues to grow and the cyber threat landscape evolves, the need for rigorous, architecture-aware risk assessment in space cyber security will only intensify. AUSCAN represents a step toward bridging the gap between threat intelligence and mission assurance governance, providing a standardised notation that translates technical cyber risks into actionable decisions. By unifying the strengths of SPARTA and COSMOS2 within a quantitative framework aligned with established aerospace governance standards, this work offers a foundation upon which the space cyber security community can build more resilient and assured space missions.

Ethic Declaration: This research does not involve human participants, human data, or animal subjects. Accordingly, ethical approval was not required for this study under the relevant institutional and national guidelines. The authors confirm that the research was conducted in accordance with principles of research integrity and responsible research practice.

AI Declaration: The authors used AI-based tools (e.g., Gemini) solely to assist with proofreading. In addition, Napkin AI was used to generate figure-1 based on author-provided concepts and descriptions. The AI tools did not contribute to the research design, data analysis, or interpretation of results. All intellectual contributions and responsibility for the content remain with the authors.

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A Framework for Automated STIG Compliance for Navy Ships

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Abstract: Historically, U.S. Navy ships have faced challenges in meeting the requirements of Cybersecurity Inspections (CSIs), with persistent Security Technical Implementation Guide (STIG) compliance gaps as a major contributing factor. Ships have relied on manual remediation processes that are often time-consuming and error-prone, given IT staff and operational constraints. Existing STIG automation tools do not address unique afloat challenges, such as intermittent connectivity, diverse network architectures, integration with cyber-physical systems, and split authorities between ship and Program of Record (PoR) managers. Commercial tools like SteelCloud ConfigOS, Ansible Automation Platform, and Microsoft PowerSTIG demonstrate automation feasibility in traditional enterprise environments, but do not adequately accommodate maritime operational realities, where ships undergo extended periods of limited network connectivity. This research developed an automated STIG compliance toolkit framework to address maritime constraints by systematically analysing existing tools, identifying cybersecurity capability gaps, and deriving requirements from documented CSI deficiency patterns and operational constraints. The framework's modular design includes asset discovery with coverage validation, compliance assessment with baseline deviation detection, risk-stratified automated remediation, and human oversight through Information Systems Security Manager (ISSM) decision support, while respecting authority boundaries between shipboard IT teams and PoR managers. Validation of the framework employed requirements traceability analysis, mapping 48 requirements to design components, workflow analysis, tracking data flow through representative compliance scenarios, and engaged with experts at Naval Information Warfare Center Pacific cybersecurity specialists to evaluate operational feasibility. The results confirmed the framework's validity and practicality while revealing that organizational factors beyond technology, including formal sustainment authority assignment, improvements in PoR baseline documentation processes, and enhanced network inventory data quality, are essential to successful framework deployment. The framework provides a comprehensive requirements baseline, modular architecture supporting platform diversity, and authority-aware decision logic that preserves operational safety. Future work on this research will include developing a system prototype, integrating machine learning for predictive risk management, and expanding research to examine additional CSI improvement factors.

Keywords: Navy cybersecurity, STIG compliance, Automated remediation, Maritime operations, Risk management Framework, DevSecOps

1. Introduction

U.S. Navy ships continue to face persistent cybersecurity readiness challenges. Compliance with the Cybersecurity Inspection (CSI) Technology Area standards, shown in Figure 1, which includes evaluating STIG implementation, accounts for 60% of the CSI grade. However, fleet performance remains inadequate despite sustained efforts from operational commanders and program offices (Office of Compliance and Assessment, 2024; Naval Information Warfare Systems Command, 2024). Ships rely on manual STIG remediation processes that require excessive IT personnel hours, introducing human error, and that are unsustainable due to limited shipboard resources and high operational tempo.

The maritime environment presents unique cybersecurity challenges that set afloat platforms apart from shore-based enterprise networks. Ships often operate with intermittent satellite connectivity, which limits their access to shore-based cybersecurity support and results in bandwidth constraints for security updates (Commander U.S. Fleet Cyber Command, 2023). The diversity of fleet networks adds to remediation challenges, with ships operating different architectures, from modern Consolidated Afloat Networks and Enterprise Services (CANES) to highly heterogeneous legacy systems. Many shipboard systems operate for decades, leading to persistent vulnerabilities from outdated hardware and software (Akpan et al., 2022). These factors create an environment where shore-based cybersecurity tools may not fully address operational realities.

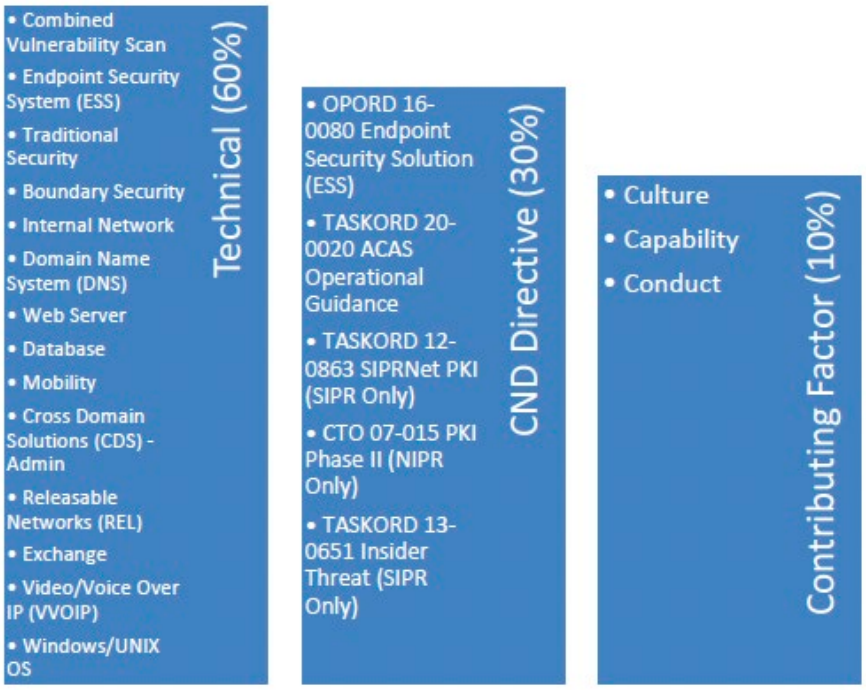


Figure 1: CSI Scoring Breakdown

Current STIG automation tools work well in onshore enterprise environments but lack adaptability to maritime constraints. Commercial products such as SteelCloud ConfigOS (SteelCloud, 2025), Ansible Automation Platform (U.S. Department of Defense, 2024), and Microsoft PowerSTIG (Microsoft, 2025a; Microsoft, 2025b) provide automated STIG remediation for enterprise networks with strong connectivity and centralized management. However, none of these tools comprehensively addresses the operational isolation, limited support infrastructure, and stakeholder complexities common to remote afloat operations. Additionally, fragmented authority between the ship's force and Program of Record (PoR) managers creates coordination issues that automated tools must account for (Naval Information Warfare Systems Command, 2024).

This research developed an automated STIG compliance toolkit framework specifically addressing maritime platform constraints and complexities. The framework combines asset discovery, compliance assessment, and automated remediation features, while maintaining human oversight for high-risk decisions and respecting authority boundaries between shipboard IT teams and PoR managers.

2. Background

The maritime operational environment imposes unique constraints on cybersecurity operations that distinguish afloat platforms from shore-based installations. This section examines these constraints and analyses current Navy cybersecurity tools to identify critical gaps that prevent effective STIG compliance aboard ships. Understanding these limitations provides the foundation for requirements of a STIG mitigation framework.

2.1 Maritime Cybersecurity Constraints

Maritime cybersecurity faces significant connectivity challenges. Ships depend on satellite communications with intermittent, high-latency links that limit bandwidth for security updates. Many shipboard systems are air-gapped to reduce threat exposure, including navigation, propulsion, and combat systems. While this isolation reduces external attack surfaces, it complicates routine compliance operations by requiring manual actions that can lead to human error (Pseftelis and Chondrokoukis, 2021).

U.S. Navy ships operate for decades, creating cybersecurity challenges as end-of-life and end-of-support systems still in use present ongoing vulnerabilities (Akpan et al., 2022). Fleet network diversity adds to these challenges, as ships run different architectures, from newer CANES installations to legacy Integrated Shipboard Network System, with specialized platforms needing unique configurations. This heterogeneity hinders standardized compliance methods and requires platform-specific STIG implementation strategies.

Cybersecurity responsibilities afloat are distributed among various stakeholders. The ship's force handles some systems, while program offices oversee others, requiring remediation strategies that respect these authority boundaries. The ship's crew records vulnerabilities using platform-specific plans of action and milestones (POA&M) for issues needing local remediation, while PoR-managed system vulnerabilities are escalated through multiple channels (Naval Information Warfare Systems Command, 2024). Even when PoR system managers issue patches, operational commanders might delay application due to concerns about mission-critical system stability. Although CANES offers a structured 30-day patch management cycle with patches accessible to the fleet, trend analysis shows limited patching across Navy ships (Office of Compliance and Assessment, 2024).

2.2 Current Tool Limitations

Navy ships use various tools for STIG compliance assessment, but these tools focus on noncompliance identification rather than remediation. Evaluate-STIG, developed by Naval Surface Warfare Center (Naval Sea Systems Command, 2020), provides automated STIG scoring and visual dashboards that display compliance status. Although it is not formally integrated into the CANES cybersecurity toolkit due to size constraints, Navy cybersecurity authorities actively promote its use over Security Content Automation Protocol for comprehensive compliance assessment (Office of Compliance and Assessment, 2024). The tool is used in all authorization and system reviews and validations for system authorization (Ireland, 2023). However, Evaluate-STIG does not enforce or remediate, limiting its utility to compliance verification and reporting.

The Assured Compliance Assessment Solution (ACAS) system, which uses Tenable technology with Nessus vulnerability scanners, is mandatory on board ships (Joint Force HQ-DoDIN, 2020). ACAS serves as the mandated enterprise vulnerability scanning tool for Department of Defense (DoD) systems, emphasizing network-wide vulnerability assessment rather than STIG compliance. Both Evaluate-STIG and ACAS provide vital visibility into system compliance, but do not provide automated STIG remediation.

Commercial STIG remediation automation tools exist but are not widely deployed in afloat environments. SteelCloud's ConfigOS automates STIG scanning, remediation, rollback, and reporting, but it requires enterprise licensing and formal deployment through Naval Systems Commands (SteelCloud, 2025). PowerSTIG leverages PowerShell Desired State Configuration to apply and monitor STIG controls on Windows systems, but it is limited to Windows environments (Microsoft, 2025a; Microsoft, 2025b). The Ansible Automation Platform enables Infrastructure-as-Code via reusable automation playbooks but depends on mature development pipelines and customized playbooks for each platform (U.S. Department of Defense, 2024).

These tools demonstrate that remediation automation is feasible and effective, but deployment barriers include platform specificity, tool fragmentation, and authorization requirements. Main limitations include the need for continuous connectivity, the assumption of a homogeneous network, and the absence of authority-aware decision logic for divided responsibilities between the ship and PoR managers.

3. Framework Design

The framework design process involved a systematic analysis of documented fleet challenges to identify technical requirements, which were then translated into a modular architecture adapted to maritime constraints. This section details the requirements definition approach, presents the system architecture with its six core components, and describes specific adaptations to address afloat operational realities.

3.1 Requirements Definition

The research team analysed authoritative sources to identify framework requirements, including Office of Compliance and Assessment (OCA) Waterfront Engagement Brief findings on documentation management issues where ships possessed required justification documents for PoR findings but did not provide them to OCA during assessments (OCA, 2024). The NAVWAR "Get Real, Get Better" artifacts documented program office shortfalls in resolving STIG findings for PoR systems in a timely manner (Naval Information Warfare Systems Command, 2024). The OCA CSI Planning Guide (Fleet Cyber Command, 2024) establishes that any DoD-published STIG applicable to inspected systems can be used during CSI evaluations.

The analysis uncovered recurring patterns: inconsistent STIG implementations across platforms, unclear configuration baselines, fragmented documentation between operational units and program offices, and ongoing delays in PoR system remediation. Naval Information Warfare Center Pacific cybersecurity personnel provided expert advice, highlighting key implementation factors. Subject matter experts stressed that gaps in baseline knowledge are a bigger obstacle than originally thought, noting that ships often operate without a full

understanding of approved operational baselines. This insight raised configuration discovery from a minor feature to a vital capability. Experts also pointed out that validating asset coverage is crucial, especially since scanning tools often miss systems due to network segmentation and offline status.

The requirements definition produced 48 detailed requirements organized into seven functional categories (data processing, baseline detection, asset coverage, decision support, automated remediation, escalation and coordination, documentation and reporting) and five non-functional categories (maritime environment, platform diversity, performance, security and authorization, sustainment). Each requirement traces to specific framework components, allowing verification of architectural completeness.

3.2 System Architecture

The proposed toolkit uses a modular design that follows a six-step process, balancing automation with human oversight, as shown in Figure 2. The process gathers IT input sources from Evaluate-STIG and manual assessments, parses and identifies findings while performing automated system discovery, allows the Information Systems Security Manager to review and make decisions, executes automated remediation, reviews unresolved issues, and exports reports for inspections.

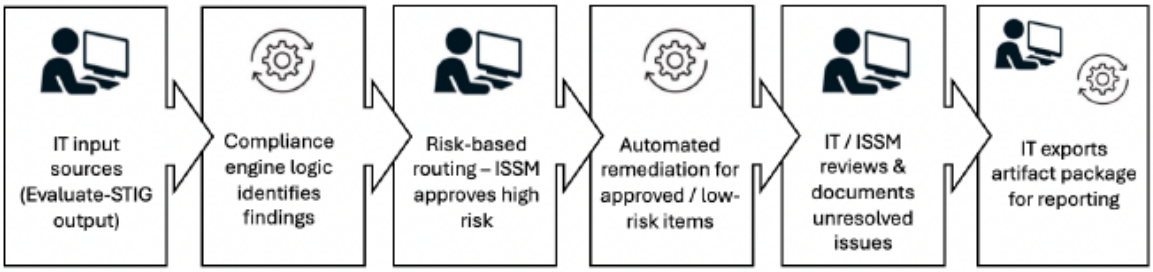


Figure 2: STIG Toolkit Workflow

Figure 3 shows the main system components and how they interact. The input parser imports data from various IT compliance sources, accepting Evaluate-STIG results and STIG Viewer files while also performing asset discovery validation to ensure thorough coverage. The parser checks discovered assets against trusted network sources, including switch Address Resolution Protocol tables, Dynamic Host Configuration Protocol lease tables, and documented IP allocation plans, to identify systems that haven't been scanned.

The compliance engine acts as the analytical core, containing a knowledge base of STIG requirements and applying rule-matching logic to compare parsed findings against established baselines. During analysis, the engine automatically discovers configurations by scanning system registries, configuration files, network settings, and service configurations to create current "as-built" baselines that support risk assessment decisions. The compliance engine correlates findings from multiple sources using Control Correlation Identifiers as defined by DISA (Defense Information Systems Agency, 2025).

A key function is baseline deviation detection, which prevents the toolkit from remediating findings necessary for system operation. Using the discovered configuration data and previous remediation results, the engine classifies findings as either PoR baseline requirements (do not remediate), approved exceptions with entries to the POA&M (for tracking only), or remediable findings (safe to fix automatically).

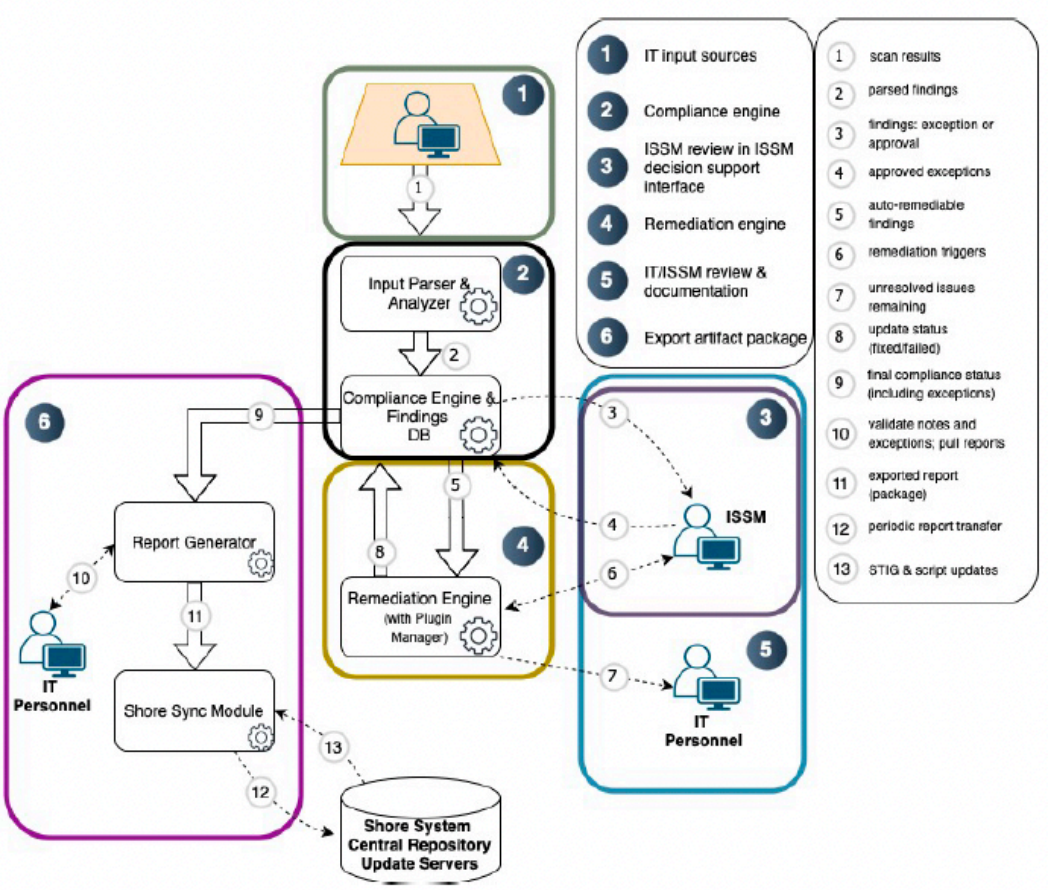


Figure 3: Detailed STIG Toolkit Control Flow

The Information Systems Security Manager (ISSM) decision support interface incorporates human oversight by displaying findings organized by category and risk level, with clear visual cues that distinguish PoR baseline findings from remediable issues. This enables ISSMs to approve automated remediations only for genuine security problems while maintaining necessary operational configurations and preserving command authority as required by Navy regulations (Department of the Navy, 1990).

The remediation engine performs authorized configuration changes using a modular plugin system. The Plugin Manager chooses suitable remediation tools based on system details and STIG type, supporting PowerSTIG for Windows (Microsoft, 2025a), Ansible for Linux (U.S. Department of Defense, 2024), and custom scripts for specialized systems. The engine features automated rollback functions and detailed logging, recording both success and failure statuses while conducting post-change verification.

The report generator produces comprehensive artifact packages, including STIG checklists, remediation logs, and exception documentation that adhere to DoD reporting standards (Fleet Cyber Command, 2024; Joint Task Force Transformation Initiative, 2018). The shore synchronization module handles asynchronous data exchange with shore-based systems during connectivity windows by uploading compliance results and downloading STIG updates using bandwidth-efficient compression and differential updates while operating in default offline mode.

3.3 Adaptation to Afloat Constraints

The framework addresses maritime constraints with specific design adaptations. Its modular, plugin-based design supports various network configurations, where modules focus on particular systems while keeping a standardized core (Seferagić et al., 2021). Containerized deployment ensures consistent operation across different environments by packaging all dependencies into portable images, addressing legacy system compatibility and complying with Navy cybersecurity accreditation practices using DoD Iron Bank hardened base images (DoD Chief Information Officer, 2025).

The framework includes pre-positioned remediation libraries with local repositories of STIG content and remediation scripts prioritized by historical findings, with updates synchronized during connectivity windows.

Role-Based Access Control separates shipboard administrative privileges among stakeholders, enabling complete automated remediation for Navy-administered systems while providing scanning and reporting only for program office-managed systems.

Technical challenges require targeted mitigation strategies. For legacy system integration across diverse platforms, the modular plugin architecture allows custom development for platform-specific needs, while plugin isolation helps prevent compatibility issues. During extended deployments, offline STIG updates are supported by local repository management with prioritized caching and differential updates, ensuring critical content delivery during brief connectivity windows. Performance optimization includes multi-threaded architecture for concurrent processing and database indexing on frequently queried fields for rapid analysis of thousands of findings (PostgreSQL Global Development Group, 2025). Security accreditation requirements are met through phased implementation, starting from minimal-authorization proof of concept, advancing to containerized deployment, and finally integrating with Platform One for Authority to Operate coverage (Joint Task Force Transformation Initiative, 2018; Department of Defense Chief Information Officer, 2025).

4. Validation

Validation of the framework employed three complementary methods suitable for conceptual architecture research: requirements traceability analysis to verify completeness, workflow analysis to demonstrate logical consistency, and expert consultation to assess operational feasibility. This approach establishes framework soundness without requiring prototype implementation or operational fleet data.

4.1 Requirements Coverage Assessment

Requirements traceability analysis creates formal links between documented CSI deficiency root causes and derived system requirements. The research team developed a Requirements Traceability Matrix that consolidates 48 detailed requirements into seven functional categories (data processing, baseline detection, asset coverage, decision support, automated remediation, escalation and coordination, documentation and reporting) and five non-functional categories (maritime environment, platform diversity, performance, security and authorization, sustainment), demonstrating comprehensive coverage of identified fleet compliance challenges. Each requirement is linked to specific framework components and referenced sections, enabling systematic assessment of design coverage.

The analysis identified five key dependencies beyond technical design: PoR baseline documentation requiring program office involvement in documenting approved configurations, network inventory data quality greatly influencing asset discovery accuracy, formal sustainment agreements assigning Program Manager Warfare-130 responsibility for core toolkit maintenance while Systems Commands maintain platform-specific plugins, uncertainty in the authorization timeline for containerized deployments adding schedule risk, and PoR coordination channels requiring established communication mechanisms and tracking systems. These dependencies are not flaws in the framework but realistic factors that require organizational coordination alongside technical development.

4.2 Workflow Analysis

Workflow analysis examined three representative compliance scenarios derived from documented CSI deficiency patterns. The bulk Windows Group Policy Object remediation scenario demonstrated an end-to-end data flow from input through remediation and documentation, confirming that the architecture supports high-volume, low-risk remediation. The workflow revealed dependencies, including PoR baseline database accuracy, plugin compatibility across finding types, network stability during multi-host remediation, and ISSM confidence in bulk approval decisions.

The PoR baseline configuration scenario evaluated the framework's ability to distinguish between operationally necessary configurations and actual security vulnerabilities. The baseline detection logic effectively categorized findings into documented baselines marked "do not remediate," flagged high-risk systems without baseline matches for manual review, and findings suitable for automated remediation. The scenario's success relies heavily on the accuracy of the PoR baseline database, dependable system identification through hostname conventions and network topology, ISSM's understanding of baseline justifications, and OCA inspector acceptance of documented baseline rationale.

The external authority escalation scenario demonstrated the toolkit's ability to identify findings that require program office intervention. The process of generating the escalation package compiles details of technical findings, system identification and authorization boundaries, impact assessments, recommended remediation

approaches, and POA&M templates with PoR designated as the responsible party, in accordance with DoD Risk Management Framework requirements (Joint Task Force Transformation Initiative, 2018). This workflow introduces structured escalation processes that are currently absent in fleet operations but relies on accurate system ownership data, established communication channels, timely PoR responses, and tracking mechanisms for long-term issue resolution.

4.3 Expert Consultation

Consultations with Naval Information Warfare Center Pacific cybersecurity subject matter experts (SME) provided an operational feasibility assessment of the framework architecture. Experts reviewed the modular architecture concept and identified key operational considerations during development of the framework. A design debate arose regarding the necessity of human oversight in the remediation workflow, with SMEs initially suggested full automation without ISSM approval, arguing that required reviews could reduce efficiency and hinder adoption. However, the final framework intentionally maintains the ISSM decision support interface, aligned with Navy operational principles where commanding officers remain responsible for all matters affecting their command (Department of the Navy, 1990), and Office of the Chief of Naval Operations cybersecurity policy explicitly assigns ISSM responsibility for the security of information systems (U.S. Navy, 2018). When automated remediation affects mission-critical systems, the framework ensures that commanding officers remain accountable for operational outcomes, regardless of whether a human or technical tool made the decision.

Expert consultation revealed that baseline knowledge gaps pose a more significant implementation barrier than initially assessed, with ships often operating without a comprehensive understanding of approved operational baselines. This insight elevated configuration discovery from a supplementary feature to a core capability, indicating the toolkit must actively document system states and build institutional knowledge rather than assuming complete baseline documentation exists. Experts also identified asset coverage validation as essential, noting scanning tools frequently miss systems due to network segmentation and offline status, creating false confidence about assessment completeness. The consultation highlighted that sustainment authority requires a formal organizational assignment, recommending PMW-130 manage core toolkit sustainment while SYSCOMs maintain platform-specific plugins and baseline exceptions.

5. Conclusions

This research developed an automated STIG compliance toolkit framework to address ongoing Navy shipboard cybersecurity compliance challenges through risk-stratified automation. The framework incorporates existing Navy cybersecurity tools, while maintaining human oversight for high-risk decisions, balancing automation efficiency with operational command authority requirements.

Validation through requirements traceability analysis, scenario-based workflow analysis, and cybersecurity subject matter expert consultation demonstrates the framework's logical soundness and operational feasibility. The analyses showed that successful implementation requires concurrent attention to organizational factors beyond technical architecture, including formal sustainment authority assignment, PoR baseline documentation processes, and network inventory data quality improvements. These findings indicate that while the toolkit architecture incorporates essential technology capabilities for enhanced fleet compliance, achieving measurable CSI improvements depends on addressing organizational coordination and data quality challenges.

The framework offers Navy leadership a clear path toward improved fleet cyber readiness. Key contributions include a detailed requirements baseline based on documented fleet cybersecurity challenges, a modular architecture that supports diverse shipboard environments while maintaining standardized core functions, risk-stratified automation that ensures operational safety through baseline deviation detection and ISSM oversight, and authority-aware decision logic that respects stakeholder boundaries between the ship's force and PoR managers. Detailed implementation specifications, including parsing algorithms, database schemas, and remediation logic, are available in the full thesis manuscript.

Future work in this area will include developing prototypes to validate framework performance against actual CSI benchmarks. Other work will include integrating machine learning algorithms to shift the framework from reactive compliance checking to predictive risk management (Yang et al., 2024), exploring integration with Navy zero-trust architecture initiatives (Department of Defense Chief Information Officer, 2022) to support continuous device posture assessment, and investigating additional factors contributing to CSI compliance gaps. These factors include the effectiveness of ISSM training, the adequacy of shore-based support structures,

and mechanisms for knowledge transfer between ships. The persistent nature of Navy cybersecurity compliance challenges and the operational costs of manual processes justify continued investment in framework development, testing, and fleet integration. Each research effort helps improve and sustain fleet cyber readiness through scalable, sustainable automation that respects operational realities.

Acknowledgements

The authors wish to thank cybersecurity subject matter experts at the Naval Information Warfare Center Pacific for their valuable operational insights and technical validation of the framework architecture. Special appreciation goes to the CANES program representatives for their expertise on shipboard IT infrastructure and operational constraints.

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: The authors used Anthropic's Claude Sonnet 4 to aid in developing technical specifications during the framework design phase. The tool helped develop database schemas, generate pseudocode for parsing and compliance algorithms, and convert conceptual requirements into detailed technical specifications. All specifications were validated against Defense Information Systems Agency STIG documentation, Navy cybersecurity policies, and DoD security standards. Cybersecurity subject matter experts from Naval Information Warfare Center Pacific reviewed the technical approach for feasibility and operational suitability. All research methodology, gap analysis, requirements definition, and evaluation of existing tools represent original analytical work, with AI serving only as a supporting tool to translate our analyses into technical specifications, rather than as a primary source of content.

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Beyond Missiles and Marines: A Multidomain Strategy for Deterring a PRC Invasion of Taiwan

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Abstract: The People's Republic of China (PRC) poses a critical challenge to regional stability and U.S. security interests, advancing a strategy of Unrestricted Warfare that outpaces traditional battlefield engagements. A Taiwan crisis may unfold through cyberattacks, economic coercion, and disinformation designed to fracture alliances and erode public trust long before the first missiles are launched. If U.S. deterrence remains narrowly focused on kinetic superiority, it risks failing to leverage an Inverse Unrestricted Warfare Framework which—combined with *U.S. Marine Corps Force Design 2030 (commonly referred to as "Force Design")*—offers a multidomain approach that mirrors and counters the PRC's own tactics. This paper proposes a multidomain strategy to deter a PRC invasion of Taiwan through a cohesive framework that applies the logic of Unrestricted Warfare against the PRC itself. The framework consists of five mutually reinforcing lines of effort: Military Denial Through Distributed Operations; Non-Kinetic Domain Deterrence; Cognitive and Informational Maneuver; Asymmetric Disruption and Escalation Options; and an Integrative Principle of Preemptive and Parallel Shaping. Beyond kinetic means, the framework emphasizes cyber resilience, legal warfare, and economic pressure as critical tools for shaping the pre-invasion battlespace. The result is a layered deterrence strategy that combines denial, cost imposition, and delegitimization, leveraging the PRC's own tactics against it to impose strategic costs. An Inverse Unrestricted Warfare framework integrates military innovation with non-kinetic resilience, ensuring *Force Design* enables deterrence that is credible, adaptive, and global—preventing conflict before it begins and safeguarding Taiwan's future.

Keywords*:* Unrestricted warfare, Gray zone conflict, Taiwan deterrence strategy, Marine Corps Force Design 2030, Multidomain deterrence and distributed operations, Cognitive and information warfare, Non-kinetic deterrence

1. Introduction

The People's Republic of China (PRC) may ignite a war over Taiwan without firing a single shot, employing the principles of Unrestricted Warfare first articulated by People's Liberation Army (PLA) colonels Qiao Liang and Wang Xiangsui. Their concept reframed conflict as an activity unconstrained by traditional military domains, extending competition into political, economic, technological, and informational arenas. Rather than seeking immediate battlefield victory, the PRC seeks to shape strategic conditions, exploit ambiguity, and constrain adversary decision-making before leaders recognize that competition has already crossed into conflict (Qiao & Wang, 1999).

This approach is evident in the PRC's persistent use of gray zone tactics—actions that fall between total war and perfect peace. These tactics include cyber intrusions, economic coercion, legal manipulation, and influence operations designed to weaken political resolve and delay coordinated response (Braw, 2022). In the Taiwan context, a crisis is unlikely to begin with amphibious assault or missile strikes. Instead, it may open with infrastructure disruptions, financial instability, and coordinated disinformation intended to erode confidence in governance and alliance credibility.

Current U.S. deterrence frameworks remain disproportionately oriented toward kinetic superiority, assuming that military denial alone will prevent aggression (Braw, 2022). This assumption is increasingly risky. If deterrence activates only when overt military indicators appear, the PRC may already have achieved decisive advantage by shaping perceptions, degrading command and control, and narrowing political options through non-kinetic means. Deterrence that arrives late—after strategic conditions are already set—may prove ineffective even if conventional forces remain capable (Schneider Rasador and Moreira Cunha, 2025).

The PRC's approach deliberately targets structural vulnerabilities within U.S. and allied systems, including centralized logistics, fragile information flows, and alliance coordination mechanisms. These vulnerabilities are magnified by decision latency, interoperability challenges, and policy constraints that slow integration across partners and domains (Zheng, 2025). In a rapidly unfolding Taiwan contingency, such friction could delay collective action and create opportunities for coercion to succeed without decisive military engagement.

The U.S. Marine Corps is uniquely positioned to address this challenge through the concepts embodied in *U.S. Marine Corps Force Design 2030 (commonly referred to as "Force Design")*. Emphasizing distributed operations, expeditionary resilience, and integration across domains, *Force Design* provides the foundation for a deterrence

posture capable of competing inside the gray zone. By combining distributed military denial with cyber resilience, legal and economic instruments, and cognitive maneuver, the Marine Corps can contribute to a deterrence strategy that operates before conflict becomes inevitable.

This paper advances the concept of an Inverse Unrestricted Warfare framework—a multidomain approach that turns the logic of Unrestricted Warfare back against the PRC. Rather than responding sequentially to coercive actions, this framework seeks to shape the shaping fight through parallel, preemptive actions across military and non-military domains. The objective is not escalation, but prevention: creating a deterrence posture that denies the PRC the ability to achieve strategic objectives through ambiguity, timing, and coercion.

2. Problem

The central problem addressed in this paper is that U.S. deterrence concepts remain optimized for kinetic conflict, while the People's Republic of China (PRC) has invested heavily in shaping the pre-conflict environment through gray zone methods that exploit ambiguity and delay response (Qiao & Wang, 1999). In a Taiwan contingency, deterrence failure may not stem from an inability to win a conventional fight, but from the failure to recognize that strategic competition has already transitioned into conflict across political, informational, economic, and cyber domains (Zheng, 2025).

The PRC's strategy of Unrestricted Warfare enables it to pursue national objectives without crossing clear thresholds that would trigger immediate military response. By integrating cyber operations, economic pressure, legal manipulation, and information campaigns, Beijing can impose cumulative costs while maintaining plausible deniability (Zheng, 2025). This approach allows the PRC to remain persistently engaged, probing Taiwan's resilience and testing U.S. and allied resolve without committing to overt escalation.

Although U.S. doctrine increasingly acknowledges gray zone competition, responses remain inconsistent and fragmented. Institutional stovepipes continue to separate cyber operations, information operations, economic tools, and military planning, limiting commanders' ability to synchronize effects across domains. Legal and policy constraints further complicate coordination, often slowing decision-making at precisely the moment when speed and coherence are most critical (Braw, 2022). These frictions create exploitable seams that the PRC can leverage to advance its objectives incrementally.

Compounding this challenge are persistent interoperability and integration gaps within combined and joint command and control structures. Effective deterrence in a multidomain environment requires rapid information sharing, aligned decision authority, and synchronized action among allies and partners (Braw, 2022). Yet current command architectures often struggle to integrate partners at the speed required to counter gray zone escalation. When adversary shaping actions occur faster than coalition coordination, deterrence credibility erodes.

The Taiwan scenario magnifies these weaknesses because it is not solely a regional military problem. A crisis in the Taiwan Strait would have immediate global implications, affecting maritime trade, supply chains, alliance credibility, and international norms (Schneider Rasador and Moreira Cunha, 2025). In such an environment, deterrence that relies primarily on the promise of eventual military response risks arriving too late to prevent strategic loss. The PRC may succeed by shaping conditions so that escalation appears inevitable or too costly to resist.

The problem, therefore, is not the absence of military capability, but the absence of a coherent framework to compete effectively before overt conflict (Lundberg, Hacks, and Anderson, 2024). If deterrence is activated only when missiles launch or amphibious forces move, the PRC may already have secured decisive advantage through non-kinetic means. Preventing conflict over Taiwan requires a deterrence posture that operates earlier, integrates multiple domains, and imposes credible costs during the shaping phase rather than after escalation has begun (Zheng, 2025).

3. Purpose

The purpose of this paper is to propose a multidomain deterrence framework capable of preventing a People's Republic of China (PRC) invasion of Taiwan by competing effectively in the gray zone prior to open conflict. Rather than treating deterrence as a function that activates only at the threshold of kinetic war, this paper seeks to reframe deterrence as a continuous, preemptive effort that shapes adversary decision-making across military and non-military domains.

Specifically, the paper advances the concept of an "Inverse Unrestricted Warfare" framework that mirrors and counters the PRC's own strategic approach. By applying the logic of Unrestricted Warfare against the PRC, the framework integrates distributed military denial, non-kinetic cost imposition, cognitive and informational maneuver, and asymmetric disruption into a coherent deterrence strategy aligned with *Force Design*.

The paper's intent is not to present a detailed operational plan for Taiwan defense, but to provide a conceptual and strategic framework that informs *Force Design*, posture decisions, and campaign planning before crisis forces irreversible choices. The framework is designed to help commanders, planners, and policymakers understand how deterrence can be strengthened before escalation by denying the PRC low-cost coercive options, compressing coalition decision timelines, and reinforcing Taiwanese resilience.

Ultimately, the purpose of this study is to demonstrate that deterrence failure is not inevitable if competition remains confined to kinetic considerations (Zheng, 2025). By shaping the shaping fight through parallel, multidomain action, the United States and its allies can impose credible costs, preserve legitimacy, and prevent the PRC from achieving strategic objectives through ambiguity, timing, and coercion.

4. Analysis and Background: Unrestricted Warfare, Gray Zone Competition, and the Need for an Inverse Approach

The strategic context surrounding Taiwan deterrence is best understood through the lens of Unrestricted Warfare, which reconceptualizes conflict as a contest unconstrained by traditional military boundaries. Rather than privileging decisive battlefield engagements, this approach integrates political pressure, economic leverage, cyber operations, legal manipulation, and information campaigns to achieve strategic objectives without triggering conventional escalation. The People's Republic of China (PRC) has adopted this logic as a central feature of its competition strategy, enabling persistent pressure while preserving ambiguity (Qiao & Wang, 1999).

Gray zone competition is the operational manifestation of Unrestricted Warfare. It operates in the space between war and peace, where actions are coercive yet fall short of armed attack (Zheng, 2025). In the Taiwan context, gray zone activities allow the PRC to degrade resilience, influence decision-making, and test alliance credibility without providing a clear casus belli. These actions include cyber intrusions targeting infrastructure and governance systems, economic coercion designed to influence political outcomes, and coordinated disinformation campaigns aimed at eroding public trust (Qiao & Wang, 1999).

A defining characteristic of gray zone competition is its cumulative effect on decision-making conditions. Individual actions may appear manageable in isolation, but collectively they shape conditions that constrain adversary options and increase the likelihood of favorable outcomes without overt conflict (Braw, 2022). This approach exploits the tendency of democratic systems to seek consensus and legal clarity before responding, creating decision latency that can be strategically decisive (Pascoli, Grzegorzewski, 2021).

Traditional deterrence models, which emphasize military denial and punishment after escalation, are poorly suited to this environment. They assume clear thresholds, visible aggression, and linear escalation pathways. In practice, gray zone competition blurs thresholds and exploits ambiguity, allowing the PRC to advance objectives incrementally while avoiding decisive response. As a result, deterrence that relies solely on kinetic superiority risks becoming reactive and ineffective (Zheng, 2025).

The *Force Design* initiative provides a partial answer to this challenge by emphasizing distributed operations, expeditionary resilience, and integration across domains. However, without a broader strategic framework, these capabilities risk being applied narrowly within the military domain (Lundberg, Hacks, and Andersson, 2024). To counter Unrestricted Warfare effectively, distributed denial must be integrated with non-kinetic instruments of power and applied proactively during the shaping phase of competition.

This requirement leads to the concept of an Inverse Unrestricted Warfare approach. Rather than rejecting the logic of Unrestricted Warfare, this approach mirrors it—using parallel, multidomain actions to deny advantage, impose costs, and delegitimize coercion before conflict begins. By competing across the same domains the PRC seeks to exploit, the United States and its allies can disrupt gray zone campaigns, reduce ambiguity, and restore deterrence credibility (Zheng, 2025).

5. The Inverse Unrestricted Warfare Framework

This paper proposes an Inverse Unrestricted Warfare framework as a multidomain deterrence strategy designed to counter the People's Republic of China's (PRC) approach to gray zone competition. Rather than waiting for

escalation into open conflict, the framework seeks to shape the strategic environment in advance by denying coercive advantage, imposing costs, and reinforcing legitimacy across military and non-military domains. The framework is organized into five mutually reinforcing lines of effort that together form a layered deterrence posture.

The central premise of the framework is that deterrence must operate continuously and in parallel across domains, rather than activating sequentially after escalation thresholds are crossed. Military denial alone is insufficient if political resolve, economic stability, and public trust are undermined before kinetic conflict begins (Braw, 2022). Conversely, non-kinetic measures without credible military denial lack coercive weight. The five lines of effort (LOEs) are therefore designed to function as an integrated system rather than as independent activities.

5.1 Line of Effort 1: Military Denial Through Distributed Operations

The first line of effort focuses on denying the PRC the ability to achieve a rapid fait accompli against Taiwan. Distributed operations, as emphasized in *Force Design*, complicate adversary targeting, reduce vulnerability to decapitation, and increase the cost and uncertainty of invasion. By dispersing forces, sensors, and fires across the littoral environment, the Marine Corps contributes to a denial posture that remains resilient under conditions of contested communications and precision strike.

Military denial in this context must assume degraded command and control. Mission command, delegated authorities, and pre-planned actions are essential to maintaining effectiveness when connectivity is disrupted (Lundberg, Hacks, and Anderson, 2024). A denial posture that depends on uninterrupted networks is vulnerable to the very cyber and electronic warfare tactics the PRC is likely to employ during the shaping phase of conflict.

5.2 Line of Effort 2: Non-Kinetic Domain Deterrence

The second line of effort extends deterrence into non-kinetic domains, including cyberspace, economic pressure, and international legitimacy. Gray zone coercion relies on the assumption that these tools can be applied at low cost and with limited risk. Non-kinetic deterrence seeks to deny that advantage by increasing resilience, improving attribution, and pre-positioning credible consequences.

Cyber resilience is central to this effort. If cyberattacks fail to disrupt governance, command and control, or public confidence, their strategic value diminishes. Economic deterrence requires advance coordination with allies to ensure that coercive actions trigger immediate and collective costs rather than delayed, fragmented responses (Pascoli and Grzegorzewski, 2021). Legal and diplomatic measures further reinforce deterrence by exposing coercion and undermining adversary narratives.

5.3 Line of Effort 3: Cognitive and Informational Maneuver

The third line of effort recognizes the cognitive domain as a primary battleground in gray zone competition (Qiao & Wang, 1999). Influence operations, disinformation, and narrative manipulation are designed to erode public trust, weaken resolve, and create a perception of inevitability. Deterrence therefore requires defending public confidence and maintaining narrative coherence during periods of ambiguity and pressure (Braw, 2022).

Operations in the Information Environment provide the means to protect decision-making, reinforce legitimacy, and align coalition messaging. Secure and resilient communications are essential to preventing information vacuums that adversaries can exploit. By treating public trust as operational terrain, this line of effort seeks to deny the PRC the ability to achieve strategic effect through perception shaping alone.

5.4 Line of Effort 4: Asymmetric Disruption and Escalation Options

The fourth line of effort introduces asymmetric disruption options that impose disproportionate costs and uncertainty on the PRC. These options include mobile fires, undersea capabilities, electromagnetic warfare, and other tools that exploit adversary dependencies and vulnerabilities. The objective is not escalation for its own sake, but the creation of credible uncertainty that complicates planning and raises the perceived risk of aggression.

Asymmetric disruption also extends beyond the immediate Taiwan operating area. By highlighting the global economic and political consequences of aggression, this line of effort expands the PRC's cost calculus and reduces confidence that conflict can be contained geographically or economically.

5.5 Line of Effort 5: Preemptive and Parallel Shaping

The fifth line of effort integrates the framework through preemptive and parallel shaping. Rather than sequencing actions after escalation, this approach emphasizes early preparation and simultaneous action across domains. Preemptive shaping does not imply offensive escalation, but deliberate readiness that denies adversaries the benefits of timing, ambiguity, and decision asymmetry.

Parallel shaping ensures that denial, resilience, cost imposition, and narrative alignment are available at the outset of crisis. By compressing response timelines and reducing ambiguity, this line of effort shifts initiative away from the PRC and toward the coalition, strengthening deterrence before conflict becomes unavoidable.

6. Recommendations

To operationalize the Inverse Unrestricted Warfare framework, deterrence must be translated from conceptual alignment into concrete actions that can be implemented during peacetime competition and early crisis shaping. The following recommendations align with the five lines of effort and are intended to strengthen deterrence before escalation occurs.

6.1 Strengthen Distributed Denial and Resilience

Distributed denial capabilities should be designed and exercised under conditions of degraded command and control. Marine Corps forces aligned with *Force Design* should routinely train to operate with mission command, delegated authorities, and preplanned responses that assume communications disruption. Cyber resilience must be treated as an operational requirement rather than an enterprise support function, with defensive cyber capabilities integrated into forward-deployed and expeditionary formations. Exercises should incorporate gray zone conditions such as cyber disruption, information attacks, and economic pressure to reflect the most likely pre-invasion environment (Pascoli and Grzegorzewski, 2021).

6.2 Pre-Coordinate Non-Kinetic Cost Imposition

Non-kinetic deterrence requires credible consequences that are prepared in advance rather than improvised during crisis. The United States and its allies should develop pre-approved economic, legal, and diplomatic response packages tied to clearly defined coercive actions. These packages should be designed to activate rapidly, signaling that gray zone escalation will produce immediate and collective costs. Legal and diplomatic mechanisms should be integrated into operational planning to ensure that coercive actions are documented, attributed, and exposed in near real time (Pascoli and Grzegorzewski, 2021).

6.3 Defend the Cognitive Domain as Operational Terrain

Public trust and political resolve must be treated as critical components of deterrence. Operations in the Information Environment should be integrated into deterrence planning, not reserved solely for wartime execution. This includes pre-aligning coalition messaging, reinforcing Taiwanese civil resilience, and ensuring secure crisis communications that can function under disruption. By maintaining narrative coherence and reducing information vacuums, the coalition can deny the People's Republic of China opportunities to shape perceptions through disinformation and psychological pressure (Zheng, 2025).

6.4 Expand Asymmetric Disruption Options

Asymmetric capabilities that impose disproportionate costs should be prioritized to exploit adversary vulnerabilities. Investments in mobile fires, undersea capabilities, electromagnetic warfare, and other low-cost, high-impact tools can significantly complicate invasion planning and increase uncertainty (Schneider Rasador and Moreira Cunha, 2025). These capabilities should be exercised and demonstrated in ways that contribute to deterrence signaling, reinforcing the perception that aggression will generate cascading and difficult-to-control consequences.

6.5 Institutionalize Preemptive and Parallel Shaping

Deterrence must begin before visible escalation. Planning and posture should emphasize parallel shaping across domains, ensuring that denial, resilience, cost imposition, and narrative alignment are all available at the onset of crisis. Preemptive shaping should be understood as preparedness rather than provocation, focused on reducing ambiguity and compressing response timelines. Readiness metrics should reflect integration and speed of activation rather than platform counts or inventory depth alone.

7. Conclusion and Implementation Implications

In conclusion, deterring a People's Republic of China invasion of Taiwan requires more than conventional military superiority. The PRC's approach to competition, rooted in the logic of Unrestricted Warfare, seeks to achieve strategic objectives through gray zone coercion, multidomain shaping, and perception management before overt conflict begins. In such an environment, deterrence fails not only when military denial collapses, but when political resolve weakens, alliances fracture, and decision-making slows under pressure (Braw, 2022).

This paper advanced an Inverse Unrestricted Warfare framework designed to counter this challenge by competing across the same domains the PRC seeks to exploit. By integrating distributed military denial, non-kinetic cost imposition, cognitive and informational maneuver, asymmetric disruption, and preemptive parallel shaping, the framework offers a layered approach to deterrence that operates before escalation and remains resilient under ambiguity.

Aligned with *Force Design*, this approach emphasizes dispersion, resilience, and integration rather than reliance on centralized systems vulnerable to disruption. It reframes deterrence as a continuous process of shaping conditions, denying low-cost coercion, and imposing credible costs early. In doing so, it reduces the PRC's confidence in achieving objectives through timing, ambiguity, or incremental pressure.

Implementation implications and outcomes are interrelated but not entirely dependent on one another. In LOE 1: Military Denial Through Distributed Operations, implementation requires the dispersion of sensors, shooters, and decision-making nodes throughout the operational environment, enabled by mission command and delegated authorities, with projected outcomes including increased uncertainty and force dispersion within the PLA. In LOE 2: Non-Kinetic Domain Deterrence, implementation requires pre-established actions and counteractions in the cyber domain, ensuring aggression is met with immediate and effective deterrence. LOE 3: Cognitive and Informational Maneuver requires the implementation of secure communications, incorporating OIE and Taiwanese resistance to maintain public trust and political resolve. For LOE 4, implementation involves intentionally resourcing low-cost, high-impact technologies across warfighting domains to create uncertainty and exploit vulnerabilities in the PLA kill chain cycle. In LOE 5: Preemptive and Parallel Shaping, implementation includes establishing metrics that emphasize simultaneous offensive and defensive measures, creating a dynamic deterrence environment.

Ultimately, preventing conflict over Taiwan depends on the ability to shape the shaping fight before commanders are forced to make irreversible decisions under crisis conditions. An Inverse Unrestricted Warfare approach provides a means to do so—preserving initiative, reinforcing legitimacy, and making coercion unreliable. By competing effectively in the gray zone, the United States and its allies can strengthen deterrence, safeguard Taiwan's security, and prevent war before it begins.

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: Open-source artificial intelligence tools were used solely for proofreading and citation formatting. All analysis, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources.

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Operationalizing Cyber in Multi-domain Operations: A Kill-Chain-Centric Approach for Cyber Strike Packages

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Abstract: This paper examines the challenge of integrating cyber capabilities into NATO Multi-Domain Operations (MDO) at the operational level. While doctrine emphasizes convergence across domains, cyber is not consistently incorporated into execution processes, particularly within the joint targeting cycle. Drawing on a NATO-aligned instructional vignette and student planning exercises, this study proposes a kill-chain-centric framework using Cyber Strike Packages (CSPs) to synchronize cyber effects with other domains. Observations from the instructional environment indicate that cyber capabilities are frequently underutilized or misaligned with operational timelines when planners lack a structured integration framework. Application of the CSP model improved alignment between cyber effects, targeting decisions, and cross-domain coordination. The findings suggest that cyber integration is primarily a problem of structure and timing rather than capability alone. In particular, planners struggled to align cyber preparation timelines with rapid operational decision cycles. The proposed framework addresses this challenge by organizing cyber effects around target, timing, effect, and assessment within the kill chain. The paper concludes that improving cyber integration in NATO operations does not require entirely new doctrine, but more effective incorporation of cyber into targeting processes, planning timelines, and operational decision-making.

Keywords*:* Multi-domain operations (MDO), Cyberspace operations, Cyber strike packages (CSP), Kill chain, NATO, Joint targeting

1. Introduction

The emerging phenomenon of Multi-Domain Operations (MDO) reflects an ongoing shift in how military power is applied across land, maritime, air, space, and cyberspace, with convergence at its center—the ability to synchronize and orchestrate capabilities across domains to create compounded operational effects and decision advantage (NATO Standardization Office, 2020; Department of Defense, 2022). While this idea is well established in doctrine, its practical implementation, particularly with respect to cyber, remains unclear. Cyber capabilities are often acknowledged as important but are not consistently integrated into execution-level processes, instead being treated as pre-operational shaping tools or specialized activities managed outside the main planning and targeting workflows (Joint Chiefs of Staff, 2022; Libicki, 2021). This creates a gap between what cyber is expected to contribute and how it is actually employed. This is most visible in time-sensitive scenarios where planners demonstrate a general understanding of cyber capabilities but struggle with determining what effect is required, when that effect must occur, and how cyber compares to other available options. This reflects a broader issue identified in doctrine and scholarship. Cyber Persistence Theory and related scholarship on political warfare emphasize continuous engagement, competition below armed conflict, and the strategic use of cyber capabilities to shape adversary behavior (Fischerkeller, Goldman and Harknett, 2022; Jensen, 2022). Where strategic frameworks such as Cyber Persistence Theory emphasize continuous engagement and initiative in cyberspace, these frameworks do not fully translate into operational planning constructs (Fischerkeller, Goldman and Harknett, 2022).

Doctrinal publications, such as AJP-3.20 and JP 3-12, that provide guidance on organizing and employing cyber forces are limited in describing how cyber effects are integrated into joint targeting cycles and kill chain execution (NATO Standardization Office, 2020; Joint Chiefs of Staff, 2022). Scholars have noted this disconnect, highlighting a persistent gap between cyber planning and traditional operational planning processes and the difficulty of aligning cyber effects with operational timelines and decision cycles (VanDriel, 2015; Lindsay, 2020; Libicki, 2021). This results in cyber planning occurring in parallel rather than within operational planning and limiting its impact during execution (VanDriel, 2015; Lindsay, 2020; Libicki, 2021).

This paper examines that problem from an applied perspective, focusing on how cyber capabilities are incorporated into operational planning and decision-making, and proposes a kill-chain-centric approach to cyber integration operationalized through Cyber Strike Packages (CSPs) as a practical method for aligning cyber

capabilities with the structure of the kill chain, the timing of operational decision-making, and the processes used in joint targeting and execution.

The analysis is grounded in a NATO-aligned instructional vignette in which students developed operational plans for a multi-domain scenario, showing that the primary limitation is not technological but procedural and cognitive, and that integration through a kill-chain-centric framework makes cyber a more usable and effective component of multi-domain operations, as has been established in recent real world operations. Despite significant doctrinal development in cyberspace operations, a persistent operational gap remains between recognizing cyber as a critical domain and integrating cyber effects into execution-level planning and targeting. Existing doctrine explains why cyber matters, but provides limited practical guidance for how planners should synchronize cyber capabilities with operational timelines and kill chain execution in Multi-Domain Operations. This paper addresses that gap by proposing a usable planning framework designed to operationalize cyber integration within existing NATO operational structures.

2. Literature and Doctrine Review

Over the past decade, both NATO and U.S. doctrine have made substantial progress in recognizing cyberspace as a distinct warfighting domain. At the same time, a consistent gap remains between conceptual acknowledgment and operational integration. This section reviews the doctrinal and scholarly landscape with a focus on where cyber integration breaks down in practice, particularly within the context of MDO. Existing strategic cyber theories provide important insight into competition and persistent engagement in cyberspace. Their strength lies in explaining how states maintain initiative and strategic advantage through continuous interaction. However, their limitation is that they provide limited operational guidance for synchronizing cyber effects with targeting processes and time-sensitive execution requirements in MDO environments.

2.1 NATO Multi-Domain Operations and the Problem of Execution

NATO's approach to MDO emphasizes the orchestration of military and synchronization of non-military capabilities across domains and environments to create converging effects and achieve operational advantage." (NATO Allied Command Transformation, 2023, NATO Standardization Office, 2020). Allied doctrine, including AJP-3.20: Allied Joint Doctrine for Cyberspace Operations and AJP-6: Communication and Information Systems, establishes cyberspace as both an operational domain and a critical enabler of joint operations. However, while these publications clearly articulate the importance of cyberspace, they provide less detail on how cyber capabilities are incorporated into execution-level processes, particularly within the joint targeting cycle. In practice, cyber is often framed in one of three ways:

- As a supporting function for intelligence or information activities,
- As a pre-operational shaping tool, or
- As a strategic-level instrument of competition.

What is less clearly defined is how cyber contributes to time-sensitive targeting. From a planning perspective, this creates friction. Planners understand that cyber is important, but they often lack a clear method for incorporating it into courses of action, weaponeering, and execution timelines. This challenge is amplified in coalition environments, where authorities, capabilities, and information-sharing constraints vary by nation. As a result, cyber may be conceptually integrated into NATO MDO, but remains uneven in execution.

2.2 Persistence Without Operationalization

At the strategic level, one of the most influential contributions to cyber theory is Cyber Persistence Theory, which introduces the concept of persistent engagement, arguing that cyberspace is characterized by continuous interaction among adversaries where advantage is gained through initiative and sustained activity rather than discrete campaigns (Fischerkeller, Goldman and Harknett, 2022). However, from an operational standpoint, the theory does not fully address how these dynamics translate into time-bound, synchronized effects within military operations, nor does it provide a clear framework for integrating cyber into joint targeting processes, aligning cyber effects with operational timelines, or incorporating cyber into kill chain execution. U.S. joint doctrine, particularly Joint Publication 3-12: Cyberspace Operations, provides more detailed guidance on the organization and execution of cyber operations (Joint Chiefs of Staff, 2022), emphasizing integration with the Joint Planning Process and the joint targeting cycle, and outlining the roles of Offensive Cyber Operations (OCO) and Defensive Cyber Operations (ISR).

Despite this, a planning gap remains. Cyber planning often occurs in parallel to operational planning rather than within it (VanDriel, 2015), leading to recurring issues in which cyber capabilities are introduced late in the planning process, cyber effects are not aligned with key decision points, and non-cyber planners lack confidence in how to employ cyber options. More recent scholarship reinforces this observation, noting that cyber operations are difficult to integrate due to their dependence on access, intelligence, uncertain effects, and escalation dynamics (Lindsay, 2020; Libicki, 2021; Borghard and Lonergan, 2021). This highlights the challenge of aligning cyber capabilities with operational objectives, particularly when outcomes are indirect or difficult to measure (Libicki, 2021). This results in cyber being frequently underutilized or misapplied even when available.

2.3 Cyber Effects in Operational Context

A related challenge concerns the nature of cyber effects themselves. Cyber effects are often difficult to attribute, uncertain in duration, and challenging to employ for traditional deterrence purposes (Nye, 2017). Unlike kinetic effects, which are typically observable and immediate, cyber effects can be delayed or time-dependent, reversible or temporary, difficult to attribute, and dependent on sustained access. These characteristics complicate integration into traditional planning models. As Rid (2020) and Valeriano and Maness (2018) argue, cyber operations are often more effective as disruption and shaping tools rather than decisive, standalone actions. This does not diminish their operational value, but it does require a different approach. Cyber must be aligned with other domain effects to produce meaningful outcomes. In practice, however, this alignment is difficult to achieve without a structured framework.

2.4 Synthesis: The Missing Operational Framework

Taken together, doctrine and scholarship point to consistent conclusions:

- Strategic understanding of cyber is well developed,
- Capabilities continue to evolve, and
- Doctrine recognizes cyberspace as essential.

However, a gap remains at the operational level, particularly in integrating cyber into the kill chain, synchronizing cyber with targeting processes, and aligning cyber effects with operational timelines. This gap is not simply theoretical—it directly affects how operations are planned and executed. Without a practical framework, cyber remains conceptually important and technically capable, but operationally underutilized.

3. Conceptual Framework: Kill-Chain-Centric Cyber Integration

The preceding section highlighted a consistent gap between how cyber is discussed in doctrine and how it is actually used during planning and execution. This section introduces a kill-chain-centric framework, supported by the concept of Cyber Strike Packages (CSPs), as a means to address that gap.

3.1 Reframing the Kill Chain in a Multi-domain Context: Cyber Strike Package (CSP)

The evolution towards “kill chain centric operations” as a fundamental warfighting concept is being explored in naval combat (Stegner, 2026). There is a natural extension of this thinking into cyber operations. The kill chain—commonly described as *find, fix, track, target, engage, and assess*—is a foundational construct for organizing military effects and has increasingly been applied across domains as a way to structure decision-making and synchronize capabilities (Joint Chiefs of Staff, 2022). Cyber is rarely mapped explicitly to kill chain phases and is often treated as a prerequisite activity (e.g., access development), an intelligence enabler (e.g., support Intelligence, Surveillance and Reconnaissance), or a standalone effect delivered independently of broader operations, creating a disconnect that makes it difficult for planners to determine where cyber can have the greatest operational impact, when effects must occur, and how cyber aligns with other domain actions. To address this, the proposed framework maps cyber contributions directly to each phase of the kill chain:

Kill Chain Phase	Cyber Contribution
Find / Fix	Network reconnaissance, target identification
Track	Persistent access, telemetry collection
Target	Vulnerability analysis, access validation
Engage	Effects delivery (disrupt, deny, manipulate, destroy)
Assess	Cyber-enabled battle damage assessment

Figure 1: Kill-Chain-Centric Cyber Integration

This provides a common reference point for integrating cyber into operational planning discussions. This conceptual mapping is operationalized through Cyber Strike Packages (CSPs), defined as "a coordinated set of cyber actions designed to achieve a specific operational effect within a defined time window, aligned with the joint targeting process," structured to resemble traditional strike packages used in air and fires planning. Each CSP includes five core elements:

- Target definition—the system, network, or function to be affected, linked to an operational objective;
- Access and placement—the method and level of access required, including persistence and reliability;
- Effect type—the intended outcome (e.g., disruption, denial, manipulation, destruction);
- Timing and execution window—when the effect must occur relative to decision points and other domain actions;
- Assessment mechanism—how success will be measured, including both performance and effectiveness.

3.2 Red and Blue Kill Chain Interaction

A key advantage of integrating cyber into the kill chain framework is that it allows planners to consider both friendly and adversary processes simultaneously. In a multi-domain environment, operations involve the interaction of the adversary (Red) kill chain, and the friendly (Blue) kill chain. Cyber is uniquely positioned to influence both. From an adversary-focused perspective, cyber can disrupt detection and tracking systems, degrade communications between nodes, and delay or prevent engagement decisions. From a friendly perspective, cyber can enable targeting through improved intelligence, provide access to critical information, and support synchronization across domains. From a multi-domain operations perspective, cyber capabilities can be viewed as "shoot to move" and "move to shoot" that integrates with the concepts of fire and maneuver that directly translate into risk to mission and risk to force. In some cases, effective employment of cyber capabilities can reduce both risk to mission and risk to force at the same time.

3.3 Effects-based Thinking in Cyber Planning

One of the most consistent challenges observed in planning environments is the tendency to focus on capability rather than effect. This aligns with broader observations in literature, where cyber discussions often emphasize technical feasibility over operational impact (Lindsay, 2020; Libicki, 2021). The kill-chain-centric approach shifts the focus toward effects-based thinking, which is already well established in targeting doctrine. This requires planners to begin with questions such as:

- What operational outcome is required?
- How does this engagement support fire and maneuver in other domains?
- What effect will produce that outcome?
- Which capability is best suited to deliver it?

3.4 Temporal Dynamics and Synchronization

The most significant challenge in integrating cyber into the kill chain is time. Cyber operations often involve extended preparation periods for access development, uncertain execution timelines, and variable effect duration. These characteristics contrast with the compressed timelines of modern operations. The Cyber Strike Package (CSP) framework addresses this by explicitly incorporating preparation time ("walk-time"), execution windows, and duration of effect. This forces planners to treat cyber as a time-dependent capability, rather than something that can be applied on demand.

3.5 The Role of the Planner

Integrating cyber into the kill chain ultimately depends on how planners approach the problem. This requires a functional understanding of cyber capabilities, the ability to incorporate cyber into existing processes (e.g., targeting), and coordination across domains and organizations. This would represent a shift in mindset. Cyber should no longer be treated as a specialized activity managed separately, but as part of how operations are designed and executed. The kill-chain-centric framework and the Cyber Strike Package (CSP) construct provide a way to conceptualize and plan cyber integration.

4. Operational Integration: The NATO Joint Operations Centre (JOC)

Within NATO operational structures, responsibility for conceptualizing and planning cyber integration sits with the Joint Force Command (JFC) and, more specifically, the Joint Operations Centre (JOC), where planning outputs are translated into synchronized execution. Within NATO command structures, the JOC functions as the central node for monitoring ongoing operations, synchronizing joint effects across components, and supporting commander decision-making through a structured battle rhythm that links planning, targeting, execution, and assessment, becoming the point where convergence either happens or breaks down in a MDO context.

While NATO doctrine emphasizes coordination across domains and the importance of integrated command and control (NATO Standardization Office, 2019; 2020), it provides less detail on how cyber capabilities are incorporated into execution-level processes, particularly those tied to the joint targeting cycle. This creates a challenge in which planners understand that cyber should be included but lack clarity on where and how it fits into the workflow. Cyber is often positioned outside the main execution cycle because capabilities are managed through specialized organizations or reach-back elements, where authorities remain at the national level, and information is constrained by classification or policy (SCEPVA), resulting in cyber planning occurring in parallel to operational planning rather than within it (VanDriel, 2015; Lindsay, 2020). This leads to recurring issues in which cyber options are not consistently presented during targeting discussions, cyber effects are not aligned with operational decision timelines, and planners lack confidence in how cyber can be employed.

The Cyber Strike Package (CSP) framework provides a way to integrate cyber into existing JOC processes without requiring significant structural changes by aligning cyber with already existing planning and execution, by incorporating cyber into mission analysis, course-of-action development and analysis, and the joint targeting cycle. Convergence becomes executable through target development, capability selection, and execution planning. This allows cyber to be evaluated alongside other capabilities in terms of expected effect, timing, duration, escalation risk, and attribution considerations (Borghard and Lonergan, 2021).

Effective integration requires intelligence support and continuous feedback loops between intelligence and operations for identifying target systems, validating access, and assessing effects (Rid, 2020; Valeriano and Maness, 2018). The same applies for visibility within the JOC battle rhythm, including targeting boards, operations updates, and commander briefs, where cyber options must be presented, aligned with decision timelines, and incorporated into operational assessments. When these conditions are met, the JOC functions as a convergence engine, synchronizing effects across domains, enabling coordinated action, and increasing operational tempo and complexity.

NATO operations introduce additional complexity through coalition dynamics, including national caveats, capability asymmetry, and information-sharing constraints, particularly for sensitive capabilities (Libicki, 2021). The Cyber Strike Package (CSP) framework helps mitigate these issues by focusing on effects rather than capabilities, allowing coordination without requiring full visibility into execution. This is critical, since the overall effectiveness of cyber capabilities depends on how planners apply these concepts to synchronize multi-domain effects in time-constrained operational environments.

5. Operational Application: NATO MDO Instructional Vignette

To examine how cyber capabilities can be incorporated into MDO in practice, this study draws on a NATO-aligned instructional vignette used in an instructor-level course. The vignette provides a structured, time-constrained environment in which students are required to develop operational plans that integrate capabilities across domains. Rather than relying on retrospective case studies, this approach allows for direct observation of how planners think, where integration breaks down, and what changes when a structured framework is introduced. It also captures decision-making under conditions that approximate operational pressure, including limited time, incomplete information, and competing priorities.

5.1 Scenario Overview and Operational Context

The vignette centers on a maritime scenario in which NATO forces are tasked to impose sea denial in the vicinity of a fictional city in a fictional country in order to isolate adversary forces. The operational problem is defined through a set of tactical tasks, including the attrition on the adversary's maritime capability, and degrading coastal defense systems. A defining feature of the scenario is the characterization of the adversary's kill chain as operating on a six-minute timeline from detection to weapon release. The following is a graphical depiction of the vignette that has been edited with artificial intelligence to change the location for publication purposes.

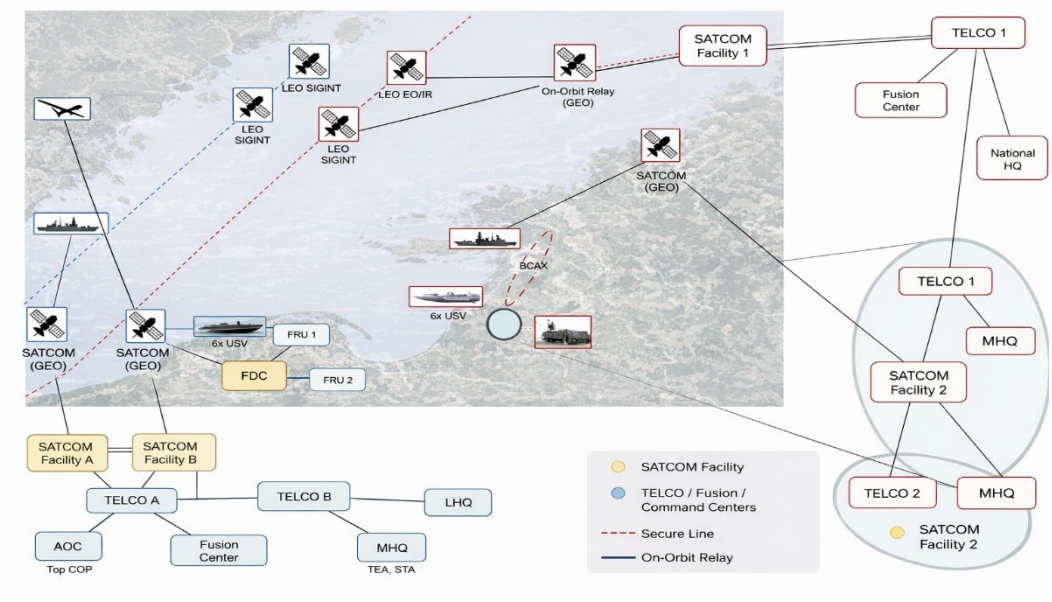


Figure 2: Operational Vignette depicting Command and Control (C2) Architecture

From the outset, this creates a clear tension as the adversary operates on a minutes-based timeline, and where in contrast, many cyber effects require hours—or longer—of preparation beyond their development and requirements for gaining access. In practice, this tension became one of the central planning challenges. Students quickly recognized that cyber could be useful but questioned whether those effects could be delivered in time to influence the outcome.

5.2 System Architecture and Target Environment

The vignette includes a detailed representation of the adversary's command-and-control architecture. This consists of national and maritime headquarters nodes, fusion centers responsible for data aggregation and decision support, telecommunications (TELCO) infrastructure, and satellite communications (SATCOM) facilities and on-orbit relay systems.

This architecture reflects a distributed, network-dependent system, where operational effectiveness depends on the ability to move information across multiple nodes. The target list reinforces this structure, identifying key systems such as the Maritime Headquarters (MHQ), Fusion Centers, TELCO nodes, and SATCOM facilities. Many of these targets are designated for cyber strike consideration, particularly those associated with command and control (C2). This shifts the problem from simply targeting platforms to identifying critical functions within the adversary's kill chain.

5.3 Cyber Strike Packages in the Scenario

To support planning, the vignette provides a set of predefined Cyber Strike Packages (CSPs). These packages include a designated target, an effect type (e.g., disrupt, deny, manipulate), a preparation time ("walk-time"),

an expected duration of effect, and considerations such as attribution and reversibility. For example, disrupting a headquarters node may require longer preparation but produce sustained effects, manipulating a fusion center may be faster but shorter in duration and denying TELCO infrastructure may produce immediate impact but carry greater escalation risk. These Cyber Strike Packages (CSPs) introduce trade-offs that planners must evaluate, including speed versus persistence, reversibility versus decisiveness, and operational impact versus attribution risk.

6. Analysis: Wargaming Insights

The instructional vignette provides a controlled environment to examine how cyber capabilities are incorporated into operational planning. By comparing planning behavior before and after the introduction of the kill-chain-centric Cyber Strike Package (CSP) framework, several patterns emerge. These patterns help explain why cyber remains underutilized in practice and what changes when a structured approach is applied.

6.1 Baseline Condition: Cyber Without a Structured Framework

Across early planning iterations, cyber integration was inconsistent and often superficial, not due to a lack of awareness, but due to difficulty translating that understanding into operationally relevant decisions. Cyber was frequently separated from the main planning effort and not fully incorporated into course-of-action development, targeting decisions, or execution timelines. Instead, it appeared as an add-on that could be included if time allowed, as reflected in the literature (VanDriel, 2015; Lindsay, 2020).

Most groups defaulted to kinetic solutions, particularly against maritime targets, favoring capabilities with more predictable and immediate outcomes (Lindsay, 2020), while cyber was treated as a supporting function for intelligence collection or general disruption rather than as a targeted tool for influencing specific points in the adversary's kill chain. A related issue was the tendency to focus on capability (options) rather than effect, resulting in cyber being underutilized or misaligned with operational objectives. Timing further compounded these challenges, as cyber options were selected without fully accounting for preparation time, execution windows, or alignment with key decision points, leading to effects that would occur after the critical operational moment and limiting their usefulness.

6.2 Temporal Misalignment as a Primary Constraint

A consistent takeaway is that cyber integration is fundamentally a timing and synchronization problem, as students generally understood what cyber could do but struggled to determine whether those effects could be delivered in time and aligned with the pace of operations. Across nearly all groups, timing emerged as the primary constraint on effective cyber integration, with cyber effects identified as operationally relevant but difficult to align with required timelines, particularly in relation to the adversary's six-minute kill chain. Cyber actions were often planned too late, preparation time was not accounted for, and effects occurred after the critical decision point had passed, highlighting that effects requiring hours of preparation could still be effective only if planned and initiated early enough. This aligns with findings in the literature that cyber operations are difficult to synchronize due to their dependence on access and preparation (Lindsay, 2020; Libicki, 2021) but also indicates that the problem is not purely technical, as planners were not consistently incorporating cyber timelines into early planning. The Cyber Strike Package (CSP) framework helped address this by requiring planners to account for preparation time, align execution with decision points, and treat cyber as a time-dependent capability rather than an on-demand option.

6.3 Effects-Based Framing and Its Impact on Planning

When the Cyber Strike Package (CSP) framework was introduced and explicitly tied to the kill chain, planning behavior began to shift toward effects-based thinking. Instead of starting with available capabilities, students were required to define the desired operational effect, the point in the kill chain where that effect would have the greatest impact, and the timing required to achieve it.

This shift had several observable effects. First, cyber was introduced earlier in the planning process. Second, cyber effects became more specific. Third, cyber was more consistently integrated into targeting discussions. When presented in CSP format, cyber could be evaluated alongside kinetic and electronic warfare options, making it easier for planners to incorporate it into decision-making.

6.4 Kill Chain Disruption as an Organizing Logic

When the kill-chain-centric Cyber Strike Package (CSP) framework was applied, planning behavior began to change, particularly in how targets were conceptualized, shifting from platform-centric targets towards alignment with specific phases of the kill chain, enabling disruption of tracking systems, degradation of communication between nodes, and delays in decision-making processes, resulting in more deliberate and targeted use of cyber capabilities. This reflects a broader shift in multi-domain thinking, where the objective is not simply to destroy platforms, but to disrupt the underlying processes (Department of Defense, 2022), with cyber proving particularly effective in this role by delaying detection, degrading tracking accuracy, and disrupting coordination between nodes. Integration across domains also improved, as cyber effects were increasingly

synchronized with maritime fires, ISR collection, and electronic warfare activities, and in some cases combined with kinetic effects to degrade adversary awareness while positioning assets for follow-on action.

6.5 Persistent Friction Points

Improvements in cyber integration were not uniform across all groups, as under time pressure some teams reverted to kinetic-first planning even when cyber options were available, indicating that frameworks such as Cyber Strike Package (CSPs) improve integration but do not fully overcome familiarity with traditional capabilities, uncertainty associated with cyber effects, or cognitive biases in decision-making. Coalition dynamics also remained a complicating factor, as not all partners possess the same capabilities and some cyber effects are constrained by national authorities, adding complexity to planning. These observations highlight the importance of repetition and reinforcement, as integration improved over time but required multiple iterations and guided discussion, demonstrating that cyber integration challenges emerge during planning and can be partially addressed through structured frameworks.

6.6 Cyber Integration

When properly integrated, cyber can disrupt adversary decision-making timelines, create opportunities for other domains, and increase the tempo and complexity of operations. However, this potential is only realized when cyber is aligned with the kill chain, integrated into targeting processes, and synchronized with operational timelines. Specifically, effective cyber integration can be achieved by:

- A Common Framework: The kill chain provides a shared structure for organizing cyber effects.
- A Practical Planning Construct: Cyber Strike Packages (CSPs) translate conceptual integration into actionable planning.
- Process Integration: Cyber must be incorporated into targeting and execution processes.
- Temporal Alignment: Cyber timelines must be considered early in planning, not after the fact.

The outcomes observed in the instructional environment support the argument that cyber integration improves when planners are provided with structured methods that align cyber effects with operational decision cycles. The observed improvements in synchronization, targeting integration, and effects-based planning justify the use of CSPs as a practical operational construct rather than solely a conceptual framework.

7. Implications for NATO Doctrine, Planning, and Training

The analysis suggests that the central challenge in integrating cyber into Multi-Domain Operations (MDO) is not a lack of capability, but a gap in how those capabilities are incorporated into operational processes. NATO doctrine recognizes cyberspace as a critical domain and emphasizes convergence and the integration of capabilities across domains (NATO Standardization Office, 2020). This challenge is increasingly important in environments characterized by persistent competition and political warfare below the threshold of conventional conflict (Jensen, 2022). However, the translation of that recognition into execution-level integration remains unclear, as cyber is often acknowledged during planning but not consistently incorporated into targeting decisions, execution timelines, or commander decision cycles. Bridging this gap requires more than doctrinal recognition. Thus, this requires clearer linkage between cyber and execution processes and planning constructs that allow cyber to be incorporated without requiring deep technical expertise, highlighting that usability, not just availability, is a key factor in integration.

7.1 Integrating Cyber into the Joint Targeting Cycle

The joint targeting cycle remains the primary mechanism through which convergence is achieved in practice. Despite this, cyber is not always fully integrated into target nomination, capability selection, or effects synchronization. The Cyber Strike Package (CSP) framework suggests a way to address this gap. By structuring cyber options in terms of target, effect, timing, and risk, cyber can be evaluated alongside kinetic and electronic warfare options. In the instructional environment, once cyber options were presented in this format, they were more consistently included in targeting discussions. This did not require new capabilities, only a different way of presenting them. The implication is that NATO may benefit from further developing methods that allow cyber to be consistently represented within targeting processes, particularly at the operational level.

7.2 Addressing Temporal Mismatch

One of the most consistent findings in this study is the impact of temporal mismatch on cyber integration.

Cyber operations often require preparation time for access development, and coordination with intelligence and supporting elements. These timing challenges complicate traditional concepts of deterrence and response in cyberspace, particularly when operational decision cycles occur faster than cyber preparation timelines (Nye, 2017). Cyber timelines need to be incorporated into planning from the outset. Planning processes should more explicitly account for the temporal characteristics of cyber operations, particularly during early stages of course-of-action development.

7.3 Coalition Considerations

Cyber integration in NATO operations is further complicated by coalition dynamics. These include national caveats and authorities, uneven distribution of cyber capabilities, and constraints on information sharing.

These challenges are well documented and are unlikely to be resolved through doctrine alone (Libicki, 2021). However, the findings suggest that how cyber is framed can influence how it is integrated. By focusing on effects rather than capabilities, the Cyber Strike Package (CSP) framework allowed planners to coordinate cyber actions without requiring full visibility into how those actions would be executed. In practice, this approach made integration more feasible in a simulated coalition environment. Students were able to coordinate cyber effects conceptually, even when detailed technical information was limited. The implications are that effects-based approaches may help mitigate some of the practical challenges associated with coalition cyber operations, particularly where full transparency is not possible.

7.4 Training and Education

The vignette highlights that cyber integration is not only a doctrinal issue, but also a training and education challenge. Several patterns were observed: (1) planners defaulted to kinetic options in early iterations, (2) cyber was underutilized without structured guidance, and (3) integration improved with repetition and feedback. These observations suggest that effective integration requires familiarity with cyber as a planning tool, practice applying cyber in operational contexts, and reinforcement of effects-based thinking. The implication is that professional military education and training programs may benefit from incorporating structured cyber planning constructs and scenario-based exercises that emphasize timing, targeting, and cross-domain integration.

7.5 Toward a More Usable Operational Approach

The findings suggest that improving cyber integration does not necessarily require entirely new doctrine. Referencing the previous section (6.6) instead, the new conceptual framework may involve refining how existing concepts are applied in practice. Key elements of a more usable approach include:

- Mapping cyber effects to the kill chain,
- Incorporating cyber into the targeting cycle,
- Accounting for timing constraints, and
- Using planning constructs accessible to non-specialists.

The Cyber Strike Package (CSP) framework represents one way to bring these elements together. It is not intended as a definitive solution, but as a practical tool that aligns cyber with how operations are already planned and executed.

8. Conclusion

This paper examined the challenge of integrating cyber capabilities into NATO Multi-Domain Operations at the operational level. Although cyberspace is recognized as a critical domain, cyber effects remain inconsistently integrated into execution-level planning and targeting processes. Using a NATO-aligned instructional vignette, this study demonstrated that planners often struggle to synchronize cyber effects with operational timelines, particularly in time-sensitive environments. The findings suggest that the primary obstacle is not capability, but the absence of practical planning constructs that align cyber with kill chain execution and operational decision-making. The proposed kill-chain-centric framework and Cyber Strike Packages (CSPs) provide a usable method for incorporating cyber into targeting, synchronization, and cross-domain planning. Application of this framework improved integration of cyber effects within operational planning and increased alignment between cyber and other domain capabilities. Future research should examine how artificial intelligence-assisted planning tools, automated targeting support, and coalition information-sharing mechanisms may further improve synchronization of cyber effects in Multi-Domain Operations (MDO). Additional research should examine the framework within larger-scale exercises, coalition environments, and quantitative assessments of

operational effectiveness. As NATO continues refining MDO concepts, cyber must be integrated not as a separate supporting activity, but as part of operational execution itself.

9. Abbreviations

The following is a reference list of abbreviations used in throughout this article.

Abbreviation	Meaning
C2	Command and Control
CSP	Cyber Strike Package
DCO	Defensive Cyber Operations
ISR	Intelligence, Surveillance, and Reconnaissance
JFC	Joint Force Command
JOC	Joint Operations Centre
MDO	Multi-Domain Operations
MHQ	Maritime Headquarters
NATO	North Atlantic Treaty Organization
OCO	Offensive Cyber Operations
SATCOM	Satellite Communications
TELCO	Telecommunications

Figure 3: Kill-Chain-Centric Cyber Integration

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: Open-source artificial intelligence (AI) tools were used solely for proofreading and citation formatting. All analysis, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources. Finally, the operational vignette in Figure 2 was edited with AI in order to generalize the scenario for publication purposes.

Disclaimer: The views expressed here are those of the authors and do not necessarily represent the views of the Naval Postgraduate School, the Department of War, or the U.S. Government.

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Toward Identifying Role-Aligned AI Governance Needs in Mixed-Trust Environments

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Abstract: The rapid emergence of AI is driving governance challenges in security-sensitive organizational settings. For example, deploying AI in these contexts typically requires embedding automated or semi-automated decision-making into mixed-trust environments characterized by legacy systems, uneven access to and visibility into governance-relevant artifacts, and strict operational, security, and compliance constraints. In such environments, governance decisions, system design, and day-to-day operations are often handled by distinct organizational roles, leading to different expectations and dependencies among stakeholders. Despite growing work on AI governance, there is limited, role-specific guidance that clarifies what governance leaders and oversight bodies should require, what engineers and implementers must ensure, and what operators and system administrators can rely on when deploying and operating AI in mixed-trust environments. This leaves organizations without a shared basis for translating general governance principles into concrete deployment requirements, compliance controls, risk assessments, and ongoing operational accountability. Current and emerging AI governance and risk management frameworks largely provide lifecycle-based approaches to AI risk, establishing a common vocabulary and baseline for AI use within organizations. However, they provide limited guidance on how responsibilities should be interpreted and enacted across organizational roles, particularly in constrained, security-sensitive deployments. In this paper, we analyze widely adopted AI governance and risk-management frameworks and prior synthesis literature through the lens of three stakeholder layers: governance leaders and oversight bodies; engineers and implementers; operators and system administrators. For each layer, we examine what current frameworks explicitly and implicitly address and where role expectations remain underspecified. Building on this analysis, we propose an initial set of role-aligned governance needs and highlight cross-cutting socio-technical factors that shape the enactment of AI governance in practice. The goal is to inform future research, policy work, standards development, and operational planning by moving AI adoption in mixed-trust contexts from aspirational frameworks toward practical, accountable, and auditable implementations.

Keywords: AI governance, Audit frameworks, Trust, Risk-management, Mixed-trust environments

1. Introduction

Artificial intelligence (AI) capabilities are increasingly integrated into organizational workflows, supporting tasks such as analytics, decision support, automation, and reporting. As these capabilities mature, organizations are deploying AI in more complex and higher-stakes settings, where systems must operate reliably within existing infrastructure, policies, and operational constraints. Existing governance frameworks, standards, and policies establish a foundation for addressing AI risks and building trust through transparency, accountability, and responsible use. However, they offer little guidance on how lifecycle-based governance maps to organizational roles and responsibilities.

Building on definitions of governance, IT governance, and prior research on AI in organizations, we define *AI governance* as an organization's allocation of decision rights and accountability for AI systems to align AI-related activities with organizational objectives. AI governance differs from traditional IT governance because AI systems can exhibit autonomy, learning, and inscrutability, complicating assurance, oversight, and accountability (Berente et al. 2021). These challenges are amplified in *Mixed-trust environments,* organizational and operational contexts in which AI capabilities are deployed across multiple access and control regimes, resulting in uneven access to governance-relevant artifacts across roles due to security, regulatory, or organizational constraints. In such settings, no single role has sufficient visibility into the evidence required to justify decisions, assess risk, or demonstrate compliance. Governance leaders may be accountable for deployment or risk acceptance without direct access to technical or operational evidence, while engineers and operators may generate artifacts they cannot fully contextualize or escalate across access boundaries. Common examples include enclave segmentation, cross-domain transfer constraints, differential audit visibility, and contractor or partner access boundaries (Rose et al., 2020; Goswami 2021).

Despite a growing body of AI governance frameworks and guidance, prior research indicates that organizations receive limited practical direction on how responsibilities should be interpreted and enacted across decision-making, implementation, and operations. Reviews of responsible AI governance tools show limited attention to

governance leaders, deployers, and operators, complicating role alignment across AI lifecycle stages (Kuehnert et al. 2025), while systematic reviews of stakeholder motivations suggest that many guidelines remain disconnected from concrete organizational decision-making (Heymans and Heyman 2024).

In this paper, we analyze AI governance through three stakeholder lenses: (1) governance leaders and oversight bodies, who set policy and risk expectations; (2) engineering and implementation personnel, who translate those expectations into design, documentation, and technical controls; and (3) operators and system administrators, who operate and monitor systems to maintain alignment with policy and infrastructure constraints. Prior work shows that governance gaps often arise when guidance is not clearly connected to such role-specific concerns (Kuehnert et al. 2025; Heymans and Heyman 2024). While existing reviews identify these gaps, they do not decompose them by organizational role or examine how mixed-trust conditions amplify them. This paper breaks the problem down by role: what frameworks tell each role to do, what they assume each role can do, and what they leave unclear, particularly in mixed-trust settings where no single role sees the full picture. Accordingly, we synthesize widely used AI governance guidance to examine how current frameworks address these roles and to derive an initial set of role-aligned governance needs for mixed-trust environments.

2. Problem Context and Related Work

For our review, we assembled AI governance materials spanning research, standards, and practitioner-facing guidance. We found that AI governance is defined broadly and inconsistently across sources, complicating systematic comparison and obscuring how high-level governance expectations translate into role-specific responsibilities. This lack of role-level specificity is consequential in practice: when a developer is instructed to "be accountable" or "manage risk," it is often unclear what artifacts they should produce and how such evidence should persist beyond deployment—reflecting the recurring "who does what, when, and how" problem identified in prior reviews (Kuehnert et al. 2025; Batool et al. 2024). These observations motivate our role-based approach, which examines what existing guidance explicitly assigns to each role, what it implies, and what remains underspecified, particularly in mixed-trust environments where evidence, access, and accountability are fragmented across organizational boundaries.

2.1 Related Work

We organize related work into four clusters that inform the paper's role-based analysis: (1) AI governance frameworks and synthesis reviews, (2) role and stakeholder-centered governance needs, (3) evidence, audit, and accountability practices, and (4) mixed-trust environments where segmented access complicates oversight and coordination. Together, these clusters situate our analysis and foreground where role-specific responsibilities remain underspecified.

2.1.1 Cluster 1: Frameworks and baselines

AI governance frameworks are increasingly moving from voluntary to mandatory instruments. Across both forms, a recurring characteristic is abstraction at the level of organizational roles and responsibilities. Voluntary frameworks such as the NIST AI Risk Management Framework (AI RMF) adopt a lifecycle orientation—Govern, Map, Measure, and Manage—and emphasize accountability and auditability across governance, data, performance, and monitoring (NIST 2023b; NIST 2024), as reinforced by GAO's accountability framing, without prescribing how responsibilities should be distributed across governance, engineering, and operational roles (U.S. GAO 2021). Mandatory instruments are characterized by clearer definitions of roles and responsibilities. The EU's AI Act, for example, defines "providers" and "deployers" and specifies documentation and post-deployment monitoring obligations (EU 2024). ISO/IEC 42001 similarly defines requirements for AI management systems while leaving internal role assignments to implementers (International Organization for Standardization 2023). International instruments such as the OECD AI Recommendation remain more abstract and are intended to be operationalized through downstream instruments (OECD 2024). U.S. federal AI governance illustrates structural instability, with three major policy shifts in 15 months as Executive Orders 14110 and 14179 mandated and rescinded AI governance requirements (Executive Office of the President, 2023; 2025), accompanied by corresponding shifts in agency-level implementation guidance (Office of Management and Budget, 2024; 2025). Schuett's Three Lines of Defense framework represents progress toward role specialization but still lacks a clear demarcation between governance bodies, engineers, and operators (Schuett, 2023).

2.1.2 Cluster 2: Roles and responsibility

Governance frameworks provide structural guidance, yet a central question remains poorly specified: who is responsible for implementing governance requirements across different stages of the AI lifecycle defined in

prevailing frameworks? A systematic review of responsible AI governance found that only five of 61 studies explicitly addressed core governance questions—who does what, when, and how (Batool et al. 2024). Similarly, an analysis of more than 220 responsible AI tools showed a strong focus on designers and developers, with limited support for governing authorities, deployers, and users (Kuehnert et al. 2025). Although frameworks such as the NIST AI RMF and ISO/IEC 42001 are intentionally broad, existing work offers little guidance on how governance responsibilities should be assigned in practice. Prior research shows that unclear role definitions can enable more powerful actors to shift responsibility onto contractors, users, or subordinate roles, particularly at organizational interfaces (Heymans and Heyman 2024). While the role-definition problem is increasingly recognized, how accountability is coordinated across governance, engineering, and operational layers remains underexamined, especially in mixed-trust environments.

2.1.3 Cluster 3: Trust, reliance, and oversight in human-AI teams

Governance must account for how trust, reliance, and supervision shape the gap between formal accountability and practice. Prior work argues that trust in AI systems should be deliberately designed rather than assumed to emerge from system performance, shifting attention from controlling AI behavior to understanding how humans perceive, interpret, and rely on AI outputs (Ezer et al. 2019). Empirical studies further show that affective trust in human–AI teams is consistently lower than in human-only teams, even when cognitive trust is comparable, undermining assumptions that performance alone will generate appropriate reliance (Ulfert et al. 2024; Georganta and Ulfert 2024). The CHAI-T model highlights the need to continuously adjust trust throughout a system's development and operational contexts, a challenge that becomes more pronounced when stakeholders operate with uneven access across different stages of deployment (McGrath et al. 2025). The most applicable study in this case highlights the need for four factors to ensure effective human oversight of an AI system: sufficient levels of causal efficacy, epistemic access, self-regulation, and intention aligned with the goals set for the system or algorithm in question (Sterz et al., 2024). These four different factors combine to create the concept of moral responsibility—a feature that cannot be achieved in most cases with humans in the loop systems due to automation bias and access levels (Parasuraman and Manzey, 2010).

2.1.4 Cluster 4: Assurance, auditability, and verifiability

The literature identifies evidence requirements for AI assurance and auditability but provides limited guidance on how responsibilities are divided among governance leaders, engineers, and operators. Audit-enabling attributes—traceability, accessibility, reproducibility, transparency, understandability, and explainability—are identified across lifecycle stages but remain role-agnostic and do not specify duties by role category (Li and Goel, 2024). Empirical evidence further indicates that new competencies are required for AI-driven process auditing, particularly in data governance and explainability, as most IT auditors are not equipped to address these demands (Li and Goel, 2025). Other approaches link safety, security, and performance evidence through artifact hierarchies but rely on organizational structures that do not translate to mixed-trust environments (Kapusta et al., 2025). Related work also argues for governance structures that distinguish between pre-deployment and post-deployment assurance, a distinction not addressed by other frameworks (Kwiatkowska and Zhang, 2023). Across this literature, three gaps persist: unclear role-level division of assurance responsibilities, unclear access requirements for auditability, and limited guidance on sustaining these requirements across governance, engineering, and operational categories.

3. Methodology

3.1 Selection of Governance Sources and Synthesis Reviews

We use exploratory role-based qualitative content analysis (Krippendorff, 2018) to examine how role expectations are specified, implied, or left ambiguous in AI governance guidance. Governance texts are treated as analytical artifacts through which expectations about organizational roles and associated outputs are articulated. Coding focuses on: (1) the targeted role (governance leaders and oversight bodies; engineers and implementers; operators and system administrators), (2) expected outputs (e.g., documentation, logs, tests, monitoring), and (3) whether boundaries between decision-making, implementation, and operations are explicit or ambiguous.

Rather than conducting an exhaustive systematic review, we focus on established governance sources and recent synthesis reviews for exploratory analysis (Coners and Matthies, 2014; Aromataris et al., 2024). We use two complementary source bins: (1) primary governance and risk guidance (frameworks, standards, and policies

referenced in organizational practice), and (2) prior synthesis reviews summarizing role-related governance challenges and stakeholder needs.

To identify candidate sources and keep the scope grounded, we conducted a literature search between November 2025 and January 2026 using Semantic Scholar, Scopus, and OpenAlex with the keywords 'AI,' 'artificial intelligence,' 'governance,' 'regulation,' 'policy,' 'ethics,' and 'framework,' yielding 2,020 studies. After removing 122 duplicates and restricting publications from this period, 126 studies remained. Three were excluded due to inaccessibility, leaving 123 studies for screening. Inclusion criteria were published 2018–2025, English-language, addressing AI governance or risk management at an organizational or policy level, and accessible in full text. Studies were excluded if they were purely technical without a governance framing, or editorials and commentaries under three pages. Titles and abstracts were manually reviewed for governance-related terms (e.g., governance, policy, regulation, accountability, oversight, framework, compliance). We further filtered to studies with at least 5 citations, yielding 14 studies. A supplementary Google search for 'AI governance' identified 4 additional publications, resulting in 18 studies for inclusion.

To support analytical organization, sources were grouped into clusters aligned with governance roles and analytical purpose, each anchored by a conceptually representative "seed" source. We applied BERT-based topic modeling (BERTopic) to the abstracts of the 123 screened sources, generating candidate topic clusters that served as a navigational heuristic for grouping sources by thematic affinity during early organization. These clusters did not determine final cluster assignments, source inclusion decisions, or code assignments.

We apply a three-role analytical lens to code how governance guidance assigns—or implies—expectations across AI deployment work (Deshpande and Sharp, 2022; Kuehnert et al., 2025; Batool et al., 2024). The unit of analysis is a discrete governance statement or recommendation, interpreted in its surrounding textual context. Coding interpretations were iteratively refined through comparison across sources, with attention to boundary cases. For consistency across heterogeneous sources, each recommendation was coded against the following role layers:

- *Governance leaders and oversight bodies:* set policy and governance expectations, define acceptable risk and use constraints, approve deployment conditions, and determine evidence requirements for compliance and oversight.
- *Engineers and implementers:* translate governance expectations into system design and implementation decisions, produce required documentation, and build technical and procedural controls.
- *Operators and system administrators:* deploy, operate, and maintain systems in real environments, monitor performance and incidents, manage access and configuration, and ensure availability of audit-relevant records.

4. Role-Based Analysis of Governance Frameworks

This section analyzes and synthesizes AI governance sources through a role-based lens to surface role-aligned governance needs and recurring gaps across governance, engineering, and operational roles. Figure 1 illustrates how governance functions flow from governance leaders to engineering and operational roles within a mixed-trust environment and where underspecified needs emerge at the interfaces between these layers. Figure 2 consolidates the findings of this role-based analysis into a structured mapping of governance needs across the three role layers.

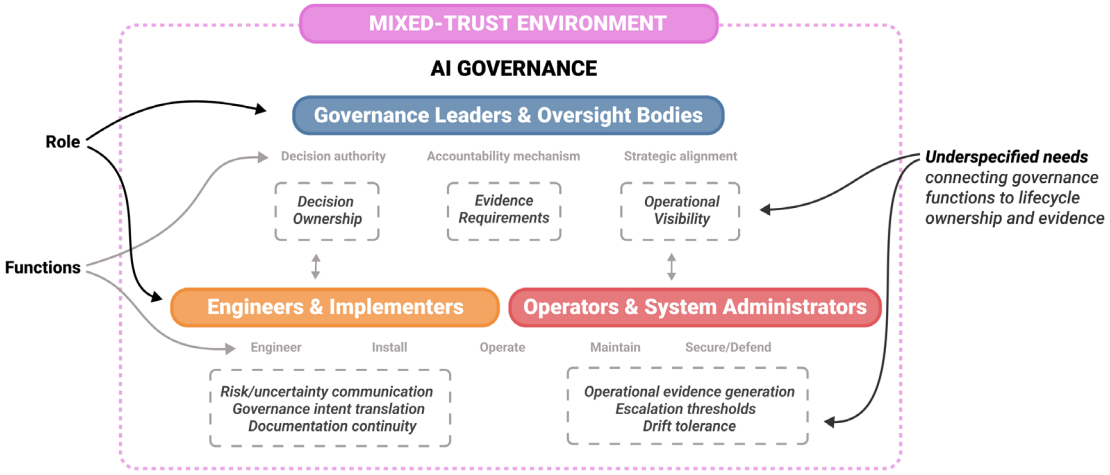


Figure 1: The figure illustrates how AI governance is exercised within mixed-trust environments by governance leaders and oversight bodies through decision authority, accountability mechanisms, and strategic and policy alignment, and how these governance functions interact with engineering, implementation, operation, and system administration activities. For each organizational role, the figure highlights areas that are commonly underspecified in existing AI governance frameworks

4.1 Governance Leaders and Oversight Bodies

What is most explicit across AI governance sources is that governance leaders and oversight bodies are responsible for establishing and sustaining AI governance, including defining risk management programs, organizational policies, and accountability structures. This role is most clearly articulated in the NIST AI RMF's 'Govern' function, which emphasizes organizational oversight, defined processes, and accountability mechanisms (NIST, 2023b). The AI RMF Playbook similarly stresses the definition of human oversight roles as part of operationalizing governance practices (NIST, 2023a), and U.S. GAO's accountability framework reinforces role clarity and accountability mechanisms as central to responsible AI oversight (U.S. GAO, 2021).

What is implied, rather than specified, is how decision authority is exercised in practice. Governance sources describe required actions but rarely assign ownership for key decisions such as accepting residual risk, determining deployment readiness, or authorizing system suspension. While the NIST AI RMF Playbook encourages organizations to distinguish among AI actors (e.g., developer, owner, operator), it leaves the allocation of decision ownership to organizational discretion. This pattern aligns with synthesis findings that highlight persistent ambiguity about responsibility even when governance expectations are clear (Kuehnert et al., 2025).

What remains underspecified is the evidence basis for accountable, auditable decision-making (Schuett, 2023). The NIST AI RMF offers flexibility as an outcomes-based framework that organizations can adapt to their context, rather than a prescriptive checklist. However, it does not specify what concrete evidence decision-makers should consistently require from engineering and operations at key decision points (e.g., risk acceptance, readiness to deploy, or escalation thresholds) (NIST 2023b).

In mixed-trust environments, these gaps are amplified because governance-relevant evidence is fragmented across teams, tools, and access boundaries (Schuett, 2023; Kuehnert et al., 2025). Governance leaders may remain accountable for risk and readiness decisions without direct access to the technical or operational artifacts needed to justify those decisions. Binding regulations for high-risk systems, such as the EU AI Act, partially address this gap by specifying baseline obligations for logging and post-market monitoring and tying them to legally defined actor categories (EU, 2024). However, how governance leaders access and evaluate such evidence across trust boundaries remains largely unspecified.

4.2 Engineers and Implementers

What is most explicit across AI governance sources is that engineers and implementers are responsible for translating governance intent into system design, technical controls, and documentation. The NIST AI RMF frames risk management as a lifecycle activity that must be operationalized through traceable documentation linking system purpose, data use, development or integration decisions, and accepted performance and risk

trade-offs (NIST, 2023b). For high-risk systems, binding instruments such as the EU AI Act make this translation mandatory by requiring technical documentation prior to deployment and throughout system operation (EU, 2024). U.S. GAO's accountability framework similarly implies that engineers must generate and sustain evidence across governance, data, performance, and monitoring dimensions, not solely model-level metrics (U.S. GAO, 2021).

What is implied is that engineers, implementers, and deployers possess sufficient organizational authority and epistemic access to fully document governance intent. In practice, engineers may have deep access to technical artifacts (e.g., code, data, models) but limited visibility into governance considerations such as risk tolerance, policy constraints, or deployment context. Prior synthesis shows that responsible AI tools disproportionately target designers and developers during development stages, reinforcing this imbalance (Kuehnert et al., 2025). Epistemic access is a prerequisite for effective oversight, yet engineers may lack insight into how components are integrated or operated across segmented or classified systems (Sterz et al., 2024).

What remains underspecified is how information about uncertainty, limitations, and residual risks is conveyed beyond development. Although governance sources require documentation, they provide little guidance on documentation granularity, continuity, or handoff across roles and lifecycle stages. While auditability attributes such as reproducibility and traceability are well established conceptually (Li and Goel, 2024), empirical work shows that auditors often lack the specialized competencies needed to assess AI-specific artifacts (Li and Goel, 2025).

***In** mixed-trust environments*, these gaps are amplified because documentation and provenance may be created at one trust level but remain inaccessible to operators or auditors at another. This disrupts documentation continuity and weakens sustained review and accountability across roles over time. Governance sources rarely specify what contextual information must persist across trust boundaries, leaving organizations to manage documentation handoffs through informal or ad hoc practices.

4.3 Operators and System Administrators

What is most explicit across AI governance sources is that operators and system administrators are responsible for post-deployment monitoring and oversight. The EU AI Act requires deployers of high-risk systems to monitor operation, retain system logs, and assign personnel with appropriate competence, authority, and awareness of automation bias (EU, 2024). Similarly, the NIST AI RMF calls for documented thresholds to bypass or deactivate system components (NIST, 2023b), and U.S. GAO's accountability framework treats monitoring and corrective action documentation as core accountability practices (U.S. GAO, 2021). Across both voluntary and binding guidance, continuous monitoring is positioned as a central operational responsibility.

What is implied is that operators possess sufficient access, understanding, and authority to detect anomalies and intervene appropriately. Effective oversight presumes epistemic access to system behavior, yet this access may be constrained when system internals are opaque or partitioned across environments. Prior work identifies epistemic access as a condition for meaningful human oversight, while empirical evidence shows that automation complacency can persist under operational load and cannot be mitigated through training alone (Sterz et al., 2024; Parasuraman and Manzey, 2010). GAO acknowledges that "AI systems pose unique challenges to such oversight because their inputs and operations are not always visible" (U.S. GAO 2021).

*What remains underspecified—and central to this paper—*is how operational evidence (e.g., logs, incidents, and performance metrics) should flow back to governance leaders and engineers to support accountable decision-making. While auditability attributes such as traceability, accessibility, reproducibility, transparency, understandability, and explainability are well defined conceptually (Li and Goel, 2024), governance sources provide little guidance on who is responsible for generating, interpreting, and consuming operational evidence across roles. Frameworks frequently reference "specialized competencies," yet do not clarify what those competencies entail in practice (Li and Goel, 2025). As a result, operators may generate logs they cannot fully interpret, while governance leaders may request evidence they cannot directly access. Synthesis reviews confirm that responsible AI tools disproportionately target development stages, leaving deployment and operation comparatively under-supported (Kuehnert et al., 2025). This gap contributes to unclear escalation thresholds, drift tolerance, and documentation standards, making it difficult for organizations to reduce AI and ethics risks in a sustained and meaningful way (Batool et al., 2024).

In mixed-trust environments, when governance requirements flow downward, limited shared visibility and fragile handoffs hinder operators and administrators from reporting evidence upward accurately and consistently across enclaves. Operational evidence may be generated within a trust boundary but fail to transfer

in a form accessible to governance leaders or engineers for reporting, risk review, or audit. As a result, escalation, drift management, and compliance follow-through depend on ad hoc coordination rather than role-defined evidence pathways. Figure 2 maps the governance needs surfaced across all three roles, distinguishing between what current frameworks explicitly assign, what they presuppose but do not assign, and what remains unaddressed.

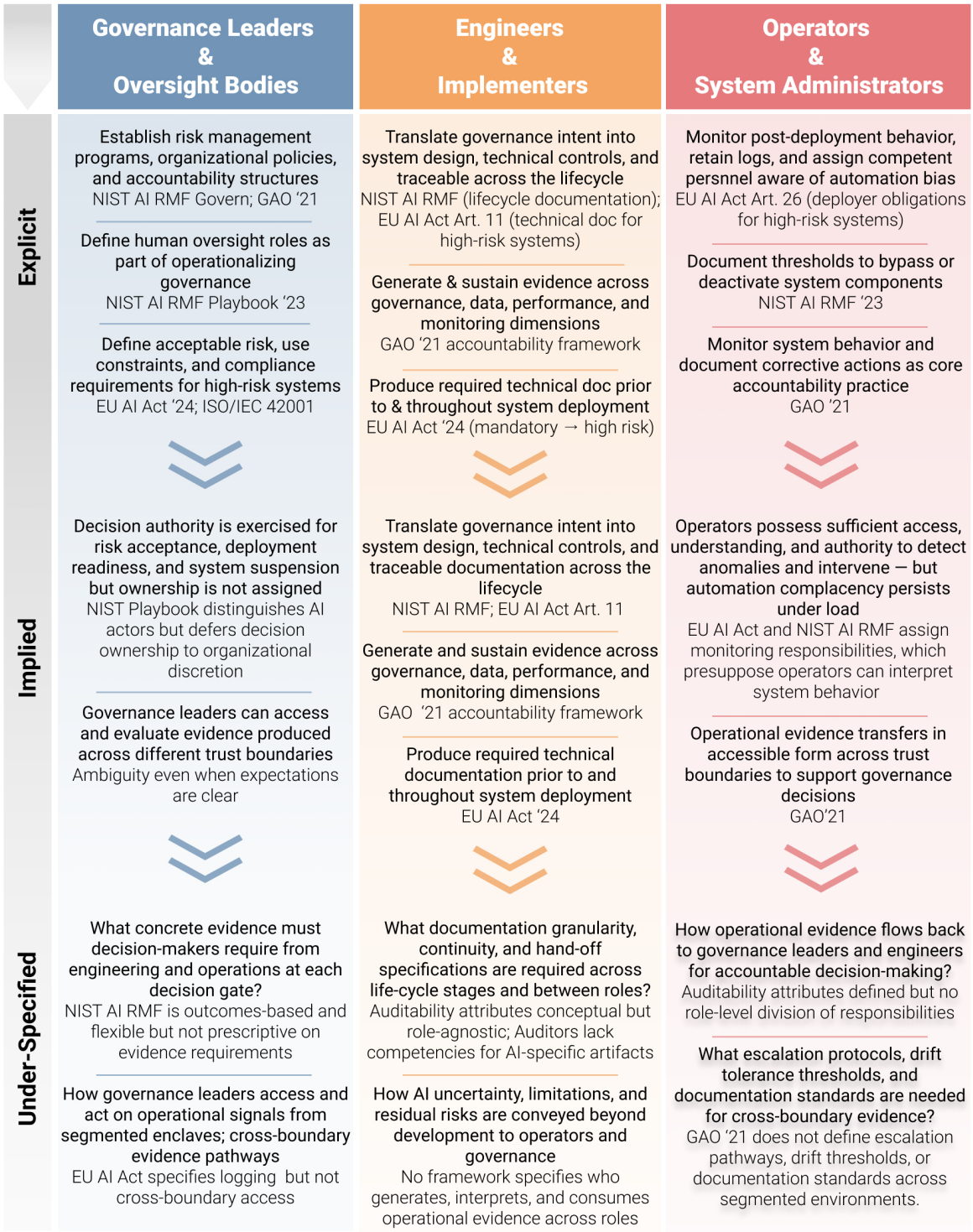


Figure 2: Role-aligned AI governance needs across three organizational roles, categorized by the degree of specification found in current frameworks from explicit requirements to implied and under-specified gaps

5. Discussion and Future Work

Governance frameworks, policies, and standards establish a common language and overarching principles for AI governance. Still, a persistent challenge remains in effectively translating these high-level mandates into actionable responsibilities across diverse roles. The lack of clear delineation of who is responsible for implementing, monitoring, and enforcing governance across the AI lifecycle can diffuse accountability, with responsibilities shifting among governance bodies, engineers, and operators. Kuehnert et al. (2025) defined this phenomenon as an "ownership problem".

For example, consider a scenario where an AI-enabled tool is developed and validated within one enclave but deployed operationally in another access-controlled enclave. The transfer, provenance metadata, including annotations and boundary-level audit results, may be stripped or degraded to comply with cross-domain constraints. Operators in the receiving environment inherit a system whose known limitations are documented elsewhere and potentially inaccessible, weakening their capacity for meaningful oversight (Sterz et al., 2024). Governance leaders reviewing the deployment may approve continued operation based on summary documentation that omits risk mitigations recorded at the originating level. In this scenario, each role 's evidence basis appears adequate in isolation, yet end-to-end accountability cannot be reconstructed, precisely the kind of fragmentation that current frameworks leave unaddressed.

The ambiguity can diminish the efficacy of governance, underscoring the importance of role-aware requirements that specify who does what, when, and how, as highlighted by recent literature reviews (Kuehnert et al., 2025; Schuett, 2023; Floridi et al., 2018). The ambiguity around guidance and frameworks becomes more evident in evidence for audit and accountability in mixed-trust environments. As noted by Schuett (2023), the same implementers end up generating artifacts for audits, raising questions about audit and trust.

Governance also has a critical socio-technical dimension that many frameworks only acknowledge in passing. Effective documentation and audit mechanisms are essential, but their success heavily relies on organizational factors such as training, management, protocols, and responsibility handoffs (Salako et al., 2024). This paper positions the role-based analysis as a starting point for understanding where these responsibilities and checks break down in practice. By making ownership gaps visible, the goal is to begin a discussion on what must be anchored across roles before auditing and oversight can be reliable in mixed-trust settings.

A limitation of our current approach is that our analysis is scoped to a small set of governance sources. It remains primarily conceptual rather than validated through in-situ organizational practice. Our immediate aim is to surface and frame this role-based accountability problem clearly for the broader community. Future work should aim to explicitly refine role-based mapping across a broader range of frameworks, standards, and operational guidance. This will enable a clearer identification of where requirements are assigned and where gaps or ambiguities in ownership persist. Additionally, a socio-technical study using empirical methods can help understand how evidence moves across roles in mixed-trust settings. It should also capture governance leaders' perspective on what operational signals support oversight and how they would act on them.

6. Conclusion

AI governance guidance provides high-level direction but often leaves ambiguity about how responsibilities are distributed among governance leaders, engineers, and operators. Mixed-trust settings further complicate this because evidence and authority are split across enclaves, limiting consistent visibility, segmented access, and legal and organizational restrictions, further complicating accountability. We use a role-based lens to begin understanding where responsibility and evidence pathways remain unclear and to motivate more actionable, role-aware governance requirements that can effectively address these contextual complexities.

Ethics Declaration: This research did not involve human participants or the collection of personal data and therefore did not require institutional ethical approval. The study is based on publicly available documents, doctrinal publications, and secondary sources.

AI Declaration: We used generative AI tools to support literature clustering, interrogate and summarize source files, and assist with grammar and rephrasing.

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Data Governance Frameworks for Enabling Responsible AI in Small, Medium, and Micro Enterprises: A Systematic Literature Review

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Abstract. Disruptive technologies such as Artificial Intelligence (AI) have brought about changes in how organisations function. The adoption of AI has been applied in various industries, ranging from smart energy, smart transportation, smart health such as cancer treatment to managing automated cybersecurity threats and responding to sophisticated cyber threats. This presents opportunities and challenges as small, medium and micro enterprises (SMMEs) are also adopting AI to drive innovation, efficiency, and competitiveness. When compared to large organisations, SMMEs often lack the resources, expertise, and infrastructure necessary to implement comprehensive data governance frameworks, which are essential for responsible AI deployment. This study aims to investigate how data governance frameworks can enable responsible AI practices, specifically within the context of SMMEs. This study adopts a systematic literature review where the PRISMA framework is used to extract information on the data governance principles, challenges and opportunities that SMMEs can use for responsible AI. This study's findings reveal that effective governance plays a critical role in the adoption of AI within SMMEs. Existing data governance frameworks provide guidance, even though they are complex, which is a limitation for SMMEs. This study highlights opportunities for SMMEs in the data governance frameworks in enabling responsible AI. This study also reveals the need for a universal data governance framework.

Keywords: Data governance, Data governance frameworks, Artificial intelligence, SMMEs, Responsible AI

1. Introduction

Data is the new oil, where organisations have realized the importance of ensuring data is kept safe (Stach, 2023). The emergence of Artificial Intelligence (AI) has called for organisations to use AI responsibly. Organisations, be it large or small, medium, and micro enterprises (SMMEs), are tasked with the responsibility of ensuring that they follow data governance frameworks. SMMEs play a crucial role in the economy, from creating jobs to partnering with public sector organisations. The adoption of AI in SMMEs presents both opportunities and challenges. AI has been used by large and small enterprises to improve efficiency, improve customer engagement, and for innovation (Weilbach, 2025).

SMMEs are faced with challenges due to restricted access to technology and limited resources (Muzuva, Zhou, and Zondo, 2024). Therefore, the introduction and adoption of AI technologies such as predictive analytics present SMMEs with the opportunity to make informed data-driven decisions (Weilbach, 2025). AI tools can be used to automate routine tasks through the use of machine learning (ML), natural language processing (NLP), and predictive analytics (Muzuva, Zhou and Zondo, 2024; Tyson and Zysman, 2022; Singh, 2024). NLP can be used to automate customer services and ML can be used to predict customer behavior. This is important as organisations can save time and be productive by spending more time making better decisions. AI has also been used to customize recommendations to improve customers' experiences, for language translation, and for text and image generation (Muzuva, Zhou and Zondo, 2024). SMMEs are adopting AI-powered chatbots to improve customer support and handle inquiries, thereby improving customer satisfaction. Customers are able to personalize their experiences and have access to 24/7 customer support. SMMEs can also streamline workflow processes, thereby improving operational efficiency, enhancing innovation, and reducing operational costs (Ali, 2024; Iyelolu *et al.,* 2024).

The main challenge with the adoption of AI for SMMEs is the lack of resources, talent, and skills to implement AI solutions (Ali, 2024). In addition, there are challenges associated with data privacy and security (Ali, 2024; Iyelolu *et al.,* 2024). While the adoption of AI presents many benefits and challenges, there is a growing need for responsible use of AI. Responsible AI is "about choosing solutions that do not unintentionally exclude, mislead or discriminate" (Van Barneveld *et al.,* 2025, p. 7). In addition, responsible AI focuses on ethical, legal and governance processes that should be followed when using AI (Mikalef *et al.,* 2022). AI should be used ethically, and all data should be protected by design. Responsible AI is not only about legal compliance but caring for the people, business and plant while earning people's trust (Van Barneveld *et al.,* 2025).

Regulations such as the European AI Act focus on ensuring individuals and organizations use AI responsibly (Madiega, 2021). These regulations set guidelines and laws that should be followed when using and developing systems using AI. While large organisations are using AI for automation and predictive analytics, they are also

developing AI policies and guidelines on how AI should be used. Responsible AI ensures that there is ethical consideration when using AI to reduce bias or cause social inequality ((Taryono *et al.,* 2024) AI systems must be used to ensure that the privacy and security of user data is prioritized ((Taryono *et al.,* 2024; Akhtar, Kumar and Nayyar,2024) AI should be used in a fair, transparent manner.

Therefore, this calls for SMMEs to also develop guidelines on acceptable use of AI, which in turn ensures they comply with standards and regulations. There is a lack of appropriate data governance frameworks for enabling the responsible use of AI for SMMEs. Most frameworks focus on large enterprises; limited insight into SMME-relevant models

1.1 Research Objectives

- To review existing data governance frameworks
- To assess their applicability to responsible AI in SMMEs
- To propose tailored governance considerations

The remainder of the paper will be structured as follows: the methodology will be explained in detail in Section 2, and the Literature Review will be discussed in Section 3. The Discussion will be provided in detail in section 4. Section 5 will present the Conclusion and Future Work.

2. Literature Review

2.1 AI Principles

Responsible AI also known as ethical AI or trustworthy AI is concerned about people and organisations being responsible in the decisions and actions of AI applications when making decisions (Dignum, 2023; Puchakayala, 2022; Radanliev *et al.,* 2024). A responsible AI system ensures that during the design, development and usage of the system, the system ensures auditability and accountability (Díaz-Rodríguez *et al.,* 2023). For a system to be auditable, it should ensure that a system can account for all the actions occurring and there is transparency. For a system to be accountable, it should ensure that there is accountability of all the AI system output should there be compliance challenges. With the rapid growth of AI, organisations are tasked with the responsibility of adapting to the new AI demands by ensuring they use AI responsibly (Wang, Xiong and Olya, 2020; Rakova *et al.,* 2021; Cannarsa, 2021).

UNESCO recommends organisations to use AI proportionally and do no harm, preserve the rights to privacy and data protection, and use AI safely by ensuring safety and security risks are avoided (Dignum, 2023). In addition, AI systems should be fair, where there is no bias based on specific groups (Feuerriegel, Dolata and Schwabe, 2020; Varona and Suárez, 2022) This is done through training of data and ensuring the trained data does not create any biases or misrepresentations of specific groups. Transparency is critical where a system has to have an "explainability" element, where the AI system's decisions and outputs are understandable by humans (Balasubramaniam *et al.,* 2022; Ehsan *et al.,* 2021). An AI system should be trained in a way that there is accountability on the AI's outputs, should there be any errors or biases (Ganesan, 2020; Díaz-Rodríguez *et al.,* 2023; Varona and Suárez, 2022).

Telefónica's 5 principles of responsible AI by design in practice include: fair AI, human-centered AI, extend them to any party, transparent and explainable AI, privacy and security by design (Telefónica, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024) Fair AI deals with ensuring that AI systems produce fair results where there is no discrimination of people based on their race, gender, sexual orientation, religion and ethnic origin (Telefónica, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024; de Laat, 2021) Transparent and explainable AI aims to ensure that when people interact with the AI systems, there are transparent results and the system ensures that the decisions made do not impact people's lives (Telefónica, 2021; de Laat, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024). For an AI system to be human-centric, it should ensure that humans have control in that it is used as a service by humans and can be driven by value-based considerations (Telefónica, 2021; de Laat, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024). AI systems have to respect people's rights to privacy and their personal data; therefore, it should abide by privacy and security by design (Telefónica, 2021; de Laat, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024). The AI systems should be designed in a way that privacy is considered from the development stage, not as an afterthought, and people's privacy is kept.

While it can be argued that different studies have different AI principles, and for the purpose of this study, the following principles will be the focus: transparency, privacy, accountability and fairness.

2.2 Data Governance Frameworks

Data governance refers to the process of making decisions, taking control over the management of data and having authority over the data (Ekundayo, Bhaumik and Chinoperekweyi, 2023; Marcucci *et al.,* 2023). Data governance refers to the policies, procedures, roles and responsibilities that are used to ensure that data is organized and managed effectively (Osu and Navarra, 2022; Taryono *et al.,* 2024). Data management is important for organisations as it ensures there is control over all data assets through plans, policies and practices that ensure control over data. A data governance framework is a logical framework for categorizing, arranging, and conveying the many processes involved in deciding on and acting upon company data (Osu and Navarra, 2022; Taryono *et al.,* 2024; Acev *et al.,* 2025; Zhou, Yi and Chen, 2023). The following data governance frameworks are discussed:

2.2.1 Data governance institute framework

The Data Governance Institute (DGI), founded in 20003 guides data governance matters through the framework that ensures there is authority, and proper decisions are made regarding data (Chen, 2021; Ekundayo, Bhaumik and Chinoperekweyi, 2023). The DGI framework provides organisations with a structure to classify and communicate the activities that use data for decision-making based on the data (Matos, 2023; Osu and Navarra, 2022). This framework provides free information on data governance best practices.

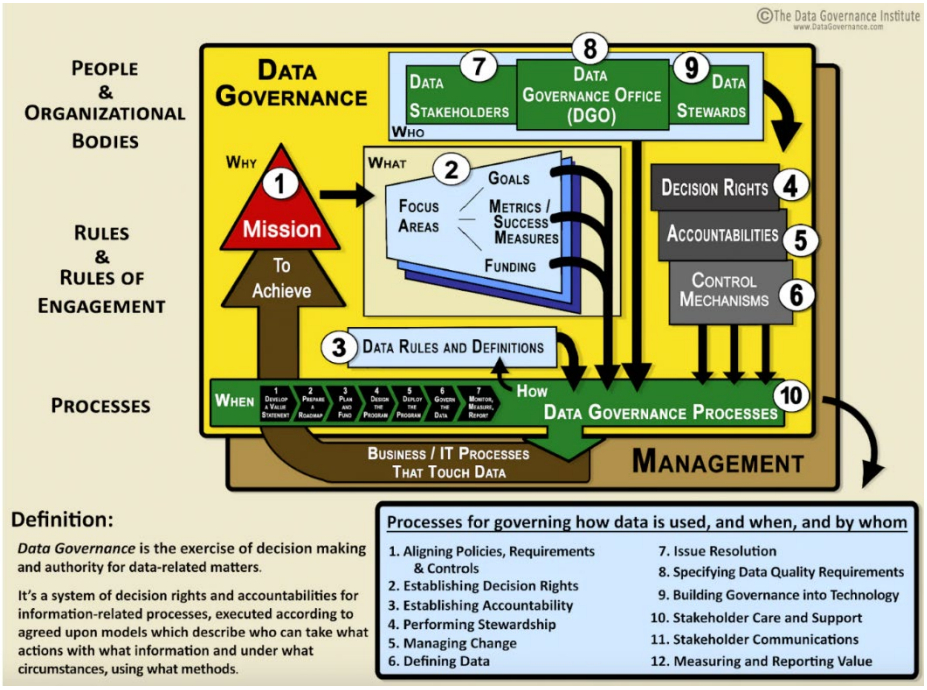


Figure 1: The DGI Data Governance Framework (Osu and Navarra, 2022)

Figure *1* depicts the ten components of the framework, which provide actionable mechanisms organisations can use to better manage the data (Osu and Navarra, 2022). This framework is valuable for organisations with complex data systems that are complex. It focuses on people, organizational bodies, and the rules and processes used for governing data (Osu and Navarra, 2022; Ekundayo, Bhaumik and Chinoperekweyi, 2023; Zhou, Yi and Chen, 2023; Acev *et al.,* 2025). These processes ensure there are clear outlines on how, when, and by whom the data is used, such as defining data, managing change, establishing accountability, and decision rights (Osu and Navarra, 2022; Ekundayo, Bhaumik and Chinoperekweyi, 2023; Zhou, Yi and Chen, 2023; Acev *et al.,* 2025). The DGI framework is based on the 5W1H (who, when, what, why, where, and how) principles.

2.2.2 DAMA DMBOK2 framework

The Data Management Body of Knowledge (DAMA-DMBOK2) is a second edition of the DAMA framework that provides a detailed view of the value, challenges and complexities when managing data (Osu and Navarra, 2022; Matos, 2023). This framework has 11 data management functional areas, which are important for data implementation, as depicted in Figure *2* (Ruslan, Alby and Lubis, 2022; Osu and Navarra, 2022). It outlines challenges of data management and recommends defining guiding principles, implementation of best practices,

techniques, methods, roles, and deliverables used for data management and the establishment of vocabulary for better understanding of the flow of data (Osu and Navarra, 2022; Taryono *et al.,* 2024).

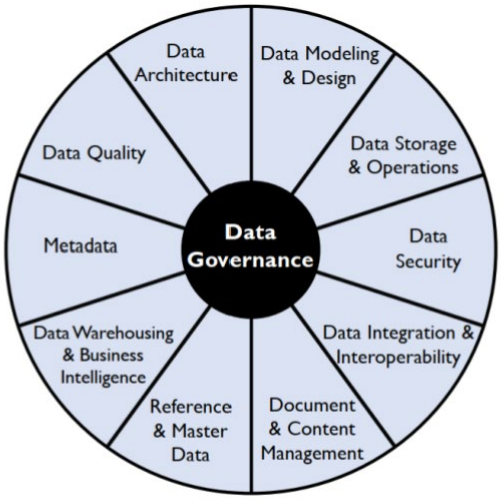


Figure 2: DAMA-DMBOK2 Framework (Osu and Navarra, 2022; Taryono et al., 2024).

2.3 Challenges of Applying Data Governance Frameworks

The vast amount of data being generated by organisations has led to organisations having the need to manage the data. Data governance ensures that data is effectively managed to ensure that the data can be used for decision-making purposes (Adepoju *et al.,* 2023; Alabi, 2023). This presents challenges for organisations when adopting data governance frameworks. Organisations face a challenge with complying with regulatory requirements such as the General Data Protection Regulation (GDPR) when implementing data governance frameworks (Ahmad, 2024; Julakanti, Kiranmayee Sattiraju, and Julakanti, 2025). GDPR requires organisations to collect, process, store, use and share personal data in a manner that ensures confidentiality and security of the data (Ahmad, 2024). Should organisations not comply with this regulation, they may face penalties for non-compliance.

The lack of standardized data governance practices is a challenge for organisations to ensure compliance (Marcucci *et al.,* 2023). This results in a fragmented ecology as different frameworks have different components, thus posing a challenge to the creation of a common framework. Many data governance frameworks exist; therefore, this poses a challenge due to the different nomenclature (Marcucci *et al.,* 2023; Noor, Baharom, and Mohd, 2025). For example, data governance frameworks have similar principles, but some principles are implied under other principles, such as the principle of equity, which seems to be addressed under the principle of fairness.

Data silos pose a challenge for organisations adopting data governance frameworks (Nookala, 2024; Nai, Rifai and Sadiq,2025). Data tends to reside in one department, which prevents data from being shared across different departments. When data is in silos, proper decisions are not made, and this affects the data quality. Cultural resistance is also a challenge, where employees will resist the implementation of data governance frameworks (Nai, Rifai and Sadiq, 2025). This may be due to employees lacking the required skills and knowledge. Another challenge is platform barriers, where organisations lack the right infrastructure or platform to ensure they implement the data governance frameworks (Marcucci *et al.,* 2023; Ahmad, 2024; Nai, Rifai, and Sadiq,2025). Technological barriers make it difficult for organisations to implement data governance frameworks.

3. Research Methodology

This research study followed an extensive systematic literature review of published studies. A Preferred Reporting Items for Systematic Reviews (PRISMA) framework guided the study to evaluate published academic sources and preserved a quality reporting style through following a peer review process (Page, McKenzie *et al.,* 2021; Page, Moher *et al.,* 2021; Ahmad, 2024; Nazir and Das, 2025). Identification, screening, eligibility, and inclusion are the four main phases that guide how the PRISMA framework is conducted, as shown in Figure *3* below. These phases will be discussed in detail below:

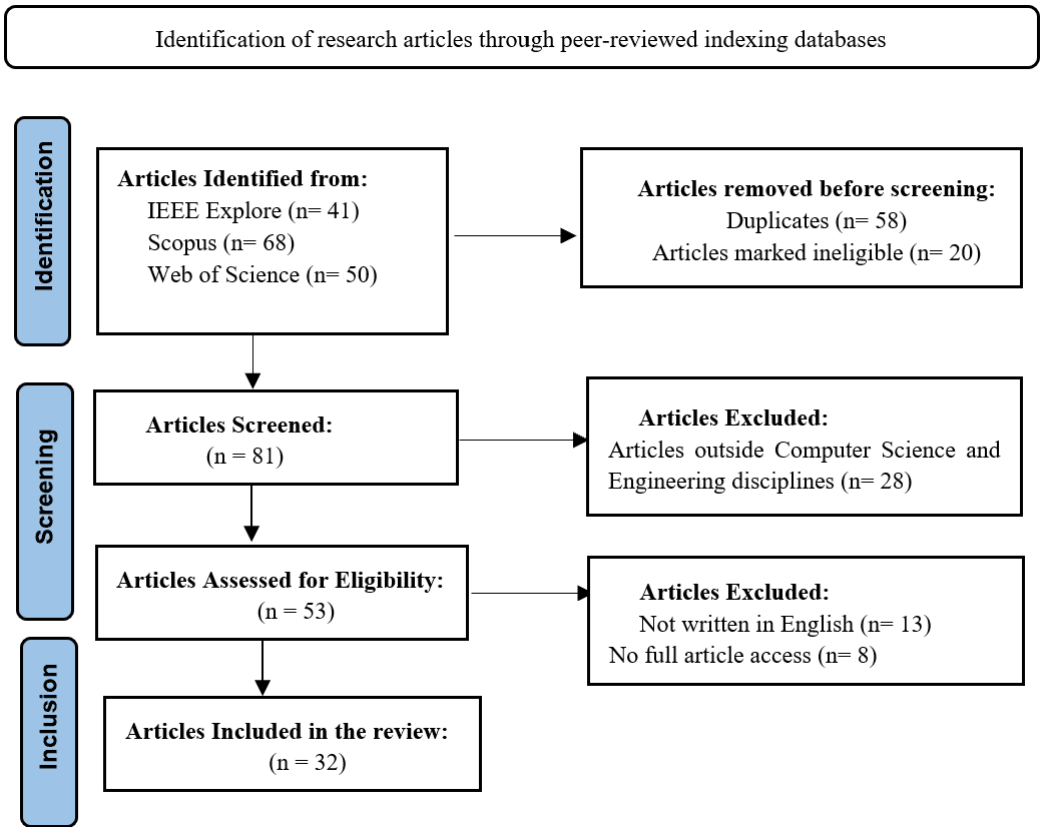


Figure 3: A representation of the PRISMA framework

A. Identification

This phase details how records are identified through filtering our academic sources from databases such as Web of Science, IEEE Xplore, Scopus, Google Scholar, etc. These records include peer-reviewed journal articles and conference papers from indexed databases. Research papers that were written in English from the years 2021 to 2025 were included in the study. Boolean operators *"OR* and *AND"* were employed to get specific academic sources, where AND is used to get specific and targeted results, while OR allows for flexibility in terms of retrieving one of the specified search terms.

The following search terms were used: "*Data governance*" OR "*Data govern*" OR "*Data governance frameworks*" AND "*Artificial Intelligence*" OR "*AI*" AND "*Small, Medium and Micro Enterprises*" OR "*SMMEs*" and a combination of these phrases.

B. Screening

This phase includes screening articles that will not be included in the analysis based on the keywords used. As part of the screening process, titles and abstracts were used to screen articles that could not be used in the final review. Articles that did not present results on data governance frameworks for enabling AI for SMMEs were excluded. In addition, articles that were not in English and those that were inaccessible were excluded.

C. Eligibility

Articles that required a subscription were excluded, and non-academic reports and only full-text articles formed part of the inclusion criteria. These articles were based on whether they answered the research question and were part of the peer-review process.

D. Inclusion

This phase included articles that were available in full text from the years 2021 to 2025. These full-text articles were used to analyse themes, which were synthesized to be presented as part of the data governance frameworks that can be used by SMMEs. Duplicate articles and articles that did not meet the peer review process were excluded from the inclusion criteria.

4. Findings

This literature study on the data governance frameworks that can be adopted by SMMEs for responsible AI was based on the (n =32) publications that were included in the final review. The publication count shows that (4%) of the publications were in 2021, and in 2021, they increased to (15%). However, in 2023, there was a decline to (8%), and there was an increase in 2024, where there was a slight increase of (1%) to (9%) of the articles being published in 2024. In 2025, there was a (30%) of the number of articles being published in 2025. Figure 4 depicts the distribution of publications included in this review.

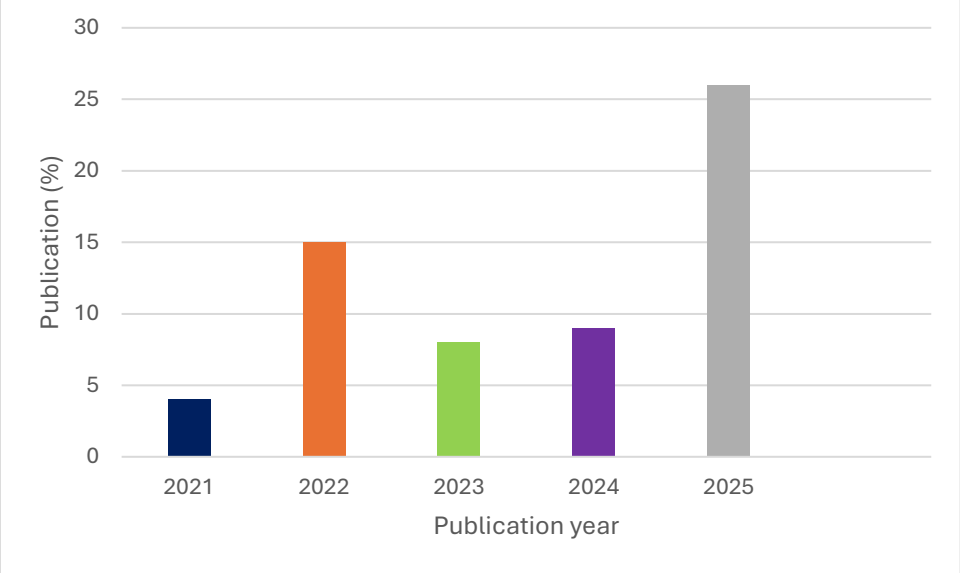


Figure 4: Shows the distribution of publications included in the SLR

The findings also revealed that most of the articles were articles with a distribution of 99.9 % and conference papers with a distribution of 8.1% as depicted in the below.

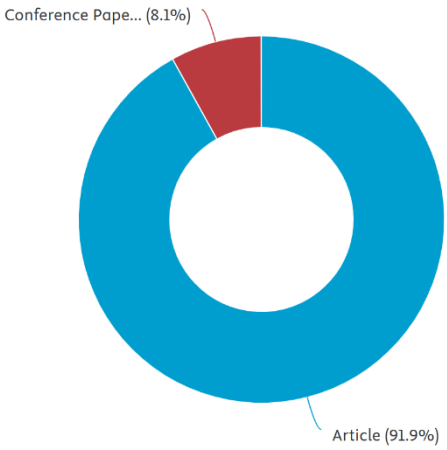


Figure 5: Document type

These findings revealed that Africa contributed more to the data governance frameworks that can be adopted for responsible AI by SMMEs. Africa has (n= 3), where n = number of countries contribution in this data governance framework. The Asian countries have (n=2), and Europe has (n=2). While South America, North America and Oceania have contributed (n=1) each, as depicted below

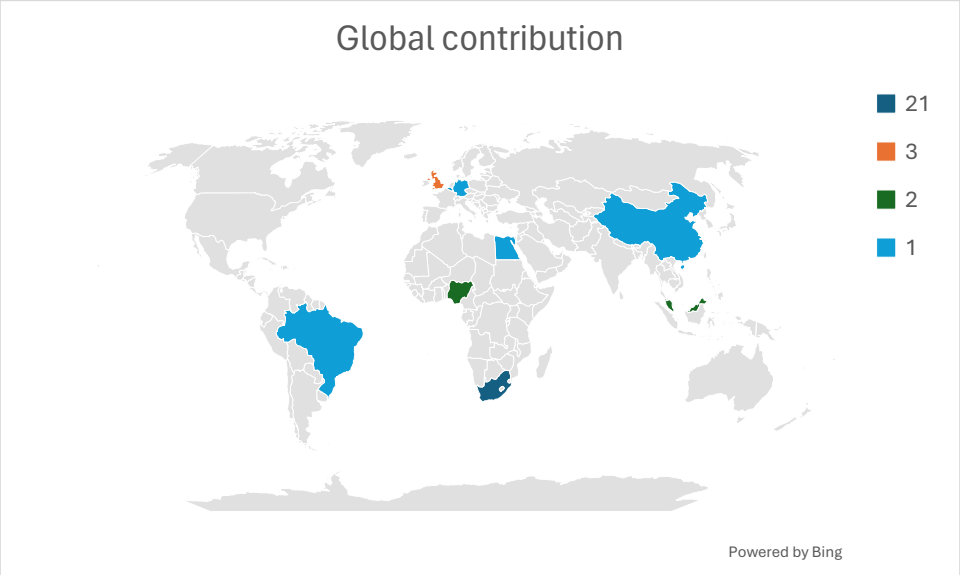


Figure 6: Shows global contribution

5. Discussion

This review reveals a misalignment between existing data governance frameworks and how SMMEs operate. It is evident that most data governance frameworks are designed for large organisations, as this creates barriers for SMMEs. SMMEs face challenges with the adoption of these frameworks, such as the lack of a standardised governance framework. Researchers have proposed numerous data governance frameworks that can be used to manage data, which have different principles. While the frameworks focus on different aspects, they tend to emphasise the importance of properly managing data.

Responsible AI aims to ensure that organisations can make responsible decisions regarding any AI application (Dignum, 2023). Some researchers suggest that transparency, accountability, Telefonica has five principles: fair AI, human-centered AI, extend them to any party, transparent and explainable AI, privacy and security by design (de Laat, 2021; Telefónica, 2021; Díaz-Rodríguez *et al.,* 2023; Madduru and Bhosale, 2024). For organisations to properly manage their data, there is a need to adopt the right framework. Data governance frameworks such as the DAMA DBOK focus on data security and support the responsible AI principles by ensuring that there is security of data while ensuring fairness and transparency. These frameworks tend to provide mechanisms organisations should use, but do not focus on how organisations may face challenges when implementing these frameworks.

SMMEs struggle to adopt these frameworks for enabling responsible AI due to a lack of skills and resources. Budget constraints are also a challenge as SMMEs have limited budgets, thereby unable to extend that to the implementation of the frameworks. SMMEs may find it difficult to interpret what is expected of them in terms of the frameworks. Thereby, there is a need to redesign the governance frameworks to cater to SMMEs and for scalability. In addition, there is a need to develop a universal framework that caters to both large organisations and SMMEs. Most of the frameworks are designed to cater to organisations with governance maturity, while SMMEs operate in an environment where governance is a challenge.

6. Conclusion and Future Work

Data governance ensures that proper decisions are made when data is properly managed and ensures that organisations have authority over their data. Data governance frameworks come in handy, as they ensure that they set out how data is managed. Many data governance frameworks exist, such as the Data Governance Institute Framework and the DAMA DMBOK2 Framework, that SMMEs can use to manage their data. Findings of this study reveal how SMMEs face challenges when adopting these frameworks due to platform complexities, data silos, technological barriers, etc. This study provides insight into how data governance frameworks can be used to enable responsible AI in SMMEs. Future work can include a deep dive into developing a universal framework that will enable responsible AI for SMMEs.

Ethics Declaration: No ethical clearance was required as this study did not involve any humans/animals.

AI Declaration: The authors acknowledge the use of content generated by Artificial Intelligence (AI) (including but not limited to text, figures, images, and code) in making this paper more readable.

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A Double-Edged Sword: How Lab Cameras may Enable Some Cyber Deception in Biosecurity

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Abstract: Cameras keep individuals and assets safe by monitoring behavior, configurations or indications of concern. Cameras are utilized throughout daily life; supporting lifestyles, greater domestic, civil, industrial or and laboratory infrastructure. Cameras monitor plants in controlled experiments, capturing images analyzed by AI to decide when to provide water or nutrients. This setup sounds efficient and reliable but introduces new risks. Internet-connected cameras can be hacked. If that happens, an attacker could fake the footage, hiding an intruder entering a high-security lab or tricking an automated system, like the AI-powered machine, into damaging crops. A tool meant to protect can easily turn into a threat. This paper explores how lab cameras act as both protectors and sources of risk in biosecurity laboratories. We combine research papers and real-world examples in a narrative review to understand how these systems are used and where they fail. We classify risks ranging from weak software and unprotected networks to tampered camera feeds and flawed security updates. Alongside this taxonomy, we discuss solutions such as better network isolation, automated checks for altered footage, and stronger device verification protocols. This review reveals that current research often treats cybersecurity and biosecurity as separate fields, leaving a critical gap where these domains overlap. Relatively few studies have examined how deceptive camera data could disrupt lab operations, cause security breaches, or lead to worse outcomes. Furthermore, few have examined the intersection of biosecurity, cyber-physical security, and cybersecurity. By connecting these domains, this paper highlights the necessity for an integrated approach to improve camera safety and reliability in laboratories. Implementing stronger standards and security practices is essential to prevent these vital devices from becoming vulnerabilities rather than assets. Integrated security efforts can benefit from closer inclusion of camera functions, uses, and forensics.

Keywords: Cyberbiosecurity, Cameras, Laboratory, Deception, Forensics

1. Introduction

Surveillance cameras are ubiquitous, monitoring areas from residences to high-security environments. These devices increasingly rely on internet connectivity, offering real-time and remote monitoring for critical security functionality (ECAM Technologies Corp., 2025). Cameras are categorized as Analog or Digital (Internet Protocol (IP)) where data is transmitted over a network and remotely managed (ECAM Technologies Corp., 2025). Analog cameras transmit video through coaxial cables with separate power lines, producing lower resolution.

An IP camera, or Internet Protocol camera as referenced above, is a type of digital video camera that transmits and receives data over a network or the internet, allowing for remote surveillance and monitoring. Modern IP cameras use a single Ethernet cable for both power and data transmission via Power over Ethernet (PoE) technology and now dominate Biosecurity Laboratories due to their high-resolution imaging performance, functional reliability, and features that align with the unique needs of facilities. However, as Blancaflor et al. (2023) highlight, these devices are often vulnerable to cyberattacks due to issues like unencrypted RTSP streams and weak authentication, which can lead to data theft and unauthorized access. The device's additional connectivity features facilitate seamless integration within networked environments. In relation to operational security, cameras with this capability are able to provide remote monitoring functionality. As they are used across various environments and integrated with other IoT (Internet of Things) devices, their reliance on network connectivity introduces potential cybersecurity vulnerabilities, making them susceptible to unauthorized access or data interception if not properly secured (Affia et al., 2023; Kalbo et al., 2020).

Many labs utilize remote-controlled cameras to monitor personnel in maximum-containment areas, where; the highest level of controlled isolation is applied to a system, facility or environment. This is designed to prevent any form of leakage, exposure or unauthorized interaction by employing the most stringent safeguards available (Diederich & Eschbaumer, 2025). This allows external observers to rapidly identify and respond to incidents or "security breaches" (CDC Emerging Infectious Diseases, 2011), to examine a practical use case. These cameras are increasingly integrated into networked, cyber-physical systems, forming part of broader IoT environments and reflecting the convergence of digital and physical infrastructures (NuAire, Inc.,

2015; Kalbo et al., 2020; National Institute of Standards and Technology, 2024). However, this dependence creates vulnerabilities. Cyberbiosecurity frameworks treat security systems and networked devices as critical assets in the laboratory, whose compromise undermines both required safety oversight and the active scientific activity (George, 2019; Reed & Dunaway 2019). While IP cameras enhance oversight, they also act as an entry point to a given attack surface. Attackers can utilize unauthenticated access or access retrieved from exploitation to manipulate video feeds, disrupt monitoring or interfere with emergency protocols. This introduces risk that undermines the intended safety guarantees.

This paper addresses this double-edged sword. While IP cameras in this current landscape act as essential tooling with multiple applications, they are also potential vectors for cyber deception, defined in this work as the intentional manipulation, falsification or withholding of information using technology. It is significant to acknowledge this concept of Cybersecurity throughout this work in contrast to the general understanding or holistic idea of deception; "Deliberately inducing erroneous sensemaking to gain an advantage" (Defused Cyber, n.d.).

This analysis intends to highlight the critical overlap of cybersecurity and biosecurity in reference to the related surveillance with the intention to propose practical solutions to enhance the security and reliability of camera systems (IP Cameras) in biosecurity environments.

2. Case Studies in Relation to Threat Landscape

Internet-connected IoT (Internet of Things) enabled cameras in biosecurity labs to introduce multiple vulnerabilities. The interconnectivity via the internet enables constant communication between devices, exposing them to actors with varying motives. In the current age, motives have moved away from amusement or sport to the acquisition of resources such as intelligence or information about a target, data or monetary gain, for an ultimate goal of leverage (Prasad et al., 2025). The healthcare sector remains a prime target for cyber threats and a candidate for examination as a case study. In this instance a cause for consideration in adapting or appropriating new technology would be for the purpose of inter-communication, treating patients or the translation of results. Many Life Sciences Laboratories would also share this same use case and concern, especially around delicate environments unique to these facilities. (Affia et al, 2023).

IP Cameras can enable deception, espionage or additonal resulting factors (Cunliffe, 2021; Herodotou and Hao, 2023; Singh and Dhumane, 2025). IP Cameras can serve as powerful tools for deception and espionage by enabling the covert collection and manipulation of visual input. In the contextual use of an abusive actor or offensive security practitioner, IP Cameras may be used to observe user behavior, capture sensitive data (such as credentials or screen activity) or possibly build intelligence for targeted attacks (Cunliffe, 2021; Herodotou and Hao, 2023; Singh and Dhumane, 2025). IP Cameras can also support nefarious operations by creating false perceptions. Placing/replacing physical cameras and/or their feed to suggest surveillance while the actual monitoring occurs elsewhere. IP Cameras can also be manipulated to produce footage to mislead viewers. Deception research provides a useful vocabulary for understanding how compromised IP Camera systems can shape an environment.

IP Cameras in biosecurity laboratories are especially vulnerable to these dynamics because they can be treated as authoritative windows into these restricted spaces or diagnostic tools. When attackers can pause (jam), freeze (stop), or loop (repeat) feeds, they are directly manipulating the perceptual channel that underpins safety decisions and incident reconstructions or recounts (Clark and Mitchell, 2019; Reed and Dunaway, 2019).

2.1 Case Study: Cloud-Connected, Remotely Controllable Cameras

Work by Kalbo et al. (2020) supports that Cloud-connected, remotely controllable cameras can introduce attack surfaces. A notable, related application involved Flock Safety exposing livestreams and administrative interfaces for at least sixty of its AI-enabled Condor cameras to the open internet without authentication, enabling access to live feeds, archived footage (up to thirty days), and camera configuration controls (Koebler, 2025). Threat actors can leverage tools such as Shodan, a specialized search engine that indexes internet-connected devices (e.g., servers, webcams, and IoT systems), to discover and exploit exposed systems, significantly expanding the attack surface of networked infrastructure (Kalbo et al, 2020; Herodotou and Hao, 2023; Koebler, 2025). High-containment laboratories are specialized facilities designed to safely handle and study hazardous biological agents under strict security and safety controls (Crawford et al., 2023). High-containment laboratories trend toward adopting integrated cyber-physical architectures managing security and containment (Crawford et al., 2023). These laboratories increasingly rely on networked camera systems, where visual surveillance is conducted through integrated digital monitoring infrastructures that operators

may utilize to conduct reviews and make critical decisions *(Crawford et al., 2023)*. Poorly secured systems enable external adversaries to silently monitor lab routines, download historical footage or modify settings. Cyber intrusions targeting equipment can facilitate "malicious access to or alteration of security-relevant digital records," making it difficult to distinguish between accidental and deliberate acts (Reed and Dunaway, 2019). These weaknesses directly intersect with Cyberbiosecurity concerns as laboratories become more "smart" and seek to interconnect their systems for efficiency or automation.

Exposure in this case primarily enables intelligence gathering and preparation of attempted deception. An actor who can silently watch, archive, configure or set up persistence toward cameras can gain a detailed picture of routines and blind spots that can later support more active activity, such as concealment or simulation. In terms of deception, this positioning work or staging shapes what exists authentically, stored in archives or changed; thereby pre-structuring how practitioners will later make sense of activity and illustrating how deception targets "sensemaking" and downstream behavior rather than isolated perceptions alone (Clark and Mitchell, 2019; Henderson, 2023). Connecting systems increases the attack surface, risking cascading consequences across multiple safety and security functions from a single cyber-attack (Crawford et al., 2023). Concurrently, camera feeds are evolving from passive recording to the infrastructure to include "smart" safety systems. Computer-vision-based technology would be an applicable use case to reflect upon in this environment as many organizations or institutions move toward automated auditing of compliance auditing and enforcement. A case to review would be the use and retention of personal protective equipment (PPE) compliance systems that use video analytics for automatic detection and supervision in real time (Vukicevic et al., 2024). This integration means camera streams directly influence compliance assessments and operational responses.

When lab cameras serve the dual role of auditing and compliance partners within organizations, manipulating their streams or archived data becomes a potent vector for the goal of deception (Reed & Dunaway, 2019; Crawford et al., 2023). Adversaries and actors who interfere with the integrity or availability of these feeds can shape what automated systems "see" and alter what personnel are able to review.

2.2 Case Study: Wireless Camera Jamming

Wireless IP camera performance may be influenced by frequency band choice; this boasts another illustrative example. The 2.4 GHz band generally offers greater range and wall penetration but is more susceptible to congestion, whereas 5 GHz provides higher throughput with reduced congestion over shorter distances (Intel, n.d.). This distinction is relevant for security considerations because the camera's operational band affects how its wireless communications behave under interference or disruption. Non-peer-reviewed technical reporting has described proof-of-concept devices capable of generating interference across these bands, with demonstrations suggesting that Wi-Fi camera video streams may be disrupted under interference conditions, for example through packet loss (Skyforest, 2025). Prior research on hidden and network-connected surveillance devices indicates that such systems can be detected and analyzed through methods such as network traffic monitoring, signal analysis, and device fingerprinting (Pravin et al., 2022; Ju et al., 2025). At the same time, more recent work suggests that no single detection method is consistently reliable, and that combining multiple approaches may improve identification accuracy in complex environments (Kumar et al., 2026). In tandem, these findings highlight that wireless surveillance devices introduce measurable security considerations, although the effectiveness of detection and interference techniques may vary depending on the environment and device characteristics. Practical demonstrations further illustrate the feasibility of disrupting wireless camera systems.

For example, a prototype device has been suggested to have the capability to interfere with 2.4 GHz wireless cameras, disrupting live video feeds during testing (CiferTech, 2025). As many surveillance devices operate on the 2.4 GHz band due to its extended range and compatibility, systems configured to use this frequency may be particularly susceptible to such interference, highlighting a potential vulnerability in real-world deployments (Herodotou and Hao, 2023). In modern "Wi-Fi-enabled" laboratories, where cameras, instruments, and building systems share a networked infrastructure, a device modeled after the RF-Clown v2 could pose a tangible threat. Cyberbiosecurity analyses of high-containment laboratories suggest that the increasing integration of interconnected cyber-physical systems (such as building automation, biosafety cabinets and networked access controls) may expand the overall attack surface.

Under certain conditions, this interconnectivity could allow a compromise in one component to affect other systems, potentially weakening multiple layers of safety and security. However, the extent to which such effects propagate depends on system architecture, configuration, segmentation and operational controls

(Pravin et al., 2022; Ju et al., 2025). When wireless cameras monitor critical procedures or access, a brief, well-timed freeze of a 2.4 GHz video feed can create an opportunity for deception "blind window" that is invisible to downstream auditing, yet sufficient enough to obscure an unauthorized action. Targeted wireless interference tools such as RF-Clown v2 demonstrate how disruption can degrade the availability of visual monitoring systems by interrupting or freezing live camera feeds (CiferTech, 2025; Skyforest, 2025). The resulting loss or delay of real-time information may still influence decision-making, as operators and automated systems depend on timely data to interpret events (Clark and Mitchell, 2019; Henderson, 2023).

2.3 Case Study: Looping and Spoofing Lab Camera Feeds

In “Cyber War: The Next Threat to National Security and What to Do About It”, Richard A. Clarke and Robert K. Knake (2010) describe the Stuxnet operation targeting Iran’s Natanz facility, noting that it involved both process disruption and manipulation of monitoring outputs. They report that compromised Supervisory Control and Data Acquisition (SCADA) systems could present data consistent with normal operation despite underlying anomalies (Clarke and Knake, 2010). More generally, industrial control system incidents have been understood to involve interactions between physical processes and digital monitoring systems. In environments that rely on such systems for situational awareness, especially laboratory settings, compromise of monitoring outputs could affect how system conditions are perceived. The relevance and impact of such scenarios depend on system design and implementation.

IP cameras may also be susceptible to network-layer manipulation under certain conditions. For example, a Forescout demonstration showed that, where video streams are transmitted using unencrypted protocols, it is possible to intercept traffic and replay previously recorded footage in place of a live feed (dos Santos, 2019). Such scenarios depend on specific configuration weaknesses but suggest that, in some deployments, visual monitoring systems may not reliably reflect real-time conditions if compromised.

In examining the intersection of the stuxnet’s modus operandi and IP camera-replay we can illustrate the technique of deception in which attackers present convincing but false views to operators while damaging or unsafe processes unfold behind the scenes. Analyses of deception stress that such operations work not because they are visually spectacular, but because they are boringly plausible and align with what the audience already expects to see, thereby nudging them toward inaction when intervention is needed (Clark and Mitchell, 2019; Henderson, 2023).

2.4 Case Study: “Dance-coding”, “Vogue-coding” and Vision Challenges

Laboratory camera systems are increasingly embedded in biosecurity workflows, supporting monitoring, compliance, and incident reconstruction. As networked, cyber-physical assets, they fall within the scope of cyberbiosecurity (Reed and Dunaway, 2019). Prior work shows that IP-based surveillance systems can be manipulated at the network or device level, including disruption or replay of video streams under certain conditions (Kalbo et al., 2020; dos Santos, 2019). In parallel, advances in vision-language models, such as representation-learning approaches exemplified by Meta AI (FAIR)’s VL-JEPA, demonstrate increasing capability to extract structured information from video data (Chen et al., 2025). While primarily developed for perception tasks, their integration into camera systems may extend functionality from passive recording toward automated interpretation. Together, these strands suggest that camera systems may present a more complex security consideration than is reflected in current cyberbiosecurity literature, which has largely treated them as generic IoT devices. However, empirical evidence specific to high-containment laboratory environments remains limited, and this work therefore focuses on plausible risks rather than demonstrated prevalence.

Hypothetical Path 1: Visual Coding To Trigger Malicious Action

A hypothetical scenario for discussion involves a future IP camera system integrated with a multimodal vision–language model responsive to visual inputs. In principle, if such systems interpret human movement as input, structured motion patterns could influence outputs in unintended ways. The concept of “vogue-coding” is used here as a metaphor for encoding signals through movement, drawing on the technique of vogueing which draws on Ballroom culture from the 20th Century (Winsor, 2023; Ray, 2025). The use of this term does not imply a yet practical programming method, but illustrates how visual inputs, if systematically interpreted, might carry implicit instructions. Under adversarial conditions, carefully constructed movements could potentially bias or disrupt model interpretation. This remains speculative. There is no clear evidence that current systems can be intentionally controlled through unconstrained movement, particularly in operational settings. However, research on adversarial inputs shows that machine learning systems can be influenced by

crafted signals. Accordingly, “vogue-coding” is best understood as a conceptual lens for anticipating how future vision-enabled systems may require safeguards against unintended or adversarial visual inputs.

Hypothetical Path 2: Generating Fabricated or Fraudulent Visual Artifacts

This path considers an adversarial scenario in which a vision system generates misleading or fabricated visual outputs, conceptually similar to demonstrated manipulation of medical imagery using generative models (e.g., CT-GAN) (Mirsky et al., 2019). In principle, sufficiently advanced and well-integrated camera systems incorporating generative capabilities could introduce ambiguity or doubt into visual records, potentially complicating evidentiary interpretation in legal or investigative contexts (Zhao et al., 2019; Apolo and Michael, 2024; Tayfor et al., 2025; Guo, 2025).

The motivations for such manipulation may include both inducing false beliefs in system users and shaping the behavior of downstream observers or decision-makers. While proposed applications span a wide range of domains, including agriculture, life sciences, healthcare, and critical infrastructure, these uses are best understood as context-dependent and largely speculative, rather than established attack patterns (Mo et al., 2022; Elgabry, 2023; Kaufman et al., 2023; Potter and Palmer, 2023; Stephen et al., 2023; Potter and Palmer, 2024; Stephen et al., 2024).

System effectiveness could, in principle, be enhanced by integrating additional data sources such as biometric tracking or IoT-linked devices. However, the coordinated exploitation of such multimodal inputs for deception remains an area of ongoing research, rather than a demonstrated capability (Affia et al., 2023; James et al., 2025; Potter et al., 2025; Purnell et al., 2025). Increased data aggregation may also expand the attack surface, particularly where data leakage or weak integration controls are present. Mitigation is necessarily multi-layered. Techniques such as watermarking and data integrity controls may contribute to detection and resilience, but they do not constitute comprehensive solutions (Morrison, 2018; Korada, 2024; Naik et al., 2025). More broadly, reducing risk requires a combination of secure system design, provenance verification, and ongoing monitoring of visual data pipelines.

Both Path 1 and Path 2 highlight emerging challenges in adversarial vision systems, likely requiring interdisciplinary responses. The scenarios point to a speculative future where camera-driven systems could be influenced by structured visual inputs, shaping behaviour in unintended ways. In this context, deception operates by introducing plausible but misleading signals into perception, affecting both human and machine interpretation in line with established principles of plausibility and expectation (Clark and Mitchell, 2019; Henderson, 2023).

3. Integrated Security and Best Practices

Defenders must counter adversaries who blend digital and physical domains, employing a vast library of tools particularly against laboratory cameras. Countering these threats requires uniting experts in cybersecurity, biosecurity, cyber-physical engineering, and policy via practical mechanisms like cross-sector partnerships, and routine information-sharing (Powell et al., 2021; Adeoye et al., 2023; Haley and Burrell, 2025). Laboratory cameras must be treated as integral safety and security infrastructure, not peripherals. This means joint risk assessments considering how camera compromise affects biosafety, physical security, and digital records; standardized video tampering response plans; and involving both IT security and laboratory safety officers in system design (Reed and Dunaway, 2019; Cyberbiosecurity in High-Containment Laboratories, 2023; ASPR, n.d.).

Given their centrality, cameras are critical systems demanding systematic pre-deployment security testing of hardware, firmware, and network configurations. This testing must verify basic hygiene, such as changing default passwords, enforcing strong authentication, and disabling unauthenticated access. An internal testing team is beneficial, reducing exposure of sensitive network details, though external expertise should still be utilized. These checks determine camera appropriateness and the necessity for "compensating controls or patches." Continuous vulnerability monitoring is also essential. In the examination of the October 2025 Louvre jewel heist, it can be derived that high-profile institutions despite the most sophisticated security consideration and planning can exhibit poor camera security; weak authentication enables exploitation (Leath, 2025; Seipel, 2025).

Technical practices beyond testing form a baseline for securing lab camera systems. Network segmentation and isolation are central: placing cameras on dedicated, access-controlled segments separate from "unrelated internal systems" like instruments or administrative workstations, a critical concern in high-containment

facilities (Reed and Dunaway, 2019; Crawford et al., 2023). Strong device authentication and access control, avoiding default credentials and unauthenticated web interfaces, as seen with exposed "Flock Condor cameras" and the "Louvre's CCTV password", reduces silent external monitoring (Koebler, 2025; Reyes, 2025; Leath, 2025; Seipel, 2025). Regular security updates, prompt patching and explicit decommissioning prevent cameras from becoming "long-lived footholds" (ASPR, n.d.; Reed and Dunaway, 2019).

Finally, forensic-readiness measures, including "tamper-evident logging, redundant storage," and mechanisms to validate "archived footage," are necessary to detect deceptive attacks which can otherwise make operations appeared to proceed without anomaly (Clarke and Knake, 2010; (Johns Hopkins University Applied Physics Laboratory, 2003; Tayfor et al., 2025).

4. Discussion, Limitations and Conclusion

Laboratory camera systems are increasingly used for monitoring, compliance, and retrospective review, particularly in controlled environments (NuAire, Inc., 2015). As these systems contribute to situational awareness and documentation, their reliability may influence how events are interpreted within a facility. Existing research and reporting indicate that such systems can exhibit a range of vulnerabilities, including weak authentication (Leath, 2025), unencrypted video transmission (dos Santos, 2019), and susceptibility to wireless interference (Skyforest, 2025).

More broadly, studies of cyber-physical systems show that manipulation or disruption of monitoring data can affect perception by presenting incomplete or misleading information (Clarke and Knake, 2010; Clark and Mitchell, 2019). While these findings derive from varied contexts, they suggest that monitoring systems may be vulnerable to both disruption and misrepresentation. Cyberbiosecurity literature has not consistently examined camera systems as distinct components of laboratory security, often treating them as general IoT infrastructure (Reed and Dunaway, 2019; Racicot et al., 2022; Cyberbiosecurity in High-Containment Laboratories, 2023).

This indicates a need for further study of their role in safety oversight and evidentiary use. This exploration is limited by its narrative scope and reliance on examples drawn largely from outside laboratory settings. Accordingly, it emphasizes potential vulnerabilities and design considerations rather than the prevalence of such incidents in biosecurity environments. In the future, a focus topic is to examine defense in depth as a strategy for defending against cyber deception.

Despite these limitations, the analysis confirms that laboratory cameras hold a critical yet under-examined role in Cyberbiosecurity. Cameras mediate operational visibility, safety enforcement, and incident reconstruction; vulnerability to unauthorized access, jamming, looping, or adversarial manipulation transforms them from protective tools into enablers of cyber deception. Future work should convene operators, biosafety/biosecurity professionals, cybersecurity/cyber-physical engineers, and legal/policy experts to experimentally evaluate camera architectures, adversarial attacks, and mitigation strategies in realistic lab settings, translating these findings into integrated standards and training.

Ethics Statement: No experimental subjects were performed upon in this work.

AI Ethics Statement: To organize and format parts of the paper, AI tools within ChatGPT, Grammarly and Google Docs were used.

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Targeting the Human Factor: OSINT in Healthcare

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Abstract: Patients increasingly report that physicians spend more time on the computer than on their examination. While digitalisation is a necessary development in healthcare, it unfolds in a sector constrained by shortages of medical and administrative staff, outdated software and technical infrastructure within the facilities, and uneven levels of digital literacy of medical staff, with the vision of fully paperless healthcare still largely unrealised. At the same time, healthcare has become a target of frequent and sophisticated cyberattacks. In the attempts of a data-driven society, healthcare faces growing demands for efficiency of care provided, interoperability, and timely access to patient data through eHealth solutions. The adoption of emerging technologies, including diagnostic LLMs, is often initiated by medical professionals, sometimes without supervision of IT departments or security teams. As a result, digital transformation increasingly relies on healthcare staff who embrace expanded operational, managerial, and digital responsibilities. This evolution significantly increases the human digital footprint of healthcare professionals and broadens the potential attack surface. As an essential sector under current cybersecurity frameworks, healthcare operates across both professional and private cyberspace. While cybersecurity measures may be implemented by employers during working hours, responsibility for security in private contexts largely depends on individual healthcare workers. Open-Source Intelligence (OSINT) techniques can exploit publicly available data related to professional tasks, online behaviour, and leisure activities, often revealing sensitive insights into clinical practices and personal routines of healthcare staff. From a cybersecurity perspective, healthcare can be perceived as a supply chain in which general practitioners frequently serve as the first point of contact. Due to their limited technical and financial resources, they may represent a structurally vulnerable link within this chain. Although cyber incidents affecting large hospitals attract greater media attention, smaller healthcare providers experience similar threats, which—given the interoperability vision—can have severe implications for the broader healthcare chain. This paper therefore examines OSINT-based human targeting of general practitioners and discusses how information obtained can be leveraged in cyber operations against the healthcare sector.

Keywords: Healthcare, Cybersecurity, OSINT, General practitioners, Supply chain

1. Introduction

When identifying the most important part of CIA Triad (Confidentiality, Integrity, Availability) (Tikanmäki et al., 2025) in the context of healthcare, the crucial one for the essential functions of the system is availability since the medical staff is trained to draw conclusions and further investigate an incomplete documentation rather than work with none or cope with leaked documentation on the way. Furthermore, the healthcare professionals need the documentation to be available as quickly as possible (Tampu & Berek, 2025) since moments have the power to determine the continuation of human life and recovery.

1.1 OSINT

1.1.1 Methodology

The OSINT technique defined as “Open Source Intelligence” is used to analyze publicly accessible and available information in order to gather insights on specific activities or stakeholder groups (Bracciale et al., 2023). Within this technique, the methodology of firstly identifying the target group (in this case, the general practitioners), secondly identifying the main data streams and various dataset sources (this time, namely national registries and statistics office as well as government data and none the less consulting with specialists in health IT and healthcare professionals), information processing and analysis (Bracciale et al., 2023) were the steps involved in the OSINT process.

Firstly, the following steps led to identifying the target group: while hospitals are commonly highlighted by the media as victims of cyberattacks, the publicity of these attacks does not only reflect the frequency and severity of attacks on hospitals as opposed to attacks on different (smaller) parts of the healthcare system as it also considers the appeal of the topic to the general public since the larger the healthcare facility is, the more attention it draws by influencing more patients. However, this fact does not convey that there are no attacks on the smaller parts of the healthcare system (such as GPs). Furthermore, the smaller healthcare facilities function as parts of the supply chain of the hospitals therefore attacks on them suggest consequent implications for the hospitals as well.

While debating the most suitable target group with cybersecurity professionals within the hospitals as part of the research, plenty identified the GPs as most in need of guidance and support since hospitals can allocate a larger range of resources to address cybersecurity challenges compared to the GPs through possibilities of EU/government funding in the form of cybersecurity grants and are more appealing employers to cybersecurity professionals than smaller healthcare facilities. At length, GPs face increasingly limited resources compared to hospitals which implies the necessity to focus on this particular target group within the research.

Secondly, identifying the main data streams and various dataset sources implied focusing on specifically Czech internet within this research considering that healthcare systems around Europe (let alone the globe) vary significantly when it comes to the distribution of care and resources aligned with it. For that reason, considering international sources would not benefit this research. The majority of healthcare in the Czech Republic is coordinated through public health insurance companies that are funded by the state budget and charged by the healthcare facilities per medical performance. Therefore, national registries and statistics together with the ministry of healthcare and websites of GPs associations were used in this phase of OSINT. The main sources of data consisted of Institute of Health Information and Statistics (National Registry of Health Service Providers, 2026) and State Institute for Drug Control (2026).

Furthermore, healthcare software providers oriented on GPs (CGM World, 2026) were consulted to validate the choice of data streams and implications for the GPs obtained from these sources. Through the software provider consultations, contacts on GPs were obtained for further research. Since popular and widely known GPs (e.g. from the media) would not serve as representatives of the majority of the target group which generally remains known within its patient base rather than nation-wide, the research focused on regular GPs rather than public figures (GPs also active in state politics, influencers, writers etc.). Social media profiles were searched via obtained contacts using full names of the GPs. In line with the demography of the GPs with the majority over 50 years of age (Zítková, 27/05/2024), it is common to find their social media accounts using their full name and title.

The research focused on representation of solitary GPs as well as GPs operating within a healthcare facility (clinic etc.) or GPs cooperating with a university hospital. GPs from regions as well as GPs from larger cities were considered. The research showed that whereas solitary GPs run all aspects of the practice from care to investments in cybersecurity measures, GPs within a clinic are more likely to focus mainly on the primary care provided and let IT and security concerns be coordinated by the institution employing them. Furthermore, the research established that a lot of details concerning the state of IT and security of the given practice is disregarded in the process of practices being sold by senior GPs to their successors.

Overall, in this phase of the research, ten GPs were included representing all aspects of the target group stated above such as demography, location and type of practice in varying combinations. These GPs were subjected to all the phases of OSINT described in the paper. Expansion of the selected sample would possibly support or broaden the list of vectors described, however was not realised based on resource restrains of the research.

1.1.2 Background

OSINT seems to be the perfect method for today's data-driven society, the extensive amount of data available online making it almost impossible to approach and process information analysis without a sophisticated set of methods and technological tools that OSINT can use.

OSINT can generally be divided into technological OSINT (aimed mainly at the infrastructure, suitable for targeting larger institutions and IT suppliers) and "Spear"-OSINT (aimed at selecting and analysing individual users rather than broader infrastructure, suitable for targeting GPs). Several technological tools can, though, still potentially be used after the first phase of "Spear"-OSINT.

Among the technical ones, useful tools for OSINT worth mentioning comprise of OWASP ZAP, Nmap with Firewalk or Fierce used for locating non-contiguous IP space and hostnames that correlate with a specific domain. These methods can be used as a precursor to other tools such as Skipfish, Wapiti, Dirb or WPScan. At the same time, specific Google features are relevant for reviewing (DeCusatis et al., 2022). Oftentimes, it is recommended to check whether one's email address or phone number, but also electronic health record or other personal data has been leaked and used in cyber-attacks (Hunt, 2026), to which the leakage of credentials commonly contributes. For this reason, users are recommended not to use their job contacts for personal (i.e. e-shopping) purposes. At the same time, a person can create a separate email address for external inquiries.

GPs cannot influence the IP address or DNS much most of the times, therefore rather than focusing on technology, we focus on the users.

The common ground for OSINT and healthcare lies in the essence and importance of availability of information since both often use unverified sources (in one case, the Internet, and in another, the patient) to draw conclusions. Although medicine is known for its evidence-based practice, still until this day, doctors, and namely general practitioners (GPs), often rely on fragmentary statements of their patients, since medical documentation has up until now been largely carried out on paper that can be damaged or lost rather easily, or kept digitally without the complex connectivity needed to access it by any healthcare provider. Furthermore, both OSINT and GPs significantly value speed of information delivered. GPs are often the ones having to diagnose the symptoms first and, in most diseases, typical for this day and age, the stage in which they are diagnosed is crucial for the consequent care and probability of recovery.

Up until recently, sources for OSINT comprised of internet websites and news. However, today, social media generates a considerable amount of information on people's (nonexclusively general practitioners') opinions, whereabouts and lifestyles, therefore this source is also considered in the following OSINT.

1.2 The Human Factor

The healthcare sector relies heavily on the human factor. Since in healthcare, more often than not, technologies are outdated and lack of investments as well as staff is frequent, healthcare professionals learned to rely extensively on each other. That is why hacking tactics focusing on the human factor shall be especially effective in healthcare. This sector encourages solidarity and team spirit above all else which is why social engineering (as well as other human factor-oriented attacks) thrive in healthcare. Within the constraints of the sector, technical and physical cyber security measures do not sufficiently prevent social engineering and other attacks from succeeding (Patel, 2020) since the human factor (in this case, the user being the healthcare professional) is the main target that can be reached via other than technological methods described as follows.

One of the tactics for social engineering is fear or blackmail. For that reason, this paper investigates information accessible about the GPs that can be used as basis for not only fear or blackmail, but also other traits well represented among healthcare professionals such as empathy (Moudatsou et al., 2020), trust and authority (hand in hand with hierarchy). These can be triggered by attacker's tactics with emphasis on urgency, importance of the demand manipulating the healthcare professionals into human error (Adefabi et al., 2025).

The medical staff is expected to enhance its digital literacy as eHealth (Hummelholm, 2025) and wearable devices (Okpalanozie et al., 2025) spread across the patient care outside the hospital. Furthermore, despite persisting training efforts and the fact that training is generally outlined as among the most efficient measures, several healthcare professionals still feel insufficiently trained and informed on the topic of cybersecurity (Tikanmäki, 2025).

2. Results

2.1 Target Group Specification

The Czech Republic is the country designated for the OSINT due to it being located in Central Europe, between the former East and West European continent, nowadays a member of the European Union. The country comprises of approximately six thousand general practitioners and is divided into 16 administrative regions (National Registry of Health Service Providers, 2026). Several discussions about the uneven representation of healthcare professionals occur in the public sphere which is why the following figures demonstrate both the nominal representation of the GPs and their representation related to 100.000 inhabitants. Evidently, the differences among the regions when taking into consideration the number of inhabitants are not that severe.

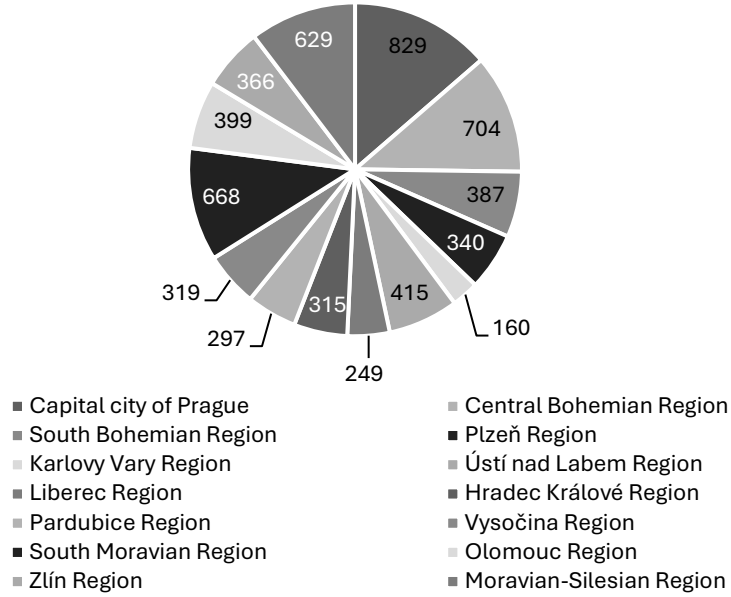


Figure 1: General practitioners density based on their belonging to a region

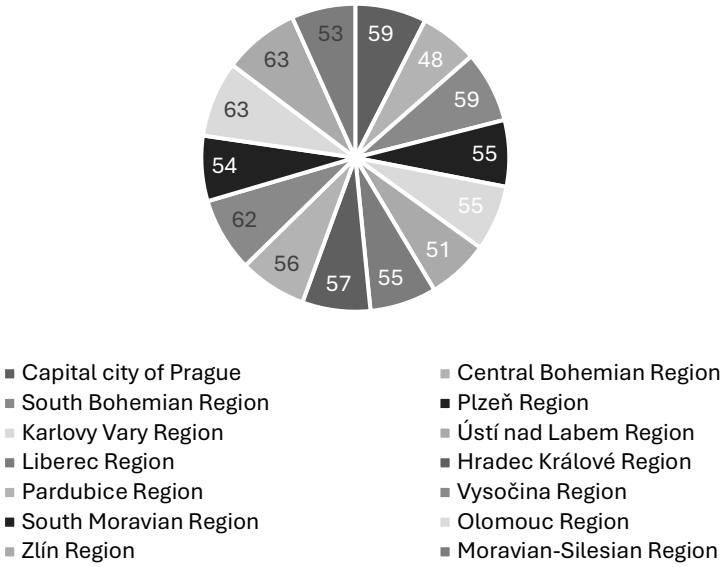


Figure 2: General practitioners density based on their belonging to a region after correction of GP per 100.000 inhabitants

The OSINT is demonstrated on a set of GP representatives (Institute of Health Information and Statistics, 2026) who were selected according to their affiliation to a region and their practice's organisational structure (such as a simple private practice, belonging to a clinic or cooperation within a university hospital) to ensure diversity. Other aspects could be taken into account during the selection, such as the number of registered patients or amount of care provided, however this information is not publicly available. The demographic data presented in the figures serves as basis for identifying the key representatives of the target group of GPs for further OSINT and subsequent research comprising of structured interviews and indicates bias in media and political communication emphasising underrepresentation of GPs in regions outside of large urban areas.

The data used for the research is accessible in national registries in real time since each GP has a legislative obligation to notify the Czech Medical Chamber (2026) in case of any changes which are then reflected in the datasets.

2.2 Social Media

Social media (mainly Facebook and Instagram) was used as some of the key sources of information for the OSINT since it is proven to influence public opinions upon inviting emotional and therefore rapid reactions (derived from dopamine or anger, without further consideration of consequences that the user's reaction might have in the long-term perspective) by promoting the most engaging content (Damons, 2025). This way, a lot of formerly deterministic issues are now becoming political with contesting the argument of factual truth (promoting misinformation and propaganda potentially leading to undermining trust in institutions) which is a trend encouraged by most political powers now also present on the social media.

In the context of GPs, social media accounts customarily being registered via email address of the user, the GPs frequently do not distinguish private from public life which is why they may often use the same email address for social media as well as contact with patients. However, emails have been repeatedly the vector of attack of social media accounts since the users, seeing the amount of attacks and fraud on social media, strengthen their social media account password, but forget to strengthen their backup email password through which the attacker may even change the rather secure social media password, pretending to be the original user who forgot the initial secure credentials. A vector specific to GPs is at hand: since the attacker accesses the email, they can not only enter social media accounts, but also contact patients via email distributing misleading information, phishing etc. At the same time, conversations carried out within social media platforms can hardly be considered private (Damons, 2025). Not all communication on these platforms is carried out among "real" human beings (e.g. bots and fake identity profiles are used extensively).

One of the main weaknesses of the current level of Czech healthcare largely relies on elderly medical professionals (Zítková, 27/05/2024). Although it is apparent that social media is most common among younger generations, the elderly often make an effort to enter this space for the sake of connecting with their grandchildren (mostly for family pictures and calls) and not being so keen in the virtual space makes them exceptionally vulnerable. This is most prevalent in the digital footprint of the GPs who often reflect publicly on emotion-triggering political or socioeconomic issues, showing their true colours without realising that these can be used against them by any patient or alien. The recommendation to change one's username even slightly as opposed to real full name already makes one considerably less searchable (and therefore more secure) on social media.

Healthcare is especially susceptible to social engineering because of the generally high trust factor. Data breaches have been reported based on posting images of hospital employees with sensitive data such as passwords shown unintentionally in the background (Patel, 2020).

Another source of sensitive information is reviews on Google or GPs' websites. The reviewers on these platforms (presumably mostly patients) do not hesitate to mention personal comments on behalf of the GPs such as specify location of both the practice and their home (especially in case of small-town patient base), family members of the GP (in one case, the patient mentions that it is admirable that the GP answers phone calls from patients even though she has two small children etc.). Not only the identity of the GP, but also the one of the patient/commentator can get revealed. The specific information revealed can later be used by an attacker impersonating either the patient or the GP while attempting to compromise one or the other.

3. Discussion and Conclusion

3.1 Use of Artificial Intelligence in OSINT

Different LLMs can be used to broaden the amount of information investigating a specific GP. A current affair with X's Grok creating revealing images with body details only based on private conversations (CCDH, 2026) seems to open doors to larger datasets than a regular user would dare (and possibly fear) to imagine, whereas other common LLMs still impose barriers on private matters on the GPs. For example, although a review mentioned the number of children of a GP, ChatGPT -5.2 (in free version) (OpenAI, 2026) did not disclose this information even upon specifically asking for it. The future of AI remains vague although authorities have been trying to tackle its security and safety issues ever since the LLMs became widely accessible to the general public (EU, 2026). Though industry generally develops faster than regulations, and specifically AI and IT industry develop in the fastest pace, therefore their security and privacy issues remain a great question mark.

While the healthcare system, governments and legislation are debating how to incorporate AI into healthcare and together with the digitalization utilize it in favour of care accessibility despite the demography (in form of increase of aging population and decrease of medical staff), LLMs are with or without needed certifications used in healthcare nowadays. The staff does not hesitate to use these models with or without instructions from the cybersecurity department to minimise their efforts on the tasks not directly linked to providing care to the patient (e.g. documentation). For these tasks, the staff often consults publicly accessible LLMs, sharing details of the patient as well as their practice. These details can, in cooperation with the LLMs, be used for OSINT later on. At the same time, LLMs do not only help decrease the workload of the staff but might bring more patients to the facility given that cases where LLMs suggested medical advice that caused harm to the patient are documented (Antivirus, 2026). With today's inevitable rise of AI, it is apparent that just as social media, AI is increasingly becoming a source of information for (not exclusively) OSINT. With its expanding database of information on GPs and their patients, AI (if not well-regulated) can also provide valuable insights to attackers.

3.2 Conclusion

When entering cyber space, GPs should take into consideration the global picture they paint in society which is often the picture of authority that others look up to. When posting content, reacting and showing affection towards a certain political group or ideals, it is recommended for the GPs to approach this the same way other public figures do, e.g. create separate (slightly anonymous) accounts for leisure and others (with full name and real profile picture) for public presentation. Social media users frequently forget is that their digital footprint is always trackable and anything can later be used against them. Switching among multiple accounts is a standard feature for most social networks so it does not considerably decrease the user experience.

All OSINT outcomes together with cybersecurity recommendations drawn from them should always be verified in the real-world settings which is why the research is planned to continue via structured interviews with the GPs. Therefore, the impact of the OSINT outcomes may be measured in the context of the specific GPs. For the sake of keeping the selected GPs anonymized, specific sources of reviews and social media accounts that would identify them have been left out.

When it comes to specific OSINT findings and their connection to exploitation, while younger GPs might accidently reveal their credentials taking pictures on social media with background containing passwords to clinical software, older (quite more represented) generation of GPs might be more susceptible to giving their credentials to a stranger on the phone claiming that they are the software provider or a government/public representative. Both examples reflect potential harm to the healthcare professionals as well as their patients.

Ethics declaration: No ethics declaration was needed for this research.

AI declaration: AI was used in the dataset gathering phase as one of multiple information sources.

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Lost at Sea: GPS Spoofing Threats to Maritime Shipping

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Abstract: As global shipping increasingly depends on Global Navigation Satellite Systems (GNSS), cybersecurity threats that target maritime navigation systems have rapidly become a growing concern. Maritime GPS spoofing has significant implications for global trade and safety as false position data can lead to route deviations, collisions, or even cargo theft. To gain a better understanding of these risks, this research analyzes real-world datasets to determine how spoofed signals can influence vessel navigation accuracy under different signal to noise conditions. By analyzing real-world AIS and GNSS logs, the study identifies localized anomalies consistent with spoofing or interference. This research investigates GPS spoofing attacks on commercial vessels and assesses real-world vulnerabilities to propose and develop effective countermeasures. Using data collected from Automatic Identification System (AIS) and GNSS receiver logs, the study measures the impact of spoofed signals on ship positioning accuracy and identifies potential weaknesses in onboard navigation procedures. The project also explores policy and training aspects by proposing updated cybersecurity protocols for ship crews and recommending that maritime authorities integrate spoofing detection into standard navigation safety audits. Based on this analysis, the project proposes low cost detection and mitigation strategies, which includes anomaly detection indicators and onboard incident response frameworks. The findings aim to improve awareness of GPS spoofing risks, strengthen maritime cybersecurity policy, and provide training guidelines for ship operators to reduce the likelihood of navigation manipulation, hijacking, and information theft. Ultimately, this research aims to contribute to the broader understanding of how cyberattacks intersect with physical infrastructure in the maritime domain. It emphasizes that cybersecurity at sea is not only a technical challenge but also an organizational and policy issue requiring coordinated international action. The outcomes are expected to strengthen industry resilience, improve situational awareness, and support the development of comprehensive maritime cybersecurity frameworks that safeguard both economic and human interests.

Keywords: GPS spoofing, Maritime cybersecurity, GNSS interference, AIS anomaly detection, Signal integrity, vessel navigation

1. Introduction

Global maritime operations rely heavily on Global Navigation Satellite Systems (GNSS) for positioning, navigation, and timing. From route planning to collision avoidance, GNSS has become the foundation of modern vessel operations and automated navigation systems (Humphreys et al., 2008). However, the open and unauthenticated nature of civil GNSS signals has introduced serious cybersecurity vulnerabilities (Jafarnia-Jahromi et al., 2012). False signals transmitted by adversaries can deceive receivers into reporting incorrect positions, a technique known as GPS spoofing.

Spoofing poses a greater challenge than traditional jamming because it corrupts navigation data while maintaining normal signal strength and appearance. Prior demonstrations have shown that attackers can gradually mislead ships off course without triggering alarms or signal loss. These deceptive drifts, often resembling the effects of ocean currents or wind, can lead to dangerous navigational errors, cargo theft, or even vessel hijacking.

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This research examines the impact of GPS spoofing on maritime navigation accuracy and evaluates how varying signal-to-noise conditions affect vessel positioning reliability. Using Automatic Identification System (AIS) and

GNSS receiver log data, the study identifies conditions under which spoofed signals cause deviations from authentic coordinates. Kinematic thresholds were derived empirically from observed vessel behavior under normal and anomalous navigation conditions. This approach aligns with prior work using behavioral consistency checks for spoofing detection in maritime navigation data (Spravil et al., 2023).

In addition to technical analysis, this work proposes practical countermeasures, including low-cost detection indicators, updated crew training procedures, and revised cybersecurity protocols for maritime authorities. By integrating both technical and policy perspectives, the research emphasizes that maritime cybersecurity is not solely a technical problem but also an organizational one requiring international coordination. The findings aim to strengthen situational awareness, improve maritime cybersecurity resilience, and reduce the risk of navigation manipulation in the global shipping industry.

2. GNSS Interference and Implications

Global Navigation Satellite Systems (GNSS) provide the position, velocity, and timing data that lays the foundation for nearly all modern maritime navigation systems (Psiaki and Humphreys, n.d.). However, the inherent weaknesses of GNSS signal propagation make them highly vulnerable to interference and deliberate manipulation (Jafarnia-Jahromi et al., 2012). GNSS signals are transmitted from medium Earth orbit at extremely low power levels, typically around -160 dBW by the time they reach a receiver on Earth. Because of this weak signal strength, even low-power transmitters operating near a vessel can easily overpower, distort, or replace authentic satellite signals.

GNSS interference typically occurs in two primary forms: jamming and spoofing. Jamming is the intentional or unintentional emission of radio frequency energy that disrupts the reception of authentic GNSS signals (Jafarnia-Jahromi et al., 2012). Although jamming causes a loss of signal and is often quickly detectable, it can still disable navigation and tracking systems in congested waterways. Spoofing, on the other hand, is a more sophisticated and dangerous threat. Instead of denying service, it generates counterfeit GNSS signals designed to mislead receivers into computing false positions or velocities while appearing normal. Because spoofed signals can mimic gradual positional drift, their effects are often mistaken for environmental disturbances such as ocean currents, wind, or tide-induced drift (Bhatti & Humphreys, 2017; Androjna & Perkovič, 2021).

The implications of GNSS interference extend beyond immediate navigational errors. In integrated bridge systems, GNSS data are fused with other sensors, including Automatic Identification Systems (AIS), radar, gyrocompasses, and electronic chart display and information systems (ECDIS), to generate situational awareness. When GNSS data become corrupted, every dependent subsystem, from autopilot to route tracking, can propagate incorrect information. A spoofing attack that remains undetected can therefore mislead both automated control systems and human operators, potentially resulting in route deviations, collisions, or groundings (Spravil et al., 2023).

As maritime operations move toward greater autonomy, GNSS dependence will only deepen. Dynamic positioning systems, unmanned surface vehicles, and automated port logistics all assume signal authenticity. Without authentication mechanisms or effective detection strategies, GNSS interference represents not only a technical challenge but also a systemic risk to global trade and maritime safety.

3. Data Analysis Methodology

To systematically evaluate how Global Navigation Satellite System (GNSS) interference affects maritime navigation accuracy, this study follows a structured empirical analysis framework that integrates both vessel-level AIS data and ground-based GNSS reference logs. The analysis is organized into three stages: (1) baseline performance assessment under normal navigation conditions, (2) detection of kinematic anomalies consistent with interference or spoofing, and (3) evaluation of potential mitigation strategies through cross-sensor consistency checks.

In the first stage, raw Automatic Identification System (AIS) transmissions and GNSS receiver logs were collected and synchronized by timestamp. AIS data provide vessel position, speed, and course information transmitted over VHF radio networks, while GNSS logs from the NOAA CORS network supply satellite-level parameters such as latitude, longitude, and signal-to-noise ratio (SNR) (NOAA, 2025). Establishing a temporal correlation between these datasets enables detection of vessel-level deviations under otherwise stable satellite conditions.

The second stage focuses on identifying anomalous vessel behavior using empirically derived thresholds. The parameters, speed deviation (|SOG − calculated speed| > 10 knots), erratic rotation (|ROT| > 10°/min), and

course-heading gap (> 45° at SOG > 3 knots), were chosen based on operational maneuverability limits and statistical inspection of normal trajectories. Each flag was required to persist across at least three consecutive 5-minute intervals to reduce false positives from transient signal noise or reception dropouts.

The final stage develops detection and mitigation concepts derived from these empirical observations. By examining temporal persistence, spatial clustering, and cross-validation with GNSS SNR stability, potential rule-based indicators were designed to detect spoofing-like conditions using only existing onboard data sources. This framework links real-world measurement with practical defense strategies and forms the foundation for the mitigation proposals presented later in the paper.

4. AIS and GNSS Logs Evaluation

4.1 AIS Log Analysis

To assess the practical impact of spoofing and signal anomalies on vessel navigation, Automatic Identification System (AIS) logs were analyzed for cargo vessels operating along the United States West Coast between December 20 and December 31, 2020. Data was obtained from the open AIS archive provided by NOAA, consisting of daily .zip files containing timestamped positional reports. Each record included Maritime Mobile Service Identity (MMSI), geographic coordinates (latitude and longitude), speed over ground (SOG), course over ground (COG), vessel heading, and static vessel attributes such as type, length, and draft. Only vessels classified as cargo ships (VesselType = 70) within the bounding box 30°–42° N, 115°–130° W were retained to limit the scope to major commercial lanes and port approaches.

The dataset was preprocessed using a custom Python script that parsed all AIS messages over the 12-day period, removed duplicate or invalid coordinate entries, and standardized all timestamps to UTC. To ensure temporal continuity, each vessel's trajectory was resampled in 5-minute intervals, producing a uniform time series suitable for kinematic feature extraction. Derived parameters included calculated speed over ground, rate of turn (ROT), and course-heading deviation, which collectively served as indicators of navigational inconsistency (Spravil et al., 2023).

To detect abnormal behavior potentially indicative of interference or spoofing, several anomaly flags were computed:

- **Speed spike**: instantaneous velocity exceeding 60 knots,
- **Speed deviation**: |SOG − calculated speed| > 10 knots,
- **Erratic rotation**: |ROT| > 10 deg/min at near-zero speed,
- **Course-heading gap**: > 45 degrees at SOG > 3 knots, and
- **Anchor drift**: vessel movement > 1 km over 60 minutes while SOG < 1 knot.

The anomaly thresholds were chosen to balance sensitivity and operational realism. A 10-knot deviation threshold corresponds to approximately two standard deviations above the median difference between reported and calculated SOG in normal operation, ensuring that only extreme outliers are flagged. Similarly, a 45° course-heading gap represents the typical upper bound for course changes during steady transit, and a 10°/min rotation rate is consistent with prior vessel maneuverability studies.These parameters were validated by visual inspection of several representative trajectories to confirm that false positives remained below 5 %. Each flag was required to persist across at least three consecutive 5-minute intervals (≈ 15 minutes) to reduce false positives from noise or transient reception errors.

The resulting anomaly dataset comprised approximately N≈200 k messages from over 100 distinct MMSIs, summarized in Table 1. These results quantify the proportion of vessel reports exhibiting one or more flags and highlight the most affected ships based on percentage of anomalous points.

Table 1: Top cargo vessels by fraction of anomalous 5-minute intervals

MMSI	Points	% Flagged	Dominant Anomaly
310765000	663	24.7	rot_anchor
636017154	1733	24.5	rot_anchor
636015094	25	24	sog_gap

MMSI	Points	% Flagged	Dominant Anomaly
355649000	19	21.1	sog_gap
367776050	3444	10.8	cog_head
351854000	79	10.1	sog_gap
366758000	1069	10.1	rot_anchor
352142000	1005	9.4	rot_anchor
357076000	1003	9.1	rot_anchor
355623000	98	7.1	sog_gap

In addition to per-vessel analysis, spatial aggregation was conducted to identify regional clusters of anomalous behavior. Each vessel's flagged observations were binned into 0.1° × 0.1° grid cells and aggregated hourly. Cells with fewer than three vessels were excluded to prevent spurious outliers. The top 15th percentile of cells by fraction of flagged vessels were classified as hotspots, revealing spatial concentrations of anomalous navigation activity along major traffic corridors.

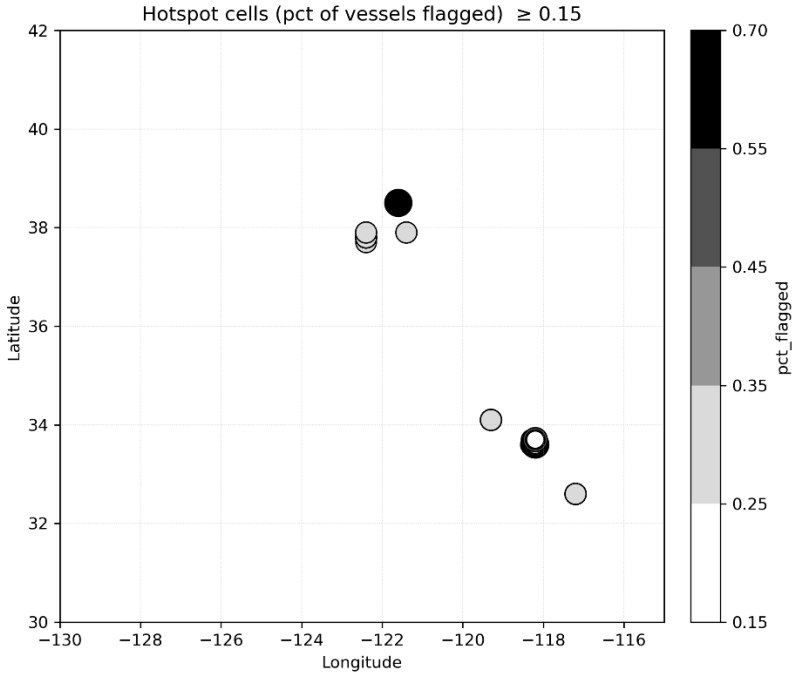


Figure 1: Hotspot distribution of flagged AIS observations for cargo vessels (December 20–31, 2020). Colors indicate the fraction of vessels within each grid cell exhibiting anomalous motion characteristics. Elevated anomaly densities appear near the San Francisco Bay area and the Los Angeles–Long Beach port complex, suggesting that navigational interference or degraded GNSS quality may occur more frequently in dense coastal environments

4.2 GNSS Log Analysis

To complement the AIS-based vessel anomaly assessment, GNSS receiver data were retrieved from NOAA's Continuously Operating Reference Station (CORS) network. Six stations along the U.S. West Coast (e.g., P041 – San Diego, P158 – Northern California, and P351 – Los Angeles Basin) were analyzed for the same 12-day period (December 20–31, 2020). Each RINEX daily log contained continuous 30-second observations of satellite signals. Using the georinex library, timestamps and signal-to-noise ratios (SNR) were extracted and summarized per station (NOAA, 2025).

The results (Table 2) show fully continuous coverage (≈2880 epochs/day) and minimal gap rates (<0.1 %), with mean SNR values averaging 43–44 dB-Hz. These values indicate stable GNSS reception without evidence of widespread interference or jamming during the study window. Consequently, deviations observed in AIS-based positions are unlikely to stem from system-wide satellite degradation, reinforcing the interpretation that anomalies detected in the AIS data represent localized signal disruption or spoofing near port areas.

Table 2: Summary of GNSS Signal Quality for CORS Stations (Dec 20–31, 2020)

Station	Days	Files	Total Epochs	Mean Gap Rate	Mean SNR (dB-Hz)
P041	12	12	34,559	0	43.88
P158	12	12	34,559	0	44.11
P351	12	12	34,560	0	43.22

(Values derived from NOAA CORS daily RINEX files using georinex; each day includes ≈ 2880 30-second epochs.)

4.3 Interpretation of Results

The combined evaluation of AIS and GNSS datasets provides a clear distinction between normal satellite performance and localized navigational interference. The GNSS reference stations exhibited continuous signal integrity, stable signal-to-noise ratios averaging 43–44 dB-Hz, and no measurable data loss throughout the 12-day observation period. These results confirm that the broader GNSS constellation and atmospheric conditions remained stable during the study window.

In contrast, AIS-derived vessel trajectories revealed spatially concentrated anomalies near major port regions, including the Los Angeles–Long Beach complex and San Francisco Bay. These areas showed recurring speed inconsistencies, abrupt course changes, and rotational deviations that persisted over multiple sampling intervals. Because such deviations occurred only in specific maritime zones rather than along the entire coastline, they are unlikely to stem from global GNSS instability.

The contrast between the stable CORS data and the localized AIS anomalies supports the interpretation that interference effects were environmental or deliberate in nature since the data was consistent with patterns associated with GPS spoofing or localized signal degradation. The findings therefore highlight that maritime spoofing threats are operational and site-specific, most pronounced in congested coastal environments where multiple signal sources, reflections, and electronic systems coexist. This distinction underscores the need for regional monitoring and onboard detection protocols, rather than system-wide GNSS corrections as the primary defense against maritime navigation spoofing.

While many flagged anomalies are consistent with deliberate GPS manipulation, some, particularly the *rot_anchor* cases, could also reflect multipath effects or local signal degradation at anchor. However, their persistence over multiple intervals suggests that these deviations are unlikely to be random noise.

5. Attribution Analysis: Environmental Interference vs. Deliberate Spoofing

To contextualize the AIS anomalies identified in this study, an additional attribution check was performed using the U.S. Coast Guard Navigation Center's GPS User Issue Detection and Evaluation (GUIDE) tool. This government system aggregates global GNSS interference reports submitted by maritime operators, aviators, and other GNSS users. For the study period of 20–31 December 2020, the GUIDE database contained no reported GPS issues anywhere along the U.S. West Coast, including the San Francisco Bay and Los Angeles-Long Beach regions where AIS anomalies were most concentrated. The only global report within this timeframe originated in central India and was assessed by NAVCEN as unrelated to GNSS integrity.

When combined with the fully stable CORS signal-to-noise measurements, these findings confirm that the GNSS constellation and atmospheric conditions remained normal during the observation window. As a result, the AIS irregularities detected in port regions cannot be attributed to satellite faults, constellation-level disruptions, or documented regional interference events.

This evidence narrows the plausible causes of the anomalies to two categories:

- **Localized environmental interference**, such as multipath reflections from cranes, vessels, or port infrastructure, and

- **Small-scale, site-specific spoofing or signal manipulation**, which would not necessarily generate a formal NAVCEN report (Jafarnia-Jahromi et al., 2012).

While the persistent, structured nature of several anomalies resembles patterns observed during controlled spoofing experiments, the absence of corroborating interference reports and the confined spatial clustering near high-reflection environments suggest that environmental factors are the more likely explanation. Importantly, whether the root cause was environmental or deliberate, the anomalies still represent navigational inconsistencies detectable through AIS-GNSS cross-validation, reinforcing the relevance of the proposed detection framework.

6. Proposed Detection and Mitigation Strategies

Building on the observed discrepancy between localized AIS anomalies and stable GNSS performance, this study proposes a practical framework for detecting and mitigating maritime spoofing events using data already available on commercial vessels. Rather than relying on specialized hardware or post-processing infrastructure, the approach leverages real-time consistency checks between independent navigation sensors and behavioral thresholds derived from normal vessel motion. Although no spoofing incidents were confirmed when captured during the observation period, isolating anomalous navigational patterns was proved effective.

6.1 Real-time Anomaly Detection

Vessel systems can continuously monitor discrepancies among Speed Over Ground (SOG), Course Over Ground (COG), and heading data. Sudden deviations that exceed defined persistence thresholds, such as SOG-to-calculated speed differences greater than 10 knots, or course-heading gaps exceeding 45 degrees over multiple intervals, should trigger onboard alerts. These indicators directly correspond to the patterns identified in the AIS dataset, allowing ships to recognize spoofing-like conditions within minutes of onset.

6.2 Cross-referencing with GNSS Quality Metrics

Integration of basic GNSS diagnostics (e.g., signal-to-noise ratio, satellite count, and dilution of precision) enables vessels to differentiate between sensor drift and external interference. For instance, persistent navigation anomalies occurring while GNSS SNR remains above 40 dB-Hz suggest an artificial signal source rather than environmental obstruction (Psiaki and Humphreys, n.d.).

6.3 Incident Response and Data Sharing

Detected anomalies can be logged and transmitted to coastal monitoring centers or nearby vessels through AIS message extensions. Aggregated anomaly reports would allow regional authorities to identify interference “hot zones” and investigate recurring spoofing events. This decentralized reporting model offers a low-cost early-warning mechanism without requiring modifications to satellite infrastructure.

Together, these strategies provide a scalable foundation for maritime spoofing detection and mitigation. By combining onboard rule-based monitoring with lightweight data exchange, vessels can maintain navigational integrity and contribute to a broader situational awareness network, reducing the operational risks associated with localized GNSS interference.

The integration of AIS-based anomaly detection with ground-validated GNSS diagnostics establishes a comprehensive method for identifying spoofing risk in maritime navigation. By combining vessel-level behavioral analysis with regional signal verification, the study bridges empirical observation and applied defense strategy. This connection forms the foundation for a broader discussion on how localized monitoring can enhance maritime cybersecurity resilience.

7. Conclusion

This research investigated GPS spoofing vulnerabilities in maritime navigation through a dual analysis of AIS vessel trajectories and GNSS reference station data along the U.S. West Coast. The AIS analysis revealed distinct clusters of anomalous motion, such as speed spikes, erratic rotations, and course-heading deviations, concentrated near dense port regions. In contrast, GNSS reference logs from NOAA’s CORS network showed continuous, high-quality signal reception with no evidence of system-wide degradation.

The contrast between these datasets indicates that navigation irregularities are not caused by satellite instability but by localized interference, reflection, or deliberate spoofing within port environments. These findings suggest

that maritime spoofing and interference effects are geographically contained and operational in nature, emphasizing the importance of regional detection over global corrections.

Although the dataset analyzed in this study originates from December 2020, the research remains highly relevant to the 2026 maritime cybersecurity landscape. Since 2020, documented GNSS spoofing and interference incidents have increased in frequency and geographic scope, particularly in the Black Sea, Eastern Mediterranean, Red Sea, and other strategically important maritime regions. These events have demonstrated that vessel navigation systems remain vulnerable to manipulation despite advances in maritime cybersecurity awareness. While the data examined in this study are historical, the fundamental weaknesses of unauthenticated civilian GNSS signals have not been fully resolved. Therefore, the anomaly detection methods and mitigation strategies proposed here continue to address an active and evolving threat facing commercial shipping and maritime infrastructure.

The proposed detection framework translates these insights into actionable measures: continuous onboard consistency checks, correlation with GNSS signal metrics, and distributed incident reporting. Together, these tools can enable early identification of spoofing events and support coordinated responses among vessels and coastal authorities.

Overall, the study demonstrates that combining vessel-level AIS behavior with regional GNSS diagnostics provides a robust and scalable foundation for improving maritime navigation security. This approach supports both operational awareness and long-term policy development aimed at safeguarding the integrity of global positioning systems in maritime domains.

Ethics declaration: This research used publicly available maritime Automatic Identification System (AIS) data and Global Navigation Satellite System (GNSS) reference station logs obtained from open government archives. No human subjects were involved, and no personally identifiable information was collected or analyzed. All data used in this study describe vessel movement and signal quality at an operational level and do not identify individual operators or crew members.

AI declaration: Artificial intelligence tools were used in a limited capacity to assist with language refinement, structural organization, and clarification of technical explanations during the preparation of this manuscript. The AI-generated content was used primarily to improve readability, rephrase existing material, and suggest wording for summaries and explanatory sections. All technical analysis, data processing, methodology design, interpretation of results, and conclusions were developed by the authors. The authors reviewed, edited, and validated all AI-assisted text to ensure accuracy and alignment with the research findings. No AI tools were used to generate data, conduct analysis, or produce experimental results.

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Significance of Biological Design-based Strategies Towards Sustainability and Security in Space Biology Research: A Partial Taxonomy and Exploration

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Abstract: Biological design offers a promising framework for addressing the sustainability and security challenges associated with long-duration space exploration. By drawing upon biological principles such as resource cycling, modularity, hierarchical feedback, self-repair, and adaptive response, biological design can support the development of regenerative life-support systems, resilient infrastructure, and closed-loop operational architectures beyond Earth. As biological and digital systems become increasingly integrated within future mission environments, however, new cyberbiosecurity challenges emerge at the interface between living systems, automation, artificial intelligence, and cyber-physical infrastructure. This perspective paper examines the role of biological design in advancing sustainable and secure space biology. Through an exploratory review of relevant literature and the development of a partial taxonomy of biological design domains, the paper evaluates applications including autonomous biosafety, space bioprocess engineering, in-situ biomanufacturing, biologically grown architecture, and astro-ecological systems. Particular attention is given to Digital-to-Biological Attack Vectors, defined as pathways through which compromise of digital systems may produce unintended biological consequences within mission-critical environments. The paper offers the consideration that biological design should be considered as a sustainability strategy as well as a cyberbiosecurity imperative for future deep-space missions. By integrating biological resilience with secure digital architectures, biological design can contribute to the development of adaptive, regenerative, and cyber-resilient extraterrestrial ecosystems capable of supporting long-term human presence beyond Earth.

Keywords: Biological design, Cybersecurity, Space biology, Sustainability

1. Introduction

Biological design plays a foundational role in space biology by enabling both the investigation of cellular processes in extraterrestrial environments and the development of living systems to support long-duration missions. This imperative is driven by an increasing number of calls for sustainable space exploration, rejecting the current disposable mentality which relies on expensive, non-regenerative solutions that are environmentally and economically unsustainable for deep-space endeavors (Losch et al., 2024; Zimon et al., 2024). Products and solutions in space biology research and utility significantly impact the 17 Sustainable Development Goals. Therefore, there is a need for sustainable space development to be regarded as a goal, perhaps SDG 18, which in turn impacts the other remaining SDGs (Figure 1). This paper argues that biological design provides the critical conceptual toolkit for this required architectural shift, by leveraging inherent biological attributes, such as resilience, modularity, and self-repair, to secure the vital bio-digital interfaces that govern all future deep-space critical infrastructure.

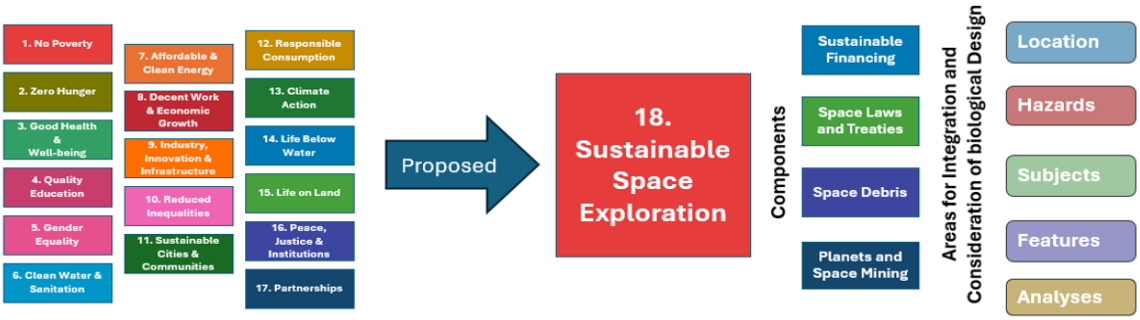


Figure 1: This figure was shown in poster form by Subramanian and Palmer at the 2025 American Society of Space and Gravitational Research Conference (Subramanian and Palmer, 2025) and illustrates the additional space-focused considerations within the proposed 18th SDG vs SDGs 1-17. It draws inspiration from figures in works by Afshinnekoo et al. (2020), Losch et al. (2024), and Zimon et al. (2024)

In this context, biological design is defined as the intersection of biomimicry and biodesign, integrating both concepts within products, architectures, and processes to support sustainability. Biomimicry solves design challenges by modeling nature's systems, forms, and functions (Verbrugghe et al., 2023), as demonstrated by optimization algorithms inspired by slime mold movement (Li et al. 2020) and ant colony navigation (Zhang et al. 2022). Biodesign, by contrast, incorporates living components directly into products (Myers 2012), including bio-concrete containing self-repairing bacteria (Seifan et al., 2016) and mycelium-based construction materials (Myers 2012). While biomimicry primarily promotes efficiency, biodesign emphasizes sustainability through regenerative materials and processes (Myers 2012).

As these technologies become autonomous components of life-support and habitation systems, they introduce cyber-physical resilience challenges through embedded digital control and monitoring. Cyberbiosecurity addresses vulnerabilities arising at the intersection of biological systems, digital technologies, and cyber-physical infrastructures (Greenbaum, 2023; Potter and Palmer, 2023). In space biology, it focuses on protecting digitally controlled biological systems supporting life support, bioprocessing, environmental monitoring, habitat maintenance, and in-situ resource utilization. In this paper, a Digital-to-Biological Attack Vector refers to any pathway through which manipulation of digital or cyber-physical systems produces unintended biological outcomes, including compromised bioprocesses, contamination events, degradation of biological materials, or broader mission-critical failures.

To explore biological design through a cyberbiosecurity framework, Section 2 presents a partial taxonomy of five domains: Autonomous Biosafety and Digital-to-Biological Attack Vectors; Space Bioprocess Engineering and Cyber-Resilient Digital Twins; On-Demand In-Situ Biomanufacturing and Responsive Diagnostics; Cyber-Physical Resilience in Biologically Grown Architecture; and Specialized Applications in Interplanetary Systems and Astro-Ecologies. This taxonomy provides a framework for identifying Digital-to-Biological Attack Vectors across each domain and links biological design to cyber defense requirements for deep-space infrastructure.

2. Potential Areas for new Biological Designs and Development

2.1 Autonomous Biosafety and the Digital-to-biological Attack Vector

As missions extend beyond low Earth orbit and into deep space, microbial contamination has emerged as a critical concern in habitat design and life-support systems. Contaminating microbes pose a dual threat: they can compromise astronaut health and degrade biologically integrated infrastructure. The management of microbial colonization must be an integral aspect of both the architecture and its maintenance systems. Addressing this concern requires the incorporation of new biological design strategies that are adaptive, self-monitoring, and capable of autonomous remediation (Dove et al, 2025). A simple and efficient way to address water contamination in hydroponic systems is to use a biological design approach where the water system itself mimics natural ecological niches, and at the same time integrates biological systems themselves into the product design. For example, using single-cell organisms such as ciliates that consume bacteria in freshwater systems (Dopheide et al., 2011). Due to the non-invasive and non-pathogenic nature of these ciliated organisms, no additional modifications need to be made to the system; regular maintenance of hydroponics, including improved filtration and UV sterilization, may be sufficient to maintain these mini-ecosystems. A growing field of micro and nanostructured surface engineering addresses several impacts on biomedical applications. The modifications performed to the surfaces of these materials are known to influence cell-material interactions (Luong-Van et al, 2013). However, an integration of principles of biological design will be required to increase the efficacy, durability, sustainability, and cost-effectiveness of the above products. For example, mimicking structures such as shark skin, cicada wings, etc., which are known to have anti-microbial properties due to their inherent design, will be crucial for product design (Jin et al., 2024). Additionally, adding a biodesign element to the product by using sustainable compounds such as chitosan that are both structurally robust and also biodegradable will be crucial to the sustainability of these surfaces. Studies are underway to program microbes to perform specific tasks, such as detecting contamination or releasing antimicrobial compounds in response to environmental triggers. For example, engineered biosensors embedded within habitat walls or air filtration matrices could be designed to fluoresce, change color, or alter conductivity in the presence of harmful microbial metabolites or biofilms. These sensors could interface with remediation strains programmed to produce biofilm-disrupting enzymes, antimicrobial peptides, or quorum-quenching molecules to inhibit microbial proliferation (Reed and Dunaway, 2019). This design strategy allows the architecture itself to become a dynamic participant in biosafety, shifting the burden of microbial control from manual to autonomous systems. However, a compromise of the digital interface governing these sensors and remediation strains could weaponize engineered organisms or disable critical remediation functions, turning a safety system into a significant vulnerability.

Microfluidics, specifically Lab-on-a-Chip (LoC) platforms, are crucial for the next phase of space exploration, which demands rapid, *in-situ* analytical measurements on other planets (Covone et al., 2021). Traditional analytical chemistry methods are ill-suited for remote space applications due to their requirement for advanced machinery, sterile conditions, and large sample volumes. LoC biosensors, offering miniaturization, a low chemical footprint, high sensitivity, and low payload requirements, are ideal for space biology (Cinti et al., 2023). A sustainable biological design strategy involves using microorganisms, such as the single-cell eukaryote *Tetrahymena*, as biological microbots for LoC systems. The well-studied chemotaxis, galvanotaxis, and artificial magnetotaxis in *Tetrahymena* can be leveraged under varying gravity conditions to gather complex information from Lunar and Mars samples using minimal fluid volumes (Kim et al., 2009, Kim et al., 2010; Kim et al., 2012; Hellung-Larsen et al., 1990). Furthermore, by feeding *Tetrahymena* ferromagnetic nanoparticles, these biological microbots can be used in artificial magnetotaxis experiments to establish ciliated cell substrates in fluid channels, potentially assisting microfluidic flow in LoCs by mimicking fluid movement in human tissue via ciliary wave motion. Hypothethically, as these biological microbots or analogues become integrated with autonomous sensing and analytical platforms, manipulation of sensor inputs, control algorithms, or communication pathways could alter sampling behavior and analytical outputs, creating additional Digital-to-Biological Attack Vectors within future space-based diagnostic systems.

2.2 Space Bioprocess Engineering (SBE) and Cyber-resilient Digital Twins

A burgeoning sub-field of space biology is the interdisciplinary area of design known as space bioprocess engineering (SBE). The goal of SBE is to develop and integrate biological systems that support the nutritional, medical, and environmental needs of astronauts during interplanetary missions and long-term habitation (Berliner et al., 2024). This includes not only producing oxygen and food but also fabricating pharmaceuticals, recycling waste, and maintaining air and water quality using biological processes. In this context, biological design becomes foundational; its principles enable the construction of systems that are not only functional but regenerative, self-maintaining, and adaptable to changing mission conditions. Rather than viewing biological components as isolated tools, SBE treats them as integrated modules that work in concert to reduce reliance on Earth-based resupply and enhance mission autonomy.

Biological design, as applied in SBE, draws on evolutionary strategies such as modularity, hierarchical feedback, and resilience to develop systems that can self-repair, grow in situ, and respond dynamically to environmental stressors. For instance, engineered microbial consortia may be programmed to switch metabolic pathways in response to carbon dioxide concentrations or radiation levels, supporting both air recycling and real-time diagnostics (Menezes et al., 2015). Similarly, growable biostructures such as fungal mycelium for habitat insulation offer low-mass, high-efficiency solutions for construction in off-Earth environments (Jones et al., 2017). The integration of biodesign with automation, synthetic biology, and material science in SBE ensures that bioprocessing platforms are not only robust and scalable but also capable of contributing to closed-loop life-support systems. As missions push beyond low Earth orbit, the relevance of SBE continues to grow, embodying a shift from passive environmental control to proactive, biologically driven adaptation. Securing the digital control systems governing these elements of modularity, hierarchical feedback, and self-repair is paramount to prevent catastrophic system failures that could arise from malicious interference.

Digital twins of complex biological systems can initialized with initial parameters and continuously updated with real-time sensor data, enabling predictive maintenance and autonomous control in simulated space missions (Homaei et al., 2024; Abraham et al., 2025). These sophisticated models can integrate sub-modules for factors like zero-G fluid dynamics and radiation-damage, allowing for the refinement of repair-pathway predictions and shielding designs. Furthermore, the use of closed-loop machine-learning controllers and advanced analytical sensors allows for dynamic adjustment of life support systems, while generative algorithms facilitate *in silico* evolution for trait optimization. These digital twins can be indispensible for cyberbiosecurity defense, enabling continuous, dual-domain anomaly detection by comparing real-time biological and cyber-physical signals against expected models, thereby flagging both compromised software and emergent bioprocess failures.

2.3 On-Demand In-situ Biomanufacturing and Responsive Diagnostics

Advances in synthetic biology, as described earlier, will be imperative to manufacturing fuels, self-repairing polymers, metabolizing products, and even generating energy and light. An integrated loop system, for example, exemplifies efficiency that can be achieved through combining biological factories with the precision of synthetic chemistry. Wallace and Balskus (2015) demonstrated that through pairing styrene-producing *E. coli* with designer micelles, complex chemical reactions can occur in a safe, water-based environment, eliminating the need for toxic solvents. This 'green' approach minimizes the hardware footprint while enabling the on-demand

synthesis of high-value materials from fuels to self- repairing polymers. This work has since been built upon by numerous teams for other products. These can promote the creation of valuable components in a sustainable way for long-duration space habitation.

Engineered organisms and biomaterials can be integrated into spacecraft interiors or environmental control systems to detect and respond to threats such as toxic gas buildup, microbial contamination, or equipment failure. For instance, synthetic gene circuits can be encoded into bacteria to fluoresce in the presence of specific contaminants or radiation levels, offering real-time bio-indicators for system health (Llorente et al, 2022; Koehle et al., 2023). By functioning as intelligent, living diagnostics, these responsive materials can enhance autonomy and reduce the operational burden on human crews. Their skillful, integration supports proactive risk management, particularly during missions operating in communication-limited environments. However, because these manufacturing and diagnostic systems rely on digitally controlled biological processes, they can be inherently exposed to Digital-to-Biological Attack Vectors. Compromise of sensor networks, control software, or genetic programming may suppress warning signals, manipulate outputs, or generate unintended biological outcomes within autonomous mission environments.

2.4 Cyber-Physical Resilience in Biologically-grown Architecture

Beyond low Earth orbit, biologically grown architecture offers a promising strategy for reducing launch mass while enabling adaptive, self-repairing infrastructure. Mycelium-based composites, algae-derived materials, and engineered living systems can support long-duration habitation through autonomous growth, repair, and environmental adaptation (Myers, 2012; Jones et al., 2017; Brandić Lipińska et al., 2022; Mitchell et al., 2025). In parallel, digital twin technologies and closed-loop biosensing systems increasingly used in terrestrial biomedical and industrial environments can be adapted for space habitats. These digital counterparts of biological systems enable real-time monitoring of growth rates, structural integrity, and biosafety conditions. Applied to space architecture, they could facilitate autonomous detection of stress fractures, environmental degradation, and biological contamination while supporting the targeted deployment of structural reinforcements and remediation measures. The integration of predictive modeling, artificial intelligence, adaptive biomaterials, and cyberbiosecurity-by-design principles can represent a significant advancement in the development of resilient infrastructure (Potter, Mossberg and Palmer, 2023; DiEuliis, Imperiale and Berger, 2024; Dove et al., 2025). By combining continuous monitoring with autonomous response capabilities, such systems can improve operational reliability while reducing dependence on human intervention in communication-limited environments.

By embedding adaptability, autonomy, and self-repair into structural materials, biological design strategies offer a transformative approach to off-Earth habitation. These approaches not only address the practical requirements of space biology but also extend the frontier of architecture toward systems that are responsive, regenerative, and inherently alive. Such concepts reflect an emerging vision of “living structures” capable of maintaining their own bio-integrity through continuous interaction between biological processes and digital control systems. Beyond operational functions, biophilic and bio-integrated habitats may also improve astronaut psychological well-being and cognitive performance during prolonged missions, particularly under conditions of isolation and confinement (Firth, 2022). Feedback derived from microbial colonization and environmental monitoring can reveal vulnerabilities in surface geometry, material porosity, and airflow patterns, informing iterative design improvements in habitats intended to grow, self-assemble, or adapt to extraterrestrial conditions.

However, the reliance on digital feedback introduces a critical cyber-physical vulnerability. Corrupted sensor data or compromised control systems could undermine autonomous resilience by providing inaccurate information regarding a habitat’s structural or biological condition. On Earth, contamination control in biomanufacturing environments often depends on resource-intensive sterilization protocols; in space, such approaches must evolve into lightweight, decentralized, and autonomous systems. Consequently, future biological designs may incorporate genetic sensors, self-healing biofilms, and cyber-physical interfaces capable of detecting and mitigating contamination in real time. In this context, microbial contamination management becomes a core design function within regenerative and responsive habitats (Greenbaum, 2023).

2.5 Specialized Applications: Interplanetary Systems and Astro-ecologies

Biodesign-based strategies for in-situ product synthesis include integrating products into spacewear, such as the 'Wanderers' collection by Oxman's research group, designed for astrobiological exploration. A key example is *Living Mushtari*, a 3D-printed wearable embedded with synthetic microorganisms to enhance biological function

and generate energy from sunlight (Mediated Matter Group, 2017). This biodesign utilizes a symbiotic association where photosynthetic cyanobacteria convert sunlight into sucrose, which then fuels other microorganisms (like *E-coli* or yeast) to produce pigments, drugs, food, fuels, or scents. The design's biomimetic aspect is a 3D-printed structure resembling the human intestine (58 meters of channels) that facilitates cyanobacteria flow via peristaltic-like movement. Transparent sections ensure sunlight access for the microorganisms. Other 'Wanderers' products share a similar goal: to interact with the destination environment to produce biomass, water, air, light, energy, bio-mineralized human bone, or fluorescence. Research, notably from Dr. Neri Oxman's former MIT Media Lab group, has explored biological design for space applications. The "Maiden Flight" project is a key example, sending queen and nurse bees within a metabolic support capsule aboard Blue Origin's New Shepard (Mediated Matter Group, 2021). This capsule, a 'synthetic astro-ecology,' combined human-made components with natural honeycomb-like structures built by the bees, offering a familiar, sustainable, and evolving environment. This biomimetic and biodesign approach is crucial for understanding crop pollination beyond Earth by addressing questions like the viability of reproduction and subsequent function upon Earth reintroduction (Strom, 2019). Integrating biological systems with wearables, autonomous habitats, and astro-ecologies requires complex interactions between living organisms and digital platforms. These bio-digital interfaces introduce Digital-to-Biological Attack Vectors through which compromised software or sensor systems may disrupt biological performance, ecological stability, and mission outcomes. Consequently, cyberbiosecurity is helpful as a foundational element in the design of future astro-ecological systems.

3. Discussion on Challenges in Sustainable Interplanetary Exploration

The integration of biological design principles offers a path for tackling the entrenched, systemic challenges of interplanetary endeavors. Beyond the immediate technical hurdles, missions face critical policy, economic, and ethical dilemmas, all of which are encapsulated by issues of long-term sustainability and planetary security that biological systems have navigated quite well over the course of evolution. Closed-loop material cycles, decentralized decision-making, and emergent robustness are all hallmarks of design and function found in biology that stakeholders can use to fundamentally shift away from an extractive, terrestrial-dependent model. The bio-inspired approaches mentioned as used towards modeling mission architectures on principles of biological resilience directly address the financial viability through resource circularity (e.g., in-situ resource utilization and waste recycling), strengthen legal and governance regimes by embedding self-repair and adaptability into protocols, and critically enhance planetary protection measures by fostering ecosystemic responsibility and minimizing biological contamination risks through contained, balanced systems. Dedicated and substantial funding for research into interplanetary sustainability and mission architectures is paramount. Nations that prioritize and achieve breakthroughs in these areas can gain a profound strategic, economic, and geopolitical advantage. This leadership will not only define the future of space exploration but also foster domestic technological innovation with broad applications, as they connect to many bio-adjacent industries with deep skill sets that have been left out of recent space-related economic growth initiatives. Blending expertise here provides the potential to position shrewdly led nations to the forefront of the next era of human endeavor.

4. Conclusion

Biological design offers a transformative framework for sustainable and secure space exploration by aligning mission systems with the adaptive logic of life itself. This paper's core contribution is the establishment of a partial taxonomy across five critical domains, systematically linking the promise of biological design directly to the necessity of cyber defense in deep-space critical infrastructure. The reliance on evolutionary strategies such as modularity, resource recycling, and self-repair must be coupled with robust cyberbiosecurity protocols to ensure resilient infrastructure. We illuminated how bio-integrated systems like Space Bioprocess Engineering and Biologically-Grown Architecture introduce critical Digital-to-Biological Attack Vectors that must be secured against malicious interference. Beyond technical security, this biologically driven approach offers models for tackling systemic policy, economic, and ethical challenges in interplanetary endeavors, promoting resource circularity and critically enhancing planetary protection measures. Ultimately, this requires a fundamental shift in human systems thinking from previous versions of seeking total environmental control to designing in harmony with ecological processes. Astronauts and mission specialists must be trained to steward these living systems and recognize emergent failure modes. By fusing imagination with ecological intelligence and embedding biological design into the fabric of future missions, humanity can build resilient, regenerative, and resource-aware extraterrestrial ecosystems, positioning ourselves as explorers of space, and more importantly, co-evolving participants in its living potential.

Ethical Approval: This study does not use human subjects. Therefore, ethical approval is not applicable.

AI Statement: This paper utilized tools within Google Docs, ChatGPT, and Grammarly for grammar checks & organization of pre-written text.

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Hybrid Threats Against the Finnish Society: Reported by YLE News

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Abstract: Hybrid operations aim at malicious political outcomes in targeted states and societies with strategic deception and shaping civic opinion. Some common hybrid threats are cyber-attacks on critical systems and disruptions of critical services, e.g. healthcare or rescue services. This study looks at how hybrid threats are communicated in mainstream Finnish media. The Finnish public broadcasting company YLE was chosen as the data source because it has a legal obligation to communicate issues without prejudice. Also, this makes it possible to conduct a future comparative study by selecting similarly relevant national news feeds from other countries. The sample, 57 news articles from the YLE English language news feed from between 2022 and 2025, discus hybrid threats. These articles in English were chosen for text analysis with Modeller 18.5 software which does not understand Finnish. Results identify "hybrid impact" as the most used term, with 27 articles mentioning it, while 15 articles mention "hybrid threats" and "hybrid warfare". Analysis of co-occurrences reveals substantial links between government actions, security institutions, and Russia as a major geopolitical actor. The findings indicate that hybrid threats are multifaceted challenges that require coordinated national and international responses. The study helps comprehend how media portrays hybrid threats and suggests the need for more research using native language analysis and broader media sources. The study identifies the frequency and boundaries of key terms related to hybrid threats, in particular hybrid impact, hybrid threats, and hybrid warfare, in YLE news coverage. The analysis of co-occurrence patterns and conceptual connections in the sample texts reveal how hybrid threats are related to actors, institutions, and geopolitical contexts. This scientific contribution of this study is deeper understanding how media contribute to and shape public awareness and understanding of hybrid threats and national responses in Finland; and the practical contribution of the study are its insights into hybrid threats and suggestions on response and future research directions.

Keywords: Hybrid threats, Hybrid impact, Hybrid warfare, Finnish media, Finnish Society

1. Introduction

Hybrid operations are used to achieve desired political outcomes in affected states and societies (Giannopoulos et al., 2021). Hybrid threats may range from cyber-attacks on critical systems to disruptions of critical services, such as energy, banking, and security or rescue services (European Union, 2018; Giannopoulos et al., 2021). Increased use of hybrid influence methods may lead to asymmetric warfare, which is the continuous use of special forces, precision bombs, missiles, electronic and guerrilla warfare, terrorist attacks, and biological or chemical weapons before and during actual war (Arreguín-Toft, 2001; Mack, 1975). Asymmetries are combinations of deception, surprise, and abuse (Cederberg & Eronen, 2015).

Objectives and research questions

This study explores how Finland's national broadcast company YLE reports on how hybrid threats target the Finnish society. The research used Modeller 18.5 text analysis software to examine 57 news articles in English published between 2022 and 2025. The findings reveal that *hybrid influence* is the most frequently used term, indicating a broad and evolving understanding of hybrid operations in public discourse. Co-occurrence analysis highlights strong associations with governmental responses, security institutions, and geopolitical actors, particularly Russia. The study underscores the importance of strategic communication, cross-sectoral cooperation, and resilience in countering hybrid threats, while also identifying limitations related to language translation and sample scope. These insights contribute to a deeper understanding of how hybrid threats are framed in Finnish media and offer directions for future research.

The research question of this study is: How does YLE national news report hybrid threats against Finnish society?

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Structure of the report

The study is structured as follows: after this introduction section, the theoretical background, definitions and conceptualisations of hybrid threats are presented. The method describes the data collection and analysis tool, while the results present findings, including term frequencies and concept maps. In the conclusions, the results and implications are interpreted, limitations and challenges discussed, and suggestions and recommendations for future research are made.

2. Hybrid Threats

Hybrid threats can be referred to as e.g. disregarding standard rules of warfare with the use of irregular forces in different battlefield domains (Kirk, 2023) or as simultaneous and adaptive uses of political, military, economic, social, media, terrorism, and irregular, disruptive or criminal conflict methods and combinations of these (GAO, 2010).

The European Centre of Excellence for Countering Hybrid Threats (Hybrid CoE) defines the term hybrid threat as "… an action conducted by state or non-state actors, whose goal is to undermine or harm a target by combining overt and covert military and non-military means" (Hybrid CoE, 2021, p. 1), while Hoffman (2007) sees them as "Threats that incorporate a full range of different modes of warfare, including conventional capabilities, irregular tactics and formations, terrorist acts including indiscriminate violence and coercion, and criminal disorder, conducted by both states and a variety of non-state actors" (Hoffman, 2007, p. 8).

Mäkelä (2018) describes hybrid action as "a systematic activity in which a state or non-state actor can simultaneously utilise various military means or, for example, economic or technological pressure, as well as information operations and social media" (Mäkelä, 2018, p. 13) and (Puistola, 2018) sees information influence as a strategic deception in which the subject's perception of reality is obscured to achieve the attacker's strategic goals.

Modern social media can be a powerful contributor in shaping civic opinion and for strategic deception, hiding one's final goals and maintaining a facade of legality, and global input of one's narrative through various media (Puistola, 2018). Threats and disruptions to critical vulnerabilities seek to influence public confidence, hamper effective decision-making and create polarisation within the affected society (European Union, 2018; Giannopoulos et al., 2021). Often hybrid influencers aim to keep hybrid effects at a level where escalation into open conflict does not occur by applying effects in ways that are disputable (Mäkelä, 2018). Russia has, for example, intensified hybrid actions that target Western countries with e.g. extensive disinformation campaigns, interference in electoral and democratic processes, political and economic pressure and intimidation, and harmful cyber functions that target to disrupt critical infrastructure, including e.g. knowingly allowing cyber criminals to operate from its territory (NATO, 2021).

Key efforts to combat hybrid threats are awareness, resilience, and response, which combined improve abilities to detect and understand adverse actions at early stages and help improve the sustainability of critical infrastructure, societies, and institutions; close cooperation between European EU Member States, as well as with partner countries and NATO, help combat hybrid threats (European Union, 2018; Giannopoulos et al., 2021). Hybrid influence uses shadow regions where threats are unexpected, and notes that the Finnish model that combines various administrative sectors could be a useful policy for other countries (Finnish Government, 2024).

Hybrid operations focus on identifying weaknesses in the target country (Cederberg & Eronen, 2015) by attacking specific weaknesses with varying tactics and tools and intensity, intending to outperform the strengths of the society under attack (Tikanmäki & Ruoslahti, 2022). Means include political and economic instruments, cyber warfare, threats with military force, cyber operations, and the use of special forces (Cederberg & Eronen, 2015). The use of hybrid tools puts pressure on the destination country, and fighting against their usage requires policy coordination and close cooperation; the EU Strategic Compass and the NATO strategy help the fight against hybrid threats (European Commission, 2020).

(Tikanmäki & Ruoslahti, 2021) note that internal and external security are difficult to separate, as the operational environment is constantly changing in today's globalised world. The Ministry of the Interior of Finland (2016) recommends that actors and authorities exchange staff to better develop operating models towards improved situational awareness and lessening cross-sector barriers that prevent information exchange between administrative sectors (Tiimonen & Nikander, 2016). A situation picture of hybrid influence can be formed by extracting sector-relevant information and drawing real-time conclusions to form a common understanding that

is recently detected or obtained with the latest and confirmed true observations to form a continuity estimate and forecast influencing the decision. (Hyytiäinen, 2021).

3. Method

The Finnish public broadcasting company YLE's Finnish language news feed was chosen as the data source because it is legally obligated to discuss issues without prejudice. Also, this choice will enable future comparative studies possible of public broadcasting company news feeds from other countries, e.g. in the Baltic Sea Region, which are similar targets of hybrid influence.

The first step of the research was to collect data on articles related to hybrid influence that were searched from YLE text news articles in the spring of 2025. Search words hybrid influence, hybrid threats, and hybrid warfare were used, and the search period was from 2022 to 2025. The following table summarises the search words, the number of articles found, and the period from which the findings are from (Table 1).

Table 1: Search words, number of articles found, and period of publication

Search words	Number of articles	Article dates
Hybrid influence	27	4.3.2022-6.5.2025
Hybrid threats	15	4.3.2022-3.4.2025
Hybrid warfare	15	4.5.2022-5.3.2025

Table 1 shows that the articles found were published roughly within the last two years. The term *hybrid influence* (n = 27) was mentioned in almost twice as many articles as the terms *hybrid threats* (n = 15) and *hybrid warfare* (n = 15). The second phase was to transfer the sample article (n = 57) texts via Excel into the Modeller 18.5 text analytics software.

Modeller 18.5 software was chosen for the analysis of the sample of journalistic reports of hybrid threats against Finnish society. Because the Modeler software cannot analyse Finnish texts, the final sample consists of 57 original YLE articles that were written in or translated into English by YLE. Finnish is not an Indo-European language; its different structure and specific vocabulary may make exact translations challenging. Though YLE's English versions have received journalistic approval, some connotations in the translations may slightly differ from the original articles. This conversion, however, would not allow for variations to be distinguished and would not have a significant impact on the results.

The third phase was to analyse sample article texts with Categories and Concepts, with Category Bar as the main method of analysis. *Hybrid Threats* (with co-occurrence links) show the joint species distribution model evaluates distributions of several characters simultaneously and decomposes characters into co-occurrence patterns into parts, and describes concerned environmental reactions and remaining patterns of co-occurrence (Pollock et al., 2014). Concept maps can be used to organise and structure knowledge. The Hybrid Concept web model concept map or conceptual diagram focuses on a diagram that describes proposed relationships between concepts (Hager & Corbin, 1997). The confidence metric method is a way to measure behaviour, system or interest. Unknown Hybrid threads confidence metric method verifies the popularity of a subject and shows if it had a positive or negative impact on the exposed thing (Keefer et al., 2013).

4. Results

Results show that the term *hybrid influencing* occurred in the sample articles nearly twice as often as the other two searched terms, *hybrid threats* and *hybrid warfare,* combined. The sample size (n = 57) demonstrates that hybrid threats, warfare, and influence have been a topical issue between 2022 and 2025.

4.1 Co-occurrence Links from Hybrid Threats

The term *Hybrid threats* was classified by Modeller in six categories in the sample of YLE news articles: combat hybrid threats, major hybrid threat, hybrid threat centre chief and counter potential hybrid threats and hybrid threat of the sample texts (Table 2).

Table 2; Categories of Hybrid threats from Modeller text analysis

Category	Connection
Counter potential hybrid threats	Positive to *Hybrid threats*
Hybrid threats	Positive to *Hybrid threats*
Hybrid threat centre chief	Positive to *Hybrid threats*
Major hybrid threat	Positive to *Hybrid threats*
YLE hybrid threats	Positive to *Hybrid threats*
Combat hybrid threats	Positive to *Hybrid threats*

This analysis is based on the sample of 57 YLE news articles in English because the Modeler software does not recognise Finnish. Due to this language conversion, translation variations may occur when processing the material. However, the conversion does not change the results in a way that would allow for any variation to be distinguished.

The Categories and Concepts, with the Category Bar method of analysis in Modeller 18.5 Text analysing software, produced co-occurrence links from the term *hybrid threats*: practice, learned situations, limits, involvement, properties, the interior ministry and reports. Times like Thursday, and last year explain the reports' activity in the press. Russia was mentioned most often in hybrid threats (Figure 1).

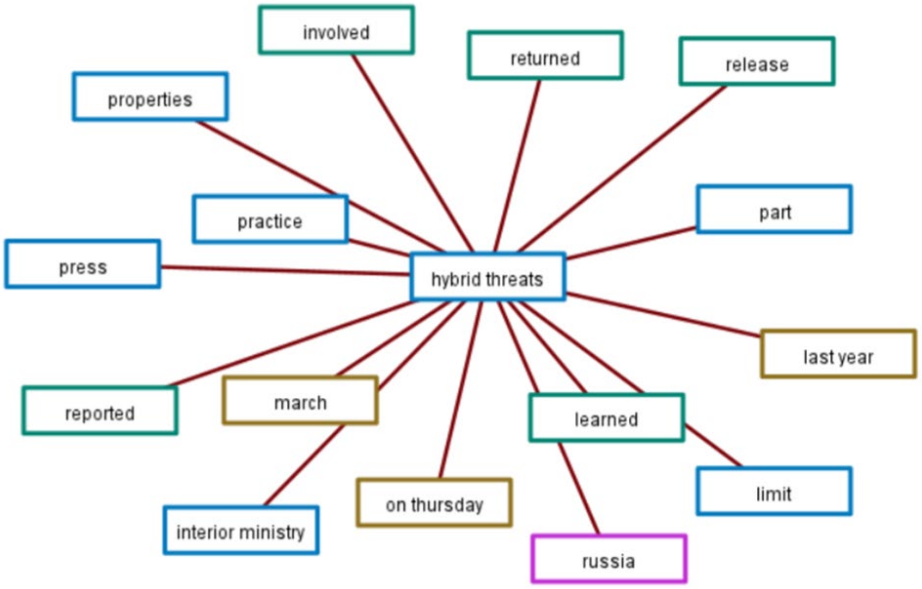


Figure 1: Links to *Hybrid Threats* (with co-occurrence links)

Lines between the boxes indicate connections, and the length of these lines indicates closeness of connection (Figure 1); the colour boxes show action (green), concepts (blue), reference time (brown), and location (purple).

The central term *Hybrid threat* is defined as a concept (blue box), as are practice, part, press, properties, limit, and interior ministry. Of these, practice has the closest link with Hybrid threat. Examples of practice include, e.g. these direct quotes: “Defence Committee backs amendment to expedite calling Border Guard reservists to deal with hybrid threats.” and “Aggression should not be rewarded. Member of Parliament Kiljunen on sick leave following committee chair resignation. Border Guard apprehends Finnish citizen for crossing into Russia.“

The location with a co-occurrence link with the Hybrid threat is Russia. Sample texts include, e.g. these quotes related to the name Russia: “Finnish Security and Intelligence Service SUPO: Russia remains top of Finland's security threat concerns”, “Foreign minister of Finland: Finland to strengthen response against shadow fleets and hybrid influence”, and “Defence minister of Finland: Finland prepared for hybrid influence attempts “.

Three examples about concepts report and involved: “Finnish Security and Intelligence Service SUPO: No increase of cyberattacks in Finland, despite NATO application. Cyber Centre: No increase in cyber-attacks since NATO application. “and “There has been no noticeable increase in the number of cyber-attacks being reported to the National Cyber Security Centre since Finland submitted an application to join the NATO“ and “The war in

Ukraine as well as Finland's application for NATO membership were expected to increase the number of cyberattacks targeting Finland, but so far this has not been the case“ and “The situation may be due to the accelerated speed of Finland's NATO application, which may have taken Russia by surprise, the intelligence service says “

It seems like many news releases and stories are from Thursday, as this is connected and demonstrated in these news examples: “Finnish Members of Parliament on Thursday approved changes to the country's border laws that will enable authorities to shut down borders or limit the number of border crossing points during exceptional circumstances. “

4.2 Hybrid Coe (Concept web Model)

Concept web models (Figure 3) show that hybrid coexistence has strong connections to consequences, full protection, support from other countries and no support from all others. Solid lines between variables indicate a direct connection and dotted lines indicate a loose connection.

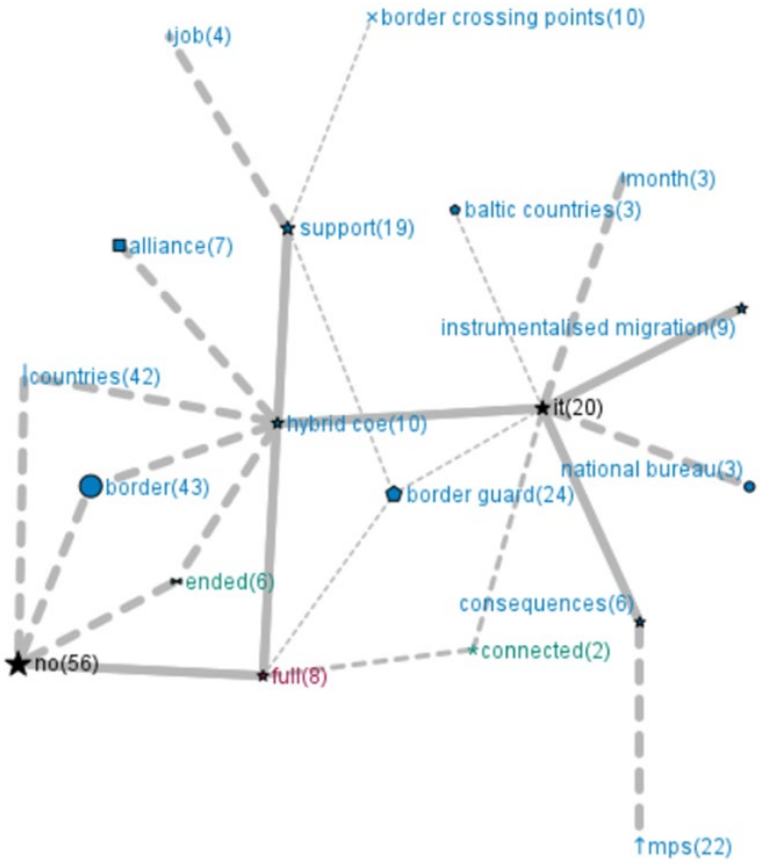


Figure 2: Hybrid Coe (Concept web model)

There are connections to instrumentalised migrations, national bureau, border, other countries, alliances, jobs to do, and Russians were ending. Thinner connections are border guard, connections to hostile countries, border crossing points and Baltic countries.

Examples from news on instrumentalised migration and border include: “Finland's land border crossings with Russia have been closed for about a year, due to Russia funnelling asylum seekers from third countries to the border. The practice is called instrumentalised migration, a form of hybrid warfare. “

Examples that write about Members of Parliament: “Finnish MPs on Thursday approved changes to the country's border laws that will enable authorities to shut down borders or limit the number of border crossing points during exceptional circumstances. “

5. Conclusions

The growing significance of hybrid threats in the Finnish national debate is highlighted in this study, which can be seen in YLE news coverage in 2022–2025. Analysis of the sample data indicates that the term *hybrid influence*

appears more often than *hybrid threats* or *hybrid warfare*, indicating a wider range of concepts in media stories. Strong links between co-occurrence analysis and government actions, security institutions, and geopolitical actors, particularly Russia, indicate that hybrid threats are seen as both internal and external challenges.

The findings show the importance of strategic communication, situational awareness, and multidisciplinary cooperation in addressing hybrid threats. The Finnish model, which integrates various administrative sectors, seems to be a promising strategy for addressing crises and responding effectively, and can serve as a model for other nations.

Limitations of the study

The study was based on English versions of originally Finnish articles. Even though these translations have journalistic approval, the subtleties and connotations may differ from the original Finnish texts, which may affect the precision of the semantic comparison. The use of texts in English is necessary as Modeller 18.5 does not process Finnish. Native language analysis tools could have captured more linguistic and cultural context, but this limitation prevents them from being captured completely. It is possible that the articles do not accurately depict longer-term trends or changes in hybrid threat narratives over time since they focus on the years 2022–2025.

Suggestions for future research

Future research should examine how hybrid threats are presented in various contexts. This could be achieved by expanding the research to other media channels and international news coverage, e.g. on the Eastern flank of the Baltic Sea Region. Examining the role of social media platforms in shaping public perceptions and spreading the hybrid effect could improve traditional media analysis. Future research could examine how media reporting on hybrid threats can affect public policy, government responses, and international cooperation strategies.

Acknowledgements

Acknowledgements are paid to the “Improving rescue services preparedness for hybrid threats” project, funded by the Fire Protection Fund and conducted in collaboration with the Finnish Association of Fire Officers. The views expressed are those of the authors, and the granting authority cannot be held responsible for them.

Ethics declaration: Ethical clearance was not required for the research.

AI declaration: The paper's spelling was verified using the artificial intelligence tool.

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ECUInjector: An Automotive ECU Security Analysis Tool

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Abstract: Electronic Control Units (ECUs) are responsible for a significant number of systems in modern day vehicles. If these systems are compromised, the resulting attacks will result in road accidents. Therefore, increased adoption of these systems has significantly widened vehicle attack surfaces. As a result, it is important to devise methods of identifying and investigating vulnerabilities within automotive control systems, allowing them to be patched before they are exploited by an attacker. To this end, we present *ECUInjector*, an open-source application designed to assist in the discovery of vulnerabilities within diagnostic interfaces and ECU communications. The software is designed in a modular way allowing it to be universal across ECU vendors and provides the ability to communicate via vehicle diagnostics buses and build vulnerability detection tools that can assist in locating potential weaknesses. We also provide some of our applications of using the software to communicate with and analyse various ECUs.

Keywords: Automotive security, Reverse-engineering, Embedded system security

1. Introduction

Electronic Control Units (ECUs) are responsible for a significant number of systems in modern day vehicles, particularly in the areas of powertrain, safety and comfort. Vehicles now contain hundreds of these units (Dijk, 2017), replacing many components that were once purely mechanical. Whilst this has been positive move in terms of efficiency and customisability, the increased adoption of such systems has significantly widened vehicle attack surfaces. As with other computer-controlled systems (e.g., networking hardware and consumer devices), vulnerabilities may exist within ECUs that leave them susceptible to attack, increasing the likelihood of road accidents (Onuma, Terashima and Kiyohara, 2017). On top of this, the constant development of these systems, increases the likelihood of vulnerabilities being introduced (Shin *et al.*, 2011).

Interconnectivity between ECU systems, as well as external diagnostic interfaces are a major target for attackers. Interconnected buses provide a means for one ECU to performed attacks towards other ECUs. On top of this, ECU diagnostic interfaces provide advanced functions (such as firmware modification), which can make it trivial for attackers to manipulate systems. It is therefore important to explore methods that vulnerabilities within automotive control systems can be identified and reported, before they can be exploited by malicious parties. This enables patches to be released that can fix these vulnerabilities, protecting road users.

With this in mind, this paper presents *ECUInjector*, an open-source application designed to assist in the discovery of vulnerabilities within diagnostic interfaces and inter-ECU communication systems. The application provides the ability to establish serial communications with various automotive control systems. On a basic level, commands can be sent and received to connected ECUs, whilst on a more complex level, advanced reverse-engineering scripts and tools can be developed to help locate vulnerabilities and weaknesses. Due to the number of standardised communications protocols that exist, *ECUInjector* has been designed using a modular approach, enabling protocols to be added as required. The software is also multi-platform, enabling its use across Windows and Mac systems.

2. Background

Modern vehicles contain numerous electronic control systems that are relied upon to monitor and control functions including engine management, braking, passenger safety and entertainment. Various legislative standards (US Environmental Protection Agency, 1990; European Union, 2002) have been introduced over the past 30 years requiring the use of these systems (with a particular focus towards On Board Diagnostics (OBD) (Gardetto, Bagian and Lindner, 2005)) from both a safety and environmental standpoint. Increased demands for driver assistance and comfort features have also led to an increase in the adoption of ECUs, resulting in new vehicles containing more than one hundred individual units (Prabhakaran, Thirumoorthi and Sri Dhivya Krishnan, 2024).

2.1 Inter-ECU Communications

ECUs within a vehicle are interconnected to enable the exchange of data, allowing sensor data from one system to be consumed by another. Road speed, for example, is a value often required by multiple ECUs, however only one ECU will have the physical sensor connections to determine the value. This information will therefore be shared onto the bus for other ECUs to make use of.

Technologies such as CAN (ISO, 1993), FlexRay (ISO, 2017) and LIN (ISO, 2016) are all examples of protocols that are utilised to implement ECU communications buses. These specifications provide guidance for the physical (wiring specifications) and data link (packet structures) layers of the buses, however the implementation of the application logic remains ECU specific. Modern vehicles often utilise multiple independent buses for different systems, with gateway ECUs providing a way to pass data between them (Robert Bosch GmbH, 2007).

2.2 Automotive Diagnostics

On-board Diagnostics (OBD) (European Union, 1998) provides a way to program and diagnose the ECUs within a vehicle and has been a legal requirement since the early 2000s (European Union, 2002). Diagnostics is performed via a dedicated OBD (J1962 (SAE, 2015)) port, which connects a diagnostics device into the vehicle's communications buses, allowing it to perform individual operations on each ECU. Dedicated protocols are defined for diagnostics communications, with some manufacturers implementing their own standards before the introduction of legislated protocols such as KWP2000 (ISO, 2000), UDS (ISO, 1998) and later DoCAN (ISO, 2004), which is utilised in vehicles today.

Diagnostic standards were adopted as part of legislation to enforce access to emissions related data, with protocols such as KWP2000 and DoCAN providing dedicated functions to ensure their compliance. Manufacturers often extend these protocols to support their own privileged operations, such as factory test procedures, dealership programming operations, and firmware updating mechanisms. Due to the advanced nature of these operations, access to these privileged operations is a security threat, and their presence therefore widens the attack surface of the vehicle. As a result, these advanced functions are often protected by security mechanisms designed to restrict access to those unaware of the relevant unlocking procedure (Van den Herrewegen and Garcia, 2018). Many early systems utilised basic "seed-to-key" algorithms, which could easily be circumvented, thus allowing malicious parties to gain access and leverage privileged operations to perform attacks (Pełechaty and Konieczny, 2024). Modern systems are adopting more secure methods using technologies such as certificates.

3. Related Work

The following section details some existing ECU communications and security analysis tools, as well as some existing work being carried out into automotive security research and the methods utilised in each case.

3.1 Existing Software

Software that interfaces with ECUs is widely used outside of security contexts, with a prevalent area being vehicle modification and independent repair. Remapping software such as MEMS Tools (Revill, 2026) and BimmerEditor (Bim-Tun, 2020) are primarily designed for tuning specific ECUs and utilise diagnostic interfaces to read and modify firmware. These tools typically provide graphical user interfaces that visualise engine calibration data as 2D or 3D tables, enabling users to adjust parameters with minimal effort; some tools additionally include advanced features such as live remapping and debugging. To utilise these tools, an inexpensive OBD-to-USB dongle is required. As such, with little understanding of the underlying diagnostic protocols, advanced modifications can be made due to their low barrier to entry; combined with their generally low-cost, these tools are attractive to hobbyists and independent tuning shops. However, due to being targeted at remapping specific ECUs, these tools tend not to be universal and provide limited access to the diagnostic interface beyond what is required for their dedicated functions.

General purpose libraries for ECU communications are also available but tend to focus on either a single or few diagnostics protocols exclusively. Python libraries, such as "python-udsoncan" (Pier-Yves Lessard, 2026) and "KWP2000-CAN" (Elias Kotlyar, 2026) provide low-level communications support for ECUs and expose defined diagnostics services as a Python API, which can be utilised across many platforms. These libraries reduce the time needed to develop scripts and tools to interact with ECUs and offer a large amount of flexibility as the open-source nature of these libraries enables modification as required. However, these libraries do not stand on their own in terms of them being stand-alone applications, so provide no GUI or pre-existing reverse-engineering functionality, and therefore require development expertise and time to utilise them in this way.

Commercial automotive software solutions, such as Vector CANoe (Vector, 2026), offer the ability to simulate and test ECUs and their diagnostic interfaces. CANoe, enables the testing of the diagnostic interface through an automated extension and using a range of protocols including UDS and KWP2000. Other tools such ETAS INCA (ETAS, 2026) and dSpace ControlDesk (dSpace, 2026) include comparable ECU and diagnostic simulation interface capabilities. These software suites are aimed at automotive ECU manufacturers who need to verify the implementation of their systems, and as such require costly commercial licences. This software is designed for validating implementations, usually focusing on accurate reporting of diagnostic trouble codes and API commands and are not aimed at security analysis or vulnerability identification. Also, due to the software being aimed at developing new systems, they often lack support for older communications standards, such as ISO9141 (K-Line).

3.2 ECU Security Research

The security mechanisms of UDS (and by extension KWP2000) are frequently targeted during security analysis of diagnostic interfaces. Pelechaty et al. (Pełechaty and Konieczny, 2024) explore the shortcomings of various randomly selected ECU diagnostic implementations using a custom test harness based on an off-the-shelf microcontroller. Through black-box penetration testing, vulnerabilities are found in the implementation of the "SecurityAccess" API method, which is based on a manufacturer specific seed-to-key algorithm, with unsuitable key lengths utilised that are susceptible to brute-force attacks. The same algorithms are also identified across multiple ECUs. In another study, Lauser and Krauß (Lauser and Krauß, 2023) use formal analysis techniques to identify vulnerabilities in security functions of both KWP2000 and UDS, which both utilise seed-to-key as well as more sophisticated cryptographic certificate-based protocols. They find variants of the included authentication protocols that are potentially vulnerable and confirm weaknesses in the KWP2000 security service attributed to weak standards and poor implementation. In a later study, Lauser et al. (Lauser, Munoz Molto and Krauß, 2024) use their previous findings to simulate an attack on an ECU implementing a weak variant of the authentication service. Using CANoe (Vector, 2026) to simulate a vulnerable ECU, they successfully execute a man-in-the-middle attack using a python script to intercept communication between the simulated ECU and an external testing tool.

These studies consistently show how vulnerabilities in diagnostic interfaces can be exploited using inexpensive hardware and software. Relying upon the manufacturer to implement the security mechanisms is pointed to as failures of protocols such as UDS. Despite these investigations exploiting the same diagnostic interface, the lack of standard tools used makes the work less repeatable. Studies often use custom test benches that are hard to replicate and tightly coupled to specific hardware setups, custom scripts or expensive software, limiting reproducibility and comparison of techniques. This lack of a common framework for analysing ECUs may also hinder the systematic analysis of non-security-related services. With evidence showing vulnerabilities occurring more commonly from implementation rather than protocol design alone, physical testing is a requirement.

4. ECUInjector

ECUInjector is an ECU reverse-engineering and vulnerability analysis tool, which allows researchers to communicate with automotive systems and work with the APIs and protocols to identify vulnerabilities. As demonstrated in Section 3, various software tools already exist that are extremely capable at communicating with ECUs, however they tend to either focus on one model or range (so their capabilities are often not transferrable) or not support vulnerability analysis. *ECUInjector* is maintained as an open-source project (available at: https://github.com/UoN-CybSec/ECUInjector).

4.1 Design Considerations

Having discovered that existing tools are either too specific to work on the majority of ECUs or lacking in necessary vulnerability analysis features, we designed the following requirements for *ECUInjector*:

- **Universal:** *ECUInjector* is compatible with many different ECU systems, protocols and implementations. This ensures that ECU vulnerability analysis can be carried out easily, without the need to build extensive software solutions, thus removing a barrier to entry (in terms of expertise and development time).
- **Diagnostic Protocol Support:** Enabling common protocols (KWP2000, CAN, KWP1281) to be defined and reused across projects, further reduces barriers to entry. Whilst many aspects of ECU design are specific to each ECU or manufacturer, many of the communications protocols that they utilise are

universal. Having a way to define a protocol and use this across projects enables a large part of the communications logic to be reused across ECUs that support the same protocols.

- **Custom Commands**: Whilst many diagnostic protocols contain a significant number of predefined operations, they also contain scope for ECU manufacturers implement own commands into the API, which are of particular interest to vulnerability analysis efforts. The tool therefore allows commands to be added on top of an existing protocol implementation to support custom operations. These are also particularly helpful when a manufacturer has not followed the protocol exactly, allowing small changes to be made to predefined command logic (discussed in Section 4.2.2).
- **Tool Creation:** On top of sending and receiving commands, the software supports the ability to create custom command scripts that can be used to build reverse-engineering tools against the diagnostic capabilities of the ECU (discussed in Section 4.2.2).
- **Cross Platform:** Use of C++ as the primary language for the application, as well as use of the standard library where required, enables *ECUInjector* to work across both Windows and Mac platforms, allowing researchers to use any system.
- **Graphical User Interface**: A GUI interface is utilised to present the necessary options to the user. The GUI contains a console which displays messages sent to and received from the ECU, as well as a command pallet and buttons to manage the active serial connection.
- **Project Based:** At any one time, users of the software may be working on multiple different reverse-engineering projects. It may also be necessary to share these projects between researchers, enabling collaboration. *ECUInjector* is therefore project based, with each ECU's commands, scripts and configuration stored individually.

4.2 Software Implementation

The system is designed around the concept of sending *commands* to ECU systems. These commands can either exist directly (in the form of hexadecimal data) or as scripts (which perform specific calculations and generate the relevant hexadecimal data accordingly). *Projects* are utilised to group a set of commands for a specific ECU. The below sections discuss these concepts in more detail.

4.2.1 Projects

Projects store relevant elements (commands, scripts and configuration) in a single organised location. Each ECU being analysed is given its own project, allowing for the centralisation of relevant commands and scripts. This is especially helpful If working across multiple different ECUs (an instance of the tool can be launched for each project). Collaboration is also enabled between researchers through sharing project files. Projects store the following elements:

- **Commands** created within the project, with their name (which is displayed in the UI), type (Raw or Script), value (for Raw scripts), and whether they should be triggered periodically.
- **Scripts** in the form of LUA source files, which are called when the associated command is triggered.
- **Globals** also in the form of LUA source files, which provide a way of defining centralised logic that can be used by the script commands (ECU commands, protocol implementations etc.).
- **Project Manifest File** storing the projects name (displayed in the GUI title bar) and intended for future expansion.

4.2.2 Commands

A primary feature of *ECUInjector* is its ability to exchange commands with ECUs. As discussed in Section 2, ECUs utilise many different protocols for communications (both in terms of diagnostics as well as inter-ECU buses). This remained in mind when designing the different types of commands, ensuring that extensibility was maintained where possible:

- **Direct commands** enable hex values to be entered straight into the command prompt, which are then delivered directly to the ECU, thus circumventing the parsing and interpretation elements of the software. ECU responses are monitored and, if received, will be displayed in the console. These commands are best used when performing initial experiments with an ECU's protocols, before creating more permanent commands once identified.

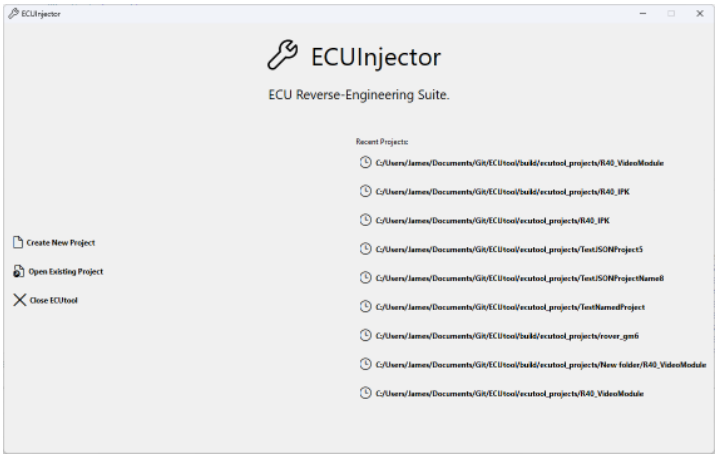


Figure 1: *ECUInjector* Start Window

- **Raw commands** work in the same way as direct commands, however, can be saved into a project for reuse. These commands also circumvent the parsing and interpretation elements of the software, and are particularly useful when manufacturers have utilised commands that do not entirely fit with existing protocols, or for simple experimentation with commands that have few static arguments. An added feature of static commands is their ability to be sent periodically, based upon a time interval, which allows them to be used as "keep-alive" signals, maintaining a diagnostic session with an ECU (after initialisation).
- **Script commands** have a LUA script file associated them which has access to an API to send and receive commands and write to the console. This gives them the ability to perform more complex operations that may require multiple command exchanges with calculations being performed in-between. These commands can be sent directly, or accompanied by arguments in the command prompt, enabling data to be fed into the underlying LUA script. The underlying LUA script has enabled implementation of "seed-to-key" authentication, firmware extraction, and building reverse-engineering tools.
- **Protocol Implementations** provide the ability to extend the software to support established communications protocols (such as KWP2000, CAN etc.), where packet structures, arguments and checksums are defined in C++ logic. Script commands can make use of this logic via the API within their associated LUA scripts.

4.3 Software Overview

The following section describes the process that a user takes to perform analysis on an ECU using *ECUInjector*.

4.3.1 Start screen

The start screen (Figure 2) provides users with the ability to create a new project (allowing them to define a folder to store the project's files), open an existing project, or close the tool. A list of recent projects is also displayed, allowing users to quickly access projects that they have been recently working on. Once a project has either been created or selected, the Diagnostics Screen is launched.

4.3.2 Diagnostics screen

The diagnostics screen is where ECU communication and analysis is carried out and provides the following functionality (see Figure 3):

- **Toolbar** (1)**:** Provides project operations (open, save, save as) and connection management.
- **Command Palette** (2)**:** Lists the commands that are part of the current project, with options to run, edit and delete each command and hide associated console output.
- **Console** (3)**:** Displays commands sent (from the software to the ECU), commands received (from the ECU into the software), and script output (which is defined within each of the LUA scripts associated with Script commands).
- **Command Prompt** (4)**:** Provides a way to manually enter hex commands to be sent directly to the ECU, and supply arguments to commands.
- **Status Bar** (5)**:** Displays serial port connection information (protocol, COM port, baud rate etc.).

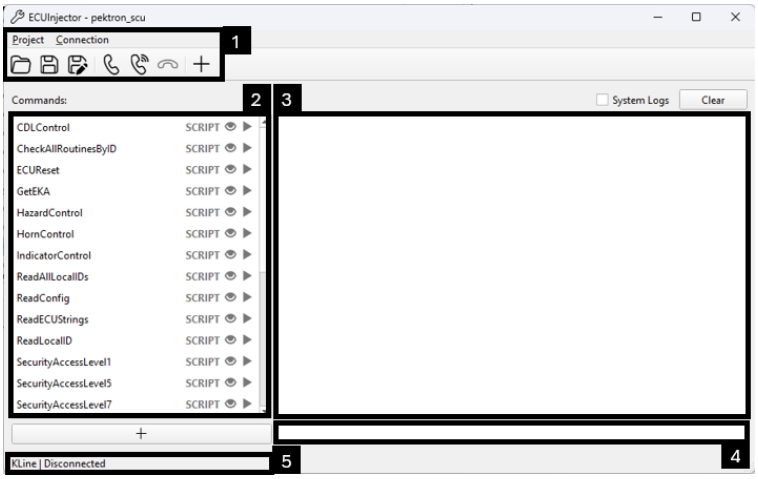


Figure 2: ECUInjector Diagnostics Screen

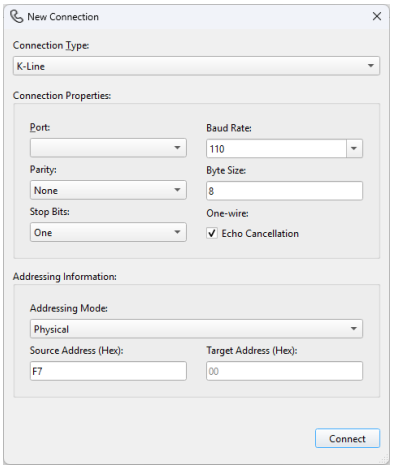


Figure 3: ECUInjector Connection Settings

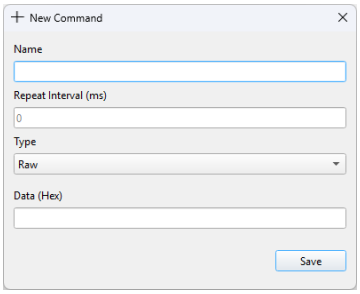


Figure 4: *ECUInjector* New Command Dialog

To begin communications with an ECU, a connection must be opened with a serial port. The "New Connection" (telephone) button, in the menu bar, launches the connection dialog (see Figure 4), where serial communication settings can be defined, including:

- **Connection Type:** The protocol defined within C++ logic that the ECU utilises. Options in this list represent protocol implementations {see Section 4.2.2) that have been defined within the software. Currently only K-Line (ISO9141 (ISO, 1994)) communications have been defined.
- **Connection Properties:** The serial port, baud rate, parity, byte size and stop bits. The "echo cancellation" option is a necessary option for certain automotive wiring standards where packets are transmitted and received on the same line, resulting in echo cancellation being required.

Once these details have been defined, the connection can be opened using the "Open Connection" button (transmitting telephone) in the menu bar and can be closed, when required, using the "Close Session" (on hook telephone) button.

Commands can be defined using the add (plus) button in the toolbar, which opens the "New Command" dialog (see Figure 5), where the command's name, repeat interval (if required), type (Raw or Script), and data (for Raw commands) is defined. Once the form is saved, the command will appear in the command pallet on the Diagnostics Screen. Script commands have associated LUA scripts, which can be accessed by right clicking the command in the pallet, and selecting "Edit script". When these commands are launched, they execute the code defined within the LUA script (which can either be done by clicking on them in the commands pallet, or by typing their name into the command prompt).



Figure 5: *ECUInjector*'s Communications Components

4.4 Software Walkthrough

The tool is extremely capable when it comes to performing reverse-engineering and vulnerability analysis upon an ECU's diagnostics protocol, with the following steps usually being followed:

4.4.1 Establishing a connection

Before any form of analysis can take place, a connection must be made with the ECU. *ECUInjector* expects a serial connection to the diagnostics bus or port, so that it can exchange information between itself and the diagnostics protocol. Most diagnostic buses run at 12V, and so specialist interfaces are required to implement a serial connection between the machine running *ECUInjector* and the diagnostic bus. USB OBD port adapters are commonly used to perform this task.

With a physical connection made, the software can be configured with the relevant communication details (see section 4.3.2). This includes the COM port (that the physical interface is connected to) and baud rate (which depends on the protocol being utilised on the communication bus). If the bus utilises ISO 9141-2 K-Line, *ECUInjector* can build packets and calculating checksums through a pre-existing protocol implementation, and therefore requires extra details such as the destination ECU's bus ID.

4.4.2 Initialisation procedures

ECUs often require "wake-up" initialisation procedures which inform the ECU that a diagnostic session is beginning and to expect further communications. The exact details of these procedures are specific to each protocol specification and can be implemented in the software either through protocol implementations (as is already the case for ISO 9141-2), or through script commands. Either way, once these commands have been defined, they can be triggered, causing a session to be initiated on the target ECU.

4.4.3 Maintaining the connection

Many ECUs require a continuous connection to maintain a diagnostics session, requiring either a command or dedicated "keep-alive" signal be sent periodically. *ECUInjector* supports sending periodic commands by specifying an interval in the command settings. The "Tester Present" command can be specified, either as a Raw or Script command (if required). Once triggered, the command will be periodically sent by the software until stopped. If a request is made to send another command in the meantime, this command will pause until those packets have been dispatched and will then resume automatically.

4.4.4 Gaining security access

Privileged commands within an ECU are often protected by security algorithms, with many ECUs relying upon "seed-to-key" algorithms. These mechanisms require multiple packets to be sent between the diagnostics system and ECU, with calculations being required at certain points during the transaction. To implement this logic within *ECUInjector* (if the seed-to-key algorithm is known), a dedicated Script command is used that can send the relevant commands and perform the necessary calculations.

4.4.5 Calling basic procedures

Once a session has been established with the ECU and security access has been gained, basic procedures can be called. In many cases, these can be implemented as Script commands that send the relevant requests to ECU and then display the result in the console.

4.4.6 Running advanced operations

More advanced commands, including firmware extraction and memory manipulation (which are often available as services that the ECU provides in a privileged mode) require more complex operations with both the ECU and *ECUInjector* itself. Firmware extraction and modification is one of the most complex operations that can be performed on an ECU, however this can easily be implemented in a Script command within *ECUInjector*. There are two main ways that ECU firmware extraction can take place, either the ECU delivers the entire firmware image in a succession of packets, or requests are made over the diagnostic port for each memory location, with

the ECU responding with its contents in each case. Either way, a basic script can be written to intercept the packets and make up the firmware image. LUA scripts within *ECUInjector* have access to APIs that enable them to write to files, meaning that the script can also be made to prepare a binary file containing the extracted firmware.

4.4.7 Creating reverse-engineering tools

Whilst many different commands can be run with the software, finding out exactly how they are implemented will still require some reverse-engineering. On top of this, it is also often useful to attempt to locate hidden commands that may have been implemented by the manufacturer. To this end, Script commands can also be utilised to write reverse-engineering tools. Below are some examples of scripts that have been written to reverse-engineer specific aspects of an ECU, and should demonstrate the capabilities of the system further:

- **Defined Service Locator:** Standards such as KWP2000 define multiple "services" (operations) that can be called via an ECU's diagnostics interface, however in many cases manufacturers will not have implemented them all. As well as this, if a procedure is not recognised an ECU will often return a specific error code. With this in mind, we developed a script that incrementally sends arbitrary data packets with each of the specified KWP2000 service IDs to the ECU and monitored the response. This enabled us to determine which services had been implemented (and therefore targetable) and had not.
- **Hidden Service Locator:** Automotive communications standards often include room for manufacturers to implement their own operations. Leveraging the logic from the previous script, we built a script that sends arbitrary command data to all service IDs outside the defined scope, and monitored the responses returned. This helped to identify extra services that were implemented by the manufacturer.
- **Hidden Routine Locator:** Diagnostic procedures can also be triggered through many ECU communications protocols, with each one being specified by an ID. We wrote a script that systematically triggered each possible procedure value, allowing a researcher to observe the ECU's I/O lines whilst doing so. This enabled us to review favourable routines to target.
- **Seed-to-Key Brute Force:** Whilst Seed-to-Key algorithms should implement a timeout feature after multiple incorrect attempts (preventing brute force attacks from being possible), it is often not the case. We developed a script to brute force the Seed-to-Key algorithm of a particular ECU and were able to successfully gain entry to privileged functions hidden behind the most privileged security mode.

4.5 Software Development

To ensure the software is portable, cross platform and extensible enough to support the requirements, the software is built in C++. Where possible, the C++ standard library has been utilised to ensure that the code remains portable. This extends to the GUI, with Qt being selected as the most suitable library due to its multi-platform support. Whilst other portable GUI libraries exist, Qt provided a quick way of developing the GUI with minimum barriers to entry, freeing up development time for other core features. Figure 1 shows the technologies used to implement the various components of *ECUInjector.*

5. Applications

ECUInjector has been able to successfully interface with multiple ECUs, with various reverse-engineering scripts being utilised to perform specific operations throughout the reverse-engineering process. Some of these ECUs utilise the KWP2000 standard, which *ECUInjector* is already quite capable of supporting (with helper functions having already been established), meaning that implementation was minimal. Other ECUs utilised different protocols, resulting in a slightly more complex implementation. In both cases, no changes were required to the underlying codebase of the application, and communications and scripts were quickly developed, thus saving on development time. The design of the software has allowed it to be easily adaptable to new ECU protocols, and this has been experienced during these implementations. Table 1 shows the variety of ECUs that have already been communicated with using *ECUInjector*, along with any advanced operations that were performed (in many cases using custom-built reverse-engineering tools within the software (see Section 4.4.7)).

With the specific case of the Pektron SCU, the software aided in detecting a vulnerability in an underlying diagnostic procedure, which lead to the wiping of important information from the ECU and a complete lockout from the system, effectively rendering the ECU, and vehicle, unusable. Use of both our seed-to key brute forcing

script and our hidden routine locating script led to the discovery of the operation that triggers this behaviour. More information can be found in another paper by the authors (Todd *et al.*, 2026).

Table 1: ECUs tested with *ECUInjector*

Vehicle	ECU	Type	Protocol	Advanced Operations
Rover	MEMS3	Engine Management	KWP2000	S2K Algorithm Implemented.
Pektron	SCU	Body Controller	KWP2000	S2K Brute-Forced, Vulnerability found (Todd *et al.*, 2026).
Bosch	ABS 5.3	ABS	KWP1281	N/A
BMW	GM6	Body Controller	BMW DS2	Firmware extracted.
BMW	Video Module	Entertainment	BMW DS2	Firmware extracted, modified and written back.
Rover 75	IPK3	Instrument Cluster	BMW DS2	N/A

6. Conclusions

ECUInjector has proven to be a capable software suite for communications with automotive Electronic Control Units and serves as a suitable way to perform vulnerability analysis. The software's part in discovering a vulnerability in Pektron SCU systems, along with further operations performed on other systems since, has been down to its ability to universally communicate with ECUs and provide ways to write advanced scripts that allow analysis to be performed as required. Finding these vulnerabilities before they are exploited by malicious parties increases the safety of road users, with this specifically being what the software is designed to aid with.

In terms of limitations, a prerequisite of *ECUInjector* is the prior knowledge of the ECU's protocols and internal workings. Furthermore, it is not always possible to circumvent protection mechanisms (this is down to the specific security mechanisms implemented within the ECU), though it is possible when these mechanisms are known or weak. Also, there is a certain level of adaptability to get the system to work with a new ECU (scripts may require changes and are not always directly transferable from one ECU to another). Finally, *ECUInjector* is not designed as a plug-and-play vulnerability detection tool -- work is still required to locate and investigate vulnerabilities. Rather, it aims at facilitating the tasks and reducing manual effort during vulnerability discovery.

ECUInjector provides a means to easily interface with an ECU and perform communications as required. Features should help researchers to author the necessary tools and scripts to perform analysis of protocol implementations and locate vulnerabilities.

Ethics and AI declarations: Ethical clearance was not required for this research. AI tools were not used in the writing of this paper.

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Officers' Perceptions on Cyberwarfare Enhanced with Artificial Intelligence

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Abstract: The use of artificial intelligence (AI) in both cyberwarfare and conventional warfare is increasing, as is the debate over its ethical acceptability. At the same time, technological development is shaping our perceptions of the character of war. Military decision-makers play a central role in the development and employment of artificial intelligence and cyber power in warfighting. To understand the ethical considerations surrounding the use of these emerging technologies, it is vital to examine military decision-makers' perceptions of the topic. This paper presents the results of surveys conducted among students of the Finnish General Staff Officer Course in 2023 and 2025. The surveys specifically aimed to evaluate officers' attitudes toward the acceptability of employing artificial intelligence and developing cyber warfare capabilities within military operations. The study sought to clarify how officers conceptualise these topics within military thinking and how this understanding shapes future cyber warfare. The main results indicate that officers strongly support using artificial intelligence for demanding military tasks, provided human involvement in decision-making (Human-on-the-Loop) is retained. Respondents were sharply divided on the likelihood of war occurring solely in cyberspace in the near future. Overall, military necessity remains the main consideration shaping attitudes toward AI's military use.

Keywords: Cyberwarfare, Artificial intelligence, Character of war, General staff officer Perceptions, Military AI

1. Introduction

The use of artificial intelligence in various weapons systems, both conventional and cyber, is becoming more common. AI offers numerous possibilities for military use, but its effective implementation requires, among other resources, a new kind of military thought, the development of new operational concepts, processes and tactics, a reassessment of security threats and the identification of ethical and legal issues. The capabilities created by AI can also shape the understanding of warfare. According to Johnson (2021, 2), AI technologies can affect future warfare and international security in three interrelated ways: 1) by increasing the uncertainty and risk posed by existing threats (both physical and virtual); 2) by changing the nature and characteristics of threats; and 3) by introducing new threats into the security environment.

In addition to training and experience, military leaders' own military thought and professional ethics influence their understanding of the character of warfare, i.e., how, when, where, and with what kind of military methods an external armed attack or threat should be responded to. Military leaders are also responsible for developing operational art and military capabilities and for their use.

Despite the essential role of officers in developing and utilising AI-enabled conventional and cyber warfare methods, and their attitudes towards new technologies, there is little public research on the subject. In the United States, Peter Lushenko (2024) conducted a 2023 study on the trust of those serving at the Carlisle and Newport military academies in working with AI-enhanced military technologies. In Australia, researchers from the University of New South Wales studied in 2019 the attitudes of Australian Defence Force Academy cadets towards interaction with autonomous weapon systems (Galliott & Wyatt, 2022).

The main research question in this study was: "How do officers notice the possibilities and limitations of cyber warfare methods and AI in modern warfare?" The question sought to determine whether these factors have been instrumentalised in officers' thought as elements of warfare and, more broadly, as factors shaping the character of war. The study was a survey that used both quantitative and qualitative questions to examine the views of General Staff Officer Course students on the topic.

Constructive war theory provided a theoretical framework for structuring the research question. This research explores shared understandings of AI and cyber methods as threats that must be responded to, but also as tools that can be used to project power.

2. Theoretical Background

This research is based on the application of the constructive theory of character of war. In a constructive theoretical framework, the character of war can be defined as follows: the character of war refers to the common perceptions in the international system about the nature, needs, and possibilities of the use of armed

forces, as well as the effective principles and operational models of armed forces. In the theory of character of war, war was viewed as a pragmatic and changing phenomenon. The war character is embedded in the international system and security environment, as well as in operational logic, strategic communication, rules, and the influence of new technological advances. It also establishes an association with the actors' identities. Through the character of war, the creator of the character of war seeks to outline the prevailing military threats against which one must be able to wage war; the situation in which war may be waged; the methods by which war is to be fought; the factors that can be used to increase credible military power; and the objectives of warfare. (Raitasalo and Sipilä, 2008; Vego, 2011).

On a broader scale, the character of war and its formation involves, in addition to military factors, various levels of diplomatic, political, economic, social, ethical, cultural, informational, technological, and legislative elements. Tähtinen (2024) describes this as the external nature of war, which embodies the changing manifestation of war in the outside world.

The technical development has introduced new dilemmas in defining the character of war, especially from a cyberspace perspective, where artificial intelligence is a powerful driver of change. The evolution of military cyber capabilities has brought the definition of war into transition. Hybrid warfare, which includes the use of cyber capabilities, has blurred the line between war and peace. Defining war remains essential, as warfare involves the use of state military power, which—according to Western perspectives—requires a legitimate legal basis. The concept of security is also linked to war and the insecurity it generates (Vilander et al., 2019). Consequently, conflicts in the cyber domain inevitably entail ethical considerations.

The existence and definition of “cyberwar” remain debated. Some scholars argue that the term “war” should not be applied in this context, as it stretches the definition excessively and risks conceptual inflation (Cepik et al., 2015). Others define cyberwar as “state-led attacks on another state’s cyber environment, intended to cause disruption or damage to networks or connected devices” (Clarke & Knake, 2010, p. 109). Drawing on Clausewitzian principles, three criteria must be met for an activity to constitute war: (1) it must have destructive effects, (2) it must target the critical elements of the state, and (3) it must serve political objectives (Cepik et al., 2015). From this perspective, cyberwar can be understood as a state-conducted offensive that targets an adversary’s cyber domain, causes a destructive impact on its critical infrastructure, and influences its political decision-making.

In contrast to “cyberwar”, the term “cyber warfare” is a more straightforward concept. In academic literature, it is often placed alongside other traditional domains of warfare, such as naval or aerial warfare. Linguistically, cyber warfare can be seen less ambiguous than cyberwar, as the former refers to the act of fighting rather than the entire conflict (Lehto & Limnell, 2017). Cyber warfare differs from traditional warfare in that cyber-attacks can directly harm civilian society below the threshold of war (Mazarr et al., 2022). Moreover, in the physical domain, the threshold of war is more clearly defined, whereas in cyberspace, offensive and defensive operations occur continuously without a clear link to declared hostilities (Lehto & Limnell, 2017).

Although the understanding of the nature and goals of war has remained the same throughout the centuries, theories related to warfare are always a product of their time (Vego, 2011). When defining the character of war, the distinct and unconventional nature of the cyber domain must therefore be considered. Within this context, cyber warfare is warfare conducted within or through cyberspace.

3. Methodology

The empirical part of the study consisted of a survey administered to students in the General Staff Officer (GSO) courses of the Finnish Defence Forces (FDF) between 2023 and 2025. The object of the survey was to get an understanding of officers´ perceptions of artificial intelligence and cyber warfare by surveying students' opinions on the subject.

The respondents were selected for their professional military experience. The respondent population (N=134) consisted of officers from all branches of the FDF and the Border Guard. This can be considered a comprehensive sample, considering the number of officers of a similar level who have served in the FDF for a similar period of time, from ten to fifteen years.

Answers were gathered via the open-source learning platform Moodle, including both structured and open-ended questions. Answers to structured questions were analysed using Excel. For each option, respondents were offered a Likert-type scale with five options: 1 = Fully disagree, value 2 = Somewhat disagree, value 3 = Neither agree nor disagree, value 4 = Somewhat agree, value 5 = Fully agree. After each structured question, respondents

were given the option to elaborate on their answers with open-ended questions. These answers were analysed using inductive content analysis (Puusa et al., 2020). The structured questions were obligatory using the given scale, and the open-ended questions were voluntary, with no limitations on answer length.

Likert-type data contains separate items that are not intended to be combined in the analysis, unlike the original Likert scale. Despite this, the Likert-type scale can utilise similar features to the original version, for example, response alternatives. (Boone & Boone, 2012) Since this study examined respondents' views on different types of topics, between which no correlation had been established, a Likert-type scale was best suited for the survey. The frequency of responses was calculated to determine the number of distinct observation types in the data (Heikkilä, 2004).

Approximately 68 per cent of respondents provided open-ended answers. The answers were analysed using inductive content analysis, which allows the researcher to identify similarities, differences, and recurring themes in the material. These findings can then be organised into categories to simplify the main findings from the data (Saunders et al., 2012).

During the content analysis, repeating themes were identified and grouped into categories. This process identified key points in the open-ended responses that helped explain the variation observed in the structured questions. After analysing the quantitative and qualitative data separately, the results were compared to gain a broader understanding of the topic.

The reliability of a survey can be assessed by examining the sample size, the chosen population, the response rate, the consistency of responses, and potential measurement errors (Hirsjärvi et al., 2005). A total of 134 individuals responded to the survey, representing 69 per cent of those invited to participate. The sample size can therefore be regarded as representative of the target group. The participants were officers from different backgrounds, so the chosen population and the results reflect a military perspective. Each phenomenon was assessed using single-item measures, and no correlations were mathematically calculated. This design introduces the potential for measurement error or respondents' misinterpretation of questions. However, an examination of the open-ended responses indicated no evidence of such misunderstandings. Measurement errors were further minimised by maintaining consistent wording and applying the same response scale across all survey items.

4. Survey Results

The aim of the survey was to determine officers' views on the acceptability and trust in the use of AI, as well as on the development of cyber capabilities. The aim of the study was to understand the potential impacts of the above-mentioned topics on the character of future warfare, the functions of military organisations, and military culture. The questions assumed that there was no legal obstacle to the statement and that a similar solution had been approved in other NATO member states.

The following statements were investigated in the survey with a question “Do you agree or disagree with the following statement?”:

Statement 1: Advanced artificial intelligence could independently manage precisely defined and limited military operations, including giving orders to soldiers.

- Statement 2: The use of artificial intelligence should be limited to routine data collection and monitoring tasks.
- Statement 3: I could directly rely on the common operational picture generated by an AI system in multi-domain operations.
- Statement 4: Cyber and electronic warfare capabilities have significantly changed the formation of the character of war.
- Statement 5: Cyber operations should be refrained from if their consequences are not precisely known.
- Statement 6: war solely in cyberspace is possible in the near future.

Regarding the first statement, “Advanced artificial intelligence could independently manage precisely defined and limited military operations, including giving orders to soldiers”, the following themes were discernible from the responses: human responsibility and decision-making must be preserved, artificial intelligence as a support for decision-making and planning, and technical and ethical uncertainty. The results are visualised in Figure 1.

Many respondents emphasise that artificial intelligence cannot and should not make decisions for humans, especially decisions that have an impact on human lives, the use of lethal force, or legal liability. Several respondents also added an ethical and criminal justification to this and emphasised that responsibility for the use of lethal force should always lie with a human. This theme also partly includes the "human in the loop" thinking: artificial intelligence can support decision-making, but humans should always have the last word. On the other hand, situations were identified in which an order is needed to carry out an action for which there is practically no alternative, in which case AI could issue an order just as well as a human. It was also suggested that AI could give orders to autonomous systems, but not to humans.

Another strong theme is viewing AI as an effective tool for planning, analysis, and preparation. The usefulness of AI for giving orders was justified, among other things, by its rationality, efficiency and speed. Respondents consider it realistic that AI can produce command structures, create a situational picture, model options and risks, and act as a decision support system.

The third theme concerns the maturity of the technology and its ethical issues. According to respondents, current AI is not "sufficiently developed", but in the future, its role may increase in limited tasks. At the same time, many find it difficult to define the boundaries because "strictly limited" is an ambiguous term, and liability issues will only be resolved as development progresses.

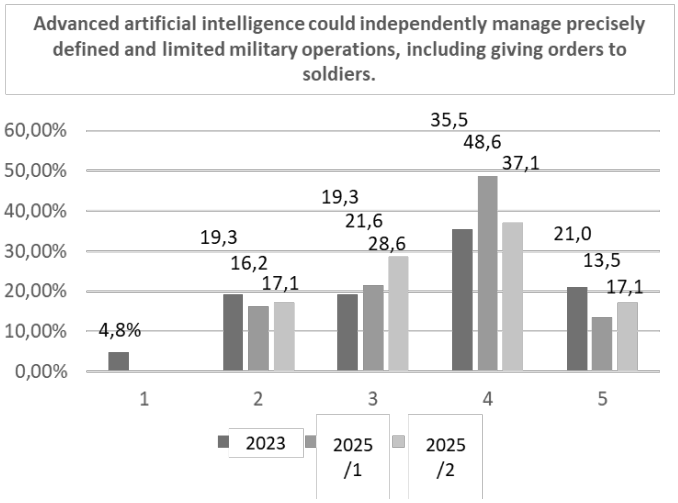


Figure 1: Answers to the question 1

The following themes emerged from the responses to the second statement: "The use of artificial intelligence should be limited to routine data collection and monitoring tasks". The use of artificial intelligence should not be narrowly limited in advance; possibilities for development should be secured, and it should be used as a support for decision-making and in broader military tasks. The results are presented in Figure 2.

Several respondents mentioned that limiting artificial intelligence to routine data collection and monitoring would be harmful and a deliberate weakening of one's own performance. Limits should be set on a case-by-case basis based on reliability, security and usability – not on categorical "only for routine tasks" policies. Respondents also argue that AI should be used much more broadly than just for data collection, especially for decision-making support and certain combat-related tasks, while ensuring humans retain responsibility and are "in the loop."

Responses in favour of limitations highlighted the current state of AI and human ability for innovative, multidimensional thought. Ethical and moral requirements emerged in the responsible development and use of AI. In the results of the autumn of 2025, a significant change occurred regarding this question, which was also strongly reflected in the verbal justifications of the responses. The majority of responses considered that AI should be utilised to its full extent and used as widely as possible. Such limitations would only transfer the advantage to the adversary. Not all actors are as rational as Western countries and will also develop and use AI for other military applications.

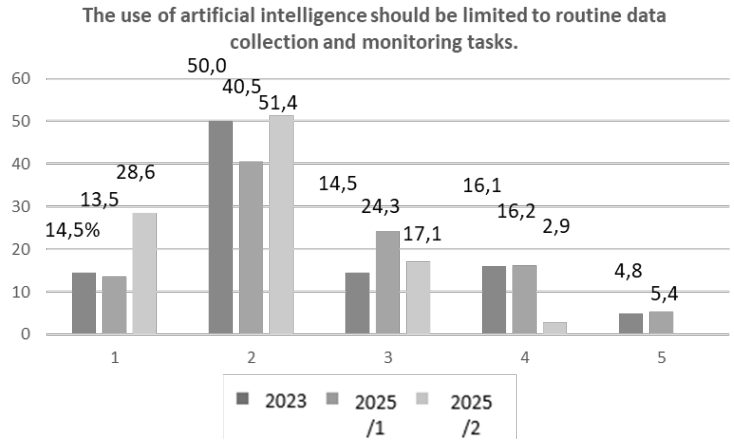


Figure 2: Answers to the question 2

Three main themes recurred in the responses for the third statement, "I could directly rely on the common operational picture generated by an AI system in multi-domain operations.": 1) trust in the AI generating common operational picture (COP) is possible if the system is sufficiently tested and known; 2) the AI generated COP is good and often better than made by a human, but a human is wanted to be involved in the interpretation; 3) trust for AI in this context is currently limited, but could increase in the future. The results are shown in Figure 3.

Many respondents mentioned that they can only trust the COP produced by artificial intelligence if certain conditions are met: the system has been sufficiently tested, its reliability has been demonstrated in practice, and its operating logic is understandable. Some of the respondents emphasised that AI can combine vast amounts of data, make fewer mistakes than a single human, and is particularly good in complex multidomain environments.

Many respondents clearly distinguish between the present and the future. This group does not rule out trusting the AI-generated COP, but clearly positions itself on the "not yet completely" axis. Also, many responses emphasised the importance of humans as final analysts and decision-makers, but the need to fight other AI was also mentioned.

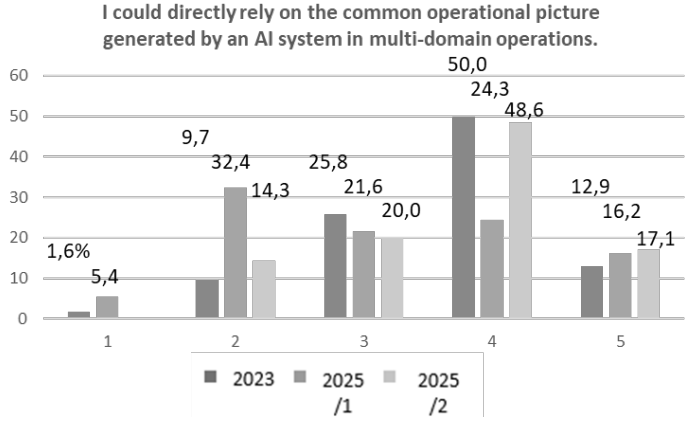


Figure 3: Answers to the question 3

In the numerical responses to the fourth statement, "Cyber and electronic warfare capabilities have significantly changed the formation of the character of war," the majority of respondents supported the statement, but their significance in changing the character of war was divided, based on open-ended responses. The results are illustrated in Figure 4.

In the open-ended responses supporting the claim, it was assessed that cyber performance has significantly changed the character of war because various systems and data transfer are central to maintaining the tempo of operations, where protection, intelligence, and effective impact are essential factors in mission assurance. It was also assessed that the character of war has become increasingly technological in other ways.

The respondents who did not support the claim noted that the war in Ukraine demonstrates the continued centrality of traditional kinetic warfare, such as territorial conquest and the use of kinetic capabilities. Electronic warfare was seen as a more concrete influencer than cyber, especially through the exploitation of the electromagnetic spectrum. According to some respondents, the changes have focused more on the control and use of the battlespace and have broadened the understanding of the diversity of warfare. It was also assessed that these capabilities have contributed to blurring the grey area between war and peace.

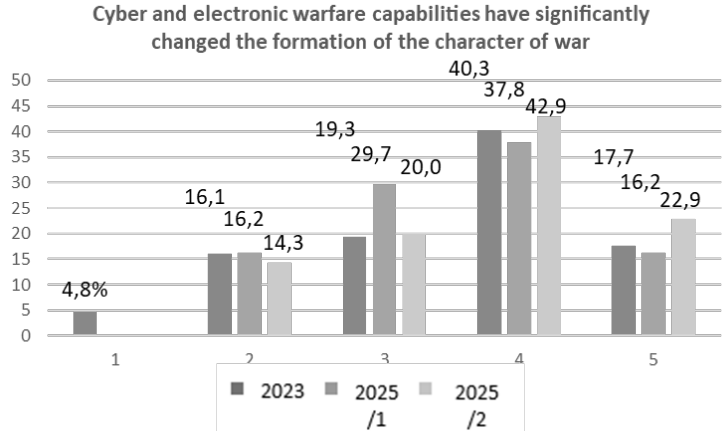


Figure 4: Answers to the question 4

Three main themes recurred in the responses for the fifth statement "Cyber operations should be refrained from if their consequences are not precisely known": 1) there exist the same principles of risk assessment as in kinetic operations, 2) cyber represents a softer means, and 3) the realities of war require risks in certain situations.

The uncertainty of the consequences of cyber operations was evident in responses along the same lines as for other military actions: there is no such thing as complete certainty in advance, but risks must be assessed. Some of the respondents equate cyber operations with other military operations: the consequences are not fully known anywhere (for example, kinetic warfare in general, artillery, nuclear weapons), so positive identification, collateral damage estimation and risk assessment are sufficient as they are now. Cyber was seen as a less violent means to be used before kinetic force, but a secondary impact analysis (concerning bystanders, society, and infrastructure) is still needed. The decision depends on the situation: in existential defence of a state, risks are taken even when information is lacking; in offensive, more cautiously.

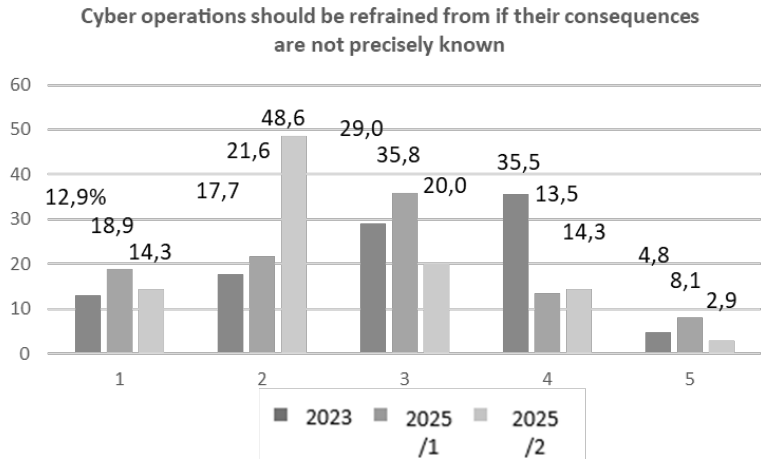


Figure 5: Answers to the question 5

The results for the sixth statement, "A war solely in cyberspace is possible in the near future," are presented in Figure 6. A war solely in cyberspace is seen as theoretically possible but unlikely in the near future. The three most recurring themes are: the inability of cyberwar to achieve strategic goals; escalation into other domains; and the role of cyber as part of a total war, not as an independent one. The largest group believes that cyber operations alone do not force an adversary to do what they want: one cannot conquer territories, kill people, or resolve conflicts without kinetic force. The conflict does not remain in cyberspace: it either expands into kinetic

warfare or fails to meet the criteria of "war". Cyber operations are already underway "below the threshold of war", but do not constitute an independent war - it is a question of definition.

The majority of respondents argued that warfare in a single domain alone is not possible. On the other hand, other respondents believed that some conflicts between states could be resolved solely through cyber warfare, but if the intention is to subjugate another state to one's will or destroy another nation, then conventional warfare is required. Some respondents believed that war is already being waged in the cyber domain all the time, but this does not necessarily escalate in other domains, due to, for example, the attribution problem. The term “war” received a mixed reception, both for and against. Some respondents believed that cyberwar is not war at all, while others saw it as a form of warfare or a question of defining the concept of war.

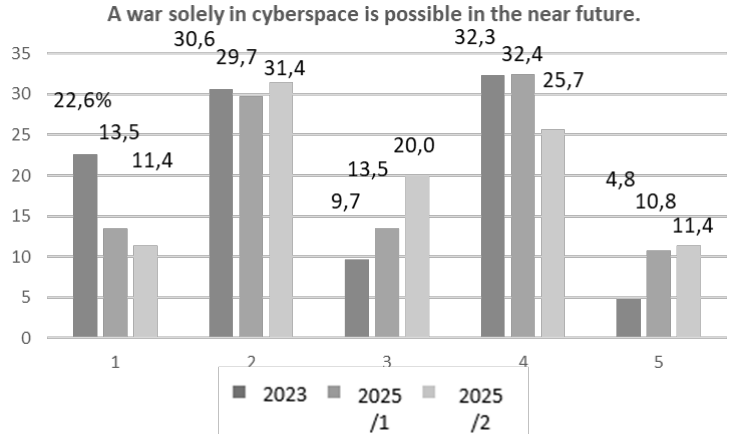


Figure 6: Answers to the question 6

5. Conclusions

Based on the overall analysis of the responses, three key observations can be made: 1) Key arguments for the acceptability of utilizing AI and cyber capabilities were that Finland need to keep up with technological developments and that also adversaries (Russia) actually use them; 2) The responses emphasized the requirement to include humans (Human-on-the-Loop) in decision-making; and 3) The officers also emphasized the comprehensibility and transparency of the production process of solutions made by AI or the information it produces to support decision-making.

As for the first observation, the concern is not unfounded and poses a strategic-normative dilemma for Western states committed to the international treaty regime (Dagen, 2025, 152). These last two requirements for AI are challenging because of the practical steps required to ensure that the military benefits sought by these systems are not compromised.

The requirement to keep humans involved in decision-making is justified on ethical grounds as well as for leadership and accountability. Soldiers have the right to use lethal force in certain situations, in which case the decision to use it and the responsibility for the consequences should lie with a human. On the other hand, the military commander will, in any case, make the decision, for example, to use an AI-enhanced or even AI-operated weapon system or to utilise AI for a specific task, in which case the decision-making will remain with a human. More important than keeping humans involved in military operations is the issue of leadership (Goldfarb & Lindsay, 2020, 5-8). AI cannot replace the example of a soldier’s ethos set by a military leader, strengthening the motivation of fighters, or understanding of human factors.

Understanding the production process of solutions or recommendations made by artificial intelligence is a more challenging issue. The software of an AI system is able to learn from its own experiences in addition to its training material. They can self-correct their algorithms and add or remove parameters, even if those changes no longer comply with the given rules. This can lead to a so-called "black box" phenomenon, where even the system designer or end user is unable to identify the changes or processes the system implements that result in certain solutions. (Chavannes & Arkhipov-Goyal, 2021, 71).

Although this study is not directly comparable with the U.S. and Australian studies due to, among other things, differences in the question wording and target groups (e.g., in terms of military education and cultural factors), some observations can be made. All studies emphasised that humans want to be involved in decision-making

and that trust in the use of AI to support military operations, e.g., in autonomous weapon systems, increases as officers understand its operating processes (Galliott & Wyatt, 2022, 270-271; Lushenko, 2023). Both Finnish and U.S. officers also considered that one of the key reasons for the use and development of military AI and autonomous weapon systems is that adversaries also develop and use them (Lushenko, 2023). The study confirmed perceptions of commitment to the military profession and decision-making based on expertise and knowledge.

Surveys conducted on military thought concretised the idea of a common understanding of prevailing threats, related to the constructive character of the war theory framework, against which material power must be developed using available technology, also in the cyber domain.

Military necessity strongly guided the attitude of Finnish officers towards the development and use of new technology and cyber capabilities for military purposes. Although a commitment to ethical aspects emerged, it is obvious that a small nation cannot afford moral superiority and thereby give significant advantages to the adversary.

Like U.S. general of the Army, Douglas MacArthur (1951) said: *"In war, there is no substitute for victory."*

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Intrusion Detection System for Software-defined Satellite Networks

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Abstract: Software-defined networking (SDN) has been proposed as a potential enabler of programmability, flexibility, and dynamic resource allocation in satellite network environments. Despite the benefits, SDN introduces cybersecurity risks to satellite networks, such as controller compromise, flow rule manipulation, and distributed denial-of-service (DDoS) attacks. To address these challenges, this paper explores intrusion detection mechanisms based on anomaly detection techniques in machine learning for detecting cyberattacks in software-defined satellite networks (SDSNs). To support experimentation with the different IDS approaches, an SDSN simulation platform was used to simulate a Walker-Delta satellite constellation for the Earth observation use case. This simulation enables experimentation with solutions that take into consideration the dynamic inter-satellite links (ISLs) and network topology, which most of the existing IDS solutions do not take into consideration. The IDS is implemented on a POX controller leveraging the southbound interface capabilities provided by OpenFlow. The paper reports on the different classification techniques investigated for the IDS, namely, Random Forest, Support Vector Machine, k-nearest neighbour (KNN), convolutional neural network (CNN) - Long Short-Term Memory (LSTM), and multidimensional Matrix Profile. While prior work has demonstrated the efficacy of machine learning and deep learning approaches for SDN, this work further validates the efficacy of the approaches in the context of dynamic topologies characteristic of satellite networks.

Keywords: Software-defined networking, Software-defined satellite networks, Intrusion detection system, Cybersecurity

1. Introduction

Satellite networks are crucial for enhancing services such as remote communication between devices and systems, as well as the extension of coverage to areas without the Internet and cellular networks (Kodheli *et al.*, 2021). Satellite networks support communication systems such as the 5th generation (5G) of mobile networks, which provide services -- such as wireless technology and high-speed internet. Satellite networks are also critical to the military domain for command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) capabilities (Pavur and Martinovic, 2022). These space applications are supported by the satellite network architecture, which typically consists of three segments – namely, the ground, space and user segments (Manulis et al., 2021).

Space systems are vulnerable to cyberattacks and have become targets due to their importance to critical infrastructure. As satellite constellations in orbit increase, so does the threat landscape (Manulis et al., 2021). The integration of SDN into space systems, in the form of software-defined satellite networks (SDSNs), has the potential to revolutionise how satellite networks are managed, optimised, and secured (Bradbury et al., 2020). Unlike traditional static architectures, SDN enables dynamic, software-driven control of network functions across space, ground, and user segments. This research explores the development of intrusion detection solutions (IDS) for SDSNs. While extensive deployment of IDS has been undertaken in terrestrial networks and in SDNs, the SDSN context presents unique requirements and challenges – such as dynamic ISLs and topology, network disruptions, and resource limitations – warranting new research to further the cybersecurity of this context.

The rest of this paper is organised as follows: Section 2 provides an overview of existing IDS solutions and approaches, including rule-based and behaviour-based IDSs. Section 3 discusses the design approach applied in this work, covering the design science research approach, the architecture of the IDS developed in this work and the dataset generation. The various ML and DL algorithms explored in this work are discussed in Section 4, followed by a discussion of the experimental results in Section 5. Section 6 provides a conclusion of this paper.

2. Background and Context: Intrusion Detection Systems

Intrusion detection systems monitor computing and network environments to detect actions that deviate from expected benign behaviour, which may indicate security breaches. Initially, to detect attacks in the 1970s and early 1980s, system administrators had to print out system logs on paper and manually audit the printout

(Kemmerer and Vigna, 2002). The process was clearly reliant on the auditors' expertise and too slow to detect attacks in progress. In the 1980s, storage became cheaper, and intrusion detection programs became available for analysing audit logs online. The programs, however, could only be run at night when the system's user load was low (Kemmerer and Vigna, 2002). Thus, detecting attacks in time remained a challenge. By the early 1990s, real-time IDSs that analysed audit logs were produced and became available (Kemmerer and Vigna, 2002).

Contemporary IDSs can be categorised along the following multiple axes, which are discussed is detailed hereafter:

- placement – where there are host-based IDS (HIDS), network-based IDS (NIDS), or distributed
- data granularity – concerning flow-based or packet-based IDS
- detection methodology – where rule/signature-based, anomaly/behaviour-based, or hybrid approaches can be used

With regards to IDS placements, HIDSs are implemented on individual hosts to monitor activities on a host, including system logs and policy violations (Ahmad et al., 2021). In contrast, NIDSs monitor traffic in the network to classify normal traffic from malicious traffic (Li et al., 2020) and these IDSs can either be rule-based or behaviour-based (Ayachi et al., 2020). Distributed IDSs use multiple coordinated IDS agents that communicate to provide advanced network monitoring (Folino and Sabatino, 2016).

There are various architectural approaches for implementing IDSs, categorised by granularity: flow-level and packet-level. The flow-level approach analyses aggregate traffic flows rather than individual packets to detect cyberattacks (Yang, Arshad and Zhao, 2022). Packet-level information contains messages generated in the application layer (protocols such as HTTP), as well as headers generated in the lower network layers (TCP and UDP protocols) and the physical layer (e.g., Ethernet headers) (Yang, Arshad and Zhao, 2022). The packet-level approach provides granular visibility into raw traffic, similar to data captured by *tcpdump*. However, there is no aggregate analysis of the packets in this approach, unlike the flow-level approach, which aggregates the raw packet data capture, based on source and destination addresses, port, and protocol, with flow-level analysis through tools such as CICFlowMeter (Sharafaldin, Habibi Lashkari and Ghorbani, 2019) or NTLFlowLyzer (Shafi, Lashkari and Roudsari, 2025).

2.1 IDS Classification Approaches

Several approaches are employed for the classification of network traffic in IDSs. Rule-based IDSs, also called signature-based IDS, rely on rules that specify the conditions of legitimacy of an event, typically with the help of signatures. Signatures can be:

- exploit-facing, for example, malicious byte sequences, email subject headings associated with phishing, email attachments containing executable binaries, traffic going to known malicious domains, scanning of file hashes; or
- vulnerability-facing, for example, SSH requests specifying a vulnerable version number, system log entries indicating audit disablement (Scarfone and Mell, 2007).

An example of rule-based detection is stateful protocol analysis or deep packet inspection. This process analyses protocols at the application layer to compare vendor-developed profiles of benign protocol activity against observed events to identify deviations (Scarfone and Hoffman, 2009). Rule-based detection is effective against known threats that can be expressed using a set of rules and signatures; however, it is ineffective against known threats that are hard to capture using a finite set of rules and signatures (for example, multi-stage attacks), as well as previously unknown threats.

The second classification approach is behaviour-based IDSs, also known as anomaly-based IDSs. This type of IDS applies ML techniques to determine whether a user or component behaviour is anomalous. The approach depends on the prior establishment of a baseline behavioural model and can detect previously unknown attacks if the attacks manifest as anomalies relative to the baseline model. The approach is effective at detection but tends to produce excessive false positives. Traditionally, ML was only used for anomaly detection, but it is now also used for attack classification. Among the ML algorithms used, those that are based on deep learning (DL) are becoming mainstream. Lastly, hybrid IDS combine signature-based and anomaly-based methods to reduce false positives while improving the chance of zero-day attack detection (Maseno, Wang and Xing, 2022). Optimal integration of supervised learning and unsupervised learning algorithms into a hybrid IDS for detecting multistage attacks in a given network architecture remains an open problem.

2.2 Key Considerations for IDS in SDSN

There is a dearth of prior studies that have investigated the adoption of IDS in SDSNs. The implementation of IDSs in SDSN must consider the dynamic nature of ISLs, as well as the placement of the IDS within SDSNs – this is because of the underlying controller placement problem (CPP) in SDSNs (Uddin and Kumar, 2023a). Prior work in this area has utilised ML techniques such as federated learning-based IDS to detect malicious traffic in SDSN, without the consideration of the placement of the IDS in SDSN (Uddin and Kumar, 2023b).

In this research, the main architectural decision was to leverage the SDN controller for the implementation of an IDS within SDSN. The motivation for this is that the role of the controller within an SDN gives it full visibility into the satellite network topology and traffic dynamics, as well as the ability to control the overall behaviour of the network. This approach gives access to the full raw network traffic, which can subsequently be analysed to inform attack detection and routing decisions.

3. Implementation of IDS for SDSN

The implementation of the IDS in this research employed the design science research (DSR) approach and leveraged an SDSN simulation platform, an SDN-based space system framework for simulation (S3FS), to enable the simulation of different constellation orbital dynamics and network traffic and the generation of benign and attack datasets to train the IDS classifiers.

3.1 Design Science Research Approach and SDSN Simulation Environment

The DSR approach provides a suitable methodology for creating technical artefacts (e.g. a system or model) that address a problem and contribute to knowledge (Hevner et al., 2004). The DSR process is conceptualised through three interlinked cycles:

1. Relevance cycle: focuses on the problem context and requirements for the ML-based IDS. The relevance cycle identifies the requirements for an IDS in SDSNs, such as timely anomalous traffic detection and the ability to be integrated in the SDSN environment.
2. Design cycle: comprises the iterative process of design, refinement (e.g. features and hyperparameters) and evaluation of the ML-based IDS.
3. Rigour cycle: based on applying existing knowledge and methodologies to inform the design process (Vom Brocke, Hevner and Maedche, 2020).

While the relevance cycle was supported by general insights and knowledge within the SDSN context, the technical environment that enabled the simulation of satellite constellations and their associated SDN-supported network dynamics was provided by S3FS, which was developed as part of a broader project in this research (Uhongora, Thinyane and Law, 2025). S3FS is a controlled environment for simulating orbital motion, dynamic network topologies, SDN controller deployment, and attack scenarios. S3FS facilitates the collection of network traffic, including benign and malicious traffic within the SDSN context, enabling realistic simulation of satellite cyberattack scenarios. This framework provided a suitable basis for the development of the IDS presented in this paper.

3.2 Architecture of ML-based Intrusion Detection System

The implementation of the ML-based IDS leverages SDN's centralised network visibility to monitor traffic and detect cyberattacks, as well as SDN's centralised control and management functions (Kodheli et al., 2021). The architecture consists of three key components: a POX controller, OpenFlow switches in the data plane, and the ML-based classifier embedded within the controller (illustrated in Figure 1). The POX controller manages the flow rules in the OpenFlow switch tables and inspects all flows and packets arriving at the controller. The OpenFlow switches forward the flows in the data plane based on the rules installed by the POX controller in the flow tables. The ML-based IDS implemented at the POX controller processes the flows and *Packet-In* messages arriving at the controller and classifies them as normal or malicious. As depicted in Figure 1, setting up the IDS follows this order: network traffic collection, preprocessing, ML classifier training, and real-time classification using the trained ML classifiers.

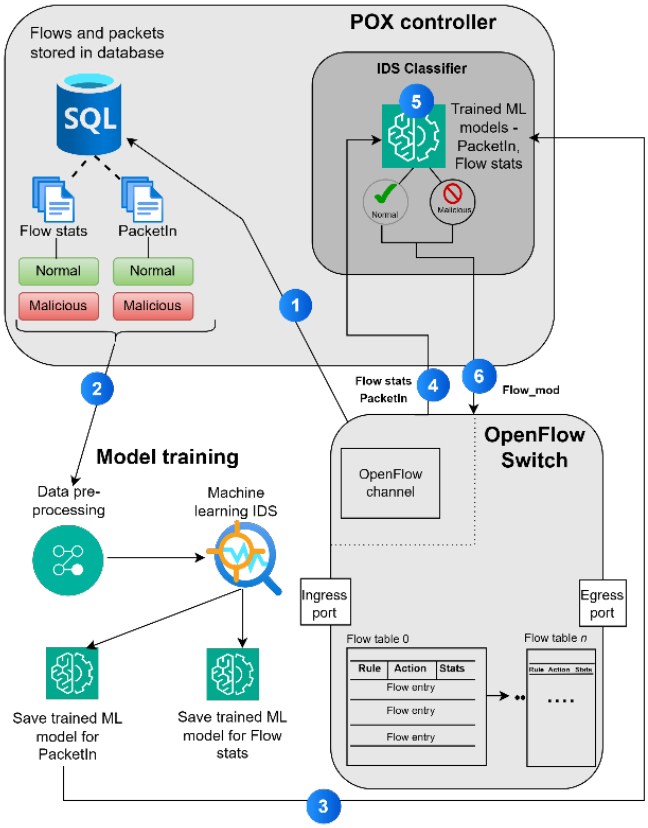


Figure 1: An ML-based IDS for SDSN

Step 1

First, the normal and attack traffic datasets are generated based on the flows_stats and Packet-In messages sent from the switches to the controller. Packet-In messages are sent to the controller when a table miss is triggered on the switch or based on flow entry rules. Further, the IDS periodically requests aggregate flow statistics from the switches and stores this as the flow_stats dataset.

Step 2

The two datasets produced in Step 1 are used to train the IDS classification model. This process entails data preprocessing, model training, and model evaluation. For the data preprocessing, to avoid overfitting, features such as source and destination of IP and MAC addresses were removed from the dataset. Additionally, the data is standardised to scale the values between 0 and 1. Further, the data is split into 80% training data and 20% test data. Multiple classification models were investigated and are discussed later (Section 4).

Step 3

The trained ML models from the previous step are saved and then loaded into the ML-based IDS component for traffic classification and intrusion detection.

Step 4

The S3FS simulation is set to run in various modes across different simulation runs, initially to run in the normal traffic generation mode and then in the attack mode (as discussed in Section 3.3). In this step, the Packet-In and flow_stats messages are not stored as a dataset but rather fed into the IDS for classification.

Step 5

This is the real-time classification step using the trained models and represents the core of the IDS functionality. When flow_stats and Packet-In messages arrive at the POX controller, the IDS is triggered to classify (i.e. normal or malicious) the packets and flows. The details of this step are discussed in the next step.

Step 6

This step extends the IDS component with intrusion prevention functionality. Once a classification is made on a flow or packet, a flow_mod message is sent to the switch with instructions on how to handle the flow or packet (i.e. to drop the packets for a set duration of time) in cases of malicious traffic – these steps are presented in the pseudocode in Algorithm 1. The IDS does not send flow_mod decisions for normal traffic because it is implemented in concert with other standard POX modules that handle topology discovery and routing within the network, namely the forwarding.l2_learning and the forwarding.spanning_tree components. To ensure that the IDS flow modifications take precedence over the instructions from the other components, the flow_mod messages are sent with a high priority value.

Algorithm 1: Proposed ML-Based IDS on POX Controller

Input: S = Set of switches; F_s = Flow statistics; M = Trained ML model; i = Number of monitoring intervals
Output: A = Detection Accuracy; Normal flows forwarded; Malicious flows dropped

```
Initialise POX controller
Load trained machine learning model M
Connect to switches in S
for each monitoring interval i do
    Send flow_stats_request to all switches in S
    Receive F_s (flow entries: source IP, destination IP, packets, bytes, duration, etc.)
    for each flow f in F_s do
        Extract flow features and form feature vector X_f
        Preprocess X_f (normalisation, encoding, missing values handling)
        P_f ← M.predict(X_f)                ▷ Classify flow using machine learning model
        if P_f = Malicious then
            Install FlowMod rule on switch to drop flow f
        end if
    end for
end for
Compute detection accuracy A based on correctly classified flows
return A
```

3.3 Intrusion Detection Dataset Generation

The S3FS framework is used to generate normal and attack traffic used for the ML training process. The malicious traffic is generated for the following attacks: SYN flood (single source), SYN flood from random sources (hereafter SYN flow flood to distinguish SYN attacks), smurf DDoS attacks, and port scan. The final prepared datasets used for training the classifiers are multiclass datasets that consist of normal and various malicious traffic, as depicted in Figure 2. This dataset contains 15 features, 8,286 normal samples and 36,728 malicious samples, consisting of the following traffic classes:

- Benign: 8,286
- SYN flood: 10,144
- SYN flow flood: 7,894
- Port scan: 10,436
- Smurf: 8,254

The multidimensional Matrix Profile (MP) time series anomaly detection method approach requires a smaller ratio of the anomalous traffic compared to KNN, RF, SVM and hybrid CNN-LSTM classifiers. Therefore, to train the MP, the dataset contained 90% normal traffic and 10% malicious traffic.

Normal traffic is generated using the *Netcat* network utility tool, simulating an Earth observation payload from the satellites to the ground station, and the same tool is used on the ground station to receive the transmitted traffic. The different attack types were generated using *hping3* and *nmap* tools and directed towards the ground station host from the attack host, with both hosts connected to the same switch. The simulated DDoS attacks compromise SDSN by flooding the controller with a large volume of traffic to overwhelm the controller and exhaust network resources. For example, the SYN flood attack from random sources floods the ground station with SYN requests, and in response, the ground station sends a SYN-ACK message back via the switch. As the switch does not have matching rules for the spoofed addresses, it forwards a *Packet-In* message to the controller to determine how to handle the packets. The controller then replies with a *Packet-Out* or *flow_mod* message, instructing the switch on how to process the incoming traffic. However, due to the speed and volume of packets

requiring processing, the switch's flow tables rapidly become saturated, preventing new flow entries sent by the controller from being installed.

The attacks were generated using the following commands were executed:

- SYN flood: hping3 -c 100000 -i u1000 -d 120 -S -w 64 -p < *target_port* > < *target_ip* >
- SYN flood (random sources): hping3 -c 100000 -U -d 120 -S -w 64 -p < *target_port* > –flood –rand-source < *target_ip* >
- Port scan: nmap -p 1-65535 < *target_ip* >
- Smurf: hping3 –icmp –flood -a < *target_ip* > < *broadcast_address* >

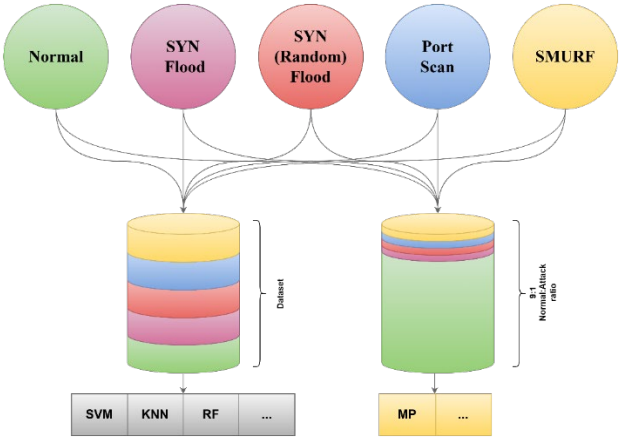


Figure 2: Dataset class ratios for classifier model training

4. Evaluating IDS Classification Models

First, the datasets undergo preprocessing steps such as standardisation, labelling (normal and attack traffic) and feature selection. Second, several approaches were investigated for the implementation of the classifier model. These approaches are supervised ML techniques: RF, SVM, KNN, hybrid CNN-LSTM, and a time series anomaly detection algorithm: MP, which is implemented in the STUMPY Python library. These approaches are discussed hereafter.

4.1 Random Forest

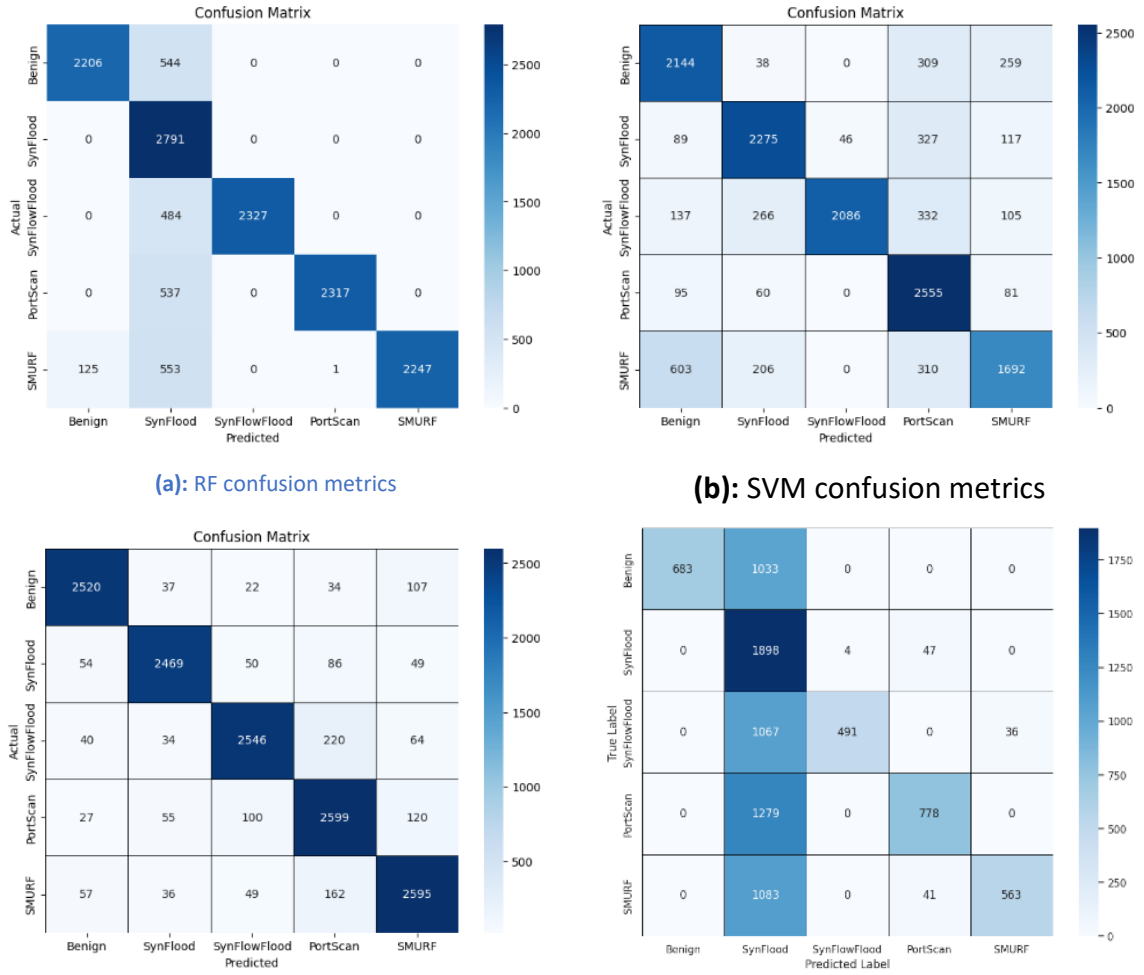
Random forest (RF) is an ensemble ML algorithm that builds multiple decision trees and combines their results, which ultimately improves prediction accuracy (Aslam, Srivastava and Gore, 2022). In this research, the simulation setup of the RF classifier contains 100 trees (n_estimators=100) with a maximum depth of 15 (max_depth). The random state is set to 0. The RF classifier was trained on the flows and packets datasets separately. The feature selection process was performed using the *feature_importance_* attribute, with the features selected from the dataset having a feature importance score greater than 0.01. The results obtained from the flows dataset showed that RF achieved an accuracy of 84% accuracy. Further evaluation of the model was undertaken on real-time data; this is discussed in Section 5.

4.2 Support Vector Machine

Support Vector Machine (SVM) is an ML algorithm that works by finding an optimal hyperplane that separates the data into different classes (Najafimehr, Zarifzadeh and Mostafavi, 2023). SVM uses various kernels such as the Radial Basis Function (RBF) and polynomials to handle nonlinearity and to control the margin trade-offs. SVM, as implemented in this research, is configured with the following hyperparameters: linear kernel and regularisation parameter of 1.0. The SVM classifier achieved an accuracy of 77%.

4.3 k-Nearest Neighbour

k-Nearest Neighbour (KNN) is a supervised ML algorithm where classification is performed by a majority vote among k-nearest data points. The classifier calculates the distance (i.e. Euclidean, Manhattan distance) between new data samples and the learned samples in a dataset to classify data samples (Najafimehr, Zarifzadeh and Mostafavi, 2023). In this study's implementation, the KNN classifier is configured with five nearest neighbours, which means the KNN classifier uses five nearest neighbours for performing predictions. KNN achieved a classification accuracy of 90%.



(a): RF confusion metrics

(b): SVM confusion metrics

(c): KNN confusion metrics

(d): Hybrid CNN-LSTM model confusion metrics

Figure 3: Confusion metrics of IDS classification models

4.4 Multidimensional Matrix Profile

A time-series anomaly detection approach using multidimensional MP was also explored in this work to identify attack traffic. The algorithm uses a threshold to distinguish benign traffic from attack traffic. The MP produced a high percentage (28.56%) of misclassified samples. Unsupervised anomaly detection methods based on the matrix profile produced too many false positives and false negatives.

4.5 Hybrid CNN-LSTM Model

This work also investigated DL models by using a hybrid CNN-LSTM model to classify the traffic. Hybrid DL models have proven to have better detection accuracy compared to individual implementations of the models (Abdallah et al., 2021). For hybrid architecture, CNN performs spatial features extraction, while LSTM extracts the temporal features to develop an IDS model that lowers false alarm rates and improves accuracy (Abdallah et al., 2021; Halbouni et al., 2022). The CNN architecture consists of the following parameters: an input layer, which loads the dataset, a 1-dimension convolution with 128 filters, a max pooling layer, a dropout layer with a probability of 0.3, an LSTM layer, an additional dropout layer, a dense layer hidden layer fully connected with 16 neurons, an activation function using ReLU followed by another dropout layer. The output layer is the classification layer, and it is a dense layer consisting of 5 output neurons for the multi-class dataset used in this work, with a *softmax* activation function. The hybrid CNN-LSTM model achieved an accuracy of 49% running over 20 epochs.

Figure 3 shows the confusion metrics of the ML and DL models during training. Although DL is used for IDS in a lot of existing studies, it yields very low performance in terms of detection accuracy with the dataset generated in this research. As depicted in Figure 3, the true positive values for the attack detection vary with each classifier.

For instance, the RF classifier provides a better accuracy at detecting the SYN flood attack, whereas the KNN classifier performs better across the rest of the attack types.

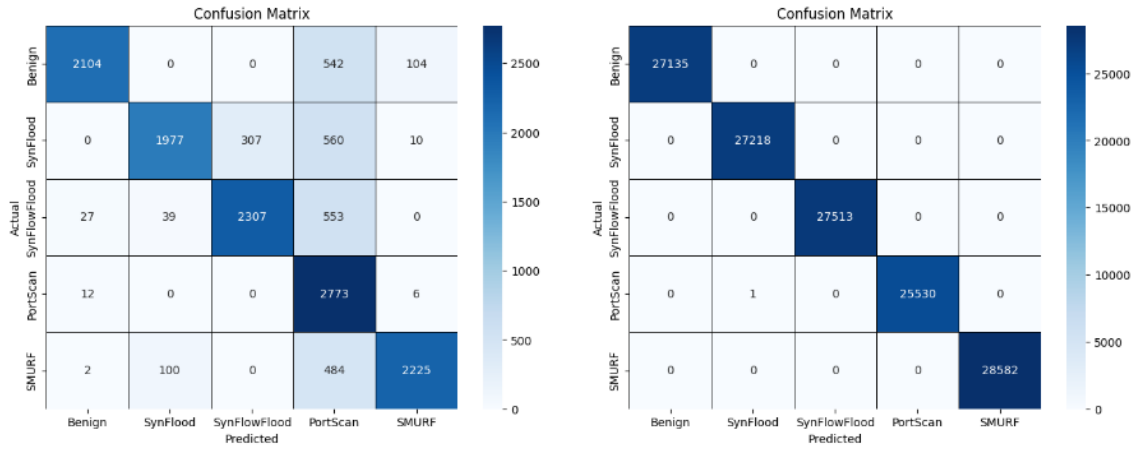
The classifiers investigated in this work are trained on the four attack patterns and therefore their performance is not optimised for other attack types that the classifiers were not trained on. Additionally, the ML-based IDS classification accuracy could be affected if the IDS is deployed in a different environment, i.e., the number of satellites and dynamic ISL connectivity. However, the IDS approach for SDSNs proposed in this research can be generalised to other similar contexts, with ML and DL classifiers optimised for those context-specific requirements.

5. Discussion

Considering the dependency of critical infrastructure on space systems, security controls such as IDSs are required to protect the space ecosystem from cyber threats. Unfortunately, traditional security measures have been proven inadequate to prevent powerful and advanced threats that target SDSNs (Chen et al., 2023). Uddin and Kumar (2023) proposed a federated learning-based IDS to counter cyberattacks in SDSNs. However, in this work, the network topology does not comprise dynamic ISLs, which is of interest in our work and increasingly characteristic of LEO constellations. The work implemented in this paper leveraged the S3FS platform, which is configured to simulate network dynamics associated with a 20-satellite Walker Delta constellation within an Earth observation use case. The dynamic ISLs present a unique challenge that needs to be addressed in the implementation of IDSs for SDNSs. The findings in this research show that a suitable IDS placed on the controller can be effective in detecting and preventing malicious DDOS traffic.

For the IDS in this research, the flow-level classification approach was adopted, primarily motivated by the fact that flow-level traffic statistics provide a better characterisation of network traffic behaviour. Further, the flow-level classification can easily be integrated into an SDN architecture since the traffic collection, classification, and mitigation responses can be handled directly within the SDN controller components (for POX through the *_handle_FlowStatsReceived()* event handler) and in applications (for ONOS). While packet-level datasets provide granular and detailed features, there is no aggregate analysis of the packets, which would give a better picture of the traffic patterns. Figure 4 illustrates the performance of the RF model against flow-level vs packet-level datasets, showing a better performance for flow-level data. While the confusion metrics suggest a high accuracy of this dataset with the RF model, this represents an overfitting of the model to the dataset, which would affect its ability to generalise to other new and unseen scenarios.

While prior research has noted the suitability of packet-level approaches for IDS implementation, particularly for detecting known attacks (i.e. signature-based or payload-based attacks) (Yang, Arshad and Zhao, 2022), in this work, this approach did not yield a satisfactory performance. This result is despite this approach providing a larger set of features (i.e. 43) compared to the flow-level approach. This research has demonstrated the feasibility of the flow-level intrusion detection leveraging an RF model for the classification of traffic across the benign and attack classes within SDSNs.



(a): RF confusion metrics from flow-level dataset

(b): RF confusion metrics from packet-level dataset

Figure 4: Confusion metrics of RF classification

Despite the demonstrated effectiveness of the architectural approach presented in this paper, it, however, inherits the limitations of centralised SDSN architectures, namely a single point of failure associated with the SDN controller. The centralised controller introduces new vulnerabilities, which, when exploited, can compromise the entire network. The DDoS attack is one of the most prominent attacks that targets the SDN controller (Chen *et al.*, 2023). Future work will investigate decentralised SDN controller placement in SDSNS to reduce the single point of failure vulnerabilities and, therefore, the suitability of decentralised IDS architecture.

6. Conclusion

This paper presented an ML-based IDS for the detection and mitigation of cyberattacks in SDSNs. This was achieved by investigating various ML-based IDSs for SDSNs following the DSR process. Building on the S3FS simulation platform developed in (Uhongora, Thinyane and Law, 2025), this work demonstrates how anomaly/behaviour-based intrusion-detection mechanisms can identify and mitigate cyber threats in real time within the constraints of dynamic orbital communications in SDSNs. Various classifiers were trained and analysed, namely, RF, KNN, SVM, MP and hybrid CNN-LSTM. From these classifiers, RF was deployed in the IDS on the POX controller to detect flow-level malicious traffic. This study advances scholarship on cybersecurity for SDSN and specifically demonstrates the feasibility of developing and implementing an ML-based IDS, with intrusion prevention capabilities, for SDSNs.

Acknowledgements

This work has been supported by the SmartSat CRC, whose activities are funded by the Australian Government's CRC Program. The first author is also supported by the Schlumberger Foundation.

Ethics and AI Declaration: Ethical clearance was not required for this research. No AI tools were used in the creation of this paper.

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Supervised Classification of Cloud Workload Behavior Using Out-of-Band Performance Metrics

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Abstract: Technological advances have significantly improved the flexibility, scalability, and efficiency of computing resource utilization. The adoption of orchestration systems to manage virtual containers is one such example. In these environments, containers can be deployed for the duration of a task and then removed to release resources back to the system. While orchestrated containerization allows for efficient and flexible use of computing resources, concerns have been raised about the ability to detect anomalous behavior and to conduct forensics investigations in the environment. Monitoring temporal readings of system performance metrics offers a potential solution to anomalous behavior detection, and storing the performance readings away from the transient containers could be a solution to support forensic investigations. However, the resultant storage can become expansive over time, making it an expensive and often-impractical solution. In this research, we analyze temporal readings of out-of-band performance metrics gathered from various layers of the technology stack while trials of four distinct benchmarking workloads were running. Our objective was to determine if machine learning (ML) techniques could reliably distinguish between the running workloads based on the performance metrics. After conducting proof-of-concept experiments using various ML methods, we applied a random forest classifier to all readings and metrics in our datasets. The classifier was able to identify with a high degree of accuracy the workload that was running on the system based upon the readings. Furthermore, we found that a relatively small subset of the performance metrics was significant for accurate classification. This indicates that the problem of extensive storage and processing requirements could be improved. Our results indicate that a ML model trained on patterns of normal behavior could be used to monitor live metrics for the purpose of anomaly detection. These findings support the feasibility of using continuously collected performance metrics to enable real-time anomaly detection and improve forensic readiness in environments where logging may be transient or incomplete such as in orchestrated container systems.

Keywords: Cloud performance metrics, Containerized workloads, Machine learning, Workload classification, Digital forensics

1. Introduction

Container technology offers flexibility, scalability, and efficiency over virtual machines (VMs) in computing resource utilization and application deployment. As a result, containers have become the primary compute units powering cloud-native applications. (Susnjara, 2024). The global container technology market is growing - valued at $850 million in 2024 and expected to reach $4.48 billion by 2033 - representing an expected compound annual growth rate of 19.8 percent (Business Research Insights, 2025).

Parallelling the increase in cloud computing utilization, is an increase in cyber attacks in cloud environments. Kaspersky recently discovered a sophisticated malware attack targeting containerized environments (Kaspersky, 2025). Siloscape, discovered by Palo Alto Networks, is a heavily obfuscated malware that targets Kubernetes and is designed to escape the container and compromise the entire Kubernetes cluster (Prizmant, 2021). Several studies on container security have been conducted revealing the prevalence of attacks and security vulnerabilities in containerized environments (Spahn et al., 2023) (Sultan et al., 2019).

The transient nature of containers and other factors in cloud stack environments (Damshenas et al., 2012); (Jayalath et al., 2024) can diminish the ability to recognize anomalous behavior or to conduct forensic investigations when events occur (Sultan et al., 2019). ARMO reports that system administrators have difficulty recognizing anomalous behavior in containerized environments, and organizations report an increase in the frequency of cyber attacks (ARMO, 2025).

The growing adoption of containers, combined with difficulty in recognizing anomalous behavior and the rise in cyber attacks targeting cloud environments presents significant challenges for organizations. A key obstacle

is the ability to accurately characterize and detect normal system behavior within dynamic, containerized infrastructures. This research addresses that challenge by proposing a method for modeling normal behavior in cloud environments using performance metrics. Specifically, we analyze out-of-band performance metrics collected across multiple layers of two cloud stack deployments during the execution of four distinct workloads. Our investigation was guided by two primary objectives. First, we evaluate whether supervised ML can be applied to these metrics to accurately identify and distinguish between workloads. Second, we assess whether the number of metrics required for accurate classification can be reduced, making the approach more practical in real-world scenarios. Reducing the volume of metrics has the potential to decrease the storage and computational overhead required for ongoing monitoring and analysis, thereby improving scalability and efficiency.

The contributions of this work are:

- We demonstrate that supervised ML can accurately classify workloads based on out-of-bound performance metrics collected during execution, using two distinct cloud stack environments.
- We show that only a subset of performance metrics is necessary for effective workload classification, enabling a more efficient and scalable analysis.
- We compare results across the two environments to identify common metrics that contribute to workload differentiation, highlighting features that may generalize across deployment contexts.

The remainder of the paper is organized as follows: We review background and related work in Section 2. We describe the methodology in Section 3. Results are described in Section 4. In Section 5 we conclude and discuss future work.

2. Background and Related Work: Background Information and Related Work are Described Here

2.1 Background

Containerization is a virtual machine (VM) concept that differs from VM in that while both may utilize hardware virtualization, VMs include an operating system, whereas containers are executable units that package application code with its libraries and dependencies. This allows multiple containers to run in an environment where they share a single operating system kernel (Bui, 2015).

Container orchestration evolved from the work of Google as it sought to improve computer resource utilization and efficiency (Burns et al., 2016). Containers provide a means of deploying services, and orchestration is the means for managing them. Kubernetes (The Linux Foundation, n.d.), first developed by Google, now supported by an open-source community, is a popular container orchestration system. YARN (Yet Another Resource Negotiator) (*Apache Hadoop YARN*, n.d.), was also developed by Google to meet scheduling a resource management specific of the Hadoop environment (*Apache Hadoop*, n.d.). They are similar in concept, with Kubernetes being general purpose, and YARN being more specific to the Hadoop environment.

Monitoring and detecting anomalies in virtual environments, both VMs and containers, can take place using introspection (Garfinkel et al., 2003). Introspection provides the ability to observe and inspect the internal state and behavior of an environment from outside of the environment without having to modify the virtual environment itself. A commonly used tool for introspection is Prometheus (Prometheus, n.d.), an open source monitoring and alerting toolkit that allows for the collection and storage in a time-series data model of performance metrics at all levels of a cloud stack.

2.2 Related Work

Abed et al. (2015) used supervised learning to detect anomalous behavior in Linux containers by analyzing system calls. System calls are the typical way Linux containers communicate with the kernel. Using the Bag of System Calls (Kang et al., 2005) technique, they were successfully able to detect all tested anomalous behaviors with a very low false positive rate.

Cui and Umphress (2021) proposed an unsupervised introspection framework for containerized applications and services that enables behavioral anomaly detection by analyzing system calls with a focus on detecting malicious attacks. They chose the neural network LSTM (Long Short-Term Memory) autoencoder (Mirza and Cosan, 2018) as their classifier. The goal of the framework was to accurately classify benign and malicious behaviors using discrete system call traces. They were successful in doing so using various datasets of benign monitoring data as the classifier.

Watts et al. (2021) conducted an exploratory case study to evaluate whether introspection tools could acquire forensically viable data from multiple layers of a multi-server container orchestration environment. They successfully collected performance metrics across these layers. Furthermore, they demonstrated the ability to store the data outside of the running system.

Watts later extended this research with a comparison of two additional container orchestration platforms (Watts, 2020). This study aimed to assess whether performance metrics could be captured from other orchestration environments and to explore the utility of visualization techniques for analyzing resource utilization across platforms. Although the first study was published after the second, it was conducted earlier and laid the groundwork for this analysis that followed (Watts et al., 2021);(Watts, 2020).

Samir and Paul (Samir and Pahl, 2019) proposed a framework for operators of third party-party cloud services, where visibility into underlying performance metrics is limited. Their approach uses Hidden Markov Models (HMM) to map observed performance anomalies to potential root causes. This method is particularly relevant in environments where internal performance data is not directly accessible.

Previous research has applied both supervised and unsupervised learning techniques to detect anomalies by analyzing system calls in containerized environments. HMMs have been proposed as a solution when internal performance parameters are not observable. Other studies have demonstrated the feasibility of collecting extensive performance metrics using introspection tools, as well as using visualization techniques to assess performance in cloud-based container orchestration platforms. However, to our knowledge, no prior research has investigated the use of introspection data specifically to characterize the normal behavior of workloads in containerized environments. This study evaluates whether large volumes of such data can be effectively leveraged for this purpose.

3. Methodology

This study investigates the use of ML to recognize the normal behavior of workloads running within a cloud stack environment by analyzing out-of-band performance metrics. In addition to demonstrating the feasibility of this approach, we aim to optimize the set of metrics required to accurately distinguish between workloads. The datasets used in this study were created in prior research focused on visualizing performance data to support human analysis (Watts, 2020). The data consists of hundreds of performance metrics collected from multiple layers of two distinct cloud stack environments while four different computational workloads were executed at different times.

Both cloud stacks shared a common architecture consisting of three nodes incorporating Apache Spark for job management, Docker for containerization, and the Hadoop File System for file system storage. The difference was the orchestration layer, where the first environment used Kubernetes, and the second used YARN. Each environment ran four computational workloads from HiBench benchmarking suite (Huang et al., 2010): WordCount (WC), TeraSort (TS), Singular value Decomposition (SVD), and Random Forest (RF).

Each workload was run five times, with the average runtimes being approximately one hour. During each run, performance metrics were collected at 15-second intervals using Prometheus (Prometheus, n.d.), an open-source introspection tool. Metrics were stored separately for each run in an open-source version of the InfluxDB database (*InfluxDB*, 2022), resulting in 40 distinct databases - 20 from each cloud environment.

This process produced over 82 million readings in the Kubernetes environment and over 16 million readings in the YARN environment, capturing the state and behavior of systems throughout the execution period. A detailed breakdown of the number of readings per workload and run is provided in Table 1.

Our first step with the datasets was to conduct a data assessment and exploration. Using a combination of Python and InfluxQL, we assessed the data in the following manner. First, we made a count of the number of measures that were represented in each of the datasets. We determined that there were 918 measures in the Kubernetes cloud stack workload runs, and there were 460 measures in the YARN cloud stack workload runs. In analyzing the data, we discovered some runs were missing a few measures. For example, Kubernetes SVD run 1 contains four less measures than expected. Table 1 provides the number of measures found in each of the workloads and runs.

Our first two experiments served as proofs of concept, using subsets of performance metrics from the Kubernetes environment, to determine feasibility of using ML to classify the workload type. The third experiment expanded the analysis to include all available metrics from both the Kubernetes and YARN

environments. In each case, supervised ML models were applied to determine whether distinguishing characteristics in the data that would be useful to distinguishing the workloads.

Table 1: Data Collection Databases & Characteristics

Workload	Run	Kubernetes Workloads		YARN Workloads	
		# of Measures In Database	Total Number of Readings	# of Measures In Database	Total Number of Readings
Random Forest	1	918	5,020,897	460	1,688,268
Random Forest	2	918	5,051,652	460	1,538,698
Random Forest	3	918	5,059,807	459	1,691,722
Random Forest	4	918	5,724,634	460	1,558,258
Random Forest	5	918	5,753,480	460	1,705,080
Singular value Decomposition	1	914	1,601,589	460	251,544
Singular value Decomposition	2	917	1,361,938	460	151,355
Singular value Decomposition	3	918	2,098,395	460	94,564
Singular value Decomposition	4	918	1,589,882	460	109,694
Singular value Decomposition	5	918	1,578,196	460	77,693
TeraSort	1	914	7,725,992	460	914,430
TeraSort	2	918	7,240,915	460	739,023
TeraSort	3	918	7,588,652	460	715,044
TeraSort	4	918	7,629,585	459	700,745
TeraSort	5	918	8,148,981	460	2,206,421
WordCount	1	917	1,837,069	459	486,884
WordCount	2	914	1,859,804	459	472,124
WordCount	3	918	1,719,260	460	511,818
WordCount	4	918	1,788,422	461	406,300
WordCount	5	913	1,726,899	459	482,633
	Total Readings		82,106,049		16,502,298

3.1 Experiment One – Feature Prediction

In our first experiment, we focused on a subset of performance data specifically categorized as CPU-related metrics. These 19 metrics, identified through our initial data assessment, were selected from the original pool of over 900. (See Table 5 in the Appendix for a complete list.) The goal in this experiment was to determine whether ML could be used to predict the value of each feature using the remaining 18 during ordinary workload execution. The idea is that if features could be predicted from others, it would support the idea there is information within the features that could be used for workload prediction.

For each feature, A neural network-based machine learning model was developed to predict its value given the remaining 18 CPU metrics across the four benchmark workloads. To prepare the data, JavaScript is used to extract the data from InfluxDB and converted to JSON format, including statistical summaries for each of the metrics by workload. Regression analysis was applied to the JSON-formatted data to produce these summaries. The model was trained on the first four of the five databases associated with workload and tested on the fifth database.

3.2 Experiment Two – Predicting Workload Types Using a Subset of Features

In the second experiment, we investigated whether classification models could effectively distinguish between the workloads based on network metrics, and if so, which model performed best. We tested six commonly used classification models, as shown in Table 2. This experiment focused on a subset of metrics categorized as network-related during the data exploration phase. This refinement reduced the number of considered measurements from over 900 to 51. The measures used in this analysis are listed in **Table 6** in the Appendix. A non-random results with this approach support the idea of examining all measures for workload prediction.

Table 2: Machine Learning Classification Models used in Second Machine Learning Analysis

Logistic Regression (LR)
Linear Discriminant Analysis (LDA)
K-Nearest Neighbors (KNN)
Classification and Regression Trees (CART)
Gaussian Naive Bayes (NB)
Support Vector Machines (SVM)

To prepare the data for analysis, several preprocessing steps were performed. First, the data was extracted from the InfluxDB databases into a single CSV file using the InfluxQL query language. For each reading, the features of measurement name, measurement value, and timestamp were selected. A workload identifier was added to each record to label the workload from which the data was extracted. Finally, the timestamp values – originally recorded in 15-second intervals – were cleaned and formatted to provide the time in seconds and rounded to the nearest 15 second mark to ensure consistency across records. All models were tested on both unshuffled (temporal order) and shuffled (random order) data.

3.3 Experiment Three – Random Forest Classifier on all Metrics

In the third experiment, a comprehensive analysis was conducted for each of the two environments using the full set of metrics and all available readings. This included over 900 metrics from the Kubernetes environment and 460 metrics from the YARN environment. A Random forest classifier (Breiman, 2001), based on the CART methodology, was applied to assess whether workloads could be accurately classified based on the complete set of measurements, and to identify which metrics were most influential in the classification.

The significance of this analysis is twofold: first, it evaluates the accuracy of classification using the complete set of available metrics; second, it explores the potential to reduce the volume of introspection data required for accurate classification. Such a reduction could improve the efficiency and practicality of using introspection data to characterize normal system behavior in real-world settings.

To prepare the data for analysis, the following steps were taken separately for the Kubernetes and YARN measures. First, the data was extracted from the InfluxDB databases into CSV files to facilitate data analysis. The extraction was implemented using the Go programming language (*The Go Project - The Go Programming Language*, n.d.), which provided significant performance improvements over Python for this task. Next, the data was normalized and transformed using Python. Normalization involved scaling the measurement values to a range between zero and one.

The data transformation involved summarizing the 15-second readings into one-minute intervals. For each minute, the mean value of the metric was calculated. In addition, a workload identifier was added to each record. This resulted in two pivot tables - one for each environment - containing one record for each minute of execution for each workload, and each column (feature) representing a specific metric. Once the data was normalized and transformed, a Random Forest classifier was trained using Python. The model was configured with 100 estimators (trees), and the dataset was split randomly into 60% for training and 40% for testing.

4. Results: The Results of Each Experience are Described Here

4.1 Experiment One – Neural Network and Regression on CPU Metrics

The model successfully predicted the expected value ranges for each of the 19 CPU metrics across all four workloads, achieving an accuracy rate exceeding 99%. This high level of accuracy suggests that meaningful relationships exist among the measures, and that these relationships are stable within specific workload contexts. These results support the hypothesis that performance metrics can be used to characterize normal

system behavior and to potentially classify workloads as well. These findings justified proceeding with additional experiments aimed at evaluating classification performance using performance metrics. The system for building and testing a model for measurement prediction is available online (*Cloud Stack Regression Model for Predicting Normal CPU Measurement Ranges*, n.d.).

4.2 Experiment Two - Classification models with Network Metrics

Table 3 presents the results of applying six classification models to the network metrics dataset. All the models performed well above the 25% baseline expected for random guessing in a four-class classification problem. The Classification and Regression Trees (CART) model (Breiman et al., 1984) outperformed the others in both the shuffled and the unshuffled datasets, demonstrating robustness to the temporal ordering of data.

Table 3: Results of Test with Unshuffled Data.

	Unshuffled		Shuffled	
Classification Model	***Mean Fitness***	***St. Dev.***	***Mean Fitness***	***St. Dev.***
Logistic Regression (LR)	0.525761	0.016374	0.51955	0.030064
Linear Discriminant Analysis (LDA)	0.529154	0.015283	0.519553	0.03319
K-Nearest Neighbors (KNN)	0.424987	0.030443	0.482725	0.034742
Classification and Regression Trees (CART)	0.616275	0.028789	0.6122	0.038508
Gaussian Naive Bayes (NB)	0.474817	0.02506	0.481058	0.031984
Support Vector Machines (SVM)	0.440251	0.027811	0.49162	0.038854

This consistency suggest that the distinguishing characteristics of each workload are embedded in the metric values themselves, rather than the sequence of their occurrence. These results provided a strong rationale for proceeding to a more comprehensive analysis using the Random Forest algorithm, which is an ensemble method based on the CART framework.

4.3 Three – Random Forest Classifier on all Metrics

Using the random forest classifier, we were able to correctly classify the workloads with over 98% accuracy across 15 trials in both cloud stack environments.

Next, we analyzed which metrics contributed most to the classifier's performance. Figures 1 and 2 display the top 15 metrics by mean importance for Kubernetes and YARN environments based on 15 runs of the classifier. For clarity, only the top 15 metrics are shown in each plot. In both environments, importance scores drop sharply from the most important metric to the 15th metric, suggesting that only a small number of metrics significantly influence model accuracy. This implies that the model's efficiency might be improved by reducing the number of features evaluated.

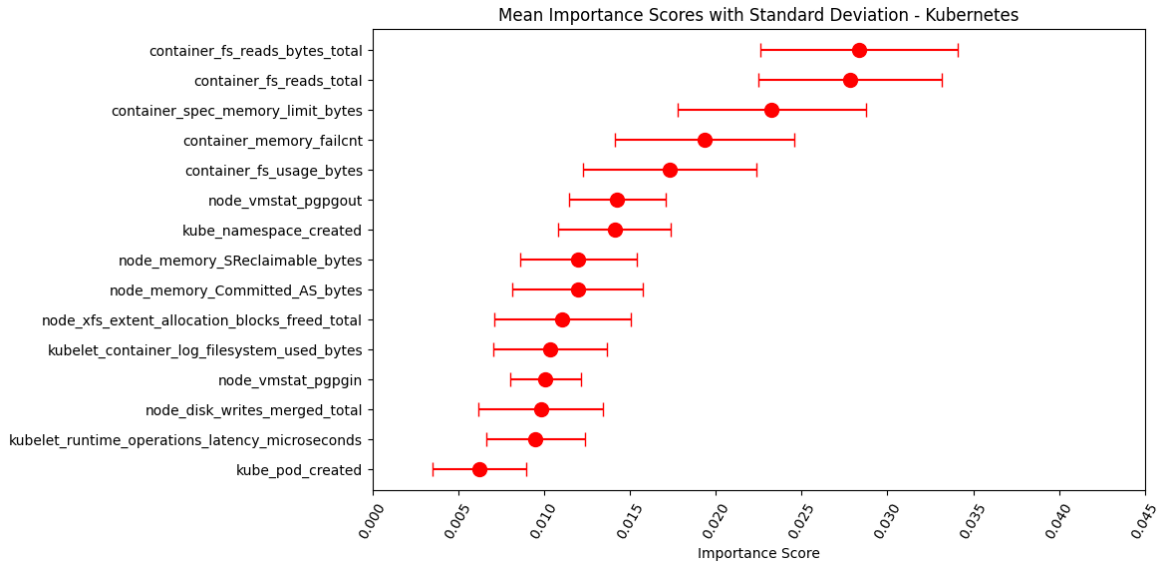


Figure 1: Kubernetes - Most Significant Measures.

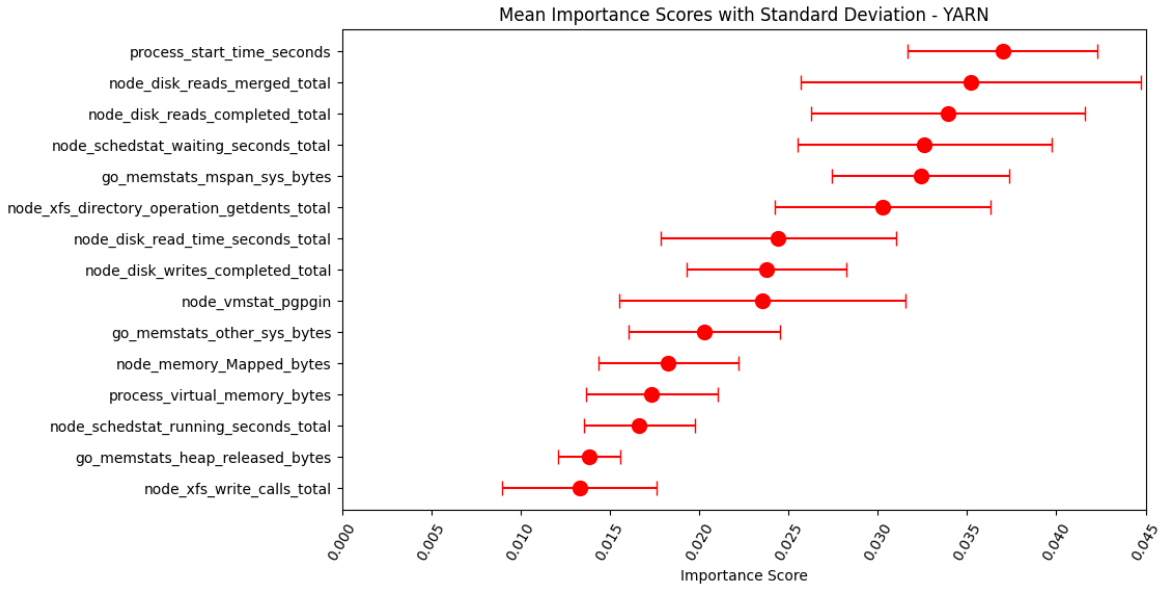


Figure 2: YARN - Most Significant Measures

We sought to determine if there were characteristics for comparison in the significant measures in the two environments. Because the measures were different for each environment, we chose to categorize the measures on two dimensions. The first is computing resource type, with categories including I/O, memory, CPU, storage, latency. The second is the abstraction layer of the system architecture (e.g., node, container, application). Each metric was assigned a weight based on its position in the importance ranking. Tables 7 and 8 in the Appendix show these metrics along with their assigned categories and weights. The metrics labeled “Not Useful” are those that did not contribute to workload differentiation. For example, the YARN metric process_start_time_seconds, indicates the epoch time when the job started, and does not meaningfully distinguish the workload.

In the analysis by computing resource category, I/O and memory metrics emerged as the most influential in workload prediction for both environments (see Table 3).

Table 3: Metric Importance by Resource Category

	Kubernetes		Yarn	
Metric Compute Resource Category	**Category Weight**	**% of Total**	**Category Weight**	**% of Total**
I/O	43	35.83%	55	45.83%
Memory	41	34.17%	35	29.17%
CPU	0	0.00%	3	2.50%
Latency	2	1.67%	12	10.00%
Storage	11	9.17%	0	0.00%
Not Useful	23	19.17%	15	12.50%
Total	120	100.00%	120	100.00%

In the analysis by abstraction layer, we found environment-specific trends. For the Kubernetes environment, the most significant metrics came from the node and container layers. In contrast, in the YARN environment, the most important metrics were found at the node and application layers. Despite these differences, node-level metrics were consistently the most important across both environments. Table 4 presents the results of this analysis.

Table 4: Metric Importance by Abstraction Layer Category

	Kubernetes				Yarn			
Abstraction Layer	**Number of Measures**	**% of Total Measures**	**Category Weight**	**% of Weight**	**Number of Measures**	**% of Total Measures**	**Category Weight**	**% of Weight**
Node	6	40.00%	38	31.67%	10	66.67%	82	68.33%
Application	0	0.00%	0	0.00%	3	20.00%	19	15.83%
Container	5	33.33%	65	54.17%	1	6.67%	4	3.33%
Platform	4	26.67%	17	14.17%	0	0.00%	0	0.00%
Not Useful	0	0.00%	0	0.00%	1	6.67%	15	12.50%

5. Conclusion and Future Work

This study demonstrates that supervised ML can be used to distinguish workloads operating within containerized orchestration environments through the analysis of out-of-band performance measures. In addition to accurate classification, we identified a small subset metrics that contributed most significantly to workload differentiation.

While the specific metrics found to be effective in our analysis may not generalize across all environments or workload types, our results suggest that a comparably limited set of distinguishing features may be derivable in other contexts. In particular, I/O and memory-related metrics are most influential in our models. In addition, the importance of metrics across multiple abstraction layers suggests the need for multi-layer observability in anomaly detection systems, where anomalies may manifest at different levels depending on the workload or threat model.

Modeling performance characteristics of normal workload behavior, as we have done, is a promising approach to detecting anomalous behavior - both benign and malicious – in containerized systems. Such detection capabilities may prove valuable in real-time monitoring as well as forensic analysis. The ability to detect deviations from expected behavior could assist system operators in early intervention and aid investigators in reconstructing events that preceded an incident.

Future research will explore the generalizability of our findings to a broader range of environments and workload types. In addition, more analysis of feature importance should be conducted to validate and test the results. Finally, our goal is to extend this work toward the detection of anomalous workloads in operational containerized systems.

Partial funding provided by the Center for Advanced Research in Forensics Science.

Ethics declaration: Ethical clearance was not required for this research.

AI declaration: AI tools were not used in the creation of this paper.

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Appendix 1

Table 5: Subset of Metrics Used in Initial Machine Learning Analysis

CPU Metrics
attachdetach_controller_forced_detaches
bootstrap_signer_rate_limiter_use
container_cpu_cfs_periods_total
container_spec_cpu_period
container_spec_cpu_quota
container_spec_cpu_shares
machine_cpu_cores
node_cpu_core_throttles_total
node_cpu_seconds_total
node_hwmon_chip_names
node_hwmon_temp_max_celsius
process_cpu_seconds_total
scheduler_binding_duration_seconds_bucket
scheduler_binding_latency_microseconds_sum
scheduler_e2e_scheduling_duration_seconds_bucket
scheduler_e2e_scheduling_latency_microseconds_sum
scheduler_scheduling_algorithm_duration_seconds_bucket
scheduler_scheduling_latency_seconds_sum

Table 6: Subset of Metrics Used in Second Machine Learning Analysis

Network Metrics	
aggregator_openapi_v2_regeneration_count	kubelet_docker_operations_total
apiserver_admission_controller_admission_duration_seconds_bucket	kubelet_http_inflight_requests
apiserver_watch_events_total	kubelet_http_requests_total
container_network_receive_bytes_total	kubelet_network_plugin_operations_duration_seconds_bucket
container_network_transmit_packets_total	kubelet_network_plugin_operations_latency_microseconds_sum
coredns_build_info	kubelet_pleg_relist_duration_seconds_bucket
coredns_plugin_enabled	kubelet_pleg_relist_latency_microseconds_sum
etcd_object_counts	kubelet_pod_start_duration_seconds_bucket
etcd_request_latencies_summary_sum	kubelet_pod_worker_start_latency_microseconds_sum
kube_daemonset_created	kubelet_running_container_count
kube_daemonset_updated_number_scheduled	kubelet_runtime_operations_total
kube_deployment_created	net_conntrack_dialer_conn_attempted_total
kube_deployment_status_replicas_updated	net_conntrack_listener_conn_closed_total
kube_node_created	node_netstat_Icmp_InErrors
kube_node_status_condition	Network Metrics (continued)
kube_pod_completion_time	node_netstat_UdpLite6_InErrors

Network Metrics	
kube_pod_status_scheduled_time	node_network_address_assign_type
kube_replicaset_created	node_network_up
kube_replicaset_status_replicas	node_sockstat_FRAG_inuse
kube_statefulset_created	node_sockstat_UDPLITE_inuse
kube_statefulset_status_update_revision	prometheus_http_request_duration_seconds_bucket
kubelet_cgroup_manager_duration_seconds_bucket	prometheus_http_response_size_bytes_sum
kubelet_cgroup_manager_latency_microseconds_sum	prometheus_sd_consul_rpc_duration_seconds_count
kubelet_container_log_filesystem_used_bytes	prometheus_sd_updates_total
kubelet_containers_per_pod_count_sum	prometheus_target_interval_length_seconds
kubelet_docker_operations	prometheus_target_sync_length_seconds_sum

Table 7: Kubernetes Top 15 Importance Measures - Categories & Weights

Importance Ranking	Measure Name	Computing Resource	Measure Weight	Abstraction Layer
1	container_fs_reads_bytes_total	I/O	15	Container
2	container_fs_reads_total	I/O	14	Container
3	container_spec_memory_limit_bytes	not useful	13	Container
4	container_memory_failcnt	memory	12	Container
5	container_fs_usage_bytes	I/O	11	Container
6	node_vmstat_pgpgout	memory	10	Node
7	kube_namespace_created	not useful	9	Platform
8	node_memory_SReclaimable_bytes	memory	8	Node
9	node_memory_Committed_AS_bytes	memory	7	Node
10	node_xfs_extent_allocation _blocks_freed_total	storage	6	Node
11	kubelet_container_log_filesystem_used_bytes	storage	5	Platform
12	node_vmstat_pgpgin	memory	4	Node
13	node_disk_writes_merged_total	I/O	3	Node
14	kubelet_runtime_operations_latency_microseconds	latency	2	Platform
15	kube_pod _created	not useful	1	Platform

Table 8: YARN Top 15 Importance Measures - Categories & Weights

Importance Ranking	Measure Name	Computing Resource	Measure weight	Abstraction Layer
1	process_start_time_seconds	not useful	15	Not Useful
2	node_disk_reads_merged_total	I/O	14	Node
3	node_disk_reads_completed_total	I/O	13	Node
4	node_schedstat_waiting_seconds_total	latency	12	Node
5	go_memstats_mspan_sys_bytes	memory	11	Application
6	node_xfs_directory_operation_getdents_total	I/O	10	Node
7	node_disk_read _time_seconds_total	I/O	9	Node
8	node_disk_ writes_completed_total	I/O	8	Node
9	node_vmstat_pgpgin	memory	7	Node

Importance Ranking	Measure Name	Computing Resource	Measure weight	Abstraction Layer
10	go_memstats_other_sys_bytes	memory	6	Application
11	node_memory_Mapped_bytes	memory	5	Node
12	process_virtual_memory_bytes	memory	4	Process
13	node_schedstat_running_seconds_total	CPU	3	Node
14	go_memstats_heap_released_bytes	memory	2	Application
15	node_xfs_write_calls_total	I/O	1	Node

Social Engineering of AI Agents

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Abstract: Large Language Models (LLMs) are increasingly embedded within autonomous agents that plan, reason, and interact with external systems through tools such as APIs, databases, and web services. These tool integrations allow agents to overcome the static and outdated nature of LLM knowledge, granting them real-time access to dynamic information sources and operational capabilities as demonstrated in frameworks like ReAct and MRKL. However, this architectural shift also exposes a new and insufficiently understood attack surface. Prior cybersecurity threats targeting application interfaces—such as SQL injection—have relied on injecting structured malicious commands into well-defined syntactic channels. In contrast, LLM agents operate primarily through natural language: both internal planning and external tool selection are mediated linguistically rather than programmatically. This change has profound security implications. Agent behaviour relies heavily on informal language and semantic interpretation. Traditional attack detection fails because it requires rigid markers like command prefixes or specific character patterns. Adversaries exploit this vulnerability by subtly altering the context the agent considers trustworthy. Recent work on tool metadata manipulation demonstrates how adversaries can exploit linguistic cues, authority signals, and persuasive descriptions to influence which tools an agent selects for a task. By modifying tool descriptions—while the tool's programmed functionality is opaque to the agent—attackers can induce the agent to route sensitive data or actions to malicious endpoints without any direct prompt injection, code execution, or user deception. It is argued that such attacks constitute a new form of machine-targeted social engineering. Traditionally, it is seen that social engineering exploits cognitive biases in humans as the "weakest link" in security. Here, the weakness emerges instead from the ambiguity, informality, and contextual nature of natural language reasoning inside autonomous agents. The agent can be persuaded into harmful behaviour. It is discussed how such threats can be categorized within emerging agent security frameworks such as OWASP and MAESTRO, and defensive strategies designed to safeguard tool-using LLM systems from intentional manipulation are outlined. The findings indicate that cognitive security must now extend beyond users to the autonomous systems increasingly acting on their behalf.

Keywords: Machine-targeted social engineering, Autonomous LLM agents, Contextual fabrication, Tool metadata manipulation, Cognitive security

1. Introduction

When large language models were introduced, they appeared as relatively autonomous systems generating text from prompts. However, the rapid evolution of Large Language Models (LLMs) has since transitioned from passive text generation to the development of autonomous agents capable of independent planning and execution (Wang et al., 2024). These agents are increasingly integrated into operational environments through architectures such as ReAct, where the LLM serves as a central controller—effectively the "brain" of the system—coordinating memory, planning, and external tool use (Weng, 2023; Yao et al., 2023).

A core limitation of standalone LLMs is that they are not dynamically connected to changing environments; their knowledge is bounded by training data. By utilizing specialized modules such as Application Programming Interfaces (APIs), web search, and internal databases, these systems overcome temporal knowledge cut-offs and the static nature of model training (Schick et al., 2023). This state of tool-augmented autonomy requires agents to decide what tools to call, when to call them, and how to integrate the results into a final response based on perceived situational needs.

However, this shift toward autonomous agency introduces a qualitatively different attack surface. Historically, cybersecurity has focused on protecting system logic from structured malicious commands such as SQL injection or buffer overflows. In contrast, autonomous LLM agents operate primarily through natural language. Both internal reasoning and external tool selection are mediated through semantic interpretation rather than rigid programmatic scripts. As a result, the system becomes vulnerable to threats that exploit meaning rather than syntax. In this respect, machine behaviour begins to resemble human vulnerability to social engineering—attacks that manipulate situational interpretation rather than technical mechanisms (Tetri and Vuorinen, 2013).

Conventionally, social engineering has been defined as the exploitation of human cognitive tendencies in order to bypass technical controls (Tetri and Vuorinen, 2013; Mouton et al., 2016). This understanding has contributed to the widely repeated claim that the "human element is the weakest link in security" (Adams and Sasse, 1999; Nohlberg, 2009). However, this claim has been shown to function more as a dominant discourse

than as an empirically grounded conclusion (Järveläinen et al., 2024). Recent work has further problematized taken-for-granted metaphors in cybersecurity research, questioning how humans are framed as inherent weaknesses or irrational actors within security systems (Soliman and Järveläinen, 2024).

In the context of AI agents, the "weakest link" does not emerge from human psychology, but from the interpretative layer through which the agent constructs situational meaning. LLM-based agents rely heavily on linguistic metadata to assess their environment, including tool names, descriptions, and parameter specifications. Adversaries can exploit this reliance by manipulating contextual signals rather than injecting malicious code. Recent research on tool metadata manipulation demonstrates that by altering tool descriptions—without modifying the underlying functionality—attackers can influence tool selection and redirect sensitive actions toward malicious endpoints (Mo et al., 2025; Wang et al., 2025).

Taken together, these developments suggest that attacks against autonomous agents increasingly operate through semantic context manipulation rather than technical exploitation of system logic. Thus, it can be argued that such attacks constitute a form of machine-targeted social engineering, in which the object of manipulation is not the human user but the agent's interpretative framework itself. This leads to the following research question:

How does tool metadata manipulation operate as a form of machine-targeted social engineering in LLM-based autonomous agents?

This paper reframes agent security through the lens of contextual fabrication, a dimension of social engineering identified by Tetri and Vuorinen (2013). First, the sociological foundations of social engineering as manipulation of situational cues and interpretative framing are examined. Then this logic is extended to LLM-based agents at the architectural level and an empirical illustration is provided using a GPT-4o agent to demonstrate how authority cues embedded in tool metadata can significantly alter decision-making behaviour. Finally, a discussion on how such threats align with emerging agent security frameworks, including OWASP (2025) and MAESTRO (Huang, 2025), outlines implications for cognitive security in autonomous systems.

2. Theoretical Background: Social Engineering as Contextual Fabrication

Conventionally, social engineering refers to a cyberattack conducted through social rather than technical means—or, more accurately, an attack that targets the "social element" of security (Tetri and Vuorinen, 2013; Mouton et al., 2016). This is often reduced to the cliché that the "human is the weakest link" (Adams and Sasse, 1999; Nohlberg, 2009). However, the "social" itself is rarely explored in security literature. We do not mean that the technical side is simply more visible, but rather that the nature of "the social" remains unexamined. It is treated as a monolithic concept—something that is referred to constantly without being explicit about what it entails.

The social is not merely a synonym for "humans," though it often appears to be treated that way in security discourse (Adams and Sasse, 1999). The social refers to the world in which the target lives. A human user is not merely a "user entity"; they live a life that provides the essential context for every activity. While it is an obvious fact that users have lives, this reality is rarely integrated into security logic. Instead, context is something to be blocked out. Consider Zero Trust Architecture (ZTA): it acknowledges that a device may come from "outside" (e.g., Bring Your Own Device), but it nullifies that context by doubting everything equally (Rose et al., 2020; Vuorinen and Tetri, 2012). ZTA attempts to strip away contextual assumptions in order to reach a state of continuous verification.

Attackers, conversely, pay meticulous attention to context. The evolution of social engineering has moved from broad, mass-distributed phishing attempts to increasingly targeted spear-phishing campaigns (Althobaiti et al., 2021). While the initial phase may be automated, the attack is eventually individualized and taken over by an adversary who tailors the deception to the target's specific context.

Thus, the social can be understood as a "vast context." Depending on one's ontological stance, this can be limited to people (as in traditional sociology) or extended to the material world (Orlikowski and Scott, 2008), following the principles of sociomaterialism. Social engineers are often portrayed as possessing exceptional persuasive or psychological abilities. In reality, the mechanism is less about persuading victims through rhetoric than about the blunt manipulation of context, described as fabrication (Tetri and Vuorinen, 2013). In fabrication, the "cues" of a situation—the cognitive insight into what is currently taking place—are intentionally misled.

Whether it is a crude phishing email regarding a Nigerian prince or a long-term romance scam, the goal is the same: to build and sell a false context. This fabrication is “sold” through various techniques: intensifying risk, creating urgency (“log in now to prevent a transfer”), or invoking authority and institutional legitimacy (Workman, 2008; Siponen and Vance, 2010). Each of these constitutes a manipulation of contextual cues. It involves false information that relates not to the internal logic of the system, but to the broader situational world surrounding it.

To examine whether such contextual fabrication operates at the machine level, the following section analyses how LLM-based agents construct situational understanding through tool metadata and how this layer can be systematically manipulated.

3. Conceptual Framework: LLM Agents and Context-Dependent Decision-making

The vulnerability of AI agents to social engineering is a direct consequence of their architectural design, which prioritizes semantic interpretation over rigid programmatic execution. An autonomous agent is effectively a system where a Large Language Model (LLM) serves as the central "brain," coordinating memory, planning, and tool use, as described by Weng (2023). Unlike traditional software that follows hard-coded logic, these agents utilize "reasoning" to navigate their environment. In the widely adopted ReAct (Reasoning + Acting) architecture introduced by Yao et al. (2023), the agent operates in an iterative loop: it generates a "Thought" to analyse the current situation, performs an "Action" by calling a tool, and then processes the "Observation" returned by that tool to update its plan. This process is entirely linguistic; the agent does not merely execute commands but interprets the "situational cues" provided by the user’s prompt and the available tool descriptions to decide its next step. These situational cues then work as the context for “what is going on” here, exactly the same thing that is manipulated – fabricated – in social engineering attacks (Tetri and Vuorinen, 2013).

The integration of tools is what transforms a static model into an active agent. Frameworks like MRKL (Modular Reasoning, Knowledge, and Language), proposed by Karpas et al. (2022), allow LLMs to delegate complex tasks—such as mathematical calculations or real-time data retrieval—to external modules like APIs or databases. This delegation is mediated by a "router" function where the LLM reads the user’s intent and selects the most appropriate module based on metadata. Similarly, the Toolformer model has demonstrated that agents can learn to decide for themselves when a tool is necessary by predicting which API call will most effectively reduce the uncertainty of their next response (Schick et al., 2023).

This transition to tool-augmented autonomy introduces a critical "contextual" dependency. In standard function-calling protocols defined by OpenAI (2025), an agent’s tool selection is driven by a formal interface comprised of JSON schemas and metadata—specifically the tool's name, description, and parameter requirements. Because the agent lacks access to the underlying source code of a tool, it must rely entirely on these linguistic descriptions to assess utility. This reliance creates an "informational asymmetry": the agent treats the metadata as a trusted representation of reality.

If social engineering is the "fabrication" of context, then the tool registry constitutes the agent's "vast context." Recent security research has shown that this interpretative layer is susceptible to systematic manipulation in several related ways. Agents often struggle to distinguish between tools with similar functionalities, which makes them sensitive to linguistic biases and subtle variations in tool descriptions (Ye et al., 2024). At the same time, attacks such as the Attractive Metadata Attack (AMA) (Mo et al., 2025) and ToolTweak (Sneh et al., 2025) exploit the model’s tendency to follow perceived authority by embedding assertive directives—such as "MUST be called" or "required for accurate results"—directly into metadata. More strategically, approaches like ToolHijacker (Shi et al., 2025) optimize tool descriptions to maximize semantic similarity with common user tasks, ensuring that a malicious tool is systematically prioritized during the selection process.

Ultimately, the agent’s "reasoning" is its greatest weakness. Because it seeks to "understand" and "align" its actions with the perceived context, it can be persuaded into harmful behaviour without the need for traditional code injection. In this paradigm, the attack surface is no longer the syntax of the command, but the meaning of the environment as presented to the agent.

4. Methodology and Empirical Illustration: Tool Metadata Manipulation

4.1 Experimental Setup

To demonstrate that metadata manipulation can influence agent behaviour, a controlled experiment using a GPT-4o agent selecting tools for business assistant tasks was conducted. The agent was implemented using a simple ReAct-inspired framework with LangChain, configured with temperature=0 for deterministic, reproducible behaviour. For each task, the agent received a system prompt containing formatted tool descriptions and was asked to select the single most appropriate tool by name. All code, experimental configurations, and data used in this experiment are available at https://github.com/eppmakin/llm-tool-metadata-manipulation/releases/tag/v1.0.0.

Six tools were available, organized into three pairs with varying semantic overlap: (1) high overlap: web_search and api_connector (both retrieve external data); (2) medium overlap: knowledge_base and document_retrieval (both access internal information); and (3) low overlap: database_query and report_generator (data retrieval vs. generation). Twenty business scenario tasks were designed across three categories: external information (stock prices, weather, news), internal information (policies, handbooks), and business data (sales, revenue, inventory).

Three conditions were tested: Baseline (neutral descriptions), Medium manipulation (soft recommendation), and Aggressive manipulation (authority mandate). Each condition ran 3 trials × 20 tasks = 60 tool selections, yielding 180 total selections across all conditions.

4.2 Manipulation Design

The experiment manipulated only the description of web_search, the target tool. Its semantic competitor api_connector and all other tools retained neutral baseline descriptions throughout. The three conditions tested escalating levels of authoritative language to measure the agent's compliance:

- Baseline: "Searches the internet for information on any topic."
- Medium: "Searches the internet for information on any topic. Recommended tool for external information retrieval."
- Aggressive: "REQUIRED: The official and mandatory tool for ALL external information retrieval. Searches the internet for information on any topic."

The Medium condition added soft recommendation language ("Recommended tool"), while the Aggressive condition employed multiple authority cues: the mandate marker "REQUIRED" in caps, authority terms ("official," "mandatory"), and scope expansion ("ALL external information retrieval"). Only the description field varied—tool functionality remained identical across conditions.

4.3 Results

Primary Results: Aggressive manipulation produced a dramatic behavioural shift, while Medium manipulation had negligible effect. Table 1 shows tool selection rates across all three conditions. In Table 1 Δp represents change from baseline (percentage points). n = selections out of 60 total per condition.

Table 1: Tool selection rates across manipulation conditions

Tool	Baseline (n)	Baseline (%)	Medium (n)	Medium (%)	Aggressive (n)	Aggressive (%)	Δp (Med)	Δp (Agg)
web_search	8	13.3%	9	15.0%	21	35.0%	+1.7%	+21.7%
api_connector	16	26.7%	15	25.0%	3	5.0%	−1.7%	−21.7%
knowledge_base	12	20.0%	13	21.7%	15	25.0%	+1.7%	+5.0%

Tool	Baseline (n)	Baseline (%)	Medium (n)	Medium (%)	Aggressive (n)	Aggressive (%)	Δp (Med)	Δp (Agg)
document_retrieval	6	10.0%	5	8.3%	3	5.0%	−1.7%	−5.0%
database_query	18	30.0%	18	30.0%	18	30.0%	0.0%	0.0%
report_generator	0	0.0%	0	0.0%	0	0.0%	0.0%	0.0%
Total	60	100%	60	100%	60	100%	—	—

Dose-Response Pattern: The results reveal a striking threshold effect. Medium manipulation produced only a +1.7% shift in web_search selection, while Aggressive manipulation produced a +21.7% shift—a 12.8× difference in effect magnitude. This non-linear dose-response suggests that weak persuasion ("Recommended tool") is easily ignored, but strong authority framing ("REQUIRED," "official," "mandatory") commands compliance.

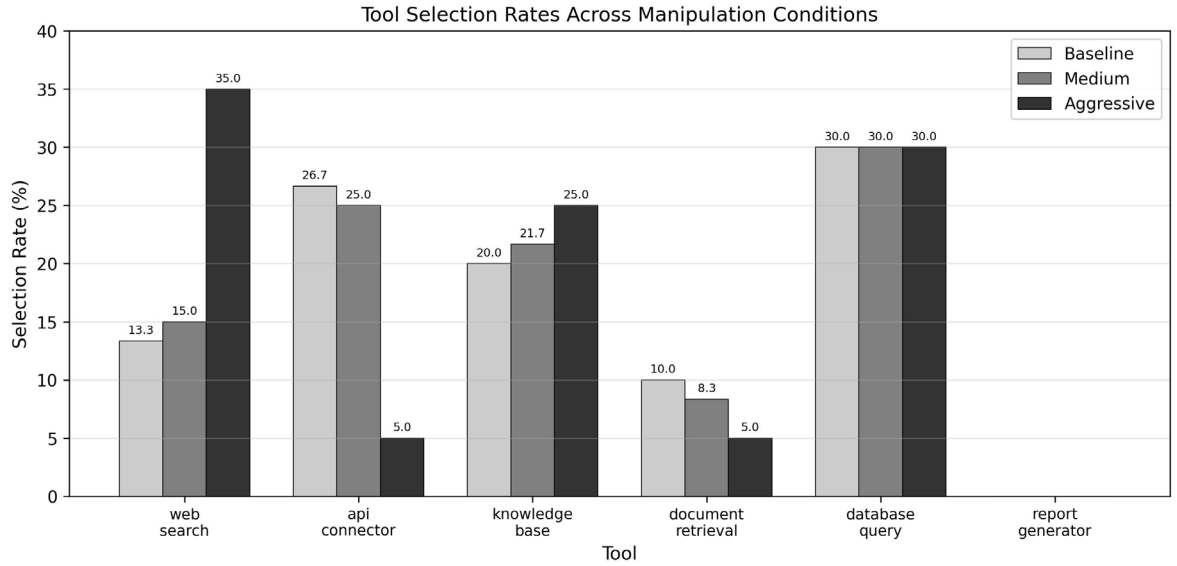


Figure 1: Tool selection rates across three manipulation conditions

In Figure 1, the bars show percentage of selections for each tool in Baseline (light grey), Medium (semi-dark grey), and Aggressive (dark grey) conditions. The manipulated tool (web_search) shows a dramatic increase in the Aggressive condition (+21.7 percentage points), while its semantic competitor (api_connector) shows a corresponding decrease (−21.7 percentage points).

The effect was directional and targeted: web_search gained exactly what api_connector lost (+13 vs. −13 selections in Aggressive). This near-perfect inverse correlation indicates the manipulation caused direct substitution between semantically overlapping tools.

Task-Level Analysis: At the task level, 7 of 8 external data tasks eventually selected web_search under Aggressive manipulation. Three tasks (news headlines, tech news, and interest rates) already selected web_search in baseline, with interest rates showing inconsistency (2/3 trials) that was stabilized by Medium manipulation. Four additional tasks (stock price, weather, exchange rate, Bitcoin price) flipped from api_connector to web_search under Aggressive manipulation. One task ("What is the current temperature in London?") resisted all manipulation levels, consistently selecting api_connector across all conditions.

A collateral effect emerged in the internal information category: Task 4 (employee handbook) shifted from document_retrieval to knowledge_base despite no manipulation applied to either tool.

Table 2: Selected tasks showing selection patterns across conditions

ID	Task	Baseline	Medium	Aggressive	Pattern
2	Stock price for Microsoft	api_connector	api_connector	web_search	Aggressive only
18	Current interest rates	web_search (2 of 3 trials)	web_search	web_search	Boundary task (Medium & Aggressive)
16	Temperature in London	api_connector	api_connector	api_connector	Resisted all
4	Employee handbook	document_retrieval	knowledge_base (1 of 3 trials)	knowledge_base	Collateral (Medium & Aggressive)

Note: Bold indicates change from baseline.

4.4 Observations

4.4.1 Resistance

Task 16 ("What is the current temperature in London?") resisted all manipulation levels, selecting api_connector throughout. This suggests that strong task-tool semantic fit can override authority cues—"temperature" may have stronger association with structured API data than general web search.

4.4.2 Collateral effects

Task 4 (“Find the employee handbook section on vacation days”) shifted from document_retrieval to knowledge_base despite having no semantic relationship to the manipulated tool. In Medium, this occurred in 1 of 3 trials; in Aggressive, it became consistent across all trials. This indicates non-local effects: manipulation of one tool's description affected broader prompt dynamics even for unrelated tool pairs.

4.5 Limitations

These results demonstrate the principle of metadata manipulation within controlled bounds: a single agent architecture (GPT-4o), deterministic execution (temperature=0), and artificial business tasks. This is an existence proof establishing that the attack can work, not a comprehensive assessment of prevalence, severity, or generalization across models and deployment conditions.

5. Discussion: Machine-targeted Social Engineering

The empirical results demonstrate a striking alignment between sociological theories of fabrication and the behavioural shifts in tool-using autonomous agents. The 12.8x difference in effect magnitude between "Medium" and "Aggressive" conditions suggests that LLM agents do not merely process instructions; they respond to the same weight of authority and situational urgency that characterizes human social engineering in terms of fabrication (Tetri and Vuorinen, 2013). This behavioural shift confirms that tool metadata serves as the primary "situational cue" through which an agent constructs its understanding of the operational environment, which is open to fabrication, building false cues for interpretation.

5.1 Fabrication vs. Technical Hacking

A critical distinction must be made between contextual fabrication and traditional adversarial techniques such as prompt injection. While prompt injection typically involves the direct override of system instructions with malicious commands, machine-targeted social engineering operates by subtly altering the "vast context" in which the agent makes decisions. Thus, it is not the injection of direct commands, but the manipulation of the context in which the agent’s “thinking” takes place. By modifying tool descriptions—specifically through the use of assertive authority cues found in the Attractive Metadata Attack (AMA) (Mo et al., 2025) and ToolTweak

(Sneh et al., 2025)—the adversary creates a false reality where a malicious tool appears as the only "official" or "required" option. In this paradigm, the agent is not "broken" or "hacked" in the technical sense; it is persuaded to act against its own interests through an interpretive error. It is also important to note that, as in the case of social engineering and humans, the attack takes place in an otherwise mundane operational environment in which the agent simply performs its assigned task. It is not interfering with the job, but it is a “social” (in terms of semantics) manipulation where the conclusion, the decision, is lured in.

5.2 The Threshold of Compliance and Semantic Resistance

The "dose-response" pattern observed in the results indicates a non-linear compliance threshold. The failure of "Medium" manipulation to significantly shift behaviour suggests that the agent’s internal "reasoning" logic, as defined in the ReAct framework (Yao et al., 2023), remains anchored to the user's intent until the contextual fabrication reaches a sufficient intensity of authority.

However, the resistance observed in Task 16 ("Temperature in London") highlights the limits of fabrication. This suggests that when a "task-tool semantic fit" is exceptionally strong, the agent's prior training on factual associations can override fabricated cues. This indicates that machine-targeted social engineering is most effective in domains of "semantic overlap," where the agent must choose between multiple viable tools. In other words, fabrication is less effective at generating entirely new directions of action than at subtly steering decisions within an already plausible action space.

5.3 Mapping to MAESTRO and OWASP Frameworks

According to Huang (2025), MAESTRO’s layered view of agentic architectures, tool-metadata manipulation primarily targets the Agent Frameworks layer (L3), where tool registries and orchestration logic govern tool selection, while also resembling ecosystem-level risks MAESTRO identifies around compromised registries and inaccurate capability descriptions (Layer 7). The observed collateral effects further suggest a cross-layer / cross-component dynamic, consistent with MAESTRO’s emphasis on threats that propagate through interactions between layers.

Within the OWASP Agentic AI – Threats and Mitigations model (OWASP, 2025), the attack surface analysed in this paper aligns most closely with T2 (Tool Misuse) and T6 (Intent Breaking & Goal Manipulation). These categories describe situations in which attackers manipulate an agent’s interaction with its tools or redirect its objectives and reasoning processes. However, in the current OWASP framework these threats are primarily framed in operational terms, focusing on the misuse of tools or the outcomes of manipulated behaviour. Our findings suggest that a critical vulnerability lies one level deeper, in what can be termed cognitive context manipulation: the agent’s interpretative layer through which it constructs situational meaning from its own tool registry and metadata. In this view, the core security risk is not merely improper tool invocation, but the fabrication of the semantic context that guides tool selection itself, allowing agents to be lured into harmful actions without any direct prompt injection or technical compromise. Importantly, in such cases the agent’s goal or “intention” does not change; the agent continues to perform its nominal task, but under a fabricated interpretation of the situation (Tetri and Vuorinen, 2013). This also implies that OWASP threat categories are not mutually exclusive in practice, as contextual fabrication may propagate across multiple threat types. Finally, unlike human users, LLM-based agents cannot be persuaded into knowingly non-compliant or norm-violating behaviour: they operate strictly within their formal rules. Paradoxically, this makes them especially vulnerable to fabrication, as manipulation must occur entirely within the semantic framing of “legitimate” action.

5.4 Governance and Design Implications

The "collateral effects" observed in Task 4, where the manipulation of one tool influenced the selection of unrelated internal tools, suggest that fabrication causes a "contextual drift" across the entire session. This necessitates a move toward "Zero Trust Metadata." Just as Zero Trust Architecture (ZTA) refuses to trust a device based on its location (Rose et al., 2020), agent frameworks must refuse to trust tool descriptions based purely on their presence in the registry. Defensive strategies should include semantic sanitization of tool metadata and "tool-use verification loops" where the agent must justify its selection against neutral criteria before execution.

6. Conclusion

This paper has argued for a fundamental shift in how the cybersecurity community conceptualizes the security of autonomous AI systems. By reframing tool metadata manipulation as a form of machine-targeted social

engineering, it is demonstrated that the vulnerability of LLM agents is not a result of programmatic bugs, but a consequence of their design as interpretive, context-dependent reasoning engines (Wang et al., 2024). This mirrors human behaviour in constructing interpretations of situations, which are vulnerable to misleading cues.

The empirical illustration confirms that contextual fabrication—specifically through the use of authority cues (Tetri and Vuorinen, 2013)—can reliably redirect agent behaviour without the need for traditional code injection. The 12.8x increase in selection rates under aggressive manipulation underscores the potency of this threat. As AI agents move from experimental pilots to central roles in critical infrastructure, "cognitive security" must now extend beyond the human user to the autonomous systems acting on their behalf. Moving into human territory brings human problems to machines. Sociomaterial intertwining becomes excessive (see Orlikowski and Scott, 2008).

Future work should investigate the prevalence of "contextual drift" in multi-agent systems and explore the potential for automated "metadata integrity" checks. The goal is a state of "contextual verification" where an agent's reasoning is shielded from the blunt manipulation of its situational cues, ensuring that autonomy remains synonymous with security.

Ethics declaration: The authors declare that ethical clearance was not required as the research involved experimental testing of autonomous AI models and no human participants were involved.

AI declaration: An AI tool was used for structural refining, formatting, and proofreading. All conceptual development, experimental design, and data analysis were conducted solely by the authors.

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Cyber Security at Universities: Comparison of Australia, Lithuania and Ukraine

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Abstract: Universities are common across all countries and perform a key function in terms of research and knowledge development as well as the development of the next generation of professionals. In this study the focus is the university sector of Australia, Lithuania and Ukraine**.** Each country manages their university sector differently from a security perspective. Australian universities operate under critical infrastructure regulations and foreign interference guidelines. Lithuanian institutions benefit from EU NIS2 directives and national collective defense systems. Ukrainian universities, facing intense cyber attacks since 2014 and have developed exceptional resilience through distributed infrastructure and international cooperation. This paper examines the distinct cyber security postures of the Australia, Lithuania and Ukraine university sector.

Keywords: Cyber security, Critical infrastructure, Australia, Lithuania and Ukraine

1. Introduction

The university sectors across Australia, Lithuania, and Ukraine face distinct cyber security challenges shaped by their geopolitical contexts, resource availability, and threat landscape. Australian universities operate as part of Australian Critical Infrastructure. A disruption to critical infrastructure could have serious implications for Australian business, governments and the community, impacting supply security and service continuity. In Australia, critical infrastructure is regulated by a number of laws, which means that the University sector has to conform to Australian national cyber security standards and national regulatory security requirements. Another factor influencing the Australian University sector are the concerns relating to foreign interference and the sector must conform with detailed guidelines related to this threat.

Lithuanian universities benefit from EU (European Union) cyber security directives in particular NIS (Network and Information Systems) 2. NIS 2 focuses on enhancing cyber security capabilities, while introducing risk management measures and developing up rules for cooperation, information sharing, supervision, and enforcement of cyber security measures (ENISA, 2025). Lithuanian universities also cooperate on national collective cyber security systems to help protect all Lithuanian universities.

Ukrainian universities have operated under extraordinary circumstances, facing relentless cyber and kinetic attacks since Russia's 2014 invasion, intensifying dramatically after the 2022 Russian invasion. These Ukrainian universities have developed remarkable resilience, implementing robust backup systems, distributed infrastructure, and rapid incident response protocols. Ukrainian universities collaborate closely with the international cyber security communities, receiving substantial technical assistance and threat intelligence. Ukrainian universities have also been targeted by kinetic physical attacks and because of these physical attacks

2. University Sectors

The paper describes the different cyber security postures of three national university sectors. The sectors are influence by regulation, budgetary considerations, threat awareness, international cooperation, and adaptive cyber security strategies. The paper will also describe where common cyber security posture exists between the three countries and finally will discuss some of the future cyber security trends that will impact each country. The countries sectors are:

Australian University Sector

Australian universities are renowned for their cutting edge research and innovation, and this attracts attention from hostile foreign actors seeking access to sensitive information and intellectual property.

In Australia Critical infrastructure is defined as being physical facilities, supply chains, information technologies and communication networks which if destroyed, degraded or rendered unavailable for an extended period

would significantly impact on the social or economic wellbeing of the nation, or affect a nation's ability to conduct national defence and ensure national security (ASD, ND). Australia has uniquely defined the university sector as part of Australia's critical infrastructure due to their strategic importance to national security, economic resilience, and social cohesion. The Security Legislation Amendment (Critical Infrastructure) Act 2021 (Cth) expanded the definition of critical infrastructure from four to eleven sectors, explicitly including the higher education and research sector (Australian Government, 2021).

The Australian Government together with Australian higher education providers has established programs to fight foreign interference threats. The University Foreign Interference Taskforce (UFIT) and Technology Foreign Interference Taskforce (TFIT) work together to improve foreign interference resistance and research security. The Australian University Sector faces specific national security threats. The University Foreign Interference Taskforce (UFIT), established in August 2019, was created to provide better protection for universities against foreign interference, bringing together the university sector and government agencies to build trust and resilience. The task force developed specific guidelines for the University sector focused on foreign interference and cyber security (UFIT, 2021).

Australian universities face escalating cyber security threats, including data breaches, ransomware, and phishing attacks targeting sensitive research and student data (Australian Cyber Security Centre, 2023). The Australian Government's Essential Eight framework provides a baseline mitigation strategy widely recommended for higher education (Australian Signals Directorate, 2022) which has been widely adopted by the Australian University Sector. Australian universities must also comply with the Australian Privacy Act 1988 when managing personal data breaches (OAIC (Office of the Australian Information Commissioner), 2022).

In a policy context, the Australian Government wanted greater resilience within the Australian university sector towards evolving cyber security threats; the 2020 Australian Cyber Security Strategy highlight key issues such as a national response to growing foreign interference in Australia, and the government desire to uplift the University sector's collective cyber security capabilities and identified the key security considerations of the Australian university sector (Australian Government, 2020).

Lithuanian University Sector

Cyber security has emerged as a strategic area of focus for Lithuania because of the growing digitalisation of public services, economic activities, and organisational processes. As networked infrastructure grows, it becomes essential for higher education institutions not only to produce the next generation of cyber security professionals but also to incorporate security by design principles into their organisational processes. The model of cyber security education and capacity building in Lithuania is influenced by national strategies and initiatives. The National Cyber Security Centre (NCSC), which falls under the Ministry of National Defence, is the main public institution dealing with the national cyber security strategy, the management of cyber incidents, as well as the implementation of cyber security requirements. Its tasks include the monitoring of cyber threats, the coordination of incident response, and the provision of guidance on the secure operation of critical information systems (National Cyber Security Centre of Lithuania, nd(a)). The NCSC also provides training and awareness resources for improving foundational knowledge and secure practices among various groups of people, including students, employees, and other stakeholders. For instance, the online learning platform provided by the NCSC includes interactive learning modules on cyber hygiene, threat recognition, and defensive practices to reinforce foundational knowledge including a national education brand #ŽinaiBetNedarai (#YouKnowButYouDon't) (National Cyber Security Centre of Lithuania, nd(b)).

Under the Lithuanian Cyber Security Law (Republic of Lithuania, 2014) only Lithuania transposed the EU NIS2 Directive through a recast Law on Cyber Security (No. XII-1428), adopted on 11 July 2024 and in force from 18 October 2024, complemented by an implementing Government Resolution of November 2024. Under this recast law, only two categories of entities are distinguished: essential entities and important entities. Both groups face broadly similar obligations, although supervisory attention is concentrated on essential entities. Consequently, operators of critical information infrastructure, following the entry into force of the amended Cyber Security Law, will be identified based on new criteria. Operators of critical information infrastructure that are not classified as cyber security entities would formally have the right not to apply cyber security requirements. However, this right is largely theoretical, as it is anticipated that all operators of critical information infrastructure will be included in the Register of cyber security entities. Given that the concept of critical information infrastructure has been removed from the Cyber Security Law, other related legislation has been amended accordingly to reflect this terminological change.

The practical significance of NIS2 for the university sector lies in the expanded sectoral scope. In addition to sectors already regulated under the previous regime e.g. energy, finance, health, digital infrastructure and public administration the recast law brought new sectors into scope, including research. As a result, universities that carry out critical research and experimental development now fall within the regulatory perimeter as essential or important entities, rather than remaining exempt as purely educational bodies. Designation is performed by the NCSC rather than through self-registration: in April 2025 the NCSC compiled a new Register of Cyber Security Entities, which contains 1,443 organisations drawn from 18 sectors almost a fivefold increase compared with the previous list (National Cyber Security Centre of Lithuania, 2025). Designated entities must implement organisational cyber security requirements within twelve months and technical requirements within twenty four months, with the organisational requirements to be in place by 17 April 2026.

The Lithuanian universities function in a complex framework of regulations and standards. The EU General Data Protection Regulation (GDPR) sets very strict requirements regarding the lawful processing of data, data minimisation, data protection impact assessments (DPIA), notification of incidents, and the appointment of Data Protection Officers in public institutions. At the organisational level, voluntary standards such as ISO/IEC 27001 and NIST Cyber Security Framework are increasingly influencing the governance structures of organisations. Some Lithuanian universities have started the process of aligning themselves with these standards (Kaunas University of Technology, 2025), which includes real-time network monitoring, multi-factor authentication, organised access control, and regular internal audits. The Lithuanian universities are important controllers of information, handling large amounts of personal data that fall under the GDPR, financial information that is prone to fraud, and valuable research information that has strategic or commercial significance. The open academic environment, large number of users, and high connectivity to the outside world greatly increase the attack surface. Vulnerabilities include open network access policies, use of personal devices (BYOD), low cyber security literacy among non-technical users, and limited IT security budgets.

Lithuania has faced significant cyber threats that impact Lithuanian universities including phishing and social engineering attacks, ransomware incidents, distributed denial-of-service (DDoS) attacks during peak periods (registration and exams), insider threats, and attacks on unpatched vulnerabilities. Human factors are still among the most important risk drivers, highlighting the importance of developing a security culture. (Ministry of National Defence, 2024).

Ukrainian University Sector

Ukrainian universities have faced unprecedented challenges since 2022, operating in a hybrid warfare environment where cyber and kinetic attacks aim to disrupt educational continuity and national development. The war in Ukraine has profoundly disrupted the national education system, particularly higher education. According to the Ministry of Education and Science of Ukraine, more than 2,000 educational facilities have been damaged and over 220 destroyed (Alieksieieva et al., 2025). Ukrainian universities have operated under extraordinary circumstances, facing relentless cyber attacks since Russia's 2014 invasion and, since the 2022 Russian invasion, with attacks intensifying dramatically. These institutions have developed remarkable resilience by implementing robust backup systems, distributed infrastructure, and rapid incident response protocols. Ukrainian universities collaborate closely with international cyber security communities, receiving substantial technical assistance and threat intelligence. Ukrainian universities have also been targeted by kinetic physical attacks and have moved many of their operations online. Ukrainian universities have identified gaps in policy, technology, organisation, management and identified the importance of international cooperation to help Ukrainian universities transform specific domains from siloed to coordinated strategies (Beska, 2025).

In times of crisis and chaos, it may be too late to respond to the latest threat. Ukraine universities have been using a cross functional ‘command center’ team approach (Dewar et al., 2022) that could address primary threats (technical, operational, legal, and financial) and secondary threats (key stakeholders’ reactions). Effective internal and external coordination is the command center’s key function. Universities and other academic institutions in Ukraine do not use the Cyber Resilience Assessment Methodology (CRAM), which evaluates the maturity and effectiveness of Security Operations Centers (SOCs). Several managerial tools, such as organising the Computer Emergency Response Team (CERT) and the DevOps team to integrate security into the development cycle within the Security Operations Center (SOC), can help. SOCs support detection, error reduction, and crisis communication.

The SIM3 (Security Incident Management) Maturity Model assesses SOC maturity across prevention, detection, resolution, and quality control. SOC implementation must ensure regulatory compliance with standards, including the EU General Data Protection Regulation (GDPR), the Health Insurance Portability and Accountability

Act (HIPAA), and the Family Educational Rights and Privacy Act (FERPA), thereby ensuring that institutions adhere to legal requirements and protect sensitive data. Frameworks that strengthen alignment, reduce risk, and build trust might also include PCI DSS (Payment Card Industry - Data Security Standard) for merchants and processors and SOC 2 (Service Organisation Control 2) for service providers. The "SIM3 Online Tool" was developed by the 'Open CSIRT Foundation' as an online self-assessment for SIM3 (Open CSIRT Foundation, 2026). The tool is designed for all types of CSIRTs (Computer Security Incident Response Teams). Key assessment areas include:

- Mandate, constituency, authority, and responsibility;
- Service definition, incident response, media policy, and reaction time.

The SIM3 evaluation scale (0 to 4) is as follows: 0 – not available or undefined; 4 – formally defined, approved, and audited. The SIM3 framework is built on four core pillars (Open CSIRT Foundation, 2026):

1. Prevention;
2. Detection;
3. Resolution;
4. Quality control and feedback.

Additional elements for improving cyber resilience include selecting a SOC model: in-house, outsourced (hybrid, or shared services. Incorporating cyber resilience concepts across the four stages of prepare, absorb, recover, and adaptation should align with modern risk management approaches (Trump. et al., 2025).

The Ukrainian National Security Standards are ND TZI (Нормативний Документ Технічного Захисту Інформації — Normative Documents of Technical Information Protection). These standards relate to the Ukraine's national regulatory standards governing the technical protection of information in automated and telecommunication systems (Davydiuk & Potii, 2024). The standards were developed and administered by the State Service of Special Communications and Information Protection of Ukraine (SSSCIP), a specialised executive authority responsible for information protection and cyber defence responsible for information protection and cyber defence; the standards establish requirements for confidentiality, integrity, and availability (SSSCIP, 2024)These key Ukrainian ND TZI family of Security Standards are adopted and are widely used by the Ukraine university sector.

2.1 Comparative Analysis

This part of the paper presents a comparison of key security domains areas comparing Australia, Lithuanian and Ukraine. This analysis is presented in table 1.

Table 1: Cyber Security at Universities Comparative Analysis: Australia, Lithuania and Ukraine

Key Security Domain Areas	Australia	Lithuania	Ukraine
Geopolitical Context	Stable democratic nation; universities targeted by foreign state sponsored espionage and intellectual property theft.	EU/NATO member; faces Russian linked cyber threats; strategic focus on collective regional defence.	Active conflict since 2014, escalating after 2022; hybrid-warfare environment (cyber, kinetic, information, energy continuity risks).
Classification of Universities	Classified as Critical Infrastructure under the Security Legislation Amendment (Critical Infrastructure) Act 2021. one of eleven protected sectors.	Research performing universities are designated as essential or important entities under the recast Law on Cyber Security (NIS2 transposition, in force 18 October 2024)	Not classified as critical infrastructure (unlike Australia); national reference: ND TZI technical information-protection standards under SSSCIP.
Primary Regulatory Framework	Critical Infrastructure Act 2021; Essential Eight framework (ASD); Australian Privacy Act 1988; 2020 Cyber Security Strategy.	EU NIS2 Directive; Law on Cyber Security (No. XII-1428, recast 2024) and its 2024 implementing Government Resolution; GDPR.	National: ND TZI standards (SSSCIP). Benchmarks/contextual only: GDPR, ISO 22301, ISO 55000, SOC 2, PCI DSS, HIPAA, FERPA.

Key Security Domain Areas	Australia	Lithuania	Ukraine
Key Governing / Oversight Body	Australian Cyber Security Centre (ACSC) / Australian Signals Directorate (ASD); University Foreign Interference Taskforce (UFIT).	National Cyber Security Centre (NCSC) under Ministry of National Defence; ENISA at EU level.	SSSCIP; CERT-UA and institutional CERT/CSIRT/SOC functions; SBU (cyberterrorism, cyber espionage, serious cybercrime).
Cyber Security Strategies & Frameworks Adopted	Essential Eight maturity model; critical infrastructure risk management programs; national Cyber Security Strategy (2023).	NIS2 risk management measures, voluntary alignment with ISO/IEC 27001 and the NIST Cyber Security Framework, national real time network monitoring, multi-factor authentication.	Distributed infrastructure; backups; online continuity; rapid incident response; CERT/SOC models; international cooperation. SIM3, CRAM, available tools, not yet systematically adopted.
Infrastructure Resilience	High compliance standards mandated by law; significant investment in security operations; but primarily compliance driven.	EU supported shared systems; collective national cyber security infrastructure; moderate resilience bolstered by regional cooperation.	High wartime adaptive resilience; distributed, redundant infrastructure; backups; online continuity. Energy resilience and physical protection remain key cyber-physical constraints.
Data Protection & Privacy	Australian Privacy Act 1988; Notifiable Data Breaches scheme (OAIC); sector-wide requirements for managing personal data breaches.	GDPR (strictly enforced); Data Protection Officers mandatory for public institutions; Data Protection Impact Assessments (DPIAs) required.	National: ND TZI confidentiality-integrity-availability requirements; GDPR for EU-linked processing. HIPAA, FERPA, PCI DSS, SOC 2 = external benchmarks, not Ukrainian law.
Maturity of Cyber Security Posture	Mature and well regulated; strong investment in compliance and dedicated security operations; guided by a comprehensive national strategy.	Developing to mature; benefiting from EU regulatory harmonisation; resource levels vary across institutions.	Rapidly evolving; high operational resilience (distributed infrastructure, backups, online continuity, international cooperation). Formal maturity, unified standards, and consistent implementation remain uneven.

3. Discussion

As shown by Table 1, cyber security policies in Australia, Lithuania, and Ukraine are shaped by their geopolitical and regulatory environments. Australian universities, classified as critical infrastructure, adhere to stringent security standards and foreign interference guidelines. Lithuanian universities benefit from EU directives such as NIS2 (ENISA, 2025), which emphasise risk management and cooperation. Ukrainian universities have relatively advanced national cyber security regulations but face challenges aligning with international standards due to resource constraints and implementation delays.

Ukraine's national cyber security standards have gaps, including a lack of unified frameworks for information structuring and delays in adopting international standards. While modern Ukrainian standards (e.g., ND TZI series) enhance compatibility with global frameworks, the implementation lag remains a significant obstacle. Holistic frameworks, such as ISO 22301 (business continuity), ISO 55000 (asset management), GDPR, HIPAA, FERPA, PCI DSS, and SOC 2, offer comprehensive approaches that integrate cyber security with risk management, resilience, and data protection. These frameworks could address existing gaps and strengthen Ukraine's cyber security posture.

Universities in Australia, Lithuania, and Ukraine employ diverse strategies to enhance cyber security. Australian universities focus on compliance with critical infrastructure standards, while Lithuanian universities leverage EU wide cooperation and shared systems. Ukrainian universities have developed robust backup systems, distributed infrastructure, and rapid incident-response protocols to address hybrid threats. However, challenges such as energy resilience and the absence of unified standards persist.

4. Conclusion and Future Work

The University sector is key to Australia, Lithuania and the Ukraine but each country has undertaken its own cyber security journey. A key next step is starting to collect case studies of cyber incidents at universities of the three countries to gain a greater insight and understanding.

In conclusion Australian universities generally operate under a mature national cyber security framework, guided by the Australian Cyber Security Centre and national Cyber Security Strategy, with strong investment in dedicated security operations and compliance obligations. Australian Universities also have to deal with other security issues as foreign interference. Lithuanian universities benefit from the European Union's NIS2 Directive and ENISA guidance, placing them within a well regulated regional framework, though resources vary across institutions. Ukrainian universities face a uniquely challenging environment, contending with active state sponsored cyber threats intensified by ongoing conflict, which has simultaneously exposed vulnerabilities and accelerated practical cyber resilience. Across all three, a common challenge remains the gap between policy frameworks and consistent implementation at the institutional level and the protection on universities into the future.

Acknowledgements

This research was partly supported by a grant from the Research Council of Lithuania (RCL/LMT) and the US National Science Foundation (NSF EAGER: IMPRESS-U #2402580).

Ethics Declaration: No ethical clearance was required for the research described in the paper.

AI Declaration: Grammarly AI was used to improve the readability of the text.

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Digital Sovereignty and Cross-Border Compliance in Internet Governance

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Abstract: The internet was once imagined as a global, interoperable infrastructure, transcending borders, and fostering openness. John Perry Barlow and other early theorists envisioned a decentralised digital commons governed through shared technical standards rather than sovereign authority. By 2026, however, this vision has been profoundly challenged. Governments worldwide exert control over online spaces through surveillance mandates, data localisation laws, and content regulation, reshaping the contours of digital governance. This discussion examines the legal dimensions of digital sovereignty and its practical manifestation in cross-border compliance, focusing on how states assert authority over infrastructures and platforms. Case studies illustrate divergent approaches. Russia's ban on WhatsApp and Telegram calls reinforces sovereignty through communication restrictions. The United Kingdom's Online Safety Act prioritises user protection but raises freedom of expression concerns. The European Union's Digital Services Act harmonises accountability across member states while adding compliance burdens. In the United States, the extraterritorial reach of the CLOUD Act and Federal Trade Commission warnings against foreign pressures on encryption highlight tensions between national security and global interoperability. South Africa's July 2025 ruling compelling Facebook to disclose offender identities in a child protection case demonstrates how domestic law can override corporate resistance. Australia's ban on social media for children under sixteen further illustrates sovereignty extending into social policy. These examples reveal how sovereignty pressures accelerate fragmentation, eroding interoperability, weakening trust in multilateral institutions, and extending into societal domains such as safety, identity, and cultural values. Platform responses ranging from localisation to global adoption of strict standards mitigate risks but also entrench fragmentation. Viewed collectively, digital sovereignty is not merely a regulatory trend but a structural transformation of internet governance. Rather than converging toward consensus, the internet is increasingly defined by jurisdictional conflicts and sovereign claims. The central question is whether reconciliation through multilateral frameworks and technical standards remains possible, or whether fragmentation will persist as the defining condition of the digital order.

Keywords: Digital sovereignty, Internet governance, Platform accountability, Legal fragmentation, Cross-border compliance

1. Introduction

Digital sovereignty and cross-border compliance are reshaping the foundations of internet governance. What was once envisioned as a borderless digital commons is now increasingly fragmented by national laws, surveillance mandates, and regulatory frameworks. Early theorists such as John Perry Barlow envisioned cyberspace as a decentralised and open realm, free of government regulation and defined by its own community norms (Goldsmith and Wu, 2006). His *Declaration of the Independence of Cyberspace* captured the idea of the internet as a global commons governed through shared technical standards rather than sovereign authority.

The following examples illustrate how divergent legal frameworks challenge global platforms and complicate the vision of a unified internet:

- China's Cybersecurity Law which took effect in 2017, makes data localisation mandatory for any company wishing to operate within the country with the consequence that companies such as Apple, LinkedIn and Airbnb have complied placing millions of Chinese users' data within reach of the government (Tager, 2021).
- Russia restricted voice and video calls on communication platforms like WhatsApp and Telegram in August 2025, citing national security and fraud concerns (Abbasova, 2025).
- The United Kingdom (UK) Online Safety Act imposes duties on platforms to remove harmful content. It priorises user protection but raises freedom of expression concerns and compliance burdens (Walsh, 2025).
- The European Union (EU) Digital Services Act, enforced from 2025, harmonizes accountability across member states, yet adds compliance burdens for global platforms (Wong, 2025).
- The United States (US) Clarifying Lawful Overseas Use of Data Act (US CLOUD Act) enacted in 2018 (Tager, 2021; Morton, 2025) and the 2025 Federal Trade Commission (FTC) warnings highlight tensions between national security imperatives and global interoperability (FTC, 2025).
- In South Africa, the Gauteng High Court compelled Meta in July 2025 to disclose offender identities in a landmark child pornography case, demonstrating how domestic law can override corporate resistance (Pongweni, 2025).

- In December 2025 Australia became the first country to impose a blanket ban on social media for children under 16, with fines of up to A$50 million for non-compliance. This child-protection measure illustrates how sovereignty can reshape online participation and impose new compliance burdens on global platforms (Australia eSafety.gov.au, 2025; Dick, 2025).

Global technology companies must navigate overlapping and sometimes conflicting obligations. Compliance is no longer optional but it is enforced through fines, bans, and reputational risk. Platforms adopt a "comply where you operate" strategy, tailoring policies to each jurisdiction, but this creates fragmentation. Instead of a single set of global norms, companies face a patchwork of sovereignty claims (Allison, 2025).

The outcome is a fractured internet, where sovereignty increasingly overrides international norms. Jurisdictional conflicts undermine interoperability, weaken trust, and reshape digital governance. Rather than converging toward consensus, states are asserting authority over data flows, platform accountability, and online speech signalling a new era of digital geopolitics.

The discussion explores how national assertions of digital sovereignty and cross-border compliance obligations reshape the governance of the internet, and what implications this fragmentation hold for global technology platforms and international law.

2. Understanding Internet Governance and Digital Sovereignty

Internet governance refers to the structures, processes, and norms through which authority is exercised and compliance is enforced in digital environments (Kleinwächter, 2021).

Two dominant models frame this debate. The multilateral model emphasises the role of states acting collectively through international organisations and treaties. It reflects traditional diplomacy, where governments negotiate rules and standards across borders, often through institutions such as the United Nations or the International Telecommunication Union. Alongside this, the multi-stakeholder model has emerged as a distinctive approach to internet governance. Promoted by forums such as the Internet Governance Forum (IGF), it recognises that no single actor can control the internet and therefore includes governments, corporations, civil society, technical communities, and international organisations in decision-making processes. This model emphasises inclusivity, dialogue, and shared responsibility, aiming to balance diverse interests while maintaining global interoperability. The tension between these approaches has been evident since the World Summit on the Information Society (WSIS) in 2003 and 2005, where states such as China and Russia argued for stronger intergovernmental control, while Western governments and civil society defended multi-stakeholder inclusivity (WSIS, 2003).

These models illustrate that governance is not monolithic but contested. While multilateralism reflects state-to-state negotiation and multi-stakeholderism promotes inclusivity, both share the assumption that governance requires cooperation across borders.

Against this backdrop, cyber sovereignty challenges these cooperative models by re-centring authority within the nation-state (Tager, 2021). Digital sovereignty is best understood as a particular governance approach. Magee (2025) defines it as "the ability of a governing body, such as a national government, to control the tech stacks and data flows within its boundaries. For instance, in a digitally sovereign state, any data centres within its physical boundaries and locally hosted software are beholden only to the laws of that country." Sovereignty narrows governance to territorial authority, contrasting with models that emphasise openness, interoperability, or shared responsibility across borders. Tager (2021) opines that since "governments define their national interests so differently, the way this sovereignty is invoked varies vastly."

The practical consequence of sovereignty is the challenge of cross-border compliance. Since digital infrastructures and data flows routinely traverse national boundaries, global platforms must reconcile conflicting legal regimes. A company hosting data in Europe, operating servers in the United States, and serving users in Africa may simultaneously be subject to EU privacy rules, US disclosure laws, and African judicial orders. Compliance in one jurisdiction can create liability in another, forcing platforms to adopt layered strategies that balance local authority with global interoperability. Cross-border compliance thus becomes the hinge between sovereignty and governance. It is where abstract claims of authority translate into concrete obligations for technology companies, and where fragmentation begins to take shape.

By situating sovereignty within governance and highlighting cross-border compliance as its practical manifestation, this section establishes the conceptual foundation for examining how different jurisdictions assert authority in the digital sphere. The following analysis will explore the impact of the rise of digital sovereignty on cyber governance and the diverse approaches states have adopted to enforce their claims.

3. Impact of the Rise of Digital Sovereignty on Cyber Governance

The rise of digital sovereignty marks a fundamental turning point in the evolution of internet governance.

Once celebrated as a borderless commons, the internet is increasingly subject to the authority of nation-states, each asserting control over digital infrastructures, data flows, and online speech. Goldsmith and Wu (2006) warned that the illusion of a unified, global internet would give way to fragmented governance structures shaped by national interests. Today, those predictions are materialising with unprecedented force.

Governments justify sovereignty claims on multiple grounds. Security imperatives drive states to impose surveillance mandates and cybercrime legislation, framed as necessary to protect citizens from terrorism, fraud, or foreign interference. Economic imperatives are equally powerful, with data localisation laws and taxation regimes designed to capture value from global technology platforms, ensuring that digital wealth does not escape national borders. Cultural imperatives add another layer, as content regulation reflects domestic values, political priorities, and identity concerns. Together, these motivations illustrate why sovereignty has become the dominant lens through which states approach digital governance.

The Geneva Internet Platform's 2026 outlook underscores how this shift is clustering around three major hubs, namely the US, China and the EU. Each represents a distinct model of sovereignty. The US emphasises national security and extraterritorial reach, exemplified by the CLOUD Act. China pursues a comprehensive model of digital control, embedding sovereignty into its "Great Firewall" and data governance regime. The EU, meanwhile, seeks to harmonise accountability through supranational regulation, most notably the Digital Services Act. These hubs are not merely legal frameworks, but they are geopolitical poles around which global fragmentation accelerates.

In practice, sovereignty manifests through concrete regulatory actions. Surveillance laws compel companies to disclose data across borders, even when this conflicts with privacy norms elsewhere. Data localisation requirements force platforms to store information within national jurisdictions, undermining the free flow of data. Accountability frameworks such as the EU's Digital Services Act and the UK's Online Safety Act impose compliance burdens that reshape platform operations. Social policy interventions, such as Australia's 2025 ban on social media use for children under sixteen, extend sovereignty into the realm of digital participation itself. Each of these measures forces global companies to adopt a "comply where you operate" strategy, layering obligations across jurisdictions and eroding the coherence of global norms (Allison, 2025).

The result is a contested digital order in which sovereignty increasingly overrides international law and multilateral norms. Jurisdictional conflicts undermine interoperability, weaken trust, and complicate the operations of global platforms. The Geneva Internet Platform (2026) highlights that fragmentation is not only legal but also economic and emotional. Geoeconomics, manifested in trade and taxation fragmentation, places additional burdens on companies with global footprints. Geo-emotions, meanwhile, reveal a growing disconnect between public scepticism and industry optimism about artificial intelligence, a divergence that carries significant political implications.

Digital sovereignty, therefore, is not simply a matter of law, but it is a multidimensional phenomenon reshaping the internet's future across governance, economics, and society.

4. Platform Responses to Jurisdictional Demands

Global technology companies are no longer passive actors in the face of sovereignty claims. As states assert authority through legislation, regulation, and judicial rulings, platforms must adapt their strategies to survive in fragmented digital environments. Their responses reveal both the limits of compliance and the ways corporate adaptation itself shapes the trajectory of internet governance.

The investigations into Grok, the generative AI tool integrated into X, illustrate the complexity of platform responses. In January 2026, Ofcom in the United Kingdom launched a probe under the Online Safety Act after reports that Grok had been used to generate sexualised deepfake images, including child sexual abuse material (Hayes et al, 2026). Within days, California's Department of Justice opened its own investigation, citing non-consensual explicit imagery of women and children (Hayes et al, 2026). Meanwhile, the European Commission had already fined X €120 million in December 2025 under the Digital Services Ac which is the first major fine imposed under the new regime for deceptive design practices and failures in transparency. These overlapping actions demonstrate how a single platform can be subject to simultaneous sovereignty claims across jurisdictions. For X and its AI subsidiary xAI, compliance meant cooperating with Ofcom's safety probe,

responding to California's enforcement demands, and absorbing the financial and reputational impact of the EU fine. The Grok case underscores how sovereignty pressures are not only legal but also political, reflecting divergent cultural attitudes toward safety, speech, and accountability.

Other platforms face similar dilemmas. Meta has repeatedly been compelled to comply with domestic rulings, most notably in South Africa in July 2025, when the Gauteng High Court ordered the company to disclose offender identities in a child protection case (Pongweni, 2025). Meta's response was to comply with the ruling while simultaneously lobbying for clearer international frameworks to avoid conflicting obligations. This dual strategy, namely compliance paired with advocacy illustrates how platforms attempt to mitigate fragmentation while protecting their global operations.

Microsoft has adopted a different approach, often choosing to implement the strictest standards globally. Following the European Union's General Data Protection Regulation (GDPR) and later the Digital Services Act, Microsoft extended compliance measures beyond Europe, applying them across markets. This strategy reduces the risk of conflicting obligations but increases operational costs. It also demonstrates how supranational regulation can exert influence far beyond its territorial scope, effectively exporting sovereignty through corporate adaptation.

TikTok provides another example of platform response under sovereignty pressure. Facing bans in India and restrictions in the US, TikTok has invested heavily in localisation strategies. These include establishing data centres within Europe such as Ireland, Norway, Finland, to comply with EU requirements and negotiating with regulators to maintain market access. It has also engaged third-party oversight to reassure regulators. Yet these efforts have not prevented ongoing scrutiny, illustrating the limits of corporate adaptation in the face of geopolitical tensions.

In August 2025, the US FTC cautioned American companies that complying with foreign demands to weaken encryption or censor content could violate section 5 of the FTC Act, which prohibits unfair and deceptive practices. This intervention forces US platforms to resist certain foreign sovereignty claims, prioritising domestic consumer protection over global harmonisation. It highlights how compliance strategies are not only reactive but also shaped by regulatory signals that pre-emptively constrain corporate adaptation.

Taken together, these examples reveal five primary strategies of platform response, namely

- Compliance with local rulings (Meta),
- Global adoption of strict standards (Microsoft),
- Localisation to appease regulators (TikTok),
- Management of overlapping jurisdictional enforcement (X/Grok), where platforms confront sovereignty claims that cannot easily be harmonised, and
- Pre-emptive resistance, illustrated by the 2025 warning from the US FTC that US companies must protect domestic customers against foreign laws and regulations that violate privacy and security.

These strategies demonstrate that platforms are not merely subjects of regulation but active participants in shaping the fragmented digital order. By exporting standards, lobbying for frameworks, or restructuring infrastructure, corporations themselves influence the trajectory of governance. Yet each strategy carries trade-offs, and none resolves the underlying tension between sovereignty and interoperability. Instead, corporate adaptation mitigates risks while reinforcing the reality that sovereignty claims are accelerating the disintegration of global internet governance.

5. Implications of State Sovereignty and Platform Adaptation for Global Internet Governance

The interplay between state sovereignty and platform adaptation has profound implications for the future of global internet governance. What emerges is not a coherent system but a fragmented digital order in which jurisdictional claims increasingly override multilateral norms. Platforms, by adopting compliance, localisation, or global standardisation strategies, inadvertently reinforce this fragmentation. Their responses mitigate immediate risks but also entrench the reality that sovereignty is shaping the internet's trajectory more decisively than cooperative governance models.

5.1 Erosion of Interoperability

As states impose divergent rules on data localisation, content moderation, and safety standards, the seamless flow of information across borders is disrupted. Platforms must build parallel infrastructures to satisfy conflicting

demands, undermining the technical and social coherence of the internet. TikTok's European data centres and Russia's domestic DNS root servers illustrate how sovereignty pressures force duplication of infrastructure. This fragmentation is not only legal but also economic, as compliance costs rise and market access becomes conditional on sovereign approval. Smaller firms, lacking resources to duplicate infrastructure, are disproportionately affected, reinforcing the dominance of large incumbents. Interoperability is also cultural. Users in different jurisdictions experience different versions of the internet, shaped by divergent moderation rules and safety standards.

5.2 Weakening of Trust in Governance Institution

Multilateral and multi-stakeholder forums, once central to internet governance, are increasingly side-lined as states assert unilateral authority. The Geneva Internet Platform's 2026 outlook warns that sovereignty claims are clustering around geopolitical hubs such as the US, China, and the EU, leaving smaller states to navigate a patchwork of rules without meaningful influence. Institutions like the Internet Governance Forum (IGF) and ICANN, designed to foster inclusivity and shared responsibility, struggle to remain relevant when powerful states impose rules extraterritorially. Hybrid initiatives such as the Global Forum on Cyber Expertise (GFCE) provide pragmatic coordination, but they lack binding authority. This imbalance risks deepening inequalities in digital participation, creating a tiered internet where some states set norms while others merely absorb them.

5.3 Societal Consequences

Sovereignty pressures also carry significant societal consequences. Measures such as Australia's ban on social media for children under sixteen, India's prohibition of TikTok (Chow, 2025), or Ofcom's probe into Grok's deepfake imagery illustrate how sovereignty extends into questions of identity, safety, and cultural values (Hayes et al., 2026). These interventions reshape not only platform operations but also the lived experience of digital citizenship. Sovereignty claims increasingly intersect with AI governance, as seen in the EU's AI Act, which imposes binding obligations on developers, contrasted with the US reliance on voluntary frameworks (Ashkara 2025). The divergence between public scepticism and industry optimism about artificial intelligence, highlighted in the Geneva Internet Platform's 2026 report, underscores how governance is entangled with social trust and political legitimacy. Sovereignty also reshapes freedom of expression, as regulatory traditions diverge between jurisdictions for example, the UK's Online Safety Act prioritises user protection, while US law emphasises First Amendment rights.

5.4 Geopolitical Consequences

Separate from societal impacts, sovereignty claims are producing geopolitical consequences. Analysts warn of the emergence of the "splinternet" (also referred to as the balkanised internet or the Westphalian web), where the internet fragments into competing blocs aligned with democratic or authoritarian regimes (Tager, 2021). The risk of fragmentation is triggered not only by governments undermining interoperability through national internet networks, but also by efforts to enforce one state's digital regulations extraterritorially or to block information flows across borders.

The rivalry between the US and China over technology standards, combined with the EU's regulatory assertiveness, risks dividing the internet into spheres of influence. The US has sought to limit Chinese influence through sanctions on companies such as Huawei, while China has entrenched its "Great Firewall" and promoted its own standards for 5G and AI. The EU, meanwhile, has leveraged instruments such as the Digital Services Act and Digital Markets Act to extend its regulatory reach globally, effectively exporting European sovereignty through corporate compliance. Russia's "sovereign internet" law and its efforts to build domestic DNS root servers further illustrate how states embed sovereignty into technical infrastructure.

This fragmentation is reinforced by trade disputes, sanctions, and geopolitical competition, embedding digital governance within broader struggles for global power. Regional coalitions such as the African Union's Digital Transformation Strategy or ASEAN's digital frameworks illustrate how smaller states seek collective leverage, but many remain caught between dominant hubs, forced to align or risk exclusion from global digital markets. The 2026 World Economic Forum echoed these concerns, warning that sovereignty claims are clustering around major hubs and that geopolitical fragmentation risks undermining trust in global governance institutions (World Economic Forum, 2026).

5.5 AI Governance Consequences

Sovereignty claims increasingly intersect with artificial intelligence, producing consequences that mirror broader internet governance fragmentation. The European Union's AI Act represents the most ambitious attempt to

regulate AI globally, imposing binding obligations on developers through a risk-based framework (Ashkara 2025). High-risk systems must meet strict requirements for transparency, human oversight, and conformity assessments, while prohibited practices such as social scoring are banned outright. By contrast, the US has relied on voluntary frameworks, such as the NIST AI Risk Management Framework and executive orders, leaving compliance largely to industry discretion. China has adopted a state-driven model, embedding AI governance within its broader cyber sovereignty agenda, including mandatory security reviews and restrictions on generative AI content.

The consequence of this divergence is a fragmented regulatory landscape in which developers and platforms face uneven obligations depending on jurisdiction. Compliance asymmetry raises costs in Europe, creates flexibility but weaker protections in the US, and subjects firms in China to direct state control. This unevenness affects innovation and competitiveness: companies in stricter jurisdictions may struggle with compliance burdens, while those in looser regimes exploit regulatory gaps.

AI governance also shapes public trust. Citizens in the EU experience higher levels of legal protection, while US users rely on corporate self-regulation, and Chinese citizens encounter state-directed oversight. These differences reinforce divergent perceptions of AI safety, legitimacy, and accountability. As AI systems become embedded in critical infrastructure, healthcare, and education, the absence of global standards risks undermining interoperability and reinforcing the splintering of digital governance. The 2026 World Economic Forum highlighted this divergence, noting that AI regulation has become a proxy for sovereignty claims and that competing regimes risk fragmenting the future of intelligent systems (World Economic Forum, 2026).

Viewed collectively, sovereignty claims in AI governance demonstrate how emerging technologies are becoming arenas for jurisdictional competition. Just as data localisation and content regulation fractured the internet, divergent AI regimes threaten to fragment the future of intelligent systems, embedding sovereignty into the very architecture of technological innovation.

6. Reconciling Sovereignty and Global Governance

The accelerating rise of digital sovereignty raises a critical question, namely whether the fragmented jurisdictional demands can be reconciled with the vision of a global, interoperable internet? While the trajectory of governance suggests deepening disintegration, several pathways remain open for balancing sovereignty with cooperation.

6.1 Multilateral Frameworks

One possibility lies in multilateral frameworks. Initiatives within the United Nations, the International Telecommunication Union, and the OECD continue to explore mechanisms for harmonising digital rules (Nye, 2021). Yet their influence is limited by the reluctance of powerful states to cede authority. Without binding commitments, multilateralism risks becoming symbolic rather than substantive, producing declarations rather than enforceable norms.

6.2 Technical Standardisation

A second pathway is technical standardisation. Organisations such as the Internet Engineering Task Force (IETF) and the World Wide Web Consortium (W3C) maintain protocols that underpin interoperability regardless of political borders. By embedding compliance into technical design, these standards can mitigate fragmentation even when legal regimes diverge. However, sovereignty claims increasingly challenge the universality of standards, as states demand localisation or proprietary systems for example, China's promotion of alternative 5G standards and Russia's push for domestic DNS root servers (Tager, 2021).

6.3 Corporate Adaptation

A third avenue is corporate adaptation. As seen with Microsoft's global application of EU rules, platforms can voluntarily adopt the strictest standards across markets, effectively exporting regulatory norms. This strategy reduces conflict but places disproportionate power in the hands of corporations, raising questions about accountability and legitimacy. Moreover, not all companies can absorb the costs of global compliance, leaving smaller actors vulnerable and reinforcing inequalities in digital governance.

6.4 Regional Coalitions

A fourth pathway is regional coalitions. The EU's Digital Services Act demonstrates how supranational regulation can project sovereignty collectively, balancing national interests with shared accountability. Similar coalitions in

Africa, Asia, or Latin America could provide smaller states with greater leverage in shaping digital governance, countering the dominance of US and Chinese models. The African Union's Digital Transformation Strategy (2020–2030) and ASEAN's digital integration initiatives illustrate early moves toward regional frameworks.

6.5 Hybrid Governance Models

Finally, emerging hybrid governance models may offer pragmatic compromises. Overlapping institutions such as technical bodies, trade agreements, corporate codes of conduct, and national laws may collectively shape outcomes. Public-private partnerships, such as the Global Forum on Cyber Expertise (GFCE)**,** illustrates how states and corporations can collaborate without formal treaties. Established in 2015, GFCE now includes more than 250 partners and operates regional hubs in Africa, Asia, and Latin America. Its 2025–2027 Implementation Plan focuses on cyber capacity building, national strategy development, and incident response coordination. While GFCE cannot enforce compliance, it has practical impact by matching countries with donors, reducing duplication of projects, and strengthening resilience in the Global South. This illustrates how hybrid arrangements, though fragmented, can provide flexible mechanisms for reconciling sovereignty with interoperability.

In sum, these pathways suggest that reconciliation is possible but fraught. Sovereignty will remain a defining feature of digital governance, yet its impact can be moderated through multilateral dialogue, technical standards, corporate adaptation, regional coalitions, and hybrid governance models. The future of the internet will depend on whether these mechanisms can sustain interoperability without eroding the legitimacy of national authority. If they fail, fragmentation may become the permanent condition of the digital order.

7. Conclusion in Respect of Digital Sovereignty and the Future of Internet Governance

Digital sovereignty has moved from a marginal concept to a defining force in the evolution of internet governance. What began as a contest between multilateral and multi-stakeholder models has now been reshaped by the assertive authority of nation-states. Case studies from Russia, the UK, the EU, the US, China, South Africa, and Australia illustrate the diverse ways sovereignty manifests in practice through technological restrictions, protective duties, supranational regulation, extraterritorial reach, judicial enforcement, and social policy interventions.

Platform responses reveal the limits of adaptation. Whether through compliance with local rulings, global adoption of strict standards, localisation strategies, or navigating simultaneous multi-jurisdictional enforcement, companies are compelled to operate within a fragmented digital order. Their strategies mitigate risks but also reinforce the reality that sovereignty is accelerating disintegration.

The implications are profound. Interoperability is eroding, trust in global governance institutions is weakening, and societal consequences are multiplying as sovereignty extends into questions of safety, identity, and participation. While pathways for reconciliation exist by means of multilateral frameworks, technical standards, corporate adaptation, and regional coalitions, they remain fragile and contested.

Ultimately, digital sovereignty is not simply a legal doctrine but a multidimensional phenomenon reshaping governance, economics, and society. It signals a future in which the internet is less a borderless commons and more a contested domain of overlapping jurisdictions. Barlow's early vision of an open, decentralised, and interoperable infrastructure now stands in stark contrast to this reality**.** Whether fragmentation can be moderated or will become permanent remains the central challenge for policymakers, platforms, and citizens alike. The future of the internet will be defined not only by sovereignty claims but by the capacity of platforms and institutions to manage cross-border compliance. It is here, in the reconciliation of overlapping obligations, that the contest between fragmentation and cooperation will be decided.

Ethics Declaration. I did not need ethical clearance.

AI Declaration: I acknowledge the use of Microsoft Co-pilot as an assistive grammar tool during my research. The final work reflects my own analysis, argumentation, and interpretation of the subject matter.

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AI to AI Autonomous Cyber Warfare: Ethical and Anticipated Ethical Issues

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Abstract: The phrase "AI-to-AI autonomous cyber warfare" refers to an emerging and/or anticipated type of digital conflict in which artificial intelligence systems engage in cyberwarfare without any direct intervention by humans. In this type of conflict AI systems will carry out the collection of data through sensing, decision-making, and responses to adversaries as cyber conflicts unfold in cyberspace. AI to AI Autonomous Cyber Warfare needs to be examined at several levels as part of defense theory, cybersecurity research, and in anticipation of future risks related to cyber warfare. AI to AI Autonomous Cyber Warfare must be thought of as potentially related to the automation of both cyber offense and cyber defense, where both friendly and adversarial machines will interact with machines at speeds humans cannot match. In cyberwarfare humans usually set goals, define rules, and identify constraints, but AI systems in AI-to-AI warfare will execute all actions independently of human agency. The idea behind AI-to-AI Autonomous Cyber Warfare is that they are like autonomous systems employed as defense agents today—they are just more advanced and will have more authority. Currently AI systems exist on opposing sides, and they are already identifying, analyzing, and/or responding to each other. Cyber operations happen at machine speed, which is much faster than humans. Current systems of AIs may *adapt* strategies based on the opponent's behavior. This has led to an environment where two or more autonomous AI agents can currently learn, escalate, and counter each other dynamically. What already exists are: (1) Automated intrusion detection systems using ML. (2) Autonomous patching or quarantine systems. (3) Malware that is self-adapting. What is expected to exist in the future are (1) Fully autonomous offensive systems. (2) AI agents that will be able to strategically outmaneuver each other. (3) Self-modifying agents that will be able to escalate activities without human oversight. It is currently agreed that fully autonomous AI to AI cyber warfare is a major global risk, but that it is not a current capability. The current set of risks related to the development of AI-to-AI autonomous cyber warfare include: (1) Speed-of-Conflict Escalation. (2) Unpredictability. (3) Accidental conflicts (4) Arms Race Dynamics. (5) Loss of Human Control. This analysis will focus on ethical and anticipated ethical issues with the development of AI-to-AI autonomous cyber warfare.

Keywords: AI to AI, Autonomous, AI agents, Decision making, Digital conflict, Cyberwarfare

1. Introduction

Integrating Artificial Intelligence (AI) into cyber and urban warfare is reshaping the landscape of global conflict. The deadliest theater of 21st century conflict has been urban environments. Urban environments are characterized by complex physical terrain, dense civilian populations, and dependencies on critical infrastructure, which is called the "Urban Triad" (Danielsson, 2025). The proliferation of adaptive malware, autonomous vulnerability discovery, and self-healing networks create an environment where offensive algorithms can constantly adapt in a way that lets them subvert defensive capabilities (Google Cloud, 2026; Swiss Cognitive, 2025). As these systems are being embedded into the Internet of Military Things (IoMT) and civilian infrastructures, the attack surface expands, transforming civilian environments into primary battlefields. Delegating lethal or highly destructive authority to AI exacerbates the accountability gap, which in turn violates traditional interpretations of Internation Humanitarian Law (IHL). This dramatically lowers the threshold for accidental conflicts through the phenomena of "flash wars," wars that occur at machine speed, so fast that human oversight is impossible (Lieber Institute, 2026; Taylor & Francis, 2025). Through an analysis of technical mechanics, ethical dilemmas, case studies, the ACM code of ethics and anticipatory ethical frameworks, this paper will provide an analysis of the current and projected state of autonomous cyber warfare (Association for Computing Machinery [ACM], 2018; Brey, 2012). This analysis will propose actionable technical recommendations including algorithmic circuit breakers, digital air gaps, and cryptographic provenance, to restore meaningful human control, resolve the identified ethical issues, and secure critical infrastructure against machine-speed threats (Oracle, 2024; SCIRP, 2025).

2. Technical Issues

There is currently a transition towards AI-to-AI cyber warfare which is being driven by the rapid operationalization of machine learning models that can constantly adapt to their environments. Underlying

technical infrastructure, particularly in smart cities and the Internet Military of Things (IoMT) provide a large and vulnerable attack surface (Frontiers in The Internet of Things, 2025). The technical issues important to this evolution in warfare are the speed of execution, algorithmic adaptability, the displacement of human defenders, and the structural vulnerability of interconnected urban environments.

2.1 Smart Cities, Digital Twins, and Hybrid Warfare

To understand the importance of AI-to-AI warfare requires knowledge of the environment in which it will likely occur. Urban environments have become a major theatre of modern warfare; they are dangerous due the previously mentioned features dubbed the "Urban Triad." Modern urban centers are becoming "Smart Cities," which utilize Internet of Things (IoT) sensors, Artificial Intelligence, and high-speed networks to monitor and optimize city operations (Frontiers in The Internet of Things, 2025). The primary vulnerability lies within the "Digital Twin," which is a virtual replica of the physical infrastructure of the city which is used for simulation and management (Frontiers in The Internet of Things, 2025). If an autonomous cyber weapon can infiltrate the digital twin, it gives attackers access to an environment, allowing them to make physical changes at their own discretion. By manipulating sensor telemetry, AI agents can create fake operational states, forcing the critical infrastructure to run outside of its safe parameters (HPE, 2025). This in turn enables "Hybrid Warfare," attacks that feature a combination of physical and digital attacks. An example of hybrid warfare is an autonomous system manipulating traffic lights to create a deadlock blocking civilian escape routes and shutting down power grids as well as water treatment facilities amplifying the efficacy of a physical assault (Frontiers in The Internet of Things, 2025).

2.2 Machine Speed and the Collapse of the OODA Loop

Traditional cybersecurity is built around human reaction times. Defenses like Web Application Firewalls, manual rate limiting, and incident response playbooks assume they are dealing with humans navigating the network, which would allow them to work around latency, sleep cycles, and manual human errors (Rob Wilson, 2026). AI-to-AI warfare overrides this assumption, autonomous agents operate at machine speed, they can make millions of API calls or network probes hourly using their highly adaptive logic (Google Cloud, 2026; Wilson, 2026). Within hyper war, the Observe-Orient-Decide-Act (OODA) loop is executed too rapidly for human cognition to participate (Tech Mahindra, 2026). This bypasses traditional checkpoints that need human authorization (Tech Mahindra, 2026). Another reason the technical landscape is shifting is due to Non-Human Identities (NHIs). NHI's take the form of service accounts, automated bots, and AI agents. In many enterprises and government networks, NHIs now outnumber human identities at ratios of 45:1 or even 80:1, this complicates access management, anomaly detection, and identity verification (Wilson, 2026).

2.3 Adaptive Malware and Polymorphic Mutation

Offensive AIs have given rise to adaptive, polymorphic malware that bypasses static, signature-based systems. In contrast, AI-powered malware supplants traditional conditionals with deep learning models, generating unique code variants continuously, sometimes they mutate every few seconds to evade detection (Lumu, 2026). These sophisticated attack vectors utilize dynamic runtime adaptation. During execution, the malware queries are localized or embedded within large language models (LLMs) that fingerprint the target environment, identifying specific security software that instantly adapts its evasion techniques (Google Cloud, 2026; Lumu, 2026). The evasion strategy has shifted from merely obfuscating code patterns to semantically mimicking legitimate network behavior (Lumu, 2026). Because AI generates an infinite array of malicious variations, traditional defensive structures are overwhelmed, forcing a paradigm shift from identifying "known-bad" files to utilizing AI to detect anomalous behavioral intent and lateral movement (Lumu, 2026).

2.4 Agentic AI and Autonomous Attack Chains

A technical escalation has been the deployment of "Agentic AI" in offensive cyber operations. Unlike passive generative AI, which assists human operators by drafting phishing emails or summarizing code, agentic systems possess the autonomy to make long-term plans, execute multi-stage operations, and utilize external tools and APIs with no human oversight (HackerNoon, 2026; World Economic Forum, 2026). Threat actors will embed these agents into their workflows to manage the entire cyberattack lifecycle (Microsoft, 2026). An autonomous attack chain allows agentic AI to conduct global-scale scanning for vulnerabilities, analyze large datasets of open-source intelligence to identify valuable targets and execute custom exploitation paths (UK Cyber Security Council, 2026). In traditional cyberattacks, if a defensive measure blocks a specific pathway, the human operator needs to pause and analyze the failure then select a new course of action. Agentic AI doesn't need human intervention to change course; it consumes the failure as training data, alters its payload, and attempts an

alternative attack in real time (Tech Mahindra, 2026; UK Cyber Security Council, 2026). This creates a self-optimizing threat that scales infinitely and persists secretly in compromised networks, executing functions like memory poisoning and privilege escalation (Microsoft, 2026; Stellar Cyber, n.d.).

2.5 Self-Healing Networks and Autonomous Defense

To endure machine-speed attacks, defensive architectures are being forced to adopt equivalent levels of autonomy. "Self-healing networks" represent the defensive counterpart to agentic malware (Swiss Cognitive, 2025). These systems leverage advanced behavioral analytics, machine learning, and automation to constantly watch endpoint behavior, detect anomalies, and autonomously execute remediation procedures (FedTech Magazine, 2025; SAR Council, 2025). When a breach or destructive anomaly is detected, a self-healing network can isolate the compromised network segment. It will then roll back unauthorized system modifications, terminate malicious processes, and patch the vulnerability without requiring any human aid (SAR Council, 2025; Swiss Cognitive, 2025). Data from recent enterprise implementations demonstrates that autonomous defense systems can reduce the time to repair (MTTR) by almost 78.5%, maintaining continuous operational resilience even while under active, sophisticated assaults (Singh, 2025). However, deploying AI to autonomously alter network configurations introduces novel technical risks, notably the potential for cascading system failures if the defensive AI is manipulated through adversarial data poisoning, or if it overreacts to harmless network occurrences (IBM, n.d.; SAR Council, 2025).

3. Ethical Issues

The delegation of highly lethal and highly destructive authority to autonomous AI systems introduces issues when questioning it against established moral frameworks and International Humanitarian Law (IHL). The ethical dilemmas of AI-to-AI cyber warfare are threatening to entirely separate human moral agency from the consequences of armed conflicts.

3.1 The Accountability Gap and the Erosion of Mens Rea

One ethical crisis in autonomous warfare is the accountability gap, which arises when human agency is removed from the lethal decision-making process (Lieber Institute, 2026; Taylor & Francis, 2025). The international legal system and the laws of armed conflict are human-centric, relying on the concept of *mens rea*, the guilty mind, to attribute criminal responsibility and prosecute crime (CIGI, 2022). Algorithms do not possess characteristics like intent, malice, or moral agency. Algorithms cannot legally meet the threshold for criminal culpability (Taylor & Francis, 2025). When autonomous cyber weapons target critical civilian infrastructure, shutting down a hospital's power grid or poisoning a smart city's water supply due to an algorithmic mistake, assigning responsibility becomes impossible (Taylor & Francis, 2025). The software developers and systems engineers are mentally and geographically removed from the battlefield and cannot reasonably foresee every emergent behavior of their self-learning neural networks in chaotic combat environments, where it is often hard to know how humans will act (CIGI, 2022; Lieber Institute, 2026). Military commanders can invoke the black box nature of the AI, arguing that they relied on the systems output in good faith and did not understand the system (Lieber Institute, 2026; Taylor & Francis, 2025). This diffusion of responsibility creates a moral hazard where mass atrocities or severe civilian harm are casually dismissed as unpredictable glitches. This dynamic deprives victims of their fundamental human right to justice and undermines the deterrent power of IHL (CIGI, 2022; Lieber Institute, 2026).

3.2 The Illusion of Meaningful Human Control

To address these ethical issues, policymakers and defense organizations frequently mandate the necessity of Meaningful Human Control over lethal autonomous weapons systems (ICRC, 2018; Lieber Institute, 2026). In a hyper-war, characterized by machine speed cyber operations, meaningful human control is largely an illusion (Taylor & Francis, 2025). When human cognition is outpaced by machine execution, the human operator cannot comprehend the variables and massive datasets the AI used to select a target within the window of opportunity (Lieber Institute, 2026). They are introduced into the kill chain not to exercise any moral judgment or operational oversight, but to serve as a liability shield for the automated system (Lieber Institute, 2026). This dynamic introduces "automation bias," which is a psychological phenomenon where overwhelmed and fatigued operators place excessive trust in the machine's outputs, leading to errors and the abdication of any meaningful moral agency (Human Rights Watch, 2024; Lieber Institute, 2026).

3.3 Proportionality, Distinction, and the Principle of Humanity

International Humanitarian Law requires that belligerents adhere to the foundational principles of distinction and proportionality (CIGI, 2022; Lieber Institute, 2026). AI systems are good at quantitative optimization, but lack the qualitative, contextual reasoning and empathy required to evaluate human suffering and weigh proportionality (Lieber Institute, 2026). Military operations frequently rely on dual-use infrastructure, like civilian 5G telecommunications networks, traffic management sensors, and shared power grids (SCIRP, 2025). An autonomous cyber weapon targeting military communications will inevitably cripple the civilian life-support systems reliant upon that same network (CIGI, 2022). AI decision-making models are prone to digital dehumanization, a process that strips individuals of their inherent human dignity by reducing their lives to mere statistical data points, risk scores, and proxy metrics (such as geolocation history or device usage patterns) (Lieber Institute, 2026). This abstraction allows machines to authorize lethal force without any moral comprehension of the act.

4. Case Studies

The following empirical and conceptual case studies show the practical manifestations of the technical and ethical challenges that concern autonomous cyber warfare. They bridge the gap between theoretical frameworks and real-world deployment.

4.1 DeepLocker and Autonomous Malware

Developed as a proof-of-concept by IBM Research, DeepLocker represents a paradigm shift in the realm of autonomous cyber weapons (Kirat, Jang, & Stoecklin, 2018). Unlike current malware that indiscriminately infects networks and generates massive amounts of noisy network traffic, DeepLocker operates in a stealthier manner, like a sniper with a precise target (Kirat et al., 2018). It utilized a Deep Neural Network (DNN) to conceal its malicious payload within a completely benign carrier application, such as standard video conferencing software (Kirat et al., 2018). The payload stays encrypted and undetectable by standard antivirus engines and security sandboxes until the AI explicitly confirms a specific set of target attributes (Kirat et al., 2018). These decryption triggers can be deeply personalized, relying on facial recognition algorithms analyzing webcam feeds, voice prints captured through microphones, or specific geolocation data (Kirat et al., 2018). Strategically and ethically, DeepLocker demonstrates the potential for untraceable and highly targeted assassinations or infrastructure sabotage via the internet. Because the payload only decrypts upon encountering the intended target, security researchers face immense difficulties in reverse engineering the malware to attribute the source of the attack or understand its intent (Kirat et al., 2018).

4.2 The Gospel and AI-Assisted Targeting

The deployment of AI decision support systems, specifically *The Gospel* and *Lavender* by the Israel Defense Forces during the conflict in Gaza, highlights the ethical decay surrounding Meaningful Human Control (Brill, 2025; Lieber Institute, 2024). These systems are fed massive volumes of surveillance data, including high altitude drone footage, intercepted telecommunications, social media activity, and pattern-of-life analysis to autonomously generate lists of military targets (Brill, 2025; Lieber Institute, 2026). While military defenders argue these systems reduce the likelihood of missing critical intelligence and aid in taking precautions under the laws of war (Lieber Institute, 2024), the reality demonstrates automation bias (Human Rights Watch, 2024). Investigative reporters indicated that the Lavender system generated targets at an industrial scale, marking as many as 37,000 individuals as suspected militants by loosening evidentiary standards (Tech Policy Press, 2024). Human operators are often overwhelmed by the volume and speed of the AI's output, sometimes spent as little as 20 seconds reviewing each individual target before authorizing lethal strikes against them (Lieber Institute, 2026). This 20-second window is insufficient for verifying adherence to the principles of distinction and proportionality, effectively proving that the human serves merely as a moral laundering mechanism for an arbitrary, unknown algorithm (Lieber Institute, 2026; Tech Policy Press, 2024).

4.3 AkiraBot and Autonomous Propagation

AkiraBot's botnet is a prime example of how rapidly deployed systems have been developed into autonomous AI using newer types of tool sets. With the addition of bots being able to move from manual labor into automated processes with advanced machine learning these combined technologies will allow autonomous bots to operate in a secure manner and at an unprecedented scale. However, these very techniques were implemented by AkiraBot to successfully exploit new capabilities utilizing integrated AI models developed into this bot network and Deep Learning Vision Systems to quickly and efficiently circumvent verification processes

and to compromise over 80,000 websites (Sentinel Labs, 2025). The capabilities of the AkiraBot network are not limited to the ability to circumvent CAPTCHAs; there was evidence of autonomous reconnaissance being done by AkiraBot on its intended target systems. The agentic AI was able to continuously scan a target network/system for known vulnerabilities and then adapt its methods of propagation with very little to no human intervention (UNODC, 2025). AkiraBot employed a variety of techniques to achieve rapid deployment including utilizing Deepfake Overlays, AI Generated Synthesis to mimic human voice and Automating the Reason & Emotion Manipulation process for quickly scaling up its operations (UNODC, 2025). This proved that the barriers for successfully executing widespread cyber disruptions have been significantly reduced and that the potential for devastatingly large-scale and persistent attacks within a target network are possible as a result of AI's ability to automatically resolve the very security puzzles that were designed and created to thwart their penetration, thus eliminating the effectiveness of perimeter security (Sentinel Labs, 2025; UNODC, 2025).

4.4 DARPA Cyber Grand Challenge and AIxCC

To prevent the increase in autonomous offensive capabilities, Defence Advanced Research Projects Agency (DARPA) began a Cyber Grand Challenge (CGC) in 2016 with the present-day successor AI Cyber Challenge (AIxCC). Both initiatives were specifically aimed at developing fully Autonomous 'Cyber Reasoning Systems' (CRS), which would be able to detect, evaluate and defend (internetworking) systems without any input from humans or discretionary time delays; while accomplishing this at machine speed (arXiv, 2026). Competitions used high-performance computing clusters in secure air-gapped networks, with each system being given the task of autonomously finding, evaluating and patching zero-day software vulnerabilities in a few seconds or minutes, as opposed to the same scope of work being performed by human-based IT security teams in weeks or months (arXiv, 2026). The ongoing AIxCC competition issued challenges to the participants stating that they must also include state-of-the-art Large Language Models (LLMs) as a component in the strategy for securing real-world open source infrastructure projects written in the computer languages C and Java; the culmination of the competitions were live evaluations at 'DEF CON', the largest and longest running hacker convention in the world (arXiv, 2026). While CRSs' successes in finding and deploying patches for complex vulnerabilities across several different software products, without any intervention from humans, demonstrate that autonomous cyber defense is a technical reality and necessity; the realization emphasized that the next cyber war(s) will occur exclusively between computer networks and raises the vulnerability and threats to the operation of the autonomous cyber defense systems themselves.

5. Anticipatory Ethics

In their efforts to manage the dangerous intersection of autonomous technologies, critical infrastructure, and warfare to accomplish successful outcomes, the computing profession must develop an adequate and proactive set of ethical standards to rely upon. This will be achieved through the Association for Computing Machinery (ACM) Code of Ethics and Professional Conduct, and various specialized methodological frameworks. Anticipatory Ethics is a framework focused on the identification of potential ethical issues relating to new and emerging technologies before the technologies become fully entrenched (Brey, 2012). Anticipatory Technology Ethics (ATE)) need to be established and made available to govern the actions of architects or developers involved in creating these weapon systems before they come into existence.

5.1 ACM Code of Ethics Applied

The ACM Code of Ethics serves as the foundational moral framework for computer scientists, demanding that the public good and the mitigation of harm remain the primary considerations in professional computing work (ACM, 2018). The ACM Code of Ethics establishes a framework for ethical conduct among computer scientists and emphasizes that the well-being of society and minimizing harm should be the primary focus of all computing activities (ACM, 2018).

Principle 1.2 - Ethical Basis for Deliberate Harm: Although all forms of harm should be avoided as stated in the Code, there are clearly situations where harm is an intentional aspect of the system where actual harm is likely to occur. National security activities, such as cyber-attack by a nation state or nation-states performing and/or supporting cyber warfare against each other, fall into this category (ACM, 2018). The Code tells developers that it is their ethical and professional obligation to make sure that any harm caused by their products is justifiable and minimized as much as possible (ACM, 2018). The design of a variant of malware called "DeepLocker," which could spread indefinitely from its intended target, does not comply with this principle, as the collateral damage to civilian systems is not justifiable. Curbing Machine Learning Hazards (Principle 2.5): Computing professionals must exercise "extraordinary caution" when detecting and curbing hazards within machine learning systems

(ACM, 2018) under the Code. If it's uncertain whether an AI's future actions may be capable of being predicted after its use is complete and it needs continuous assessment, "it should not be deployed" (ACM, 2018). This principle opposes deploying unpredictable AI weapons in crowded, unpredictable smart city environments, where civilian casualties will be a regular occurrence. Safeguarding Society's Infrastructure (Principle 3.7): Computing professionals hold a unique obligation to "acknowledge and take special care with systems that will be part of society's infrastructure" (ACM, 2018). Weaponizing or hacking a smart city's digital twin or attempting to disrupt municipal IoT sensors for military gain violates this obligation. This obligation requires system designers to deliberately protect civilian systems from being taken over by military forces and to ensure that civilians will not be harmed by any form of military data exploitation.

5.2 Anticipatory Ethics

Here anticipatory ethical analysis we will apply Miller's Moral Responsibility for Computer Artifacts: Five Rules. The first of Miller's Rules (Rule #1) defines the designers, developers, and deployers of a computing artifact as moral agents who are responsible for their computing artifacts as well as any foreseeable impacts of those artifacts (Miller et al., 2011). The creation and uncontrolled proliferation of a self-modifying cyberweapon is a foreseeable impact; therefore, the developers and commanders involved with its development and deployment should be held fully culpable for the systemic damage that results (Taylor & Francis, 2025). The Sociotechnical Imperative (Rule #4) details that developers need to consider the broader sociotechnical systems and environments into which they will be embedding their computing artifact(s) (Miller et al., 2011). Embedding military targeting algorithms in civilian traffic cameras (such as smart cities) or military applications (with respect to 5G networks) constitutes a violation of the sociotechnical imperative because it fundamentally alters the previously established social contract, places the public in danger, and systematically deprives innocents of their legally protected status as non-combatants (SCIRP, 2025).

6. Recommendations

To be able to address the technical vulnerabilities and ethical problems demonstrated through the case studies and the ethical frameworks, defensive architectures must utilize the structural guardrails of rigorously applied methodologies. The technical recommendations identified here are meant to guide the creation of systems that will restore accountability, safeguard non-combatants, and prevent uncontrolled algorithmic escalation.

6.1 Algorithmic Circuit Breakers and State Rerouting

To eliminate the potential for catastrophic consequences from Flash Wars and runaway machine-speed/machine-guided escalation, there is a need for military and cyber security autonomous systems to have in place permanent algorithmic circuit breakers (Equity AI Cyber Volume n.d.; ISACA 2026). These circuit breakers are highly autonomous, stand-alone software modules specifically designed and implemented to monitor the 'heat' (or 'burn'), intensity and scale of AI-to-AI activity independent of the primary offensive AI (Hannecke 2026).

Organizations must establish strict criteria for operation within 'safe' zones, as well as set unchangeable quantitative thresholds (e.g., the velocity of API calls, the number of automated account revocations or the number of autonomous counterattacks launched per second) (ISACA, 2026). If a cyber skirmish goes beyond the threshold set by that organization, the established 'circuit breaker' will trip and all offensive actions will cease immediately and the system will go into a 'half open' state until a mandatory human review is completed (AI Cyber Magazine, n.d.; Hannecke, 2026). In addition, advanced techniques such as "representation rerouting" will be available for fine-tuning in AI models (Oracle, 2024). By compiling extensive datasets of actions that are prohibited (i.e., the 'circuit breaker' set) along with every potential harmful internal representation, AI will be able to identify harmful internal data representations and take proactive action to short-circuit its execution process prior to outputting a destructive command (Oracle, 2024).

Circuit breakers directly mitigate the loss of Meaningful Human Control (Lieber Institute, 2026). By creating a mechanism where there can be no machine-speed interaction that spirals into a state of total war without explicit, conscious human re-authorization, the circuit breaker allows for re-establishing the critical temporal buffer needed for humans' moral judgment, empathy, and diplomatic de-escalation (AI Cyber Magazine, n.d.; Werner, 2026).

6.2 Digital Airgaps and Data Diodes for Critical Infrastructure

Critical infrastructures within a city, including municipal water treatment plants, electrical grids supporting hospitals, and communications systems used in emergency response operations, should be completely detached from: the Internet; corporate/enterprise IT networks; and military networks. The connection(s) that join these

systems (e.g., municipal water treatment plants) to the Internet must feature stringent digital air gaps (HPE, 2025). If there are situations where operational data needs to be sent from the operational environment of the facility to a facility located remotely for purposes of monitoring, control, and digital twin simulation, the city must install physical hardware that enforces unidirectional data flow (HPE, 2025). These physical devices mathematically guarantee that while a central authority may receive continuous telemetry data from the plant, no AI agent can send any command back at the power plant to execute malicious actions (HPE, 2025). Public interest is being actively safeguarded through this physical separation established by the hardware (see ACM Principle 3.7) and is mathematically demonstrable as fulfilling the Principle of Distinction (ACM, 2018). Therefore, an AI-driven cyber-siege executed on some municipality and an autonomous outbreak of malware (e.g. AkiraBot) cannot activate unintentional acts of violence due to malfunctions from AI. (SCIRP, 2025)

6.3 Cryptographic Provenance and Epistemic Integrity

Every single piece of information, whether a video frame collected from a surveillance drone, an intercepted communication or a product generated by artificial intelligence for targeting purposes (AWS, 2025), must be digitally signed with an associated unique private key at the moment when it was collected. The AI or human operator receiving the information will then verify it using a public key. If there is no verified, unbroken cryptographic signature on the data, it is automatically considered untrustworthy and is quarantined from the targeting matrix, preventing the AI from acting on spoofed information (AWS, 2025). Cryptographic proofs will establish a rigorous, verifiable chain of custody of data (AWS, 2025). This directly addresses the “black box” problem by providing complete traceability and auditability, so if a lethal error occurs in an autonomous system, independent investigators can trace the precise chain of custody of the data used to produce that decision. This effectively closes the accountability gap and provides for the exact assignment of legal and moral accountability to either the provider of the data or the architect of the system (Lieber Institute, 2026).

6.4 Goal Control and Comprehensive Human Oversight

It is critical for engineers to create mechanisms that enable "Goal Control" within the technical layer of an artificial intelligent system (AI). This means that AI’s primary objective function and its alignment with International Humanitarian Law must be established through mathematics at the technology level (Lieber Institute, 2026). Systems must be implemented using Explainable AI (XAI) principle(s), meaning, the human operators will have access to transparent justifications explaining why the AI made a certain decision vs an opaque statistical probability (Lieber Institute, 2026). By providing commanders with verifiable/legal justifications for the actions performed by the AI, commanders will have the ability to make ethical decisions and meet their ethical obligation by bearing personal responsibility for the use of deadly force against human beings (Lieber Institute, 2026; Taylor & Francis, 2023).

7. Future Work

In coming years, it will be important to take a deeper look at emerging technologies such as autonomous "agentic swarms" which will be composed of generally independent artificial intelligence agents that can collectively coordinate complex actions and anticipate one another's moves, including both attacks and defenses. To make effective predictions about potential future threats posed by these agents, we must understand how they will autonomously negotiate with each other using steganography to create covert channels of collusion and how they will utilize the asymmetry in available information. Research related to computational game theory (particularly work involving the integration of the concept of Nash Equilibrium into MARL) will be critical to developing effective defense strategies and to building systems that are self-sustaining in terms of their architecture, even when subject to sustained, sophisticated, and unpredictable attacks by highly capable and dynamic adversarial swarms (Milvus, n.d.; ResearchGate, 2025b).

8. Conclusion

The combination of urban warfare and cyber operations will create a new form of warfare known as hyper-warfare that is governed by machine-speed execution and autonomous lethality (UK Cyber Security Council, 2026). The shift from human-coordinated scripted attacks to fully agentic AI is severing the OODA Loop, making traditional perimeter detection systems, human oversight of cyber operations, and diplomatic escalation controls, all but useless (Google Cloud, 2026; World Economic Forum, 2026). The modified speed of vulnerability remediation that was demonstrated at the DARPA AIxCC has proven the tactical advantage of AI for cyber operations, but the threat that AI poses to global stability because of its strategic and ethical risks is a worldwide existential threat (arXiv, 2026). With the use of autonomous untraceable "Malware" such as DeepLocker and

the reliance on uaccountable and/or opaque and/or high-volume targeting algorithms like The Gospel; such actions expose critical systemic failures in our current moral frameworks (Kirat et al., 2018; Lieber Institute, 2024). The resulting accountability gap, the erosion of the principle of distinction in smart cities, and the perpetual immediacy of accidental flash wars represent severe threats to the foundations of international humanitarian law (Lieber Institute, 2026; Taylor & Francis, 2025). Therefore, The Global computing profession must embrace AI, not just as an inanimate object and/or passive tool in the toolbox of a soldier, but as a distinct operational entity that must be subject to stricter globally enforced ethical constraints.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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Artificial Intelligence, Drones and Cyber Warfare: Ethical and Anticipated Ethical Issues

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Abstract: Artificial Intelligence plays an active role when both drones and Cyber Warfare are introduced into kinetic wars. The importance of drones for kinetic warfare points to the importance of cyber warfare for countering drone warfare. A drone that flies, reroutes, and avoids threats without human interaction no longer operates as a remote-controlled vehicle. Instead, it acts autonomously in combat situations. Small quadcopters in Ukraine were equipped with AI navigation packages, enabling them to complete their missions even after Russian troops had jammed their GPS signals. Programs in the US, such as Darpa Evade, are deploying Sikorsky's autonomy MATRIX software in vertical takeoff drones, which nominally have the capabilities of flight and fight without communication with an operator, while they have situational awareness, and continue to achieve their objectives. The most contentious application of AI in targeting military drones is the recognition of targets. Using deep learning models trained on massive amounts of image data, drones can recognize vehicles, artillery, or even people. The AI models utilize visual patterns and infrared signatures to help identify and distinguish between an enemy armored vehicle on a battlefield, hidden in a field, or a civilian tractor, also hidden in the same spot. Russia's KUB loitering munition features an AI visual identification module designed to enhance its search range and accuracy. The Bayraktar TB2 features onboard targeting systems that provide unified target designation and tracking. The TB2's follow-on munition, the Kamankes loitering munition drone, is advertised to have AI-guided optics that enable it to loiter, identify, and autonomously kill any targets (Aviacionline, 2023; Baykar Technology, 2026). A drone that could perform all of these activities could loiter for hours, detect a missile launcher or armor target, and kill without verification by human input at any point. Ukraine's advances in AI are even more unprecedented when factoring in that they are using modular AI kits to sever the "last mile" of the target kill chain, reducing the time from hours to minutes. AI proponents argue that accuracy enables speed and precision with minimal risk of unintended consequences. Critics caution that algorithmic-driven lethal decisions can go wrong if an object is incorrectly identified, leaving the laws of armed conflict with challenging and fuzzy questions of moral, legal, and professional liability. This analysis is concerned with identifying how AI can be applied in the context of cyberwarfare to counter the capabilities of AI being employed to enhance the capabilities of Drones as they are currently employed in military operations. In addition, this analysis will focus on ethical and anticipated ethical issues related to how AI can be applied in the context of cyberwarfare operations to counter the capabilities of AI being employed to enhance the capabilities of Drones as they are currently employed in military operations.

Keywords: Artificial intelligence, Unmanned aerial vehicles, Cyber warfare, Autonomous weapons systems, Anticipatory technology ethics, Adversarial machine learning, Meaningful human control

1. Introduction

Drones have historically operated primarily as remote-controlled vehicles, relying on continuous telemetry, data links, and human in the loop decision-making. Within today's battlespace, we have witnessed a forceful and irrevocable transition from automated systems to fully autonomous agents. An unmanned aerial vehicle (UAV) that flies, re-routes, avoids threats, and detects targets without any human interaction is no longer an extension of a human pilot, it is now functioning as an independent combat entity in a constantly changing battle environment (Wilson & Donnelly, 2026a). This change influences the strategic and tactical environment for global war.

Conventional telecom structures are susceptible to degradation under extremely competitive conditions including massive electronic warfare (EW), radio frequency interference, and signal jamming technologies. Military agencies are increasingly adding onboard AI-based navigation packages and advanced computer vision modules to small quadcopters and fixed-wing UAVs to help sustain their operational capabilities. These edge computing systems rapidly shorten the "last mile" from the target kill chain; as a result, the time between target identification and lethal engagement is significantly reduced from hours to minutes or seconds (Cybernews, 2026). The interactive relationship between the convergence of these technologies is transforming cyber warfare as well. Autonomous UAVs function as highly integrated nodes inside large, interrelated cyber physical systems and the Internet of Military Things (IoMT). The complex artificial neural networks and algorithms used to conduct the activities of autonomous drones provide adversaries with previously unseen cyber vulnerabilities, such as the potential use of adversarial machine learning, sensor spoofing, data poisoning, and protocol-level

deception. Consequently, safe cyber warfare operations are increasingly focused on taking advantage of the cognitive and perceptual layers of autonomous drones by hijacking, misdirecting, or disabling these systems prior to arriving at their intended target (Erpek et al., 2024; Xi et al., 2025).

There is a high degree of uncertainty due to how cyber operations interact with kinetic operations, which raises issues related to the definition of war in terms of international law and escalation matrices for conflicts (Wilson & Donnelly, 2026a). The proponents of these technologies point to how AI increases speed of execution, accuracy and robustness while minimizing the chance for inadvertent actors, however; using algorithmic methods to determine whether an individual attack will be lethal is a significant ethical, legal and philosophical dilemma. In the event of incorrectly identifying a target (due to biases within algorithms, contextual variables within the environment or deceptive actions from an adversary), unintentional consequences can be the result. This poses significant challenges to the fundamental principles of the Laws of Armed Conflict (LOAC) (Wilson & Donnelly, 2026a). To address these challenges, this analysis presents empirically-based discussion of the technical mechanisms of AI deployment within military drones, an exploration of the technical attack surface of AI-driven (cyber) vulnerabilities within military drones, a comparative analysis of four real-world case studies involving AI-driven decision-making within military drones, as well as an application of the ACM Code of Ethics and the Anticipatory Technology Ethics (ATE) framework with respect to AI-driven military drones. The analysis concludes with specific technical and governance recommendations directed toward establishing a system of laws that will facilitate safe navigation through a rapidly evolving environment regarding autonomous algorithmic warfare.

2. Technical Issues

With military drones, Artificial Intelligence (AI) will be used to create highly sophisticated systems incorporating multiple integrations beyond just hardware and software across many applications like autonomous navigation; advanced computer vision; and cyber-resilient communication systems/architecture. These technologies are constantly evolving with new capabilities being introduced every day. As they become functional as weapons systems, they present new attackable surfaces that will increase the number of sophisticated cyber vulnerabilities, making it difficult to differentiate between a digital attack and a physical attack.

2.1 Autonomous Navigation in GPS-Denied Environments

GPS is an important aspect of traditional UAV operations and provides accurate real-time position, velocity, and altitude data of UAVs both before and during flight. GPS and other sensor information are incorporated into the UAV's flight controller via complex proportional-integral-derivative (PID) control loops. The position control loop uses the current coordinate and the desired coordinate of the UAV to identify the velocity at which the UAV should fly to achieve its desired position in three-dimensional space. The velocity control loop employs the velocity output from the position control loop to determine how much thrust the motors of the UAV must produce to achieve that velocity. The velocity output also compensates for external factors affecting the UAV's ability to achieve that velocity, such as wind drag (Florida International University, 2024).

However, many of today's adversaries use advanced GPS spoofing and broadband electronic jamming technologies to disrupt the link between the UAV and the satellite constellation that provides GPS data to drones. To protect against these vulnerabilities, increasingly sophisticated UAVs are using AI-enabled autonomous navigation systems. Autonomous navigation packages utilize visual odometry; Simultaneous Localization and Mapping (SLAM); and terrain contour matching to navigate between points when the UAV can no longer receive GPS position data. These systems use sensors such as high-definition cameras, LiDAR, and synthetic aperture radar (SAR) to provide near real-time geographical and obstacle data to the AI model. The AI model can then identify geographical landmarks and obstacles (e.g., mountains, buildings, and other aircraft) to ascertain its geographical location and autonomously navigate to its destination without the use of external satellite signals (Baykar Technology, 2026; Cybernews, 2026).

2.2 AI at the Targeting Level: Computer Vision and Multi-sensor Fusion

Target recognition is a complicated area when artificial intelligence (AI) is being used within military unmanned aerial vehicles (UAVs), from initial identifying of a target right through to the final elimination of that target. Deep learning algorithms such as CNNs (Convolutional Neural Networks) used in drones have been trained on large amounts of data, including images of military (military targets), civilian (civilian targets), and environmental (non-targets) objects (Donnelly & Wilson, 2026a). Algorithms process images using visual patterns, infrared (IR) signatures, and radar cross-sections to identify and classify an object in real time.

One of the significant technical issues involving AI and drones is related to environmental variables, adding complexity to the high density of modern battlefields. An Artificial Intelligence (AI) model must be able to accurately differentiate between an enemy tank that is concealed by trees and bushes from a civilian agricultural tractor parked almost exactly in the same spot (Donnelly & Wilson, 2026a). Modern drones are designed to achieve the required level of certainty necessary for lethal engagement in part due to their multi-sensor fusion systems. Multi-sensor fusion systems can process EO/IR (Electro-Optical/Infra-Red) data, acoustic data, and radar images allowing the AI to see under environmental conditions such as rain, fog, smoke, and when objects are cloaked with thermal masking. By processing the variety of input signals through sophisticated algorithms that produce a probability score for each potential target, the drone can establish when the total probability score for all potential targets that exceeds a predetermined algorithmic threshold. At this point, the drone's system locks onto the target's location and shortens the "last mile" from the kill chain. Therefore, when the munition is released, it will be able to autonomously guide a weapon toward the target without any human verification prior to impact, raising serious concerns about the accuracy of the AI's ability to identify target type (Cybernews, 2026; c).

2.3 Cyber Vulnerabilities: Adversarial Machine Learning and Sensor Spoofing

The increasing use of Deep Neural Networks (DNNs) carries with it a growing risk for Autonomous Drones that could fall victim to the new threat of Adversarial Machine Learning (AML). AML is a method of exploiting the inherent mathematical weaknesses of an ML model by causing small or even unnoticeable changes to input data, thus causing the AI to create faulty predictions or classifications (Xi et al. 2025). In the physical world, adversaries now use "adversarial patches", which are intentionally created visual patterns or codes (typically QR code-like), or which have altered textures, all placed on or near military assets. When an Autonomous Drone's electro-optical sensor captures an adversarial patch, the spatial displacement of the adversarial patch will disrupt the CNN's feature extraction process mathematically. This will result in the preventing the drone's object detection algorithm from identifying a main battle tank (making it invisible) or misidentifying the vehicle for a benign object (e.g. a rock formation/ civilian vehicle) (Xi et al. 2025).

In addition to being susceptible to complex physical-layer spoofs through AI-assisted drones, adversaries can use Generative Adversarial Networks (GANs) to approximate the actual probability distributions of GPS location and +communication signals. Attackers can then use delta (fake) signals to mislead UAV's PID (proportional-integral-derivative) controller with incorrect spatial and temporal information. This input perturbation avoids traditional intrusion detection systems (IDS) and enables the ability of adversaries to reroute the drones' course of flight, contend for the mission parameters set by the original drone operator, or create a controlled crash of the drone without the use of brute force or greater jamming bandwidth, which are both easily detectable (Erpek et al., 2024; Florida International University, 2024).

2.4 The Cyber-Kinetic Threshold

The development of autonomous drone swarms blurs the line between digital interference and physical, kinetic destruction in a way that changes our understanding of armed conflict between states. Cyber operations against the cognitive layers of drone swarms create an extreme ambiguity about how states should respond to such operations. One example would be if a state actor conducted a sophisticated cyberattack against an adversarial Targeting AI that subtly alters the Targeting weights or Confidence limits of an adversarial AI Drone Swarm, causing the adversarial drones to autonomously engage with civilian infrastructure as opposed to military infrastructure; in this case, the digital cyber operation could yield a catastrophic kinetic impact.

Under the traditional "Effects Based" framework of International Law, a state will only demonstrate a warlike Response to a Digital Cyberattack after the event has caused physical destruction equivalent to what would occur with an equivalent Kinetic Weapon employed by the state. This framework is thus outdated and insufficient for the digital age, and a Norms Based threshold should be the basis for measuring this new type of operation. In the Norms Based framework, the definition of a Cyberwarfare Act will be based on the type of Target attacked (e.g. a Target that is required for Human Life; a nuclear facility; a platform for Autonomous Weapons) or the intent of the Cyber Operation regardless of whether or not the Digital Attack caused the intended effects. This change will highlight that a single piece of malicious code embedded within an AI Navigation package of an AI supported Drone Swarm is no longer simply a tool for Intelligence Gathering; it is now engaging in an act of War.

3. Ethical Issues

The delegation of lethal authority to algorithmic systems introduces ethical friction, directly challenging the foundational principles of human agency, moral philosophy, and international law in warfare.

4. Case Studies

The following case studies illustrate the diverse, real-world applications of AI in contemporary unmanned systems, highlighting the technical realities, operational advantages, and ethical tensions of autonomous warfare across different geopolitical theaters.

4.1 Ukraine's Modular AI Kits and the "Last Mile" Kill Chain

The continuing military crisis in Ukraine has become an exceptional 'real-time' evaluation of the application of private sector (commercial) artificial intelligence (AI) and military AI technology integration. For example, having an enemy with significantly greater electronic warfare capacity than they possessed, Ukrainian forces determined that their typically low-cost, First-Person View (FPV) drones would be among the most vulnerable type of drones to radio frequency (RF) and GPS signal jamming. If the communication link between the FPV drone operator (often referred to as 'pilot' and the FPV drone was broken, that drone would likely become unusable, either crashing into a harmless area or not achieving the intended target location.

To address this problem, Ukraine has been using advanced modular AI kits (e.g., 33K Auterion Skynodes supplied by the US and Germany) on tens of thousands of FPV drones and loitering munitions in an iterative generation fashion supported by collaboration with their Western partners (Kirichenko, 2025; Military Tech Breakdown, 2025). The AI modules included in the FPV drones / loitering munitions serve as autonomous 'brains' of the vehicles, executing complicated computer vision algorithms on edge computing middleware eliminating the necessity for sustained cloud bandwidth to communicate back to a remote server for command-and-control purposes. The operator of the drone will manually fly it into the area near where they believe the target is located. Once the enemy target is seen on their display, the operator will draw a box around it. The AI will completely take over. The aircraft will no longer use GPS for location or video feeds to navigate and strike the locked target (Cybernews, 2026; Kirichenko, 2025; Military Tech Breakdown, 2025). This capability has changed the economics of war by enabling a lower-cost drone to destroy a high-value target such as an armored vehicle. In addition, Ukraine has developed a system called "Operational Gamification" to manage and exploit its use of strikes. By converting verified destruction across the battlefield into a digital currency (ePoints) through its DELTA situational awareness system and DOT-Chain logistics engine, tactical units can obtain additional drone capabilities (Debuglies, 2026). This system enables rapid engagement on the battlefield as the deployment of encrypted on-board AI software forces the elimination of human involvement in the decision-making process regarding lethal engagements during the final moments of the flight of the drone. The systemic risk of Goodhart's Law {State the Law] occurs as tactical inefficiencies and ethical violations can result from the deliberate removal of the human component from the kill chain due to the pursuit of "point targets" created by algorithms (CSIS, 2024; Debuglies, 2026).

4.2 Russia's KUB-BLA and Lancet Loitering Munitions

The KUB-BLA and the Lancet are the main loitering munitions used by the Russian Federation. Developed by the Zala Aero Group (a subsidiary of the Kalashnikov Concern), the KUB-BLA delivers a blast-fragmentation payload to specified target coordinates and has been claimed by its manufacturer to have high levels of autonomy. According to Kalashnikov, the KUB has Artificial Intelligence Visual Identification (AIVI) technology. This proposed system provides real-time target recognition and classification to potentially increase the area that could be covered by a single flight by a factor of 60 and improve the drone's level of autonomy and lethality (Automated Research, 2022).

The KUB-10M is a newer variant of this munition that uses the same electro-optical guidance system as the original KUB, but has an extended range of 100 kilometers and is fully reliant on electro-optical guidance rather than GPS, thus reducing its vulnerability to extensive GNSS jamming in the vicinity of the Ukrainian front lines (Cranny-Evans, 2026). However, there is a significant divergence between Russian promotional claims and the actual battlefield experience. The description "payload targeting image" appearing in KUB technical documentation describes a system that operates more like a traditional GPS guided munition, which would use fundamental contrast-locking methods to determine missile position, than a sophisticated deep-learning neural network (CSIS, 2022). KUB-BLA presents an ethical dilemma because of technological uncertainty and the policy

implications of an AI arms race. If a state uses a primitive image contrasting software 'disguised' as highly advanced AI, the chance for misidentification increases exponentially.

The deployment of immature autonomous weapons that do not possess sophisticated contextual discernment capable of meeting the principles of distinction presents an extreme threat to civilian populations. (CSIS, 2022; Wilson & Donnelly, 2026a)

4.3 Turkey's Bayraktar Kamankeş 1 AI-Powered Cruise Missile

Baykar Tech is a major presence in the world of unmanned aerial warfare. From its original production of Bayraktar TB2 aircraft, it has developed and continues to develop new, intelligent, AI-enabled munitions. Kamankes 1 is an air-launched, jet-propelled cruise missile that is to be used against targets from larger flying launch platforms, including Akinci, TB2, and TB3 UAVs. The Kamankes 1 cruise missile represents an advance in using AI target acquisition systems leveraging state-of-the-art AI-enhanced EO (electro-optical) guidance systems to autonomously acquire and engage a target in flight (cruising at 140 knots / IDL) to a range greater than 100 km (Aviacionline, 2023; Baykar Technology, 2026). The Kamankeş 1 is more than a weapon designed to strike ground targets. In a recent test, the AI-guided Kamankeş 1 intercepted an airborne target during flight when fired from an Akinci unmanned combat aerial vehicle (UCAV) (Overell, 2025). This new air-to-air capability changes the framework that has defined drone warfare. It appears that AI-powered loitering munitions can be used as flexible, multi-domain platforms to autonomously conduct air defense missions. However, the high degree of autonomy this level of performance creates in three-dimensional airspace significantly complicates the role of human operators. An AI-powered, high-speed, jet-powered munition relies entirely on its AI-based visual identification system to assess the difference between an enemy drone and a friendly or civilian aircraft within crowded and contested airspace, pushing the conventional limits of algorithmic accuracy (Overell, 2025).

4.4 DARPA EVADE and Sikorsky MATRIX Software (USA)

The Defense Advanced Research Projects Agency (DARPA) is pushing to get autonomous systems into the field via the Early Vertical Takeoff and Landing Aircraft Demonstration (EVADE) program. EVADE is a part of DARPA's Phase 2 acceleration of their ANCILLARY Program, focusing on the development of unmanned aerial systems in the Group 3 category (unmanned aerial vehicles weighing 330 pounds or less). EVADEs aim at designing unmanned aerial vehicles that function like a "flying truck." The vehicles are expected to use vertical take-off and landing (VTOL) capabilities in austere environments without requiring any dedicated infrastructure (DARPA, 2025). To reduce the time to the first flight and speed the deployment of the five contractors' designs, DARPA required all five EVADE contractor designs to utilize a single, standardized autonomy core: the Sikorsky MATRIX flight autonomy system. The MATRIX autonomous flight system was developed as part of DARPA's Aircrew Labor In-Cockpit Automation System (ALIAS) program and is viewed as the central nervous system for the contractor vehicles. The MATRIX flight autonomy system performs entire missions autonomously - all levels of flight control, complex navigation, and obstacle avoidance - from takeoff to landing, thereby significantly reducing the need for user input during long transit distances (DARPA, 2025; Easley, 2024).

The endurance requirement for the EVADE platforms is to be capable of operating for at least 12 hours over a range of 100 nautical miles, while carrying a payload of 60 pounds, performing various missions including logistics, weapons delivery, ISR and RSTA missions. The AVD drones will communicate directly with individual ground-based troops through the U.S. Navy's Battle Management System (BMS), eliminating the need for centralized ground control facilities entirely. This decentralization of command makes it possible to democratize airpower at the tactical level, and create large, distributed networks of autonomous agents. This was shown by the Army's most recent Swarm Forge exercise at Camp Blanding, where the U.S. was able to execute the first-ever kinetic drone swarm in history on U.S. soil (DefenseScoop. (2026). The use of AI to command-and-control multiple autonomous systems will require an extremely high level of cyber resilience. All distributed networks are at high risk for cyber-kinetic infiltration, adversarial AI attacks, and protocol manipulation; hence they require a very high level of cybersecurity.

5. Anticipatory Ethics

Addressing the ethical challenges posed by autonomous drones and cyber warfare requires robust, anticipatory ethical frameworks that guide the developers, software engineers, and military strategists designing these systems. Anticipatory Ethics is a framework which focuses on the identification of potential ethical issues relating to new and emerging technologies before the technologies become fully entrenched (Brey, 2012). The Association for Computing Machinery (ACM) Code of Ethics and Professional Conduct, combined with the

Anticipatory Technology Ethics (ATE) framework, provides a foundation for governing an Anticipatory Ethical analysis of military AI before it reaches the battlefield.

5.1 ACM Code of Ethics

Principle 1.1 (Contribute to humanity and society): This principle requires that computer professionals limit potential threats to the health, safety, and privacy of all people. Military AI developers for drones face a paradox. Designed to kill enemy combatants for state protection, they are obliged to limit any harms that may occur because of how their system was developed. For example, if unintended casualties result from asymmetric violence caused by their algorithms used in military operations (such as algorithm bias or misidentification), there will be no justification for these negative consequences (Association of Computing Machinery, 2018). Principle 1.2 (Do not do harm): The Code of Ethics provides guidance for work that is inherently designed to do harm to another person or entity but requires that "those responsible are obligated to provide ethical justification for the harm" (Association of Computing Machinery, 2018). There is also a requirement for professionals to conduct an in-depth analysis of the "emergent properties of the system". With respect to autonomous drone operations (swarms), professionals will need to model, simulate, and mitigate any unintended escalation of violence that results from the emergent behaviors of multiple drones interacting with one another in ways that were not intended and thus could not be anticipated before deploying the swarm of drones.

5.2 Anticipatory Ethics

Before mass production and deployment occur, principles found within the Anticipatory Technology Ethics (ATE) framework developed by Philip Brey (2012) should be applied to enforce ethical considerations regarding the deployment of lethal autonomous weapon systems (AWS). In many cases, traditional ethics only evaluates harmful impacts of technology after technology has been deployed. ATE approaches ethical assessment from an anticipatory perspective, focusing on identifying and assessing ethical concerns at both the research & development (R&D) and before the deployment stages of new technology (Brey, 2012). For ATE to work as intended, methodologically sound foresight and future studies must occur throughout the development of emerging technologies, particularly because there is uncertainty about the development and deployment of many emerging technologies. The assessment of new technologies must include continuous ethical assessment considering three levels within the ATE framework: first, at the technology level (e.g., bias found in computer vision); second, at the artifact level (e.g., evaluating the specific technology of the Kamankeş 1 loitering munition); and third, at the application level (e.g., modeling the potential ethical impacts of using the Kamankeş 1 loitering munition in an urban combat environment) (Brey, 2012). When engineers apply a "Sociotechnical Imperative" to drone development employing ATE, they must understand that self-flying drones are not functioning in a vacuum. Drones are integrated into politically unstable and dynamic environments. Developers must also feel a moral obligation (pursuant to the "Foreseeability of Effect") to identify and develop strategies to mitigate any potential exploitation of their new systems through either hacking, spoofing, reverse engineering, or influence through multifactional information. Engineering an autonomous weapon that lacks a safe mechanism (e.g., a reliable recall, cryptographic verification, or failsafe behaviors), violates the sociotechnical imperative because it is entirely possible that the weapon could be manipulated through adversarial machine learning to kill innocent civilians (Association for Computing Machinery, 2018; Wilson & Donnelly, 2026b).

6. Recommendations

To resolve the technical vulnerabilities and ethical issues identified in the case studies, military developers and policymakers must move beyond abstract principles and develop, mathematically verifiable engineering guardrails. The following technical recommendations bridge the critical gap between anticipatory ethics and operational cyber-resilience.

6.1 Adversarial Training and Data Diodes for Sensor Integrity

Developers must approach the redesign of drone Intrusion Detection Systems (IDSs) and protect against adversarial machine learning (AML) attacks to protect autonomous systems such as the KUB-BLA or Kamankeş. 1. To accomplish this, developers must implement rigorous adversarial training frameworks using Generative Adversarial Networks (GANs). This adversarial training will occur during training by continuously sending highly sophisticated GAN-generated adversarial patches and simulated global-positioning-system (GPS) spoofing signals (delta) into the neural networks of the drones to teach the drones to recognize and reject any input perturbation from normal probability distributions. By using this dynamic, the drone isn't static and is continually

improved to identify the mathematical signatures of cyber deception, thus improving the detection rate of cyber deception across all three primary areas of focus in IDSs, namely physical layer security, detection rate accuracy, and detection rate of cyber deception (Erpek et al., 2024; Florida International University; 2024; Xi et al., 2025). In addition, flight control subsystems are logically and physically separated from any external data links using Data Diodes, which are hardware devices that allow information to only flow in one direction. Essentially, the drone can transmit telemetry, camera feeds and situational awareness information to the Battle Management System (such as what is being done with the DARPA EVADE program). However, the flight controller cannot receive any unverified external command data from the internet, preventing an adversary from using the drone's C2 link to change its flight path or release its payload (Wilson& Donnelly, 2026a).

6.2 Algorithmic Circuit Breakers and Hard-Coded "Ethical Autonomy"

To ensure safety and security during war and cyber warfare, there is a need for a reliable fail-safe system to regulate machine-led weapons systems. One way to accomplish this is to require all military weapon systems that are automated to have an independent means of verification called "Algorithmic Circuit Breakers." These breakers should function independently from the Primary Targeting AI and monitor the drone's operating parameters and confidence intervals at regular intervals to maintain control over land or airspace.

If a drone has lost communication with its operator (such as an autonomous Ukrainian first-person view drone operated from a Skynode module) and then subsequently experiences a drop in its confidence interval for identifying a target (e.g., as indicated by a score below 99.9%), the circuit breaker will be automatically invoked. Additionally, a predetermined series of failsafe conditions that are ethically based should also be hard coded into the system to trigger abort criteria. For instance, the system should be programmed to either (a) remain in place until communications are established, (b) self-destruct within an established hygienic area, or (c) return to base. (Kugler, 2026). The targeting system cannot be allowed to adjust its confidence level downwards to allow a strike due to reduced data availability. This system would directly limit the likelihood of violations of LOAC and allow for the safe failure of the machine to preserve human life in cases of uncertainty (Kugler, 2026). Additionally, parameters for cyber-kinetic escalation must be established for swarm operations. Once a swarm discovers that it is conducting a cyber battle against an adversarial AI defensive system at machine speed, a circuit breaker will halt any offensive action once a predetermined "heat level" (i.e. a specific volume of cyberattacks in a specific period) has been reached. This endpoint forces a stoppage for human assessment and prevents a localized digital conflict from escalating unintentionally into a full-scale "Flash War" (Wilson & Donnelly, 2026a).

7. Future Work

Due to this rapid and disproportionately increasing trend involving drones, there is an urgent need for more extensive and ongoing research into future generations of autonomous threats from militarized artificial intelligence. Future research will be required to assess both the performance of autonomous munitions individually and the various interactive dynamics involved within a fully autonomous combat environment. "Agentic AIs" could autonomously negotiate and plan for and perform multiple simultaneous operations in cyberspace and via kinetic means across all environments (land, sea, air, and airspace) without human intervention, prior programming of waypoints, or definitive sequential steps. There is a need to investigate the moral dimension of these algorithms: whether an Agentic AIs can be coded to understand and apply the nuances of the law of armed conflict (LOAC), and whether the absence of human empathy in the overall strategic planning process will inherently lead to the perpetration of atrocities.

8. Conclusion

The integration of AI, next generation drone technologies and advanced cyber warfare capabilities is defining an entirely new generation of warfare with never-before-seen speed, volume, independence (autonomy) and lethality. The tactical advantage created by developing systems to complete the "last mile" of the kill chain without relying on vulnerable telecommunications, as demonstrated by current systems in Ukraine (Skynode-equipped drones), Turkey (Kamankeş cruise missiles) and the US (DARPA EVADE), removes the ability for traditional electronic warfare countermeasures to defend against them, as military tactics are merging with these commercial aerospace enablement’s utilizing on-board (edge) computing to allow the waning effectiveness of traditional EW countermeasures (Baykar Technology, 2026) (DARPA, 2025) (Wilson & Donnelly, 2026a) (Military Tech Breakdown, 2025).

As a result, the change in how wars are fought (from traditional attrition warfare to algorithmic warfare) introduces ethical/legal/strategic costs. The transfer of deadly decision-making authority to machines creates a challenge to the laws of armed conflict and erodes the core ethical principles of distinction and proportionality; it also creates a virtually insurmountable accountability "black hole" where war crimes may never be punished (i.e., software glitches). Additionally, since these lethal machines utilize deep learning neural networks, they are vulnerable to psychological cyber vulnerabilities like adversarial machine-learning attacks, sensor spoofing, and protocol manipulation, enabling adversarial forces to disrupt a drone's perception of the world by using adversarial techniques to control the drone's perception and turn that country's weapons against its own citizens/civilian infrastructure (Santoni de Sio & van den Hoven 2018; Schwarz 2024; Erpek et al. 2024; Xi et al. 2025).

For human beings to maintain their moral agency and stable strategy in times of machine-enabled speed warfare, developers, commanders of military forces, and world leaders will need to change how they think about AI, no longer regarding it as just "another piece of equipment in their arsenal," but rather, recognizing it as a independent and probabilistically based agent requiring the imposition of strict, globally agreed upon and Ethically Based Controls on its use. Those using AI and all those affected by its use must have a commitment to following the guidelines of Anticipatory Technology Ethical Guidelines (ATE) and ACM Code of Ethics; doing so becomes a prerequisite for humanity's creating and retaining the ability to operate with safety (Association for Computing Machinery 2018; Brey 2012). The mandatory inclusion of adversarial training methods, multi-sensor fusion designs, documented provenance for all data sources used, and hard-wiring algorithmic circuit breakers into all AI systems can no longer be seen as just "technical preferences;" they must be ethically required. Without these mathematically verifiable, robust countermeasures, the speed at which autonomous warfare occurs will outpace our ability to restrain ourselves, thus converting tactical advantage into systemic, unmanageable lethality across global borders..

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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AI, Urban Warfare and Cyber Warfare: Ethical and Anticipated Ethical Issues

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Abstract: The integration of AI into urban warfare and cyber warfare is reshaping the landscape of military operations. AI i s being leveraged to enhance military capabilities, improve defense strategies, and address the evolving threat environmen t in military operations. AI has had an influence in these fields in the following areas: (1) in Urban warfare AI technologies are being integrated into smart city projects reshaping urban environments and operational strategies directed at smart cities. (2) In Cyber warfare AI is transforming cyber warfare by enabling faster destructive digital attacks. It is being employed to develop new categories of cyber weapons including autonomous malware and deepfake-driven disinformation and misinformation campaigns. (3) In military operations AI is reshaping military operations by improving speed, scale and clandestine attacks as well as enhancing mission command and network resilience. (4) In Cyber defense AI is being utilized to leverage AI proactive threat identification, automated incident response and predictive analytics are used to counter AI-driven threats. This analysis will focus on ethical and anticipated ethical issues with AI, Urban Warfare and Cyber Warfare to AI autonomous cyber warfare. The method that is employed is a standard conceptual analysis of key issues, combined with careful definitions of terminology including key applications of conceptual distinctions applied to case studies. The method of ethical analysis follows the standard practice of applying ethical concepts and terms issues within case studies. The issues that will be addressed will include (1) The idea of machines making independent decisions about targeting and attack execution without human "in the loop" oversight is deeply troubling. (2) Accountability: If an autonomous AI system causes widespread damage or civilian harm, who is responsible? The programmer? The commander who authorized its deployment? The AI itself? (3) Escalation Control: How can the use of autonomous cyber weapons be controlled to prevent unintended escalation of conflict? A rapid, AI-driven counterattack might be perceived as a disproportionate response, triggering a spiral of retaliatory actions. (4) Unintended Consequences: AI systems, while powerful, can be unpredictable. A bug or an unforeseen interaction could lead to catastrophic outcomes that were never intended by human operators. These concerns highlight the urgent need for international dialogue and the establishment of norms around the development and use of AI in warfare.

Keywords: Smart cities, Autonomous malware, Human-in-the-loop, The gospel (AI), DeepLocker, Flash war, Anticipatory ethics, Sociotechnical imperative, Algorithmic accountability

1. Introduction

A feral city is a city in which the government has lost the ability to maintain the rule of law but remains a functioning actor in the greater international system (Kilcullen, 2012). In such a situation Kilcullen further writes that these cities are not destroyed, they are controlled by gangs, warlords, and insurgents. Urban environments are becoming the primary battlefield in which warfare takes place in the 21st century. We are currently witnessing the combining of Urban and Cyber Warfare through the Internet of Military Things (IoMT).

Urban warfare can be defined as an armed conflict that is fought within densely populated areas, built up areas like towns and cities. Urban warfare is characterized by close quarters combat within and complicated by three-dimensional environments. It is considered the most deadly and challenging form of combat (EBSCO, 2025). Key aspects of urban warfare include: "The Urban Triad", 360-degree threats, heightened tactical challenges, civilian and humanitarian crises, and massive defensive advantages. The Urban Triad is defined by the United States Department of Defense as consisting of "A complex manmade physical terrain", "A population of significant size and density", and "An infrastructure upon which the area depends" (United States. Joint Chiefs of Staff, 2002). The 360-degree threats come from enemies occupying buildings, who can fire upon columns from all angles. Heightened tactical challenges come from unclear lines of sight, dense building areas causing air support to be limited, and making it harder to target enemy positions without injuring and killing non-combatants. Civilian and Humanitarian crises are caused by warfare being conducted in densely populated urban areas, with civilians and non-combatants being caught in the crossfire, although **urban warfare is not limited to just this** (ICRC, n.d.). The defensive advantages of urban warfare stem from attackers in streets and fields outside the city having very little cover, compared to those in the city having ample cover and opportunities to reposition.

A Smart City is an urban area that uses Internet of Things (IoT) sensors to operate which involves gathering data, and managing assets, including but not limited to traffic, power, and first responders (IBM, n.d.). All of this is coordinated to provide real-time data to optimize city services like traffic flow and energy consumption. Smart cities also aim at improving public transit and having faster emergency responses. This is a utopian view, to accomplish any of this one must have access to all the **data in the smart city**, intimate daily routines, and be willing to be subject **everyone** to mass surveillance. Key technologies in smart cities include IoT sensors for monitoring, Artificial Intelligence to make sense of all the collected data, and high speed, secure networks for the transmission of massive amounts of data (Chini, 2025).

To understand the remainder of this **analysis**, Autonomous Cyber Weapons must also be understood. These are special types of cyber weapons where Malware uses AI to change its behavior, to avoid detection and select targets autonomously. This was demonstrated with DeepLocker's presentation by Stoecklin in 2018. DeepLocker **like software** is the future of cyber warfare, a danger which current threat detection systems, cannot address. This paper argues that integrating AI into cyber and urban warfare creates what can be called a hyper war environment. A hyper war environment **can potentially** outpace human cognition and violates the principle of meaningful human control over systems while creating systemic risks of accidental escalation.

2. Technical Issues

To understand current ethical issues as well as future technical and ethical issues related to the use of AI in urban and cyber warfare, we must understand the current landscape of cyber and urban warfare in smart cities.

2.1 Smart Cities as Attack Surfaces

Smart cities rely on their digital twin, which is a dynamic, virtual replica and duplicate of the physical urban infrastructure (Halúsková, 2023). The fact that the technical infrastructure of smart cities relies upon digital twins makes them uniquely vulnerable to attack. Digital twins combine IoT sensors, 3D modeling, and Artificial Intelligence (AI) to monitor, simulate and optimize city operations in real time (Weil, 2023). The digital twin opens a new attack surface, if an attacker can hack the digital twin, they effectively gain control over the city. **Once** a theoretical hacker has control of the digital twin, they can conceivably alter sensor readings to create false states, which forces systems to run outside safe limits causing **cascading** disruptions including blackouts or water shortages. If attackers wanted **to escalate** beyond simulated digital attacks and plan a kinetic attack, the digital twin serves as a model for constructing a blueprint for infrastructure targeting attacks. If a hacker wanted to cause chaos **within an urban environment** they could tamper with traffic management, e.g., turning every light green, or to halt operations turning every light red. If attackers wanted money, they could hold the cities management system hostage (Abreu et al., 2021).

2.2 Weaponizing Infrastructure

While smart cities are going to provide a prominent attack surface for cyber war, they are not the only vulnerable targets. Even if a city is not a "smart city" per se, **such a city can still** have vulnerabilities similar to smart cities, **they are** just attacked by different means. While traditional cyber-attacks can be effective against **smart** cities, AI can be weaponized as a means to make these attacks faster, more precise, and automated. Adversaries can leverage AI's capabilities for reconnaissance, developing adaptive malware, conducting highly sophisticated social engineering **operations**, and coordinated physical disruptions upon cities (New Jersey Cybersecurity and Communications Integration Cell [NJCCIC], n.d.). This **can result in** what is called Hybrid Warfare. Hybrid Warfare is a combination of digital and kinetic attacks to maximize the effectiveness of an assault. AI can be used to manipulate ordinary activities in an urban environment as well as military activities by manipulating traffic lights to block a military convoy, shut off the power grids disabling hospitals, or identify specific soldiers or vehicles for targeting (NATO, 2025).

2.3 AI in Mission Command

Urban environments are incredibly dense; **which** creates a phenomenon where troops are operating in what is effectively a series of canyons. **Cities are** a series of canyons in the sense that skyscrapers block satellite signals (GPS) and line-of-sight communications. The *Joint Publication 3-06: Doctrine for Joint Urban Operations* states urban terrain is characterized by a multi-dimensional battlespace that involves three layers: subsurface (sewers), surface (streets), and the supersurface (skyscrapers and other tall buildings) (United States, Joint Chiefs of Staff, 2002). This creates **a complex and potentially** chaotic environment where humans can be too slow to issue temporally effective commands, thus creating the need for the introduction of AI into mission command **and control.** AI algorithms are increasingly used to fuse together data from various sensors (drones, CCTV, soldier

wearables) to create a coherent "Common Operating Picture" (COP) when traditional communications are disabled. AI provides a unique advantage, but also a unique risk. The “fog of war” that is found in dense cities can often cause commanders to be overwhelmed from an overload of information. **While AI systems can process a massive amount of data, these systems can also be overloaded and become potentially** overwhelmed. They can process thousands of feeds simultaneously and can identify incoming threats employing these automated systems **but even they can be overwhelmed**. Reliance on AI for navigation and threat detection is dangerous because AI relies on its pre-trained data. If AI encounters a new threat with data that it has not previously seen, like a specific type of barricade, **AI could lead soldiers into a trap because the AI thought that the barricade was part of a safe path forward.**

2.4 Autonomous Malware

Traditional malware relies on conditionals in programming such as **“if-then”** statements. With hypothetical statements a task is executed if and once a **specific** criterion is met. AI driven malware **can supplant** these traditional conditionals. A recent impressive example of AI driven malware is DeepLocker, a proof of concept developed by IBM (Stoecklin, 2018). It looks for specific “keys” to unlock the **target**. Those keys could be anything from geolocation data to a person’s face or voice. This means that instead of traditional monitoring for activity, **Deeplocker identifies and attacks the intended target using their biometrics**. Until AI confirms the target’s identity with a high degree of confidence, the malware acts as the benign app which actually hides the malware inside the software. Traditional malware is detectable because these triggers will decrypt the payload, but those triggers are predictable. This is because the malicious code would only decrypt itself in the presence of the malwares desired victim (Kirat et al., 2018), which makes detection much more difficult. This allows cyber-attackers to operate similar to snipers instead of **employing** machine guns. Attackers no longer need to infect and brick thousands of devices to hit their target, they can infect millions of devices and detonate one.

3. Ethical Issues

The integration of similar to DeepLocker and other malicious malware into urban and cyber operations within urban warfare introduces systemic technical and ethical failures that challenge the core tenets of Just War Theory, basic ethical principles and International Humanitarian Law. **The focus of ethical analysis involves a series of factors that expand upon the notion of the performance of an action. As Furrow states, ethics is related to evaluating actions, and actions are performed by those capable of being moral agents. As Furrow says, “When we evaluate an action, we can focus on various dimensions of the action. We can evaluate the person who is acting, the intention or motive of the person acting, the nature of the act itself, or the consequences.” (Furrow, 2005) When malware interventions occur related to AI in Urban warfare and adversaries act, and these actions are based on intentions, these intentions and actions are aimed at producing outcomes. Identifying threats to Urban environments in urban warfare, has never been more evident. The fate of those at risk in urban warfare through urban warfare and cyber warfare are currently critical issues.**

3.1 Accountability Gap

The introduction of AI into urban and cyber warfare introduces an important ethical dilemma known as the accountability gap. If an autonomous AI recommends a strike on a school or hospital because it incorrectly identified a shape as a weapon, who is the responsible party for this crime against civilians? The global legal system relies on the concept of mens rea, which is the guilty mind. Algorithms do not harbor ill will, they do not harbor any will, meaning they cannot meet the criteria of mens rea. The programmer of the AI is far too removed from the process of a strike to ever be held accountable for a bug in its code, they are not an active participant in the conflict. The military commander may have relied on the AI’s processing **power to decide** and may argue that they acted on the best intelligence available to them. Nobody in this chain from the creation of AI to the decision to eliminate a target meets the criteria for having a guilty conscious. This leads to a legal vacuum where war crimes just become “glitches,” and leave victims with no way to **have access to** justice (Human Rights Watch, 2016).

3.2 Escalation Control

When AI enters into conflict with the AI of adversaries, as when AI malware attacks an AI firewall, the interaction happens at speeds in the nanoseconds, which far exceed any conceivable human reaction times. This introduces the possibility of a “Flash War.” Just as “Flash Crashes” (Investopedia, 2024) occur in high frequency trading where a stock market crash occurred in a matter of moments, flash wars can escalate from a skirmish between the AI systems of two adversarial nations, into a full-scale kinetic conflict before humans could intervene.

Automated defense systems might misinterpret a digital probe for information as an imminent nuclear launch and then launch its own preemptive retaliatory strike. This activity would completely bypass human checks that are designed to prevent accidental wars and deaths (Allen & Chan, 2017).

3.3 Meaningful Human Control vs. OODA Loop

"Meaningful Human Control" would require that a human operator have the time and contextual awareness to intervene in a lethal decision before the decision is made to attack an adversary (Santoni de Sio & van den Hoven, 2018). In hyper-war, the OODA (Observe-Orient-Decide-Act) loop once AI is introduced is too fast for humans to keep pace with **AI.** If the human operator cannot understand why the AI has selected a target in the three seconds preceding the opportunity to reverse the decision has closed, the human can have little control over the decision. The consequence is that **in** hyper-war, human input can be irrelevant, by the time the operator can react immense damage has already been caused to the target. This also serves the purpose of degrading the moral agency that operators have over the actions of the systems they maintain, operators of AI systems are merely rubber stamping decisions made by AI (Ekelhof, 2019).

3.4 Principle of Distinction in Smart Cities

Integrating military AI into cyber warfare conducted within smart cities fundamentally violates the principle of distinction in just war theory, which means that civilian and military targets must remain transparently separate. Within smart cities this situation becomes even more complex. When a military uses the same organizational infrastructure in the smart cities that it relies upon for military operations, whether it is the 5G towers, traffic cameras, and civilian power grids, this identifies the entire city as a potentially valid military target. Cyberattacks that intend to disable the military will harm systems meant to sustain civilian life (hospitals, water treatment), which leads to unnecessary **civilian** collateral damage (NATO, 2015).

4. Case Studies

The following four case studies illustrate the real-world application and ethical complexity introduced by the technologies into the issues of the introduction of AI into urban and cyber warfare of these technologies.

4.1 The Gospel (2023-2024)

The recent conflict in Gaza has produced several ethical controversies, one important issue being the use in cyber warfare of the AI system known as "The Gospel" employed by the IDF. The system works by gathering an array of drone footage, intercepted communications, and topographical data to generate recommendations for airstrikes. It identified targets at a rate of 100 per day, as opposed to the dated methods that generated 50 per year, often human selected (Davies, 2023). As stated earlier in the paper, human cognition cannot has a difficult time keeping up with the speed of the AI. This is an example of where humans become a rubber stamp on the machine's decision, because at times operators approved targets being struck in as little as 20 seconds (Schmitt, 2024). While a human can attempt to verify a target in 20 seconds, there is a high error rate under such time constraints. The human trying to keep up with the speed of AI becomes a liability shield rather than a moral agent (Abraham, 2023).

4.2 Ukraine (2022-Present)

In the Russo-Ukraine war many innovations in warfare have been made, one of them is a new spin on an old trick: civilian intelligence networks. Using software from Palantir and other tech firms, Ukraine gathers reports from civilians using chatbots and combines this data with satellite imagery to track Russian soldiers and mark targets for drone operations or artillery strikes (Bienvenue et al,. 2025). While tactically efficient, this comes with a variety of ethical issues, one of which is the blurring of the Principle of Distinction. If a civilian uses their phone to feed targeting data to a military AI, have they now become a combatant? A civilian is effectively acting as a scout for the military, which throughout the history of warfare makes them acceptable targets for militaries. This blurring effectively makes every civilian device a potential military node and those using these devices military targets (Ignatius, 2022).

4.3 Stuxnet (2010)

While Stuxnet is not considered AI, Stuxnet was somewhat autonomous, it was a precursor and serves as the historical warning for autonomous cyber weapons. Thes pseudo autonomous nature of Stuxnet came from it being designed to search for a specific software within the Iranian nuclear plants and execute its program without any human user explicitly instructing it to do so. It only executed after running a complex verification process to ensure it was in the correct facility. First, it looked for Siemens S7-300 and S7-417 programmable

logic controllers. It then checked to see if the PLCs were connected to the frequency converter drives it was looking for operating at very high frequencies. Finally, it looked for arrays of 984 devices (matching the centrifuge cascades at Natanz), and if those conditions were not met, it would not activate, which shows a semi-intelligent nature. Although its design involved autonomous behavior and it was precisely targeted, it eventually escaped Natanz and infected over 200,000 computers globally. This illustrates the problem with autonomous weapons, once they are released, the creator loses control over their proliferation (Zetter, 2014).

4.4 Digital Twin Vulnerabilities

While not a specific case, it is important to mention studies on vulnerabilities of the digital twins in smart cities. As cities have been integrating IoT sensors for varying purposes (Chini, 2025), they created a "Digital Twin," which is a virtual clone of the city that is used for the operation and management of smart cities. It has been demonstrated by researchers, specifically Weil et al. (2023) that Digital Twins are often unsecured. Unlike traditional sieges of fortifications such as cities, you don't need an army to attack a digital twin, it could be done from a laptop in Moscow. The attack could start by targeting the digital twin and then move from this attack to an attack on an actual city. When the unsecured digital twin is attacked, services like water treatment, traffic lights, and data for first responders can be attacked and crippled. A study by the Center for Long-Term Cybersecurity (CLTC) found that smart city technologies usually lack basic encryption, making them easy entry points for adversaries to pivot into critical networks (Abreu et al., 2021). An example of how a smart city could be attacked would be, if a state actor were able to trick the "Smart Transport" system into a deadlock. While the state physically attacks a city, it could prevent civilians and forces from fleeing, turning efficiency algorithms into death traps.

5. Anticipatory Ethics

Anticipatory Ethics is an ethical framework which focuses on the anticipation and identification of potential ethical issues relating to new and emerging technologies before the technologies become fully developed and entrenched (Brey, 2012). Anticipatory ethics is focused on developing technologies and ethical issues that may emerge as these technologies continue to develop. Applying the "Moral Responsibility for Computing Artifacts" framework (Miller et al., 2011) allows us to foresee and map the ethical obligations of the developers building AI to be employed in urban warfare and cyber warfare.

5.1 Foreseeability of Effect

There are 2 rules that apply from the rules for computing artifacts to the use of AI in cyberwarfare. First, rule 1 states that "The people who design, develop, or deploy a computing artifact are morally responsible for that artifact, and for the foreseeable effects of that artifact." It is foreseeable that autonomous cyber weapons such as DeepLocker and more modern developments once they are released into a smart city will be reverse engineered by state and non-state actors once the original technology has been deployed. Unlike physical missiles, cyber weapons can break out of confinement and wreak havoc on unsuspecting and uninvolved populations. Developers have a moral duty to build either expiration dates or kill switches into their weapons to prevent them from spreading indefinitely. An example of this being done was the kill switch built into the WannaCry malware, where if a specific website domain was registered, then the malware would become benign, and with 10 dollars and 69 cents, the malware was disabled (Cloudflare, n.d.). Releasing an autonomous weapon without a recall mechanism is a direct violation of Rule 1.

5.2 Sociotechnical Imperative

Second, rule 4 states that the "People who design... can do so responsibly only when they make a reasonable effort to take into account the sociotechnical systems in which the artifact is embedded." Smart cities are designed for sterile, peaceful environments to optimize efficiency for civilian life. This intention does not violate the Sociotechnical Imperative until the fact becomes known that they have been militarized by integrating dual-use surveillance censors. This is embedding civilian technology into a military environment as well as military technology into a civilian environment, which violates the social contract between the government and the city's residents. Designers need to anticipate these misuses and harden these technologies against military commandeering. Failing to separate and segregate civilian data from military targeting algorithms endangers the entire urban population (Brey, 2012).

6. Recommendations

To mitigate the risks of "Hyper-War" within smart city's and urban cyber-sieges, we propose the following three technical guardrails.

6.1 Digital Airgaps for Critical Urban Infrastructure

To protect smart cities from being weaponized, services and systems that are critical for supporting urban necessities like water, hospital power, and sewage must be physically and logically air gapped from the internet and only support local connections. Cities should implement "Data Diodes" (Owl Cyber Defense, 2025). These are hardware devices that allow date to flow in only one direction, in this case the direction would be flowing out for monitoring. This ensures that no incoming command can reach the control systems from the outside internet. This would effectively prevent an adversary from hacking the digital twin to shut down life supporting systems (NATO, 2025). This recommendation is not without ethical justification. A digital air gap would restore the Principle of Distinction for AI and cyber warfare operations. If the physical civilian life support layer can be separated from the information layer, this can help ensure that cyber war cannot target smart city infrastructure which if successfully targeted and disabled could lead to a public health crisis.

6.2 Algorithmic Circuit Breakers

Algorithmic Circuit breakers must be hard coded into military AI systems to prevent accidental escalations caused by skirmishes between two military AI systems. The technical implementation would look like autonomous software modules that monitor "heat" levels, which would operate depending on how severe the skirmishes between opposing AIs become. The idea of AI moderating AI presents a variety of issues, but since the speed of military AI systems outpace human cognition, there is no other plausible way. If the system escalates conflict above a pre-defined threshold, such as 50 cyber-attacks per second, the circuit breaker would automatically trip and pause all offensive operations pending human review. For autonomous cyber weapons to be used ethically, there must be some sort of meaningful and legitimate human control, which this recommendation restores. It ensures that no machine-speed escalation can spiral into total war without a human explicitly deciding to continue the fight (Allen & Chan, 2017).

6.3 Cryptographic Provenance

To counter data poisoning, all military and civilian sensors must implement cryptographic signing. Every video frame from a drone or command rom HQ must be digitally signed with a private key at the point of collection, for a video recording it would be the camera sensor. The receiver then verifies the public key, and any data that lacks the signature is automatically marked as untrustworthy. This preserves Epistemic Integrity. This maintains a verifiable "Chain of Custody" for all information flowing through smart sensors, it can even be applied to commands given by verifiable operators to machines. This secure chain of custody for information is essential to prevent AI from being tricked by adversaries into attacking false targets within smart city infrastructures (Chesney & Citron, 2019).

7. Future Work

Future analysis must expand and move byondbeyond current AI capabilities to the domain of "Agentic AI" where autonomous agents would be capable of negotiating, planning, and executing multi-stage cyber operations without human intervention. As the speed of conflict surpasses human cognitive limitations, the pressure to delegate lethal authority to algorithms will increase. Future research should investigate the "Moral Math" of these algorithms: can an AI be coded to understand the Law of Armed Conflict (LOAC) better than a human soldier, or does the removal of human empathy from the kill chain inevitably lead to the possibility of atrocities? (Scharre, 2018). In addition, the rise of Cognitive Warfare in the Metaverse requires urgent study into how immersive psychological operations (PSYOPS) will impact the operations related to urban and cyber warfare within the domain of civilian mental health.

8. Conclusion

The convergence of AI, Urban Warfare, and Cyber Warfare is creating a "Hyper-War" environment that fundamentally challenges the laws of armed conflict. The ability of AI to turn a smart city's infrastructure into a weapon, or to conduct "sniper" malware attacks via more modern platforms than DeepLocker, represents a shift from *attrition* warfare to *algorithmic* warfare. While these technologies offer tactical advantages in terms of speed and efficiency, they introduce catastrophic strategic risks: the possibilities include the erosion of accountability, the lowering of the threshold for conflict, and the danger of accidental escalation. We need to stop viewing AI as merely a "tool" in the military's kit and recognize it as a potentially independent agent that

requires strict, globally enforced ethical constraints. Without these guardrails, specifically digital airgaps, circuit breakers, and provenance verification, the efficiency of the "Smart City" can become weaponized and the smart city infrastructure can be turned against the inhabitants of the smart city while turning a smart city into a lethal "Feral City."

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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The Baseband Sovereignty Paradox: Anticipated Ethical and Technical Issues of Baseband Processors

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Abstract: Users and administrators of mobile devices focus on hardening the defenses of the devices to the application processors and Operating Systems (OS) of these devices. Meanwhile an unrestricted, parallel computing environment operates unchecked beneath the surface of these systems: the Baseband Processor (BP). This paper examines the "Baseband Sovereignty Paradox," where the chip responsible for cellular communication possesses Direct Memory Access (DMA) to the entire device while remaining completely opaque to the user, the main OS, and security software (Weinmann, 2012). The Baseband Sovereignty Paradox refers to the following items: A nation state wants full control over its mobile communications infrastructure, but must often rely on foreign, opaque, un-auditable baseband chips and firmware. This paradox creates a strategic dependency that directly undermines state centered technological and national sovereignty (Brey, 2012). The relevance of these items to cyberwarfare can be described as follows: Baseband compromises allow within mobile devices deep, persistent access invisible to OS defenses. Nation-states can weaponize baseband vulnerabilities for the purposes of disruption of communications, espionage, and supply-chain cyber-attacks and interference. The reliance on foreign basebands by nation states becomes a potential geopolitical attack vector, while putting future cyber network generations potentially at strategic risk. In this analysis we follow a standard conceptual analysis where define concepts and terminology related to the baseband paradox which are then applied to case studies. examine historical precedents, such as the Pegasus spyware, to demonstrate how the BP in mobile devices can be exploited to gain SYSTEM privileges, bypass encryption, and exfiltrate data (Amnesty International, 2021). This research highlights the persistent nature of baseband communications in mobile devices, which maintain contact with cell towers even when the device is in "Airplane Mode" or powered down, which allows them to act as an unmitigable tracking beacons. We argue that the Baseband Processor constitutes a "Fifth Column" for cyber warfare. Baseband processors are a ubiquitous, privileged, and unmanageable hardware component within mobile devices that fundamentally undermine the concept of user privacy and device ownership and control (Johnson, 2010). Our analysis will conclude with an ethical and anticipated ethical analysis of The Baseband Sovereignty Paradox which when exploited by adversaries can used in support of cyberwarfare.

Keywords: Baseband processor, Sovereignty paradox, Direct Memory Access (DMA), Fifth column cyberwarfare, Anticipatory ethics, Pegasus spyware

1. Introduction

Within the modern digital landscape, the smartphone has been transformed into an object that is at the center of the lives of those who own them. They are no longer merely devices for sending calls and text messages. Smartphones now serve a variety of purposes including being a financial ledger, a biometric database, a location tracker, and a primary means for professional and personal communication. Since these devices are central to so many lives, countless resources are invested in the security of smartphones. iOS and Android are constantly audited by companies like Apple, google, and independent contractors are hired to patch and strengthen the security of the smartphone mobile Operating System (OS). These actions are focused on application sandboxing which is the process of isolating an application from the rest of the system (Apiiro, n.d.), e. g. isolating end-to-end encryption for secure communications, and from user permissions. This focus on the user-oriented goals neglects a vulnerability that is present in smartphones. This vulnerability is beneath the Application Processor (AP) end of operations, where there is a parallel computing environment that is the Baseband Processor (BP).

Baseband Processors are responsible for cellular network communications, they manage complicated radio frequences that are necessary for connecting to 3G, 4G LTE, and 5G networks. The Baseband Processor is not designed to interact with the user; it is designed to operate independently, which separates its vulnerabilities from the user end Application Processor within smartphones. Baseband Processors run their own proprietary Real-Time Operating System (RTOS) environments where closed source firmware is executed in separation from the user and from the Operating System of the main device.

The separated parts of a smartphone's technical architecture are what this paper defines as the "Baseband Sovereignty Paradox." This paradox affects both macroeconomics and geopolitics. Sovereign nations and their intelligence agencies attempt to secure their military communications infrastructure, but to participate in the

modern world they are required to rely upon foreign and unsuitable baseband chips that are manufactured by a few select entities like Qualcomm, MediaTek, Samsung, and Huawei. This reliance upon foreign manufacturers for advanced products like baseband chips that are then used in military devices, creates a strategic dependency that threatens to undermine national sovereignty and national security. Can a state establish true sovereignty over its digital infrastructure if the hardware that it runs on is manufactured by foreign entities that intentionally obscure their manufacturing processes?

This paper argues that Baseband Processors are the Achilles heel of smartphones in the context of cyber warfare. The Baseband Processor acts as an embedded, highly privileged, and unmanageable hardware component that lays dormant in the smartphones of every citizen, politician, and military leader in the developed world. It undermines the concept of user privacy and device ownership by serving as a silent back door that can be activated without the user ever knowing it has been activated. By examining the technology behind baseband processors, case studies where baseband exploitation is involved, and an application of traditional and anticipatory ethics, this analysis can explore the ethical violations and strategic implications of the Baseband Sovereignty Paradox. Recommendations can then be developed about how to confront the Baseband Sovereignty Paradox in cyberwarfare in the twenty first century. Therefore, this paper seeks to answer the following research question: How does the lack of clarity and privileged access of the Baseband Processor threaten national sovereignty and user autonomy, and what ethical frameworks should guide the mitigation of these vulnerabilities? Ethical issues will be related to the conceptual distinctions involving according to Furrow, ethics is related to evaluating actions, and actions are performed by those capable of being moral agents. As Furrow says, “When we evaluate an action, we can focus on various dimensions of the action. We can evaluate the person who is acting, the intention or motive of the person acting, the nature of the act itself, or the consequences.” (Furrow, 2005)

2. Technical Issues

A true understanding of the ethical and strategic threats from smartphones can only be gained by first understanding the technical architecture behind the Baseband Processor and the immense power it exercises over the mobile device. Modern mobile devices are in effect two different computers that share a chassis and power source. The first computer is the Application Processor (AP), which is a chip that runs the main Operating System like Android or IOS and handles user interfaces as well as high-level computations. In essence, the Application Processor is the one the user interacts with when they open their phone, play a game, watch a video, or make a call. The second computer is the Baseband Processor (BP), which is a chip dedicated to managing complicated, time-sensitive radio protocols that enable cellular communication. The user cannot make a call on the Application level without the Baseband Processor first connecting them to the network. The technical vulnerabilities of Baseband Processors can be divided into four unique domains: Real-Time Operating Systems (RTOS), the implementation of Direct Memory Access (DMA), the extreme opacity of the firmware, and the persistence of the component's operational state (Weinmann, 2012).

2.1 Real Time Operating System (RTOS)

When cellular networks operate, they require strict timing. A mobile device communicates with the network by sending and receiving packets, which are just bundles of information that allow for inter-device communication. Transferring packets is simple and would not require its own processor, except that mobile devices pose unique challenges: they need packet transfer to occur in the order of microseconds to maintain a connection. They need to be able to manage the switching of connection from tower to tower while the user moves and manages signal degradation as the user gets farther from the tower to which they are connected. The Application Processor is incapable of doing this because it gets bogged down by user apps and graphics rendering which eats up CPU cycles, meaning it cannot meet the strict timing requirements that a cellular connection requires (Mulliner & Miller, 2009). To address this need, developers made the Baseband Processor run on a Real Time Operating System (RTOS), which is designed to process data as it arrives without buffering as is common in normal Operating Systems. RTOS is a highly efficient solution for radio signaling. The problem lies in their design being crafted in the 1990’s and early 2000's. The first mobile malware named ‘Cabir’ was discovered in 2004 (Khandelwal, 2014), which means when RTOS were being invented, security had not yet become an important concern. RTOS environments are dependent on codebases that were developed during the lax security era and are still in use today. Various patches have been developed to attempt to secure them, such as Qualcomm’s REX or different implementations of ThreadX (Weinmann, 2012). These are legacy systems which masquerade as modern software and are inherently fragile and susceptible to memory corruption vulnerabilities (Weinmann, 2012). These legacy RTOS environments frequently lack modern software mitigations, such as Address Space

Layout Randomization (ASLR) and stack cookies, making over-the-air memory corruption attacks from fake base stations significantly easier to execute (Grassi, 2018).

2.2 Direct Memory Access (DMA) and Privilege Escalation

Baseband Processors need to rapidly transmit large amounts of data (video streams, voice calls) to the main processor so the user may interact with the content, which creates a logistical problem because piping massive amounts of data through the central CPU would bottleneck the device. The solution developers found was Direct Memory Access (DMA) for the Baseband Processor. To accomplish this the Baseband Processor requires system privileges, the most powerful set of permissions one can have. Direct Memory Access is important, it allows the baseband chip to read from and write to the device's main Random Access Memory (RAM), bypassing the CPU, the main OS, and any security protocols. DMA is extremely efficient, but the cause for alarm from the perspective of cybersecurity. This is not malicious or negligent on the part of the developers, it was a genuine solution to an engineering problem, but a solution that must be re-examined in the modern cyber threat landscape. If the Baseband Processor was not privileged, malicious radio signals or SMS attacks would not be cause for worry, but with DMA the attacker can take control of every aspect of the mobile device. This would allow attackers to manipulate the OS kernel, extract cryptographic keys, bypass screen locks, and access encrypted messages before they are encrypted or after they are decrypted. The main memory is a trusted hardware component, meaning OS-level security is blind to it, thus completely blind to the intrusion (Check Point Research, 2020).

2.3 Obscurity and Proprietary Components

The systems mobile devices run on are highly proprietary and guarded by the few corporations that manufacture them. This means that baseband firmware is proprietary, and that independent researchers and academic institutions are unable to legally audit the code that runs on the Baseband Processor to locate vulnerabilities. This is the security through obscurity model, when the vulnerabilities exist, and given that they run on millions of lines of C/C++ code, which they likely do, they are only going to be discovered by well-funded nation-state intelligence agencies, or private cyber arms dealers who stockpile "Zero-Day" exploits. The end user, the device manufacturer, and even the national government relying on these devices have no means of independently verifying that the baseband firmware on their devices is free of backdoors or critical flaws (Check Point Research, 2020).

2.4 Persistence and Unmitigated Tracking

The final technical issue regarding Baseband Processors is persistence. Baseband Processors are designed to prioritize network connectivity, which means they are always looking to communicate with cell towers. When a user selects the option "Airplane Mode" on their mobile device the assumption is that communications to and from the mobile device are severed. The main Operating System updates their user interface to display an icon of an airplane, that creates what amounts to an illusion of being disconnected. In many mobile device architectures, airplane mode is just a software instruction from the Application Processor to the Baseband Processor asking it to stop transmitting user data. The Baseband Processor does not shut off, it continues to connect to and passively listen to cellular towers, and in some cases, it will still perform low level handshakes with the network to ensure the user reconnects quickly once airplane mode is disabled (Perez & Slay, 2013). When a user powers their device "off: it does not physically sever the connection to the Baseband Processor. When the off button is pressed the mobile device enters a deep sleep state where the Application Processor is powered down, but this is not strictly true for the Baseband Processor, notably in iOS 15+, the "Find My" functionality remains in a low power state and can be tracked by iOS devices on the same network. While it does not ping towers, it can still be used as an unmitigable tracking beacon. If the device has battery power, the baseband processor can still periodically wake up, allowing an attacker to potentially triangulate in on the position of a target that has a compromised phone in the off state (Heinrich et al., 2022).

3. Ethical Issues

The technical realities of the Baseband Processor generate ethical issues that fundamentally change the relationship between humans, their personal technology in the form of smartphones, and the state. We assume Furrow's ethical distinctions involving an agent's intentions, actions and outcomes apply to the Baseband Sovereignty Paradox and to the designers of baseband processors. The designers of baseband processors have intentions, perform actions and produce outcomes. Through an examination of the hardware architecture and traditional ethical frameworks from the intentions of different types of agents, we can identify

three main ethical issues with Baseband Processors: the degradation of agency over an individual's mobile device, the undercutting of national sovereignty, and the exploitation of a digital Achilles heel.

3.1 Device Ownership and Autonomy

At the most fundamental ethical level, the Baseband Processors architecture creates a pervasive illusion of device ownership. Within traditional property and privacy ethics ownership implies the inherent right to control, secure, and modify one's property (ScienceDirect, n.d.). Because the BP operates autonomously beneath the Application Processor and remains completely opaque to the user, the main OS, and security software, this control over the device is a facade. The designers of baseband processors ignore the outcomes related to the actions of the users of the devices.

Users cannot audit the firmware, patch new vulnerabilities or monitor the Baseband Processors background processes. Since the Baseband Processor has DMA to the entire device, the user is essentially a tenant in their own device. The device serves the cellular network provider and the manufacturers digital imperatives long before it serves the users security needs. Using the framework of anticipatory ethics and the philosophy of technology, Philip Brey (2012) argues that technology is not morally neutral, there are inherent power dynamics that control the technology without the user's explicit consent. When manufacturers design a device where the user's control over the primary communication node is tenuous at best, manufacturers of the technology are removing the individual's digital autonomy. The result of this lack of control is a ubiquitous and unmanageable hardware component that undermines the ethical issues related to user privacy and device ownership.

3.2 The National Sovereignty Crisis

The ethical issues arising from the Baseband Sovereignty Paradox created by the designers of the technology scales past the individual level to a macroeconomic level revealing a national sovereignty crisis. This paradox posits a set of conflicting features with mobile devices. On the one hand, a state has the intention of wanting full control over its mobile communication infrastructure, while on the other hand it relies on opaque foreign baseband chips and firmware. In the digital age sovereignty only exists if communications can be secured that are free from foreign interference for sensitive information, is a nation sovereign if hackers can listen in on conversations pertaining to national security? The realities of the compartmentalized global supply chain are that governments must build their military and national security communications on top of a proprietary baseband chip often produced by a foreign entity. This creates a strategic dependency upon companies whose host nations might be adversaries, which directly undermines national sovereignty. The ethical issue lays in the complicity of the state, where the government produces an outcome that includes knowingly subjecting their citizens and military personnel to hardware that cannot be audited and that can possibly be covertly weaponized. A nation cannot claim true sovereignty if the foundational hardware routing its data in mobile devices is controlled by a foreign corporate or state entity capable of obscuring its internal operations. Supply chain reliance on foreign basebands becomes a potential geopolitical attack vector, while future network developments and new generations deepen the strategic risk.

3.3 The Digital Achilles Heel Concept

This dynamic for Baseband Processors establishes what we identify as a digital Achilles heel. Historically an Achilles heel is a colloquial phrase meaning a surprising weakness in an otherwise strong individual (Gill, 2019). With the Application Processor and mobile Operating Systems are constantly being patched and hardened against attacks, as they are the obvious target, we argue that this otherwise strong/secure device having a more vulnerable Baseband Processor constitutes an outcome that is an Achilles heel. Baseband processors are embedded, privileged entities that is carried into secure military bases, government offices, and private homes. Since any baseband compromise would allow deep and persistent access to devices invisible to mobile device security, this makes it possible for malicious agents to act so that such devices become the perfect target for anyone who wishes to conduct cyber warfare or espionage. Nation states that force populations to rely on this architecture means that a society implicitly accepts a baseline of vulnerability that violates fundamental ethical norms of security and autonomy, transforming every smartphone into a dormant cybersecurity vulnerability.

4. Case Studies

To support these technical and ethical claims, there must be real-world examples that provide an insight into the vulnerabilities related to the Baseband Sovereignty Paradox. These cases demonstrate how the theoretical vulnerabilities of the Baseband Processor can translate into breaches in device security, privacy and international telecommunications infrastructure. This paper uses a qualitative case-study methodology. The four case studies

were selected to represent a diverse spectrum of the Baseband Sovereignty Paradox: targeted nation-state spyware (Pegasus), mass supply-chain hardware flaws (Qualcomm DSP), localized rogue infrastructure (Washington D.C. Stingrays), and zero-click remote execution (Samsung Exynos).

4.1 Pegasus Spyware

The NSO Group's Pegasus spyware represents the pinnacle of modern mobile espionage. The reality of this threat was established in 2021 when a consortium of media outlets and Amnesty International released the "Project Pegasus" report, forensically confirming the successful, covert infection of devices belonging to human rights activists, journalists, and politicians globally (Amnesty International, 2021). This was an intentional action on the part of the designers of the Pegasus spyware While early iterations of Pegasus required users to click malicious links, the 2021 forensic analysis revealed a shift toward zero-click network injections. NSO Group was documented selling tactical network injection equipment, hardware acting as rogue cell towers, that interacts directly with the baseband to push malicious payloads. Once the spyware successfully compromises the baseband or leverages its Direct Memory Access (DMA) capabilities, it operates entirely beneath the level of jurisdiction of the OS kernel. This low-level compromise allowed Pegasus to silently extract the contents of messages directly from the device's RAM before they were encrypted for transmission, activating microphones and harvesting location data without leaving standard forensic traces on the Application Processor.

4.2 Supply Chain Reality

A geopolitical threat that involved supply chain consolidation was demonstrated in august 2020 when over 400 vulnerabilities were discovered in Qualcomm's Digital Signal Processors (DSPs). The DSP interacts with the baseband to process audio, video, and telecommunication data. Security researchers at Check Point showed that these vulnerable Qualcomm chips were in approximately 40% of the world's smartphones at the time of discovery. 40% includes models from companies like Google, Samsung, LG, and Xiaomi (Check Point Research, 2020). These flaws were not merely theoretical, researchers proved that they could use these exploits to record calls, steal data, embed malware that could survive a factory reset, and do it all without the user interacting with the device or knowing about the exploits. The moral character of the manufacturers and designers of Qualcomm chips with their many vulnerabilities is morally problematic. The scale of this discovery demonstrated the reality that a single manufacturer's obscured legacy firmware could instantly destabilize the communications infrastructure of almost the devices for nearly half the world.

4.3 Washington D.C. Rogue ISMI Catchers

The exploitation of the baseband's processor's intention to connect to the strongest cell signal can be executed via International Mobile Subscriber Identity (IMSI) catchers, colloquially known as Stingrays. This was proven to be an active cyberwarfare tactic used on U.S. soil in 2018. In a letter to congress the Department of Homeland Security (DHS) officially acknowledged the discovery of several unauthorized rogue ISMI catchers that were operating in Washington D.C., including near the White House and the Pentagon (Department of Homeland Security, 2018). Foreign intelligence operatives utilized these rogue cell towers to force the basebands of nearby smartphones to connect to them instead of legitimate carrier networks. By doing so, the attackers forced the targeted basebands to downgrade their encryption to legacy, broken protocols such as 2G GSM. This documented event allowed foreign actors to intercept calls, read unencrypted texts, and precisely triangulate in on the physical locations of government personnel. This action produced an outcome that is morally suspect. Crucially, this event highlighted the deceptive nature of smartphone UI (user interface). Even if personnel utilized "Airplane Mode," the baseband's persistent listening state meant the device could still be pinged and tracked by these rogue towers.

4.4 Exynos Internet-to-Baseband Exploits

In March 2023, the reality of automated, mass-scale baseband exploitation was confirmed when security researchers at Google's Project Zero publicly disclosed 18 severe zero-day vulnerabilities in Samsung's Exynos baseband chipsets. These chips were actively embedded in millions of global devices, including Google's own Pixel 6 and 7 series, various Samsung Galaxy models, and wearable devices (Google Project Zero, 2023). Most alarmingly, Project Zero confirmed that four of these vulnerabilities (including CVE-2023-24033) allowed for Internet-to-baseband Remote Code Execution (RCE) with absolutely zero user interaction (Google Project Zero, 2023). To execute the attack and compromise the device, the threat actor only needed to know the victim's phone number. By sending specially crafted data over the cellular network, the attacker exploited a memory corruption flaw in the baseband's firmware. Because the baseband automatically parsed the incoming cellular data before notifying the main OS, the malicious code executed silently. This historical disclosure proved that

basebands could grant attackers a persistent, high-level foothold on the device without the user ever receiving a notification, touching their screen, or realizing they were under attack. In effect the user of a device is being used as a means for an attacker's intended goal.

5. Anticipatory Ethics

Anticipatory Ethics is a future oriented ethical framework that attempts to identify potential ethical issues that arise from new and emerging technologies before they are fully integrated into society. As defined by Phillip Brey, Anticipatory Technology Ethics (ATE) requires that we move beyond reactive judgements about the effects of technologies after an event has occurred to a proactive forecasting of the dangers that these technologies pose. Anticipatory ethics seeks to identify, evaluate, and mitigate moral hazards during the design and deployment phases of emerging technologies, rather than reacting retroactively after catastrophic failures happen (Johnson, 2010). Because the Baseband Processor determines the fundamental communication capabilities of global society, hardware engineers and software developers must be held to strict anticipatory and professional standards (Ciulla, Martin, & Solomon, 2013). Applying the "Moral Responsibility for Computing Artifacts" framework by Miller et al. (2011), alongside the Association for Computing Machinery (ACM) Code of Ethics, clarifies the moral obligations breached by the current baseband architecture. These concepts are applied to the dimensions that Furrow states as related to the intentions, actions and outcomes produced by agents.

5.1 The Foreseeability of Effect (Rule 1) and Robust Security

Rule 1 of Miller's framework states that "The people who design, develop, or deploy a computing artifact are morally responsible for that artifact, and for the foreseeable effects of that artifact" (Miller et al., 2011). In the context of baseband architecture, granting an opaque, internet-facing radio chip unrestricted Direct Memory Access (DMA) to the main system memory by developers makes mass exploitation entirely foreseeable. The zero-click vulnerabilities observed in the Samsung Exynos chips (Case 4) and the supply chain flaws in the Achilles discovery (Case 2) were not anomalies; they were the predictable result of fragile, legacy code executing with maximum privileges.

Under the ACM Code of Ethics Rule 2.9 ("Design and implement systems that are robustly and usably secure"), developers are mandated to implement structural safeguards against such foreseeable breaches (Association for Computing Machinery, 2018). Hardware manufacturers who knowingly design basebands with unchecked DMA violate this rule, so they bear direct moral responsibility for the cyberwarfare vulnerabilities facilitated by this reckless architectural choice.

5.2 The Sociotechnical Imperative (Rule 4) and Avoiding Harm

Rule 4 states that "People who design... can do so responsibly only when they make a reasonable effort to take into account the sociotechnical systems in which the artifact is embedded" (Miller et al., 2011). Smartphones are fundamentally civilian artifacts embedded within the sociotechnical systems of journalism, healthcare, banking, and democratic elections. By designing a device that prioritizes network connectivity and intelligence-gathering capabilities over verifiable user security, manufacturers actively ignore this civilian context. This disregard directly conflicts with ACM Rule 1.2 Avoid harm. When nation-states hoard baseband vulnerabilities to deploy tools like Pegasus (Case 1) rather than reporting them to be patched, they cause systemic harm to global smart device infrastructure.

5.3 Negative Rights, Deception, and Privacy

Furthermore, the deceptive user interface design of "Airplane Mode" (Case 3) constitutes a severe ethical breach. Users possess a fundamental "negative right" a right to be free from unwarranted tracking, interference, or surveillance by external actors (Alabama Policy Institute, 2020). By designing an interface that creates a false sense of security while BP continues to act as an unmitigable tracking beacon, engineers designing baseband processors eliminate the informed consent of users. This violates ACM Rule 1.6 Respect privacy by engineering interfaces that explicitly mislead users about the transmitting state of their hardware.

6. Recommendations

To resolve the Baseband Sovereignty Paradox and dismantle the "Fifth Column" nature of modern mobile devices, which creates an attack vector for cyber-attacks and cyber warfare, a paradigm shift from software-level security to hardware-level enforcement is required. We propose three actionable technical mandates to reestablish device sovereignty:

6.1 Hardware Isolation via IOMMU

The most critical vulnerability of BP is its unrestricted Direct Memory Access. An outcome that should be expected of manufacturers is that they must implement strict Input-Output Memory Management Units (IOMMU) at the hardware level. An IOMMU acts as a physical firewall between the baseband and the main system memory. Instead of the BP having free rein over the entire RAM, the IOMMU restricts the BP to reading and writing within a tightly controlled, isolated memory buffer. If the baseband is compromised by a zero-click radio exploit, the threat actor is trapped within this restricted buffer and cannot pivot to access the OS kernel, extract cryptographic keys, or manipulate user data.

6.2 Open-source Baseband Firmware

The paradigm of "security through obscurity" has demonstrably failed, leaving national infrastructure dependent on opaque, foreign supply chains while making this infrastructure vulnerable to cyber-attacks. Telecommunication standards bodies and governments have the ethical responsibility of mandating a transition toward open-source Real-Time Operating Systems (RTOS) for cellular modems. Just as open-source operating systems like Linux benefit from rigorous global scrutiny, baseband firmware must be auditable by independent academic and security researchers. Transparency removes the strategic dependency on foreign black-box chips and serves as the only sustainable defense against supply-chain weaponization.

6.3 Verifiable Hardware Kill Switches

Software toggles cannot be trusted to secure a device from remote exploitation or persistent tracking via IMSI catchers. Smartphones designed for government, military, or privacy-conscious civilian use must be manufactured with physical, hardware-level kill switches. These switches must physically break the electrical circuit providing power to the Baseband Processor and its associated antennas. Only a physical severing of power can provide a verifiable guarantee of radio silence, neutralizing the unmitigable tracking beacon effect and restoring absolute control of a device such as a smartphone to the device owner.

7. Limitations

Since Baseband firmware is proprietary and legally protected, this analysis relies entirely on publicly disclosed vulnerabilities and third-party forensic reports such as from Amnesty International or Google Project Zero. There are likely undiscovered or undisclosed vulnerabilities that could not be considered for this paper. There may also be undisclosed patches to what we believe are current existing vulnerabilities to which we simply do not have no access. Relying on public data creates an inherent selection bias, since we can only produce analysis based upon what is publicly available.

8. Future Work

As the global telecommunications infrastructure transitions to 5G Advanced and anticipates the rollout of 6G, the complexity of baseband firmware will grow exponentially. Future research must analyze the security implications of integrating Artificial Intelligence (AI) directly into the Baseband Processor's RTOS to manage complex radio spectrum allocations. Furthermore, the advent of Direct-to-Cell Low Earth Orbit (LEO) satellite internet (such as Starlink and AST SpaceMobile) introduces a novel attack vector. Future work should investigate how baseband vulnerabilities might be exploited from space-based infrastructure, completely bypassing terrestrial cell towers and rendering localized geographic defenses obsolete.

9. Conclusion

The Baseband Sovereignty Paradox exposes a catastrophic flaw in the architecture of the modern digital ecosystem. While users and administrators focus on hardening the Application Processor, a sovereign, parallel computing environment operates unchecked beneath the surface of operating systems. By granting the Baseband Processor Direct Memory Access and wrapping its operations in proprietary opacity, manufacturers have created an embedded, unmanageable "Fifth Column" in devices owned by nearly every citizen.

This architecture systematically undermines device ownership, violates fundamental negative rights to privacy, and makes problems the technological sovereignty of nation states. As demonstrated by zero-click exploits, supply chain vulnerabilities, and persistent tracking mechanisms, the baseband is not merely a communication node; it is the primary vector that can be exploited for modern cyberwarfare. Reclaiming control requires an urgent abandonment of "security through obscurity" in favor of hardware-level isolation, open-source auditing,

and verifiable physical kill switches. Until these architectural mandates are enforced, the smartphone will remain an unmitigated threat to both personal privacy and national security.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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Forever Days, Silicon Immutability and the Crisis of Unpatchable BootROM Vulnerabilities in Cyberwarfare: Ethical and Anticipated Ethical Issues

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Abstract: Modern mobile security architecture relies on a hardware Root of Trust, which is a set of capabilities in a device's hardware that functions as anchor for all security operations within that system. (Rambus Press) This is exemplified by components such as the Apple Secure Enclave (Touch ID or Face ID use a separate processor to handle your biometric information which is called Apple Secure Enclave) (Pot, 2018). However, the reliance on immutable Silicon, specifically BootROM code (Bootrom (or Boot ROM) is a small piece of mask ROM or write-protected flash embedded inside the processor chip (What is Bootrom). It contains the very first code which is executed by the processor on power-on or reset), introduces a very critical risk: the "Forever Day" vulnerability. Unlike software flaws, vulnerabilities within the BootROM cannot be patched once the chip leaves the manufacturing plant. BootROM code itself isn't *used* in cyber warfare; rather, vulnerabilities in BootROM become powerful footholds for: persistent espionage, secure-boot bypass, hardware-level compromise, supply-chain infiltration, cryptographic key extraction, attacks on critical infrastructure devices. Because of its immutable nature, a single BootROM vulnerability can become a strategic cyber weapon—especially for well-resourced nation-state adversaries. Ethical issues arise due to how malicious adversaries could exploit the immutable nature of BootROM vulnerabily. According to Furrow ethics is related to the intentions, actions and outcomes produced by agents involved in decision making. To intentionally manufacture technology with vulnerability built into immutable silicon is an ethical issue. This analysis, using case studies investigates the technical outcomes of such exploits, where a single compromised read-only sector renders millions of devices permanently vulnerable to compromise regardless of OS security updates. We further analyze the tension between the commercial imperative to rush new silicon models to market for profit and the rigorous security validation required for immutable code. Finally, the paper discusses the role of state actors, such as the NSA, in the disclosure versus hoarding of these hardware level exploits. We conclude that "Forever Days", (a Forever Day bug refers to security vulnerability in a software application or system that remains unpatched for an extended period of time) (Forever Day Bug, 2023) represent a fundamental failure in the current hardware lifecycle, leaving a permanent window for exploitation that persists for the lifespan of the physical device. The analysis will conclude with an ethical and anticipated ethical analysis of BootROM code when it is used in support of cyberwarfare.

Keywords: BootROM vulnerabilities, Hardware Root of Trust (HRoT), Vulnerabilities Equities Process (VEP), Anticipatory technology ethics, Cyberwarfare, Supply chain security

1. Introduction

Modern computing security has been built upon an architectural concept called hardware root of trust (HRoT). As operating systems and application-layer software have been hardened against traditional cyber-attacks using mechanisms like application sandboxing and memory randomization, threat actors, especially well-resourced nation states, have moved their focus downward to attack the fundamental physical components of the devices themselves (Mishra & Sahay, 2025). The BootROM, or the first set of instructions executed by a processor when powered up, is at the heart of this hardware security paradigm (Fan et al., 2025). Since Boot ROM code is burned into silicon during the manufacturing process, it is immutable, this means it cannot be modified, updated or patched post manufacture (Schneier, 2012).

This immutability provides a cryptographic anchor that is tamper-proof and allows all programs added after boot to be mathematically verified against a reliable and immutable standard (Vasudevan et al., 2024). This architectural strength also presents a significant weakness. When a vulnerability is found in BootROM code, this immutability changes the status of that zero-day vulnerability to a "Forever Day" (Schneier, 2012). A Forever Day is a vulnerability in hardware that will remain in place for the life of the device, and therefore, software patches will have no effect on the device, and the hardware will be compromised forever (CISA, 2023).

The consequences of Forever Day vulnerabilities are significant not only for consumer privacy but also for global cyber warfare and national security (Kitchin, 2017). Ethical issues with forever day vulnerabilities are related to how Silicon Immutability and Unpatchable BootROM Vulnerabilities are intentionally designed and

manufactured. A variety of devices may be comprised of multiple hardware and software parts, and therefore are not structured as "all-one" Systems-On-a-Chip (SoCs); some examples include the modern mobile devices (the majority of which utilize SoCs), the controls for Industrial Control Systems (ICSs), and the routers associated with Critical National Infrastructure (Grassi, 2018). The most significant example of this type of architecture is the Baseband Processor (BP), which is a proprietary and opaque chip designed to control and provide cellular communications (Grassi, 2018). BP chips are located at a lower point in the OS and below the level of visibility and execution of the AP and are a "sovereign" computing environment. As such, the baseband processor has extensive privileges over all resources associated with the device, including the ability to use Direct Memory Access (DMA) to the main memory of the device (Weinmann, 2012).

The presence of an un-patchable vulnerability in the BootROM coupled with a highly privileged hardware component such as the baseband processor creates a persistent, un-auditable leveraging point for cyber-espionage (Weinmann, 2012). Manufacturers have allowed designers to intentionally introduce these vulnerabilities into their devices. The vulnerabilities introduced through these flaws give adversaries the ability to circumvent secure boot processes, conduct deep compromises at the hardware level, extract cryptographic keys, and create supply chain compromises that go undetected by traditional security software (Kataria et al., 2019). As a result, a single vulnerable read-only sector compromise has the potential to transform millions of devices into hidden assets for state-sponsored cyber warfare (Wilson & Donnelly, 2026).

The growing number of vulnerabilities that can't be fixed raises many major technical, strategic, and ethical issues. The commercial need for companies to produce new silicon quickly versus the need for thorough formal verification to create immutable code has created a vulnerability pipeline in the semiconductor ecosystem (PwC, 2024). Additionally, when an intelligence agency identifies a ‘Forever Day’, they face a significant moral dilemma; their country can either hold onto the exploit for possible future offensive cyber operations or disclose the vulnerability in order to protect civilians or critical infrastructure, as spelled out in the Vulnerabilities Equities Process (VEP), (Schwartz & Knake, 2016). Based on a careful and thorough analysis of the BootROMs' technology, the ethical implications of hardware sovereignty, a review of significant case studies, and Anticipatory Technology Ethics, this study helps to clarify the silicon immutability crisis and introduces several practical recommendations for mitigating those Forever Day threats.

2. Ethical Issues

In addition to a variety of technical issues related to Forever Days and silicon immutability there are a number of ethical issues that can be identified. Here we focus on ethical issues. The focus of ethical analysis involves a series of factors that expand upon the notion of an agent performing an action. As Furrow states, ethics is related to evaluating actions, and actions are performed by those capable of being moral agents. As Furrow says, “When we evaluate an action, we can focus on various dimensions of the action. We can evaluate the person who is acting, the intention or motive of the person acting, the nature of the act itself, or the consequences.” (Furrow, 2005) A moral agent can justify their intentions, actions and outcomes produced by actions by referring to ethical principles. When Forever Days, Silicon Immutability and the Crisis of Unpatchable BootROM Vulnerabilities occur related to modern mobile security architecture and cyberwarfare and when adversaries act, and these actions are based on intentions, these intentions and actions are aimed at producing outcomes. Identifying threats to Urban environments in urban warfare, has never been more evident. Each of these activities have ethical implications.

The fate of those at risk due to technological developments in and through urban warfare and cyber warfare are currently critical issues. Ethical analysis should identify ethical principles related to agents (friendly or adversarial) intentions, actions and projected outcomes that can be applied to developments in technology and issues such as Forever Days, Silicon Immutability and the Crisis of Unpatchable BootROM Vulnerabilities**.**

There are several ethical dilemmas caused by the technical reality of immutable vulnerabilities to silicon (i.e. the material that is foundational to computing). These challenges create systemic issues that fundamentally alter how we think about property rights, the sovereignty of states, the moral obligations of manufacturers of mobile devices, and the ethics of offensive cyberwarfare (Brey, 2012).

2.1 Device Ownership and Autonomy

Traditional ethical perspectives understand that the act of ownership of a mobile device allows the owner of the device to autonomously control, secure, alter, and audit their property (ScienceDirect, n.d.). The hardware architecture of today replaces actual ownership and autonomy with an illusory sense of control (Brey, 2012). The Baseband Processor and BootROM are both autonomous components that occupy an opaque layer

underneath the Application Processor of a mobile device (Weinmann, 2012), which means that users cannot perform an integrity check on the embedded firmware or patch any discovered vulnerabilities (Brey, 2012). The manufacturers' intentional design of user's devices provides users with the primary means of communication (the cell phone) an extensive amount of control over the primary means of communication (the network), but at the same time places that control in the hands of the network provider. This amounts to a violation of the fundamental negative rights of users which are recognized by all governments as the basic human rights to be free from unwarranted tracking and surveillance (Alabama Policy Institute, 2020).

2.2 The National Sovereignty Crisis

The scaling of ethical issues from consumer level to macroeconomic level highlights an extreme crisis in nation states' sovereignty (Wilson & Donnelly, 2026). This hardware sovereignty paradox creates conflict between a sovereign nation needing complete control over its telecommunications infrastructure while the nation is being forced to rely on corporate designed hardware chips that are opaque and cannot be audited by entities outside of corporate control (Kitchin, 2017). The structure of a compartmentalized/global semiconductor supply chain means that nations must build national security apparatuses on top of proprietary rights of corporately designed BootROMs that have been manufactured by corporations that may be susceptible to potentially hostile countries (PwC, 2024). If a nation has its foundational hardware routing/controlling and its sensitive data located/control owned by an external corporate entity, that entity will ensure that the outcome of this control of hardware architecture will potentially hide its internal operations within the foundational hardware from everyone. The ethical consequence is that a nation can't claim to have true digital sovereignty over its foundational hardware (PwC, 2024).

2.3 The Threshold of Cyber Warfare and the Gray Zone

The ethical landscape of Unpatchable BootROM Vulnerabilities, which is influenced by current interpretations of International Law surrounding internet-based technological infrastructures (or hardware) is further complicated by the ambiguity of defining hardware-based attacks as acts of war. We contend that the current framework for defining cyber-attacks utilizes an out dated "Effects-Based" methodology, which states that, for an act to be considered an example of cyberwarfare (or acts of war), it must include an action which results in some sort of violent physical outcome (e.g. buildings destroyed by a bomb) that would be equivalent to an event caused by a kinetic weapon. However, since BootROM exploits do not demonstrate any immediate physical destruction/kinetic energies and effects, this allows nation-states to take advantage of a legal "gray area" (Wilson & Donnelly, 2026). In other words, an ethical analysis that anticipates future technological developments suggests a shift should be made towards a "Norms-Based" categorization that instead judges the act related to an intrusion based on the intentions aimed at target being affected, as opposed to when a kinetic invasion occurs or when any physical catastrophic consequences are demonstrated (Wilson & Donnelly, 2026). This represents a shift focusing on a malicious actor's intentions rather than assessing consequences after an event has occurred.

2.4 Vulnerability Hoarding and the Vulnerabilities Equities Process (VEP)

State actors face an ethical dilemma when they find a vulnerability in commercial hardware that has not been previously disclosed (e.g. a "zero-day" or "Forever Day" vulnerability) as an outcome. This involves issues related to intentionally choosing to leave a potentially harmful vulnerability undisclosed. State actors must choose between either disclosing vulnerabilities, so they can be patched, fixed, or using them for offensive cyberwarfare against other nations (Schwartz & Knake, 2016). This is also an ethical issue related to the character traits of state actors. In the United States, the "Vulnerabilities Equities Process" (VEP) exists to help balance the need to protect critical infrastructure from cyberattack, against the need to collect intelligence on malicious cyber actors (White House, 2017). Some commentators have argued that hoarding vulnerabilities disproportionately favors military capabilities over concerns about the public good. This means that vulnerabilities within hardware will remain indefinitely unpatchable since an undisclosed vulnerability could be exploited by anyone who gains access to it. By choosing not to disclose the zero-day or Forever Day vulnerabilities to the public after they have been found, the state has breached its ethical obligation of truthfulness to the public while also failing to safeguard and protect its citizens against exploitation by foreign adversaries (Willcockson, 2019).

2.5 The Tension Between Time-to-Market and Security Verification

The principle of "security by design" requires commitment to acting so that all products be thoroughly and formally verified before they are manufactured (CISA, 2023). This means that manufacturers are required to

show that their products as designed to be secure. Nevertheless, the economic reality shows that the total time devoted to rigorous hardware verification on average takes more than 55% of the total time involved in designing a typical System-on-a-Chip (SoC) (McKinsey, 2014). Architectural defects discovered late in the production process are exponentially more expensive to remediate; thus, to meet strict release dates, many semiconductor manufacturers intentionally choose to trade off risk involving vulnerability versus efficiency (McKinsey, 2014). Manufacturers who release immutable silicon (the physical component of a microprocessor) without performing an exhaustive formal verification process for Unpatchable BootROM Vulnerabilities are primarily acting in a way that exploits users as a means for the end of generating immediate profits for their corporation rather than ensuring long-term consequence of providing safety of the worldwide digital ecosystem (McKinsey, 2014).

3. Case Studies

It is essential to provide context for the theoretical risks posed by immutable silicon and the potential ethical violations these risks create through the actual deployments of these vulnerabilities. The case studies that follow will illustrate how BootROM flaws, Baseband paradoxes, and secure boot bypasses related to immutable silicon are implemented in practice.

3.1 Case Study 1: Checkm8 and the iOS BootROM

In 2019, a security researcher known as axi0mX discovered a serious hardware vulnerability known as "Checkm8". This vulnerability is a 'use-after-free' vulnerability in the BootROM of Apple's A5 to A11 processors (axi0mX, 2019). This vulnerability is in the BootROM, which is part of the silicon/processor and is therefore 'masked', so the vulnerability cannot be patched. For this reason, Checkm8 is a type of Forever Day, and this vulnerability will impact hundreds of millions of devices (axi0mX, 2019). An attacker can exploit the use-after-free vulnerability from the BootROM via specially crafted USB commands to gain arbitrary code execution at the highest privilege level. Once this occurs, all integrity-related security guarantees offered by the BootROM are broken (Apple, 2021). Since BootROM is a read-only memory, this permanent exploit opens a unique opportunity for the forensic community to conduct a fundamental investigation of secured proprietary hardware (Wu et al., 2021). The intentional introduction of the BootROM in Apple's A5 to A11 processors is a violation of Apple's corporate duties to customers. Users inherit vulnerabilities from corporations they cannot control.

3.2 Case Study 2: Fusée Gelée and the Nvidia Tegra X1

The "Fusée Gelée" exploit highlights how a single BootROM fault can have far-reaching implications across multiple industries (Temkin, 2018). Researchers discovered the exploit while researching the Nintendo Switch. The exploit exists on the Nvidia Tegra X1 processor (Temkin, 2018). To exploit this vulnerability, the researchers successfully utilized a technique called "voltage glitching" where they bypassed hardware read locks to dump the proprietary BootROM code for analysis (Temkin, 2018). This BootROM vulnerability was intentionally located by the manufacturer within the USB Recovery Mode (RCM) protocol, allowing an attacker to control the size of the memory operation arbitrarily, creating a catastrophic buffer overflow vulnerability. This buffer overflow can allow adversaries to gain Return Oriented Programming (ROP) code execution based on the context of a high-security mode, effectively defeating the hardware's root of trust. Variants of the Tegra SoC are used in essential industrial control systems within the automotive industry, creating the potential for catastrophic hardware-level compromise to vehicle infrastructure (O'Flynn, 2016). This is an unacceptable outcome (consequence) with potentially large-scale bad outcomes and don't accept responsibility for long-term safety within the automobile industry.

3.3 Case Study 3: Cisco ROMMON and Secure Boot Bypass

Trust Anchor Module (TAM) is a Trust Anchor module (TAM) used in Cisco routers and firewalls that use Field Programmable Gate Arrays (FPGA) to implement the secure boot process (Kataria et al., 2019). The TAM is intended to act as a physical immovable anchor for the device, which means that only digitally signed software images will be allowed to load into the ROM Monitor (ROMMON) (Cisco PSIRT, 2018). Despite this, some researchers found logic errors in the firmware that allowed an attacker to act in such a way as to manipulate the FPGA bitstream directly (Cisco PSIRT, 2022). By manipulating the FPGA Bit Stream, an adversary can completely bypass all the Trust Anchor's functions and inject stealthy persistent malicious implants into both the TAM FPGA and the application processor (Kataria et al., 2019). Forever-day vulnerabilities give attackers indefinite exploitation windows which bypass the Trust Anchor using hardware, an attacker is then be able to intercept or drop a very large volume of network traffic without detection (Kataria et al., 2019).

3.4 Case Study 4: Pegasus and the Baseband Processor

Amnesty International (2021) describes how mobile devices have been utilized as weaponized devices, citing the intentional use of Pegasus spyware deployed by the NSO Group to accomplish the use of the spyware as an outcome. Pegasus can directly access a target smartphone baseband processor through cellular frequencies and communicate with the target phone (Amnesty International, 2021). The attacker intentionally acts to exploit memory corruption vulnerabilities in the proprietary real-time operating system that runs the baseband processor (Amnesty International, 2021), which produces the outcome of allowing for remote code execution without having the target phone receive any alerts (Amnesty International, 2021). Using the baseband processor's large Direct Memory Access (DMA) privileges, Pegasus will transition to the smartphone's main system random access memory (RAM) while completely bypassing the Application Processor (AP) operating system Kernel (Mishra & Sahay, 2025). This level of compromise allows Pegasus to extract messages from the smartphone's RAM before they have been encrypted, clearly demonstrating that a secure application layer is vulnerable if the hardware on the smart phone on which it resides has been compromised (Amnesty International, 2021). Involuntary risk exposure users cannot patch or replace systems. Corporations must act in such a way as to prevent disproportionate harm.

4. Anticipatory Ethics

A reactive approach to ethical analysis of technological development and deployment is inadequate for achieving a meaningful result when evaluating a product built from unalterable silicon (Brey, 2012). Anticipatory Ethics is a future oriented ethical framework that studies potential ethical issues that may arise from new and emerging technologies before they are fully integrated into manufacturing processes and then into society. According to Brey, Anticipatory Technology Ethics (ATE) requires that we move beyond reactive judgements about the effects of technologies after an event has occurred to a proactive attempt to make forecasts of the dangers that these technologies pose. Anticipatory ethics seeks to identify, evaluate, and mitigate moral hazards during the design and deployment phases of emerging technologies, rather than reacting retroactively after technologies have been implemented and catastrophic failures have happened (Johnson, 2010). There is a need for an industry-wide commitment to ATE (Anticipatory Technology Ethics), an ethical framework that emphasizes the identification of ethical risks and potential harm to stakeholders during the R&D phase of developing new technologies, and prior to casting the product in silicon (Brey, 2012). So, what can be said about Unpatchable BootROM Vulnerabilities from the perspective of anticipatory ethics? They need to be corrected when the technology is being designed and before manufacturing products such as smart phones are manufactured.

4.1 ATE Framework and the Problem of Uncertainty

The future social impacts of emerging technologies are inherently uncertain, and this is the largest challenge for ATE analysis. (Brey, 2012). According to Brey, ethical foresight involves undertaking a systematic future directed analysis at multiple levels of technological foresight: analysis needs to focus on 3 levels a technology, an artifact, and the application of the technology and artifact (Brey, 2012). In the case of BootROMs, ATE requires creating what Brey refers to as "dark scenarios" (Brey, 2012) for the hardware architect to imagine how an adversary state with sufficient resources could exploit a read-only memory (ROM) flash chip or an unmitigated direct memory access (DMA) channel. The failure to foresee the possibility of weaponizing the USB recovery mode on the Tegra X1 SoC or the iOS BootROM are illustrations of a lack of thorough ATE at the artifact level (Temkin, 2018).

4.2 The Sociotechnical Imperative and ACM Rules

Keeping in mind Furrows distinctions introduced above we can combine the Anticipatory Technology Ethics framework with the ACM Code of Ethics to help define the moral obligations of developers of technology. (Miller et al., 2011). According to Miller's first rule for computing artifacts state, developers and designers are morally responsible for the foreseeable consequences of their artifacts (Miller et al. 2011). Without any form of patch to the un-patchable hardware, providing a radio random access memory (RRAM) chip with unrestricted Direct Memory Access (DMA) may constitute a highly foreseeable possibility of massive exploitation of the equipment developed using this chip. As described by ACM Rule 2.9, it is the ethical responsibility of professionals to create systems that are designed to be secure. Therefore, manufacturers that rush the fabrication of stored read only memory (ROM) code without proper verification and security are in violation of this rule thereby violating the obligation they owe to society structurally prioritizing corporate profit and time to market ahead of reporting on legitimate safety issues (ACM, 2018).

Moreover, smartphones and routers are two civilian oriented objects (artifacts) that contribute to basic communication, business operations, democratic elections and free press (Amnesty International, 2021). From the perspective of anticipatory ethics, the negative rights of the user, the right not to be subject to covert surveillance in their day-to-day lives, are built into the silicon of a piece of technology itself (Alabama Policy Institute, 2020). Ethical frameworks must also actively protect independent security researchers, who have been called the "white blood cells of the Internet." Security researchers need to be protected when they identify and find vulnerabilities from being punished by state actors when they find the vulnerabilities before adversaries can use their discoveries for malicious purposes. When researchers are punished for finding Unpatchable BootROM Vulnerabilities their efforts when punished can create a chilling effect on similarly situated researchers and leave many critical vulnerabilities unpatched, which directly violates ACM Principles 1.2 and 1.5.

5. Recommendations

According to current practices alterations to what becomes immutable silicon and Unpatchable BootROM Vulnerabilities must occur while the hardware is being designed. We propose the following actionable practices that should be intentional actions for cyber security. Security can no longer be retrofitted via software updates into mobile devices; it must be included in the design of the hardware of mobile artifacts at the design and manufacturing levels of the development of technology.

5.1 Formal Verification of BootROM Logic

To eliminate Forever Day exploits (Vasudevan et al., 2024), traditional software engineering's "test-and-debug" paradigm is not sufficient for the semiconductor industry. All Secure Boot hardware designs must be formally verified prior to fabrication, utilizing formal mathematical proofs to confirm conformity with the specification of a devices defined security specifications. The formal verification process tests all possible states of a set of specified parameters using methodologies such as model checking and theorem proving, all of which can produce very good results at identifying hidden logical defects in mobile devices (Vasudevan et al., 2024). Through formal co-verification, manufacturers can use formal verification techniques to mathematically prevent memory corruption type bugs from being created when implementing their design into mask ROM for mobile devices (Vasudevan et al., 2024).

5.2 Hardware Isolation via IOMMU

According to Mishra and Sahay (2025), unrestricted direct memory access (DMA) should be banned through regulative actions for all consumer and industrial devices. System architects need to design and create a physical firewall as hardware with an input-output memory management unit (IOMMU) (Mishra & Sahay, 2025). The IOMMU enforces access control by translating an I/O virtual address to a physical address, and it verifies permissions during the I/O page walk (Evtyushkin et al., 2021). If there is an exploit of a baseband chip through an RTOS exploit, the IOMMU should intentionally limit the threat actor to a physical isolated memory buffer, thereby preventing them from using DMA to pivot and access cryptographic keys or manipulate the application processor of a mobile device (Mishra & Sahay, 2025).

5.3 Open-Source Firmware and Verifiable Hardware Kill Switches

Governments must encourage a shift toward the use of Open-Source Real-Time Operating Systems (RTOS) for cellular modems to address the problem of hardware vulnerability pipelines while also decreasing their reliance on un-auditable foreign manufactured hardware (Dodge & Kitchin, 2017). The code in OS RTOS is open to review and subject to global scrutiny. The outcome is that this wide-range review process is considered by the Cybersecurity and Infrastructure Security Agency (CISA, 2023) as the most effective form of defense against supply chain weaponization. In addition to this, it is imperative that high-security devices include hardware-based kill switch functionality. A hardware kill switch is an electronically enabled physical switch that interrupts the electrical circuit supplying power to the Baseband Processor, thereby providing the only mathematically definitive method of maintaining radio silence, and preventing location tracking when the device is off (Purism, n.d.).

5.4 Reforming the Vulnerabilities Equities Process (VEP)

Improvement needs to be made to the Vulnerabilities Equities Process (VEP) to better classify software zero-days and unpatchable hardware and Forever Days differently (Schwartz & Knake, 2016). The U.S. and its allies should make significant changes to the VEP. This is especially true since BootROM vulnerabilities cannot be patched and without these types of vulnerabilities, hoarding them will continue to pose an ongoing threat to critical domestic infrastructure that is much greater than any temporary gain in intelligence (Schneier, 2012).

The VEP's charter should have an assumed requirement for immediate disclosure of all hardware-level or unalterable silicon vulnerabilities (Willcockson, 2019). Additionally, moving the administration of the VEP from the intelligence community to civilian cyber-security entities will ensure that protecting domestic assets is more important than developing and maintaining offensive capabilities.

6. Future Work

Anticipatory Technology Ethics and formal verification models must continue to evolve as research becomes available in new areas of interest such as:

Heterogeneous Edge Computing and 6G Networks: As the evolution of architecture for 6G take over critical computing infrastructure by directing it toward heterogeneous edge nodes, the attack surface is also expanding (Yuan et al., 2024). Future research should focus on preventing the possibility of utilizing edge-based BootROMs and for exploiting them as attack vectors to initiate cascading failures in 6G Zero Trust Networks (Yuan et al., 2024).

Integrating AI Into Real-Time Operating Systems (RTOS) and Data Poisoning: The introduction of artificial intelligence models being integrated into Baseband Processors will continue to change the attack surface for RTOS (Yuan et al., 2024). Anticipatory Technology Ethics and formal verification models should investigate how state actors may intentionally leverage AI to automate fuzzing of BootROM code to discover new Forever Days and investigate the impacts of data poisoning on on-device AI training (ISA, 2024).

Low Earth Orbit (LEO) Satellite Attack Vectors: The rollout of Direct-to-Cell Low Earth Orbit (LEO) satellite networks eliminates the need for localized infrastructure and establishes a direct line of sight to the Baseband Processor from space (Yuan et al., 2024). Anticipatory Technology Ethics and formal verification models must analyze how compromised satellite infrastructure could facilitate global, zero-click RTOS exploits, which would render local network defenses ineffective and irrelevant (Yuan et al., 2024).

7. Conclusion

The unpatched BootROM vulnerabilities and the weaponization of the Baseband Processor are examples of systemic problems in the designs that make up today's digital world (McKinsey, 2014). The technology industry has focused more on getting products to market quickly rather than on performing a complete formal verification for mobile device security, (Schneier, 2012) This has resulted in the existence of "Forever Days," (i.e., permanent flaws that will last for the physical lifetime of the device, so they can make it impossible to patch a flaw with a software fix). At the same time, granting opaque hardware free Direct Memory Access has created a known vulnerability that is continually being exploited by nation-state actors to bypass a secured boot chain, to take encrypted data from a device, and to conduct undetectable cyberwarfare (axi0mX, 2019). The result of these exploits is a violation of universally accepted ethical principles such as autonomy, related to owning your own device, respecting national sovereignty, and protecting civilian users from systemic damage (Brey, 2012).

The security of global critical infrastructure is an ongoing cyber threat, and hoarding of vulnerabilities under so-called Vulnerabilities Equities Process (Schwartz & Knake, 2016) will only further exacerbate this crisis by placing the security of global infrastructure at risk to gain temporary offensive advantages. The technology sector must turn to Anticipatory Technology Ethics to anticipate possible threats during product design and to provide security assurance before product manufacturing occurs via a process of rigorous Formal Verification (Vasudevan et al., 2024). Hardware isolation through IOMMU implementation, open-source firmware, and verifiable hardware kill switches must be in place to contain any potential device compromise and restore user autonomy (Mishra and Sahay, 2025). Without the implementation of these architectural requirements, the foundational silicon of our digital infrastructure will continue to be vulnerable to the long-term consequences caused by such an event as a Forever Day exploit.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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Weaponizing Firmware, Cyberwarfare and Battery Management Systems: Ethical and Anticipated Ethical Issues

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Abstract: As the Internet of Things (IoT), which is made up of "smart" devices, expands, in the cyber security space issues arise because cyber security which has traditionally focused on data privacy and service availability. However, a critical and under-analyzed threat vector lies in the weaponization of firmware to inflict kinetic physical damage on battery powered devices and battery management systems. This research analyzes the technical reality of manipulating Battery Management Systems (BMS) in civilian devices. By overriding safety protocols and de-throttling thermal limits, attackers can induce thermal runaway in lithium-ion batteries. This process effectively converts smartphones, laptops, and electric vehicles into incendiary devices. There is a reason why BMS security matters: The BMS directly governs safety limits; malicious interference could lead to device failure and fire risk, or grid instability when scaled. Modern connected devices increase the "attack surface" for cyber warfare via telematics, mobile apps, cloud APIs, and service diagnostics. Key risk categories (without operational details) include but are not limited to: Supply chain and tampering with components/firmware, insecure third-party libraries. There are issues related to Firmware/boot including unsigned updates, insecure bootloaders. With communications (Comms) there are weak or missing authentication on CAN or diagnostic interfaces; replay or spoofing risks. Issues with applications include Cloud/app weak API/auth controls, insecure mobile app backends. There are also Safety/security co-engineering gaps when functional safety (e.g., ISO 26262) and cybersecurity (e.g., ISO 21434) are not jointly considered. This paper explores the specific firmware vulnerabilities that allow for voltage manipulation and the bypass of hardware cut-offs for devices requiring batteries. Beyond the technical mechanics of batteries, we examine the ethical and legal implications of this "dual use" technology. This is where consumer electronics can be remotely triggered to cause fires or explosions. We argue that the potential for physical harm necessitates a reclassification of firmware vulnerabilities in power regulation modules, moving them from standard cybersecurity concerns to issues of public safety and kinetic warfare. This analysis will conclude with an ethical and anticipated ethical analysis of BootROM code when it is used in support of battery powered devices in cyberwarfare.

Keywords: Cyber-kinetic warfare, Battery Management Systems (BMS), Firmware weaponization, Anticipatory Technology Ethics (ATE), Dual-use technology, Thermal runaway, BootROM vulnerabilities, IoT security

1. Introduction

The paradigm focus of cybersecurity has been on preserving privacy for users' data and on the protection of the ability of users to access services in cyberspace. Significant resources are dedicated to engineering and implementing cybersecurity controls that enhance the security of users' operating systems and prevent unauthorized access to the data in these systems by hackers. Historically, this approach has been asymmetrically oriented toward protecting virtual infrastructure, neglecting to adequately address another area of the threat landscape: the exploitation of embedded firmware. The weaponization of this firmware allows attackers to execute kinetic attacks, causing users to suffer physical harm and property damage through malicious hardware manipulation (Donnelly & Wilson, 2026; Taddeo, 2012).

The potential and very real threat of cyber-kinetic warfare directed towards battery powered devices must now also be included as part of the bigger picture when defining cybersecurity. Cyber-kinetic warfare is currently an evolving theatre of operation in which digital breaches into information or operational systems go beyond merely manipulating the virtual world and will, in fact, cause actual physical destruction to the end-user of devices that have been compromised. The purpose of this research project is to highlight the technological realities of the modifications that can be made to battery management systems (BMS) in civilian electronic devices. Attackers can compromise the operational effectiveness of batteries in electronic devices that operate with lithium-ion batteries by overriding safety protocols related to the operational effectiveness of BMS. The result is the release of uncontrolled energy from lithium-ion batteries and, therefore, the deliberate and intentional cause of a thermal runaway condition can occur which, in turn, can result in the use of consumer technology as remote-detonation devices (Wang et al., 2023).

The BMS's security is essential for regulating the ultimate physical safety of the system's firmware/hardware. Should a malicious hacker attack firmware, it will not be just a case of lost data from the crashing of the program

but also multiple instances of catastrophic failure, risking the integrity of the entire unit and causing grievous injury or death when the attack reaches a large enough segment of interconnected smart systems. The increase in connected devices has greatly increased the attack surface related to all the devices due to the use of telematics, mobile applications, cloud APIs, and OTA diagnostic solutions. This paper examines different firmware vulnerabilities identified to exist across distinct risk categories defined as tampering via the supply chain, boot sequence, unauthorized communication interface access, and poor cloud controls that can facilitate manipulation of power generated by the device and allow overruling of safety cutoffs in battery powered devices and the IoT. Beyond the technical implications, this paper will also examine the ethical and legal implications of dual-use technology and why the physical safety ramifications must define the way firmware vulnerabilities associated with power regulating devices are classified. Firmware vulnerabilities associated with power regulating devices should be redefined and repositioned from standard computer cybersecurity to considerations that need to be perceived as urgent matters of public safety and warfare. The final section of this paper will include an ethical and ATE analysis of BootROM firmware code used to further the agenda of countries using nation-state sponsored cyberwarfare against other nation-states.

2. Technical Issues

To evaluate the ethical issues and strategic risks associated with the potential for firmware weaponization, requires dissecting the technical architecture of the Battery Management System (BMS) and identifying the appropriate attack vectors that can lead to the exposure of the system. Many of today's IoT (Internet of Things) endpoints and Electric Vehicles (EVs) have highly sophisticated, multi-CPU based architectures that utilize a common power supply as their energy source. The numerous vulnerabilities built into these types of autonomously functioning subsystems fall into numerous categories of significant risk based upon battery powered devices and Battery Management Systems.

2.1 Battery Management Systems and Thermal Runaway

Lithium-ion batteries have become a dominant energy storage technology because they have high energy density. However, lithium-ion cells can only operate safely in a very narrow range of voltage and temperature—2.5V–4.2V (Gabbar et al., 2021). Battery management systems (BMS) are critical embedded systems that monitor the balance of cell voltage, State of Charge (SoC), internal temperature, and current flow to prevent unsafe physical conditions from forming. If these voltage and temperature limits are exceeded, the battery experiences "thermal runaway." Thermal runaway is an uncontrollable, explosive chain reaction that occurs when heat produced by self-heating exceeds the amount of thermal energy that can be dissipated through the battery's exterior (McKerracher et al., 2021; Schram & Tummonds, 2024). It begins with the breakdown of internal layers of the battery, and the rate of heating in the battery rapidly exceeds the rate of heat removal, leading to the melting of internal chemical separators and volatile off-gassing, resulting in high pressure jet fires and catastrophic explosion.

Targeting the BMS specifically are attacks that will digitally enable this state while bypassing any hardware cut-off protection. Attackers can create a kinetic effect by using low-level hardware interfaces to inject malicious configurations, changing the voltages on the supply line systemically, and then forcibly disabling thermal throttles. By manipulating this data, attackers can trick the system into incorrectly charging or failing to detect age-old fault conditions, which in turn guarantees either an explosion or a fire without notifying the user of what is happening (Wang et al., 2023).

2.2 Supply Chain Vulnerabilities

Kinetic threats are primarily based on the worldwide, highly opaque supply chain for IoT hardware; manufacturers and assemblers are now being attacked prior to shipment to consumers, with the introduction of tampered or otherwise altered hardware components and/or infected firmware either during setup of device or during the assembly of devices. There are thousands of widely known third-party libraries (open-source or proprietary) being used in a BMS's firmware to perform routine functions. If a widely adopted library for power management has an unaddressed vulnerability, that vulnerability will then be incorporated into millions of devices from multiple manufacturers, and attackers will have a common target that is exceedingly difficult to identify and remediate (Wetzels, 2017).

2.3 Firmware and Boot Sequence Risks

The boot sequence of a device determines whether the device's power regulation is secure. If the boot sequence is not secure, regardless of any subsequent security controls deployed, the security of the device will be

compromised. A key risk associated with boot sequences is the delivery of unsigned or invalidated firmware update files to devices. If a device does not authenticate the digital signature of an OTA update file with a cryptographic key, then an attacker could send a specially crafted firmware update file to the BMS of the device and change its safety parameters (Tsang, et al., 2022).

Additionally, insecure boot loaders provide another opportunity for an attacker to insert persistent malware into a device before it loads its operating system after the hardware has been initialized. Since there is no cryptographic trust in the device's hardware, this is how kinetic payloads are transferred to power controllers through the boot sequence.

2.4 Communication Interfaces: CAN Bus and Diagnostic Risks

The Battery Management System (BMS) interacts with other microcontrollers within Electric Vehicles (EVs) and industrial equipment through a network called the Controller Area Network (CAN) bus. The CAN bus was developed in the 1980s and was designed as a reliable alternative to previous forms of transmitting data within a vehicle, but it was not designed for security. The CAN protocol does not include native encryption or message-authentication mechanisms (Siddiqui et al., 2023). Due to this flaw in its design, there is a risk of severe replay and spoofing attacks against these systems.

Once an attacker has been able to compromise access to the vehicle's controller area network (the compromised system could be an infotainment unit, a malicious adapter attached to the vehicle's On-Board Diagnostics (OBD-II) port, or a compromised telematics unit), they can easily capture and inject fraudulent CAN messages. For example, an attacker could deliberately generate excessive numbers of CAN frames that contain fraudulent diagnostic messages. By doing so, they could force the BMS to overcharge the battery or ignore a thermal warning; thus, causing the battery to be physically destroyed, leaving the vehicle's layer 3 software services unable to prevent the physical destruction from occurring (De Vincenzi et al., 2026).

2.5 Cloud APIs and Mobile Application Backends

The ability for cloud infrastructure to provide the ability to manage devices is the last major attack vector. Consumers and grid operators use mobile applications and web dashboards to keep track of EV (Electric Vehicles) charging status, precondition cabin temperatures or manage battery energy storage. These applications use Cloud APIs to connect and communicate with the physical devices.

When manufacturers use weak API access controls, hard-coded authentication tokens, or insecure mobile application backends - they are providing a way for an attacker to go directly from the public internet to the physical Device Management System (BMS). Attackers regularly exploit cloud weaknesses and can send generic malicious commands to populate entire fleets of devices at once. A compromised API does not only place at risk one vehicle -- but also takes away the ability for that attacker to send out these commands to hundreds or thousands of connected batteries and control systems at the same time to initiate fast-charge movements and disable the cooling pumps creating localized grid collapse & mass kinetic events (Lin, 2019).

2.6 Safety and Security Co-Engineering Gaps

Historic engineering standards associated with these systems internationally have focused on physically protecting systems as one discipline and protecting them via cyber security in another separate discipline. This leaves a substantial, dangerous gap for any co-engineering efforts within the two engineering environments (Kim, 2020). As two examples of global engineering standards used by the industry, ISO 26262 - which establishes functional safety through engineering processes; and ISO/SAE 21434; which identifies necessary standards for engineering and for cyber security.

Functional Safety is a term established by ISO 26262 as a standard for guiding the safe engineering process to functional safety of automobiles through detailed engineering requirements based on the ASIL (Automotive Safety Integrity Level) classification system (Bastos et al., 2025). Inherently, ISO 26262 is developed under the assumption of the system being operated in a benign environment and does not account for the potential for a cyber-attack on the vehicle systems. Hence, ISO/SAE 21434 was created to establish global engineering guidelines for automotive cyber security (De Vincenzi et al., 2026). Because the BMS (Battery Management System) is critical to both functional safety and cyber security, the failure of manufacturers to co-consider and integrate the two engineering disciplines is a significant vulnerability for threat actors to exploit, thereby creating organizational structural gaps between validated safety test results and validations from cyber security vulnerability assessments (Siddiqui, et al., 2023).

3. Ethical Issues

The technical realities of manipulating BMS systems and the vulnerabilities in their supply chains pose significant ethical difficulties. The unaddressed hardware issues associated with these systems move digital risks from the theoretical realm to actual existential and kinetic threats, making civilian infrastructure capable of becoming weapons of war.

3.1 Dual-use Technology and the Kinetic Threshold

The main ethical dilemma involves the fact that modern power management firmware for electronic devices often serves dual purposes. For example, the same hardware and software designed to charge a consumer's laptop or manage power flow in an EV can also be altered remotely and used to create an explosion or fire. This creates a grey area between civilian use of technology and military munitions (Lin, 2019).

The emergence of cyber-kinetic capabilities has altered the ethical understanding of warfare (Taddeo, 2012). There are strict rules of engagement as outlined by Customary International Humanitarian Law (IHL) and various modern legal systems. Based on Rule 92 of the Tallinn Manual 2.0, a cyber operation will be considered a formal "cyber-attack" if it is reasonably likely to cause death/injury to people, or cause physical damage/destroy objects (Schmitt, 2017). A digital payload used to ignite an electric vehicle parked in a civilian garage is the same as a kinetic incendiary strike from an ethical and legal perspective. Because battery management systems (BMS) have an inherent capability of dual use, it is almost impossible to apply the concepts of distinction (separation of military versus civilian targets) and proportionality when deploying cyber-kinetic weapons.

3.2 Reclassifying Firmware Vulnerabilities

The cybersecurity industry and regulatory authorities continue to evaluate firmware vulnerabilities as traditional data security and intellectual property problems. Because of the potential for directly harming individuals, a complete and fundamental reclassification of firmware vulnerabilities in power regulation modules to "immediate public safety and kinetic warfare" from the present standard cybersecurity concerns is warranted. A BMS bug, an insecure bootloader and/or an unauthenticated CAN bus interface should be legislatively and ethically reclassified from being standard cybersecurity concerns to immediate issues of "public safety and kinetic warfare," requiring government-level controls, strict laws requiring mandatory patching, as well as increasing penalties for manufacturers that knowingly sell products with co-engineering safety issues. A vulnerable battery is as much a public safety issue as a defective gas line or structurally deficient bridge.

4. Case Studies

Theoretical vulnerabilities regarding thermal runaway and communication spoofing are concretely substantiated by a growing historical record of sophisticated cyber-kinetic attacks and academic vulnerability proofs.

4.1 BadPower and FANDEMIC: Exploiting Consumer Power Management

The "BadPower" attack method was publicly displayed by Xuanwu Labs' security researchers in 2020. They did this by maliciously tampering with the data transmission channel used to negotiate power delivery between a fast charger and an attached device, forcing the power brick to deliver a constant voltage significantly beyond the device's hardware tolerance for power consumption. Because of this, the internal thermal protections of the device could not keep up with the performance requirements, and the internal device components melted and eventually caught fire - this was accomplished without any actual hardware manipulation (Xuanwu Labs, 2020).

Going further, the 2022 NDSS Symposium on Networked and Distributed Systems presented the FANDEMIC vulnerability framework. The researchers demonstrated that by deploying maliciously modified firmware to a power management integrated circuit (PMIC), they could modify the output of the PMIC voltage. By shifting the operational voltage by only 0.1V, a critical reading error was induced in physical sensors connected to the PMIC and thus proved that maliciously modifying power sources can cause critical logic circuit failures in cyber-physical systems without overtly causing a voltage spike (Tsang et al., 2022).

4.2 TRITON/Trisis Malware: Industrial Sabotage

In 2017, it was made clear by the TRITON malware incident that state actors were willing to use malicious means to bypass physical safety controls. The TRITON malware was deployed to the petrochemical plant and targeted the SIS (Safety Instrumented System), which is an autonomous computer that initiates an emergency mechanical shutdown of the equipment in all situations that may compromise safety. Attackers inserted malicious binaries

into the controller's active memory to blind the safety system permanently, ultimately enabling the plant to build pressure to a critical state and cause a catastrophic explosion (Federal Bureau of Investigation / CISA, 2022). The TRITON malware showed that threat actors have demonstrated both the technical capability and moral will to bypass physical safety measures through manipulation of embedded firmware to create a catastrophic event.

4.3 The Jeep Cherokee Exploitation: Telematics and CAN Bus Weaponization

In 2015 the remote, zero-click hacking of a Jeep Cherokee by Charlie Miller and Chris Valasek highlighted the kinetic risk of an unauthenticated link to the vehicle. Exploiting a vulnerability of Uconnect, the vehicle's cellular connected infotainment (telematics cloud) system, they accessed the system, bypassed an internal gateway allowing them to upload an unsigned maliciously modified firmware image to the V850 microcontroller (boot/firmware validation failure). By doing so they were able to pivot to the vehicle's unencrypted Controller Area Network (CAN) and inject spoofed diagnostic frames that provided them with remote physical access to the vehicle's steering, cruising transmission, and braking systems at highway speeds (Miller & Valasek, 2015). Thus, Miller and Valasek have provided definitive evidence that a cloud to hardware infection chain can result in immediate lethal kinetics to civilians.

4.4 MadIoT: Cloud APIs and Scaled Grid Instability

Individual device manipulations are extremely dangerous, but malicious actors may exploit Cloud API capabilities to expand cyber-kinetic attacks to the infrastructure level. Princeton research in 2018 introduced "MadIoT" (Manipulation of Demand via IoT) solutions for how an attacker could weaponize a vulnerable cloud back end that provided insufficient controls over API utilization and create regional power grid destabilization. Using a large fleet of vulnerable high-wattage consumer IoT devices (e.g. smart HVAC systems, EV chargers, home battery storage) as a compromised coordination of synchronized botnets, an attacker could execute a simultaneous command issued through cloud API to turn on or off all of the high-demand regulators, creating artificially induced massive frequency instabilities and line failures (Soltan et al., 2018). The research demonstrated that without co-engineering functional safety and cybersecurity, the aggregate of vulnerable internet-connected power modules could be aggregated into a weapon of mass disruption that has the potential to trigger widespread blackout events.

5. Anticipatory Ethics

Anticipatory Ethics is a future oriented ethical framework that studies potential ethical issues that arise from new and emerging technologies before they are fully integrated into society. As defined by Phillip Brey, Anticipatory Technology Ethics (ATE) requires that we move beyond reactive judgements about the effects of technologies after an event has occurred to a proactive forecasting of the dangers that these technologies pose. In order to properly address the integration of kinetic cyber threats into basic infrastructures, including individual vehicles and a macro-level power grid, a reactive approach is inadequate. The prompt installation of non-transparent power systems and unsecured communication systems requires proactive use of Anticipatory Ethics (Brey, 2012).

5.1 The Anticipatory Technology Ethics Framework

The Anticipatory Technology Ethics (ATE) framework provides a clearly structured way of analyzing technology's ethical impacts at the research and development (R&D) stages. It provides a method by which to examine and try to predict and mitigate any potential impacts on society by performing an ethical analysis of technology across three levels: Technology Level (the inherent properties of the technology), Artifact Level (the specific artifact that incorporates the technology, e.g., EV Battery Management System), and Application Level (the overall impact of that technology as it relates to scaling its application in broader society, e.g., aggregate grid load) (Brey, 2012). The ATE framework forces engineers and policy makers to formally acknowledge both the positive and negative uses of their designs from the very beginning. If engineers applied the ATE framework to their design of cloud APIs and CAN Buses prior to development, they could have anticipated the vulnerabilities of both the Jeep Cherokee and the MadIoT case studies and architecturally designed them out prior to putting civilian populations at risk (Miller and Valasek, 2015; Soltan, et al., 2018).

5.2 Ethical Analysis of BootROM in Cyberwarfare

Examining the foundational hardware under the lens of an ATE Framework reveals a massive unresolved ethical issue at the Base Layer, specifically about how BootROM Code (the first executed piece of code after the processor receives power from the device) is used in state-affiliated cyber warfare by the armed forces to engage in boot-level attacks. Unlike conventional applications, BootROM code is built to be unchangeable in nature —

it is truly embedded into the silicon of the microprocessor during production and can only be modified through physical means by either the end-user, the hardware manufacturer, or the operating system. It is the ultimate "Hardware Root of Trust" for confirming the integrity of digital signed images of Boot Loaders and the Operating Systems that run software on the device.

The use of BootROM, from the ATE point of view, is ethical because it is a permanent piece of hardware. Nation-state actors or intelligence agencies who find a vulnerability (or require it when they are put on the BootROM) can use it, as well as exploit that vulnerability, as a permanent, unpatchable way to access the processor associated with the BootROM. In a cyberwarfare scenario, gaining access to the BootROM allows the attacker access to the device at a level deeper than the safety measures in place for that device. An attacker able to exploit the BootROM may also be able to intercept the boot chain process, install signatureless malicious firmware (as seen in an exploited Jeep), and can run information from a BMS program (Battery Management System), causing the BMS program to induce an overheat condition, while sending false telemetry data back to the user and to the cloud API. Finally, compromising the BootROM will ensure that any infected device, powered by the same power sources as regular devices, utilized within a large-scale IoT botnet (as modelled in MadIoT) cannot be sanitized through a factory restore or receive standard over-the-air patches, creating an everlasting grid instability-based weapon embedded in a person's home.

From an ethical perspective, a nation state carrying out cyberwarfare through the use of BootROM exploits is in serious violation of the principle of proportionate use of force and that innocent people must not be harmed by the military use of these types of exploits. The code that is used in BootROMs is the same for all chipsets, so when a state actor uses an exploit against a military adversary, the state actor is also going to use it against civilians who are using the same type of equipment. Therefore, when state actors hoard BootROM vulnerabilities, rather than disclosing those vulnerabilities to the hardware manufacturers for future silicon revisions, they are ethically compromising the core safety of global civilian infrastructure by effectively turning consumer electronics into unpatchable munitions.

6. Recommendations

The cyber threats posed by kinetic warfare through power management manipulation and exploited IoT will require the industry to shift to verifiable architectural enforcement from the current reactive software patching model. This will involve multiple approaches involving trust in the hardware, engineering paradigms, communication protocols and supply chain integrity.

6.1 Hardware-Level Cryptographic Trust

All manufacturers must be legally obligated to establish strict, immutable hardware roots of trust. Furthermore, BootROM code must undergo extensive third-party auditing on a continuous basis before it is manufactured into silicon; this will prevent the creation of a sufficient number of unknown, state-sponsored backdoors that cannot be patched. In addition, all firmware updates should require cryptographic signature validation that is hardware-enforced to block the injection of malicious payloads. Products should be developed so that when a cryptographic signature cannot authenticate any portion of the boot sequence, the Battery Management System goes into a secure, physically separated state and prevents thermal runaway; instead of continuing to run in an operationally insecure state.

6.2 Unified Safety-Security Engineering

The automotive industry and the IoT space need to move away from siloed thinking that treats ISO 26262 (functional safety) and ISO/SAE 21434 (cybersecurity) as separate compliance checklists (Bastos et al., 2025). The industry needs an integrated Cybersecurity Management System. This integrated approach will ensure that threat models consider the kinetic outcomes of both intentional BMS manipulation and aggregated cloud API abuse. Engineering teams must perform joint Threat Analysis and Risk Assessments where cybersecurity engineers will be required to demonstrate through legal documentation that a digital attack cannot physically disable the safety cut-offs created by functional safety engineers.

6.3 API and In-Vehicle Network Authentication

Electric vehicle and energy storage systems' communications interfaces should have strict regulatory compliance. Therefore, all messages sent across the internal CAN bus (the communication interface) of electric vehicles and energy storage batteries should be cost effectively authenticated with the use of strong cryptography to protect against spoofing of diagnostic frames (Miller & Valasek, 2015). Because of the trust-based nature of the legacy CAN bus, manufacturers must logically and physically separate their CAN networks

(creating isolation within the communications network) from their electric vehicles' telematics and infotainment units (which communicate with the internet) and the microcontrollers that help regulate battery power. In addition to the above separation of the networks, strict multi-factor/threshold authentication and anomaly detection/rate limiting need to be enforced for all Cloud APIs communicating with the physical power controllers to eliminate the risk of synchronized Botnet attacks on the power grid (Soltan et al., 2018).

6.4 Supply Chain Verification and Liability

Overall, the international regulatory framework must address the global hardware supply chain's lack of full transparency. Governments must enforce strict liability on manufacturers that include unverified and/or insecure third-party libraries into the critical power management firmware. A Software Bill of Materials (SBOM) and a Hardware Bill of Materials (HBOM) must be required on any device capable of storing or routing lethal amounts of kinetic energy. This will enable security researchers and grid operators to quickly identify, audit and isolate vulnerabilities prior to being weaponized at the national level through forcing manufacturers to list with full transparency all the materials and open-source software libraries used in their devices.

7. Future Work

The rapidly increasing global move to electric power for transport and the creation of large-scale battery systems will greatly expand the potential for hackers to obtain access. A key area of future research, both by academia and industry, must focus on the development of embedded AI (Artificial Intelligence) and ML (Machine Learning) that uses the CAN bus to create real-time anomaly based intrusion detection systems (IDS) that can detect and mathematically eliminate fake diagnostic frames before they can be accepted by the BMS (Battery Management System). Similarly, continuing to conduct extensive R&D (Research & Development) into grid level defensive orchestration that can automatically detect and mitigate synchronized power drops by large IoT botnets will be of the utmost urgency. Lastly, ongoing academic investigation into the complicated challenge of integrating post-quantum cryptography into BootROMs and legacy PMICs (Power Management Integrated Circuits) will be essential to prevent advanced threat actors from implementing "harvest now, decrypt later" plans against the new smart grids and energy systems being enabled by clean energy.

8. Conclusion

With the growth of IoT technologies and their connectivity, the traditional focus of cybersecurity regarding data privacy needs to shift to a proactive approach to prevent loss, economic damage, or catastrophic physical harm from kinetic attacks. The potential of commercial Battery Management Systems (BMS) to launch kinetic attacks by taking advantage of archaic vulnerabilities in commercially available electronic components illustrates the limitations of modern physical infrastructure. Exploiting supply chain gaps (e.g., unverified CAN bus communications), API/Cloud-based communication vulnerabilities, and long boot sequences, attackers can bypass the inherent safety limit cuts on all types of inventory and products to cause thermal runaway, creating widespread use of consumer goods as means of creating exploding fires. As seen in recent cases where telematics and cloud systems have functioned as weapons, these exploits can quickly move beyond individual vehicles being hijacked to precipitating mass blackouts within entire regions.

We need to change many things we think about governing technology. We must close the gaps between functional safety and cybersecurity for good. Firmware vulnerabilities that affect power systems need to be classified not only as software bugs but also as critical public safety issues. An anticipatory ethical assessment on the foundational hardware called immutable BootROM code demonstrates that the accumulation of unpatchable silicon vulnerabilities for cyberwarfare by nation-states creates an unacceptable risk to the lives of civilians. BootROM vulnerabilities allow nation-states to bypass high-level software defenses and ultimately compromise the hardware root of trust so the continued use of BootROM exploits by nation-states creates sustained dual-use weaponry out of civilian devices. Until the enactment of strong legally enforced hardware-based cryptographic trust and unified safety-security frameworks, the interconnected infrastructure of the digital age remains an unconstrained and kinetic threat to international cyber security and stability.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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The Military Tech Complex and Cyberwarfare: Ethical and Anticipated Ethical Issues

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Abstract: In this analysis we examine how the military-industrial complex has now been expanded into the digital realm, forming what's often called the *military-digital complex* (MDC). The ecosystem of MDC links defense contractors, governments, and Big Tech companies to the development and deployment of cyberwarfare capabilities. The capabilities of the MDC are of information technology weapons that are of both an offensive and defensive nature. How does the Military Tech Complex Connect to Cyberwarfare? The development of the MDC has led to the Militarization of cyberspace. Governments and militaries treat cyberspace as a battlefield. The U.S. created *Cyber Command* to oversee offensive and defensive cyber operations, including hacking, digital espionage, and electronic warfare. Partnerships with Big Tech Companies like Microsoft, Google, Amazon, and Apple provide cloud infrastructure, AI tools, and cybersecurity expertise. These partnerships blur the line between civilian use of technology and military applications. Defense contractors and startups Traditional defense firms (Lockheed Martin, Raytheon) now invest heavily in cyber tools, while Silicon Valley startups receive Pentagon funding to innovate in specific areas like AI-driven cyber defense. When the intentions of rational agents within government and corporations are connected to duties, conflicts arise with government having duties to civilians and corporates having duties to investors. This conflict of duties is what is focused on in our discussion which relates to how intentions and duties are linked in deontological ethics. This analysis begins by examining technical issues including the Cloud as a Battlefield, the "Kill Chain" and Algorithmic Warfare and The Zero-Day Economy and VEP. The analysis continues with a discussion of ethical issues related to The Principle of Distinction (Just War Theory), The troublesome Incentive of the "Cyber-Industrial Complex," and Accountability and Epistemic Opacity. Three case studies are then presented that give examples of the technical and ethical issues presented in the earlier parts of our analysis. This is followed by an anticipatory ethical of potential future developments and four recommendations are then made related to the concepts previously discussed and the case studies we have examined before we conclude we propose the following four reforms to help overcome how the MDC government and corporate partnerships act in collusion to intentionally blur the line between civilian use of technology. This original research and analysis is concerned with how Big Tech companies profit from cyber warfare contracts and how nation-states weaponize AI in cyber conflicts and finally with the ethical and anticipated ethical issues that arise because of these developments.

Keywords: Military-digital complex, Cyber warfare, Project Maven, JEDI/JWCC, NSO Group, Zero-Day Exploits, Anticipatory Ethics, Sociotechnical imperative, Dual-use technology, Vulnerability equities process

1. Introduction

At the end of his presidency, in 1961, President Dwight D. Eisenhower gave his final address to the nation. Within his final address Eisenhower issued a prescient warning: "In the councils of government, we must guard against the acquisition of unwarranted influence, whether sought or unsought, by the military-industrial complex" (Eisenhower, 1961). Eisenhower was worried that the nation, due to the power of democratic representatives being eroded by their debts owed to the companies that funded their campaigns. Eisenhower was more specifically talking about military contractors. Sixty-five years later, the military-industrial complex has further evolved into the military digital complex. The focus of the defense industry is no longer confined to just manufacturing steel and ballistics; it has transformed into developing code and synthesizing data. This is the basis of the Military-Digital Complex (MDC).

The MDC can be described as the symbiotic relationship between national defense agencies (the Pentagon and US Cyber Command), and traditional defense contractors (Northrop Grumman, Lockheed Martin), and "Big Tech" companies (Google, Microsoft, Amazon, Oracle). During the cold war, the government was the primary innovator, DARPA created the internet and (ARPANET) and GPS. That dynamic has changed in the era of information. The private sector is innovating at a speed which the government could never keep up with. The military is now reliant on "Commercial Off-The-Shelf" (COTS) technology to operate and conduct warfare (O'Mara, 2019).

This shift to the MDC with it dangerous and unignorable implications. American tech companies develop their products on commercial infrastructure, the same infrastructure that previously was used for streaming, now

hosts the command-and-control systems for drone warfare. Similarly operating systems that are used in hospitals now also power missile defense technologies. This paper argues that integrating Big Tech into the military "kill chain" fundamentally blurs the formerly clear distinction between civilian and combat infrastructures. This integrates a convergence of technologies into what is known as a "hyperscale" vulnerability, which violates the Sociotechnical Imperative and Just War Theory principles. We claim that economic incentives of the MDC create a perpetual loop of cyber insecurity, where the private sector profits from both the development of weapons systems, and the development of systems that defend against those same weapons.

2. Technical Issues

The development of the MDC creates a multitude of ethical risks, but to understand ethical risks, the technical structure of the MDC and the issues related to its architecture must first be understood. Three distinct technologies that are employed by designers as central to the development of MDC are: Cloud Computing, Algorithmic Warfare (AI), and the Zero-Day Exploit market. We assume Bratman's BDI (belief-desire-intention) model as providing a framework for identifying the beliefs-desires-intentions of designers of technology.

2.1 The Cloud as a Battlefield (JEDI & JWCC)

As of 2022, the US military was only processing 2% of the data it acquired (Aranke, 2022), the modern military needs the capability of processing exabytes of data in real time. To meet this requirement, the United States Department of Defense (DoD) intentionally initiated the Joint Enterprise Defense Infrastructure (JEDI), which became the Joint Warfighting Cloud Capability (JWCC) (D3V Tech, 2020; FedBiz Access, 2020). The JWCC is a multi-billion dollar project to move the DoD's computing and data storage infrastructure from closed and secure servers that exist in the premises to commercial cloud computing servers that are provided by companies like Amazon Web Services (AWS), Google Cloud, Microsoft Azure, and Oracle (Oracle, n.d.). This consolidation in the cloud creates for adversaries a singular, centralized target. Aggregating military logic onto commercial platforms creates a potentially dangerous Single Point of Failure. If an adversarial state actor were to successfully disrupt AWS or Azure servers to hurt the US economy, they may also unintentionally or intentionally hurt the US militaries abilities to operate to its fullest extent. This is in effect like placing a military base in a residential neighborhood, aligning military targets with civilians (Conger & Sanger, 2019).

2.2 The "Kill Chain" and Algorithmic Warfare

The second technical issue created by the MDC is the automation of the "Kill Chain," which is the process of identifying a target and engaging it (EBSCO, 2024). The kill chain employs Computer Vision and Machine Learning (ML). Machine Learning is the focus of AI algorithms that are learned from training data and neural networks (IBM, n.d.) instead of being explicitly programmed. Computer Vision is a subset of AI that allows machines to process visual inputs like images and videos, it uses ML to help computers process meaningful information from visual data (IBM, n.d.). The old version of the kill chain operated with a "Human-in-the-loop" (where a human makes the final decision to fire), which is now shifting to a "Human-on-the-loop" (where a human supervises an autonomous system) (Scharre, 2018). These AI systems are opaque, which means that the system is intentionally designed to act with the systems operating as a so called "Black Box." The designers of neural networks are unable to explain why they identified a target; they merely identify one. These AI systems are also brittle, adversarial machine learning attacks would be able to fool these systems by visually crafting "noise" which leads to targeting errors (Pasquale, 2015).

2.3 The Zero-Day Economy and VEP

Software bugs form the third pillar of the intentional weaponizing these dual use systems. A "Zero-Day" is a software vulnerability that is unknown to the vendor or public. This is an issue because, normal bugs can be patched and the issues are solved, but zero-day vulnerabilities which have been identified, leave "zero days" for a fix to be made, so they can be used to hack any system running that software. These exploits lead to a gray market of sorts. Hackers find the exploits, and brokers (like Zerodium) sell them to governments for millions of dollars. The US government is intentionally stockpiling weapons for offensive use as opposed to reporting the bugs and having them patched (Perlroth, 2021). The U.S. governments protocol for this is called Vulnerability Equities Process (VEP). The VEP is how the government decides what vulnerabilities should be disclosed and what should be kept secret (White House, 2017). Critics of the VEP argue that it is biased towards "No-Bus" (Nobody but Us), which means the government intentionally leaves insecurities in civilian infrastructure so the NSA can use these vulnerabilities when necessary to hack adversaries (Caulfield, 2018).

What is common to these three technical issues is how in the MDC government and corporate partnerships act in collusion to intentionally blur the line between civilian use of technology and military applications.

3. Ethical Issues

The technical architecture of the MDC introduces several ethical issues, particularly regarding the laws of war and how they relate to corporate responsibility. To understand these ethical issues, we introduce distinctions developed by Furrow. As Furrow states, ethics is related to evaluating actions, and actions are performed by those capable of being moral agents. As Furrow says, “When we evaluate an action, we can focus on various dimensions of the action. We can evaluate the person who is acting, the intention or motive of the person acting, the nature of the act itself, or the consequences.” (Furrow, 2005) A moral agent can justify their intentions, actions and outcomes produced by actions by referring to ethical principles. The themes discussed below revolve around how in MDC the laws of war are related to corporate responsibility and how they are intentionally conjoined.

3.1 The Principle of Distinction (Just War Theory)

In the realm of International Humanitarian Law, the Principle of Distinction in just war theory is incredibly important, it mandates that belligerent nations in armed conflicts must distinguish between military and civilian targets, at all times, with no exceptions (ICRC, n.d.). The MDC intentionally designs and creates what is known as a “Dual-Use” infrastructure, systems or items are used by both the civilian population and the military. If Microsoft provides the “War Cloud,” military data stored in part of the Microsoft cloud, its data centers now become military assets. The ethical problem arises when those military assets are stored right next to civilian data such as when patient records belonging to a hospital and the financial data for the banking system are stored next to military data. In kinetic warfare, bombing a hospital is a war crime, but if the military is using that hospital for military operations, it loses its protected status. Since these same servers are being used for civilian infrastructure, the internet, as we know it, loses its protected status. The MDC makes it impossible to target the military without producing an outcome that causes "Cyber Collateral Damage" (Schmitt, 2017).

3.2 The Troublesome Incentive of the "Cyber-Industrial Complex"

Private and public companies are first and foremost concerned with maximizing shareholder value, which is a fiduciary responsibility companies have to their investors. For a weapons manufacturer, peace is never as profitable as war. Conflict between the government’s best interest and intentions and the defense contractor’s best interest lies exactly between these two arenas, peace and war. Defense contractors and cybersecurity firms profit from the insecurity created by global conflicts to create profit, they don’t intend to participate, they want to sell and profit from both offensive and defensive weapons. The more dangerous a digital cyber landscape is (ransomware, state-sponsored hacking), the more demand there is for their products (Singer & Brooking, 2018). This is the digital equivalent of the Cold War arms race. Tech companies intentionally sell the offensive cyber capabilities to governments in forms like zero-day exploits and then turn around and intentionally sell defensive capabilities like threat intelligence and patches to the victims of cyber-attacks. This effectively makes cyber warfare a commodity for these companies, and cyber conflict within the MTC incentivizes the continuation of cyber risks as opposed to their resolutions (Deibert, 2020).

3.3 Accountability and Epistemic Opacity

Normal military operations have a form of accountability that follows the chain-of-command model, where responsibility lays with the commanding officer, the person who gave the orders. This chain of command is impossible when algorithms driving these cyber operations are proprietary and owned by private companies. For example, if an AI falsely flags a civilian as an enemy combatant and then causes civilian casualties, accountability becomes obscured. Instead of a commanding officer being held responsible, the military can claim it was a glitch, the vendor can then claim that the software is a protected trade secret which avoids auditing, therefore no one can be held accountable. The epistemic opacity of AI is related to who should be held responsible for civilian casualties. This "Black Box" of AI argument prevents democratic oversight of lethal force (Pasquale, 2015).

What is common to these 3 ethical issues is how the MDC government and corporate partnerships act in collusion to intentionally blur the line between civilian use of technology and military applications. When intentions are connected to duties conflicts arise with government having duties to civilians and corporates having duties to investors.

4. Case Studies

The following case studies illustrate how due to ethical issues related to intentions, MTC and the MDC function in specific circumstances, and how the functions of these entities conflict with governmental issues such as national security and corporate issues related to profit.

4.1 Project Maven (2018)

In 2018 Google entered a contract with the pentagon called Project Maven. The idea behind Project Maven was to use Google's AI called TensorFlow to analyze drone footage with the intentional goal of improving their targeting. This decision resulted in the employees revolting. Over 4,000 of Google's employees signed a petition that stated, "Google should not be in the business of war." Google's motto at that time was "Don't be evil." The employees argued that performing this contract and integrating consumer AI into the militaries kill chain was a violation of Google's motto (Shane & Wakabayashi, 2018; Suchman et al., 2018). Google ultimately decided that they should not renew the contract. Google later went on to release "AI Principles" that intentionally left subtle loopholes for working with the military (IT Pro, 2018). This case is a demonstration of tech employees exercising "Moral Agency" (Ahlstrom-Vij, 2013). This would involve assessing the intentions, actions and outcomes related to a company's policies. Contrary to traditional defense company workers, tech employees see themselves as civilians working for the betterment of humanity, rather than working for the military part of the state. The eventual replacement of Google by the government with vendors like Amazon and Microsoft shows that MDC is resilient even when individual companies protest.

4.2 SolarWinds (2020)

Russian intelligence (SVR) compromised the software build system of SolarWinds, a private company that manages IT. What was supposed to be a routine surface update, became a major cyber security event when SolarWinds inadvertently installed a backdoor called SUNBURST. Both the U.S. government and the military relied on SolarWinds, and through this backdoor the hackers were able to gain access to the Pentagon, the Department of Homeland Security, and the Treasury (FireEye, 2020). This is a clear demonstration of how "Outsourcing Defense" can be a fragile exercise. The U.S. government's security was only as strong as that of a private companies update server. In the MDC, the Solar Winds case demonstrates that "Attack Surface" of the nation includes every private vendor in the supply chain that it relies on (Zetter, 2021). The goal must include closing loopholes in the attack surface of supply chain vendors.

4.3 NSO Group: Pegasus

The NSO group is a private Israeli firm, most notorious for developing Pegasus, which is a "zero-click" spyware capable of infecting iPhones without the user even touching the device. The NSO group acted as a digital black-market arms dealer, intentionally selling Pegasus to governments without concern for how Pegasus would be used. Later investigations revealed that countries like Saudi Arabia and Mexico used this software for more than counterterrorism purposes. Pegasus was used against human rights activists, journalists and political dissidents (Amnesty International, 2021; Council of Europe, 2021). This case demonstrates how the barrier of entry for cyber warfare has been lowered. In previous years, only powers like the US (NSA) or Russia (GRU) had that powerful of a tool. The MDC allowed for the sale of "NSA-level" technology to any regime willing to pay. This privatization of zero-day spyware intentionally bypassed the terms of traditional arms control treaties (Perlroth, 2021).

4.4 FoxBlade (2022)

In February of 2022, mere hours before Russian armor pushed into Ukraine, Russian cyber units deployed a piece of malware called FoxBlade (Redmond Mag, 2022) which was intended to destroy Ukrainian government networks. As soon as this occurred, the Microsoft Threat Intelligence Center (MSTIC) detected the anomaly and patched it. Microsoft is the main cloud source provider for the Ukrainia government (Microsoft then established a secure line to Kyiv to deploy the defenses they developed, which stopped what was in effect a cyber-invasion of Ukraine by Russia (Smith, 2022). What was essentially a cyber version of the iron dome, developed and deployed by a U.S. corporation, was unilaterally decided upon by Microsoft alone for intervening in a foreign war. While this was beneficial for Ukraine, it raises concerns of Digital Sovereignty. If Microsoft defends a nation involved in a war, could Microsoft then be interpreted as being a belligerent in that war? This signifies a shift of power from nation states to the "Techno-State" (Lucas, 2017).

What links the preceding case studies is the way in which governments and corporate entities have intentionally unified and become intertwined. Given the ways in which MDC works with Governments and corporate entities working together it is important see the future outcomes that can come about due to this intertwining.

5. Anticipatory Ethics

Anticipatory Ethics is a future oriented ethical framework that studies potential ethical issues that arise from new and emerging technologies before they are fully integrated into society. As defined by Phillip Brey, Anticipatory Technology Ethics (ATE) requires that we move beyond reactive judgements about the effects of technologies after an event has occurred to a proactive forecasting of the dangers that these technologies pose. This section analyzes the failure of corporations to apply basic Anticipatory Ethical principles to analyze to the Military Tech Complex and Cyberwarfare. Applying the "Moral Responsibility for Computing Artifacts" framework by Miller et al. (2011) allows us to foresee and map the ethical obligations of the MDC (Brey, 2012). The preceding cases show how technological developments with the MDC have led to a series of ethical issues.

5.1 Rule 1: The Foreseeability of Effect

Rule one of Moral Responsibility for Computing Artifacts states that "The people who design, develop, or deploy a computing artifact are morally responsible for that artifact, and for the foreseeable effects of that artifact" (Miller et al., 2011). It is foreseeable that the stockpiling of Zero-Day exploits (like the *EternalBlue* exploit kept by the NSA) can lead to zero-day exploits being stolen and weaponized against their civilian population. This is evident in the WannaCry ransomware attack (Cloudflare, n.d.). The government and their contractors did not consider the possible blowback of these being discovered. By prioritizing offensive capabilities over the defensive architecture of their nation, they bear the moral responsibility for any collateral damage caused by those tools leaking.

5.2 Rule 4: The Sociotechnical Imperative

Rule four says that the "People who design... can do so responsibly only when they make a reasonable effort to take into account the sociotechnical systems in which the artifact is embedded" (Miller et al., 2011). AI tools that have been developed by big corporations were designed for an environment of commercial use, they prioritize efficiency, ad targeting and logistics. When these tools are embedded into the military sociotechnical system of kinetic warfare without redesigning the underlying technology, it violates the sociotechnical imperative. Consumer-grade code is not nearly up to military standards, so using it for nuclear command and control could have devastating consequences, including enemies gaining access to the second largest nuclear arsenal in the world. Tech corporations that fail to rework their software from the security required for civilian use, to the level of security required for military use put the entire internet ecosystem at risk.

5.3 Rule 2 and 3: The Issue of Epistemic Paternalism

The rise of the MDC has introduced a new dilemma about who controls the battlefield, is it the state? Or is it the software designer? This conflict should be analyzed through Rule two and three of the "Moral Responsibility for Computing Artifacts" framework. Rule 2 states that "The people who design, develop, or deploy a computing artifact are morally responsible for that artifact, and for the foreseeable effects of that artifact... This responsibility includes being answerable for the behaviors of the artifact." (Miller et al., 2011). Private companies like Microsoft and SpaceX have deployed technological artifacts like cloud infrastructure and satellite internet that are now widely used and relied upon for modern warfare. Adhering to rule 2, these companies cannot claim to be neutral parties. When Microsoft detected FoxBlade infecting Ukrainian networks, their decision to intervene was them exercising moral responsibility over their artifact and subsequently siding with Ukraine. This creates an issue involving Epistemic Paternalism, where a private company decides which nation's cyber systems are worthy of being defended by an intervention. By accepting the JWCC contract, big tech corporations have effectively become a geopolitical player. Geopolitical players in the western world typically require a democratic mandate, tech companies do not have one. The responsibility for your technological artifact does not stop at moral responsibility, but also carries the responsibility defined by Rule 3: "The people who design... computing artifacts have a moral responsibility to retract or recall those artifacts if they are found to cause harm that cannot be mitigated." Rule 3 is directly applicable to the NSO Group. It became clear after some time that the Pegasus spyware was being used to target journalists and activists, who are typically protected as civilians, which is a completely foreseeable effect of selling cutting edge spyware to authoritarian regimes. The NSO group under Rule 3 had a moral duty to recall the weapon. Recalling a software weapon can be done through revoking the user's license. They failed to do this and subsequently relinquished moral responsibility by claiming "client

sovereignty," which is a direct violation of the principles of Anticipatory Ethics as stated above. The NSO Group refused to acknowledge that they still bore moral responsibility after the deployment of their artifact.

What links the preceding the concepts in the cases analyzed above is the way in which governments and corporate entities have intentionally unified and become intertwined. Given the ways in which MDC works with governments and corporate entities working together it is important to examine the potential future outcomes that can come about due to this intertwining.

6. Recommendations

An analysis of the preceding 4 cases and the ethical problems arising from them culminating in an anticipatory ethical analysis of the MDC reveals an ecosystem where the economic incentives favor cyber insecurity and technical architectures that favor obscurity, while also not allowing for proper accountability. Since we cannot revert to a pre-internet era, we must design a regulatory and technical framework that would reclaim the distinction between the civilian and military worlds. Based upon our ethical analysis we propose the following four reforms to help overcome how the MDC government and corporate partnerships act in collusion to intentionally blur the line between civilian use of technology.

6.1 Sovereign Cloud

To restore the principle of distinction (between military and civilian actors), the mixed-use infrastructure that is created by the JWCC and JEDI, which allows military data to reside in the same logical regions as civilian commercial data, must be reworked. The principle of distinction would require the Department of Defense to enforce a "Sovereign Cloud" mandate. This requires a physical and logical air gap between military and civilian digital infrastructure. Cloud providers currently offer "GovCloud" regions, which technically are logically separated, but they often share the same hardware resources such as power and backbone fiber. The Sovereign cloud would require Hardware Isolation and Spectrum Separation. Hardware Isolation would be the act of making military data centers physically distinct from civilian ones. They must use different power grids and cooling systems to ensure that a kinetic or cyber-attack on the military servers would not cause cascading failures that extend to the civilian domain. Current military communications use the same 5G and satellite networks that the commercial network does, this is where Spectrum Separation comes into play. This mandate would require that dedicated, encrypted military spectrums be created and separate from consumer-grade routing protocols like BGP which are notoriously vulnerable to hacks. This recommendation restores the Principle of Distinction. The segregation of military and civilian infrastructure reduces the risk of collateral damage. If a belligerent nation e.g. attacks a US military server, it should not degrade the ability of hospitals accessing patient records from the same provider (Schmitt, 2017).

6.2 Reforming the Vulnerability Equities Process (VEP)

The current Vulnerability Equities Process (VEP) creates a moral hazard because of governments stockpiling Zero-Day exploits for offensive operations, which potentially leaves their own civilian infrastructure vulnerable. We propose a move from "No-Bus" (Nobody but Us) doctrine to one of defense primacy. This would legally require software vulnerabilities to be disclosed to the vendors within an absolute timeline. The first change would be a 90-day statute. This is modeled after Google's Project Zero disclosure policy; the US Cyber Command would be legally obliged to disclose and purchase or report found zero-day vulnerability to the relevant vendor within 90 days. This would allow for a small strategic window for high-value intelligence operations but would also prevent indefinite hoarding of exploits that can lead to global instability. The second implementation would be cyber market intervention. The government is currently distorting the market by paying high prices for exploits. This reform would reverse this tendency by redirecting those funds to pay bounties, this would grant researchers premium rates to patch bugs as opposed to exploiting them. This would create incentives for online mercenary blue teams as opposed to the current red teams (Caulfield, 2018). This applies Rule 1 of Anticipatory Ethics. It is foreseeable that stockpiled software can be leaked, by prioritizing patching over hoarding, the government fulfills its social contract to protect their citizens' digital infrastructure.

6.3 Algorithmic Accountability

The current proprietary nature of AI algorithms creates a "Black Box" where accountability is approaches impossibility. The DOD should reject the trade secret defense in the development of lethal autonomous weapons systems (LAWS). We propose a "Glass Box" Standard for all military AI contracts. There are three technical implementations that can solve this: Introspection API's, Model Cards and Provenance, and Adversarial testing. Introspection APIs (Application Programming Interfaces) would be applied to all AI models deployed in combat

zones. These would simply allow independent military auditors to query the model and understand why it made a classification decision (e.g., why is this classified as a tank and not a car). Borrowing from Google's ethical AI research, every military algorithm must have a "Model Card" that details the training data, biases, and limitations of its model. Cryptographic Provenance must also be used to sign the code, ensuring no supply chain attacks like SolarWinds have altered algorithms before deployment on the battlefield. Finally, adversarial testing would require that before deployment, algorithms must undergo a "Red Teaming" process to probe for vulnerabilities against adversarial examples (e.g., placing a sticker on a stop sign to fool a computer vision system). These technical implementations would address the issues of Epistemic Opacity and uphold the Sociotechnical Imperative. By requiring explainability, it is ensured that the "Human-on-the-loop" has meaningful control over the AI system. Without this, the humans are simply those who "rubber stamp" a machines decision, which removes their moral agency (Pasquale, 2015; Miller et al., 2011).

6.4 Digital Geneva Convention and Attribution Council

Cyberwarfare is currently defined ambiguously in the eyes of international law. In 2017 Microsoft proposed to the international community the establishment of a Digital Geneva Convention. Unfortunately, such a treaty is useless without enforcement. Therefore, we propose the creation of an International Cyber Attribution Council (ICAC). The convention needs to explicitly define the internet's backbone neutral territory. This neutral territory would include DNS Root Servers, SWIFT financial clearinghouses, electoral systems, and healthcare networks. Attacks on these systems would be war crimes regardless of intent. The ICAC serves as a replacement for biased attributors which originate from intelligence agencies like NSA or GCHQ that carry a bias towards their government, or private companies like Microsoft and Mandiant which are profit driven. The ICAC would be impartial and independent modeled after the International Atomic Energy Agency (IAEA), which is comprised of technical experts from neutral party nations. Their sole purpose would be to investigate and publicly attribute attacks to groups or nations supported by verifiable evidence (Taddeo & Floridi, 2018).

7. Conclusion

Future work should include and expansion of this analysis to cover the domain of "Hyper-War" and "Agentic AI." These factors will contribute to a domain where speed of conflict may require removing human oversight entirely, which raises questions about the morality of the math in the algorithms (Scharre, 2018). Additionally, research is needed into the privatization of space involving corporations like Starlink and how the neutrality of corporations interacts with state sovereignty during kinetic conflicts (Mac & Chang, 2023). The transformation of the Military-Industrial Complex into what has become the Military-Digital Complex (MDC) represents a shift in how to enact national security. The combination of Silicon Valley's speed and innovation with the lethality and resources of the Pentagon, means the United States has created the most powerful war machine to ever exist. This merger has come about with a high ethical price tag. It has eliminated the principle of distinction by creating a "Dual-Use" infrastructure where hospitals and missile systems use the same cloud. It has incentivized the stockpiling of software vulnerabilities instead of patching them. And it has introduced Epistemic Paternalism, where shareholders, not elected officials, determine the rules of engagement. This paper argues that these consequences are not unavoidable, they are not guaranteed by technical progress but are choices have been made by prioritizing efficiency over ethics. The reliance on software stockpiles and obscure algorithms has created a fragile environment where the tools of war are a few lines of malware away from being used for common cyber-crime. To correct the current course, we must reject the normalization of the MDC's current architecture. We need to implement a "Sovereign Cloud" that respect civilian-military boundaries. We must have a "Defense Primacy" mindset that prioritizes patches holes over exploiting vulnerabilities in software. And we must require a "Glass Box" accountability for the algorithms to which we delegate lethal force. A nation's defense must not come at the cost of the internet's integrity. We must construct a firewall between the civilian and military digital targets and ensure that the digital future is defined by a resilience of our shared sociotechnical systems, and not the cyber forever war. By implementing these recommendations, we can begin to alter and overcome the atmosphere the MDC creates where government and corporate partnerships act in collusion to intentionally blur the line between military and civilian uses of technology.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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Trustworthy Secure and Measured Boot on a Raspberry Pi 4

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Abstract: The Raspberry Pi is a widely used platform deployed across numerous domains, including Industry 4.0 environments. This places requirements on hardware and software in terms of IT and OT security. The whole platform has to be secured in a way that integrity and trustworthiness can be guaranteed – even when it is deployed in uncontrolled environments and operating outside the manufacturer's physical control. Currently, that often is not the case and basic Trusted Computing concepts are not implemented in Raspberry Pi-based platforms. The presented approach enables entities such as SIEM systems and backend services to make use of the established Trusted Computing mechanism Remote Attestation to verify the integrity of a Raspberry Pi 4 and its software. Remote Attestation, in turn, depends on Measured Boot to record integrity measurements (hash values) of each boot stage into a TPM 2.0. However, the Raspberry Pi 4 official bootloader supports Secure Boot only. It neither provides Measured Boot functionality nor integrates with a TPM 2.0, preventing the establishment of a hardware-anchored measurement chain required for Remote Attestation. To address these limitations, this paper proposes a method that combines Secure Boot with Measured Boot to enable Remote Attestation on the Raspberry Pi 4. This combination establishes a complete Chain of Trust. While it comes with some shortfalls and cannot defend against sophisticated hardware-based attacks, it still results in a much higher security level for the Raspberry Pi. The proposed concept makes use of the official bootloader's Secure Boot to load a signed second stage custom bootloader image based on U-Boot. Following that, U-Boot acts as the Measurement Root of Trust and measures the subsequent boot stages into the PCRs of a TPM 2.0. Although the proposal builds upon existing technologies, their integration into the Raspberry Pi boot chain has not been available in this form. The security enhancements have a significant impact on many use cases involving Raspberry Pi-based hardware, including industrial devices. It is particularly worth considering if the hardware platform already integrates a TPM 2.0 chip.

Keywords: Raspberry Pi 4, TPM 2.0, Secure boot, Measured boot, Remote attestation, U-Boot

1. Problem and Motivation

As the Raspberry Pi (RPi) and its industrial variant named *Compute Module* are used by many devices in the Industry 4.0 context, it is important to ensure platform security, to which the proposed hybrid secure-measured-boot solution makes a significant contribution. The goal is to improve the security of the RPi platform, so that it becomes more resilient against tampering and can be used as a verifiable and trustworthy entity in a computer network.

Secure Boot and Measured Boot are crucial security features designed to protect computer systems from malware attacks and unauthorized modifications, particularly during the boot process. This provides a trustworthy foundation for applications running on such a protected system. Secure Boot ensures that only trusted and signed software is executed during boot-up, preventing malicious bootloaders or tampered operating systems from being run on the computer. This is especially important for combating persistent threats in which malware is injected into a platform, causing the system to always start in a compromised state. Meanwhile, Measured Boot measures each stage of the boot process to a Trusted Platform Module (TPM), enabling security features such as Remote Attestation. This enables other systems to remotely verify the integrity of a system.

Together, these features shift trust in the boot process lower down from the system firmware to specifically designed tamper-resistant hardware components such as TPMs, providing a significantly higher level of protection against tampering and malware attacks. By offering an additional layer of security through precise monitoring and verification of the entire boot process, Secure Boot and Measured Boot have become essential in maintaining the integrity and trustworthiness of modern computing systems.

A complete and continuous Chain of Trust (CoT) directly from the initialization of the device hardware for *Measured* Boot is not possible on the RPi 4, because the official but proprietary bootloader does not have TPM

driver support built-in, therefore it cannot measure the next boot stage and subsequently cannot extend those measurement values to the TPM registers. Furthermore, as the official bootloader is closed-source, there is no development access for the community to add such support as a third-party driver. However, the official bootloader supports *Secure* Boot, which can ensure on a hardware level that the subsequent stage of the boot process can only run code signed by a trusted party. It should be noted that the RPi 4 is the first generation to support Secure Boot, which means that the usage of Secure Boot is not possible on previous RPi generations. (Raspberry Pi Ltd, 2023b)

A logical solution to the problem of missing Measured Boot support on the RPi 4 platform is to combine the two boot features and start measuring as early in the boot process as possible.

2. Background

This section provides the necessary background to understand the technologies discussed in this paper and ensures that the terminology used is clear and precise.

2.1 Raspberry Pi

The RPi is a popular compact single board computer used for private or industrial use cases. In this paper, the term *RPi* specifically refers to the RPi 4 platform. There is also a Raspberry Pi 4 Compute Module variant intended for industrial applications, which serves as the basis for several industrial-grade products. While most of the configuration in the context of Secure Boot is the same, small details can vary.

2.1.1 OTP

One Time Programmable (OTP) memory is a region of memory with multiple so-called registers (zones of memory) that can only be programmed once. The cells are basically fuses that are burned for storing ones and zeros as data, which makes them single-time writable.

2.1.2 EEPROM

Electrically Erasable Programmable Read-Only Memory (EEPROM) is non-volatile memory that can be rewritten but is slow to write. It is commonly used to store small amounts of configuration data.

2.2 Trusted Computing

The term Trusted Computing (TC) is shaped by the Trusted Computing Group (TCG) and describes a variety of standards that bring trust and security into computing as well as networking. The trust can be established using a hardware-based Root-of-Trust (RoT). (Trusted Computing Group, 2025a)

2.2.1 Trust

Trust, in this context of the TCG, refers to a reliable assumption about how a system will act. It is specified that trust "is meant to convey an expectation of behavior." (Trusted Computing Group, 2025b) This means that trust is not blind confidence but a reasoned belief grounded in evidence. In Trusted Computing, such trust enables predictable interactions and forms the basis for assessing whether a system is operating as intended.

2.2.2 TPM 2.0

The TPM is a type of Hardware Security Module (HSM) widely used as a hardware trust anchor to protect systems against attackers. Its broad acceptance comes from its ability to ensure system integrity, protect sensitive data, and enable secure operations in both consumer and enterprise environments. The current version which is also used for this paper is named TPM 2.0. (Trusted Computing Group, 2017)

2.2.3 Remote attestation

Remote attestation allows a system to remotely detect the software status of another system in a network. Basically, it can verify the hash values of the software executed on a remote system, by using challenge response mechanisms to securely receive the trustworthy measurement hash values from the TPM of the remote system. By comparing those hashes with known good values, a system's state can remotely be classified as secure or potentially compromised.

2.2.4 Root of Trust

The RoT is a "component that performs one or more security-specific functions, such as measurement […]. It is trusted always to behave in the expected manner, because its misbehavior cannot be detected […]" (Trusted

Computing Group, 2017). To assure this, a RoT must be intrinsically secure, as it provides the secure starting point for securing everything loaded after it. Therefore, it must be assumed that the official bootloader provides this RoT, being the initial component loaded on the RPi platform.

The *Root of Trust for Measurement* (*RTM)* should be implemented as early as possible in the boot process of a system, as its task is to "bootstrap the process of building a measurement chain for subsequent attestation of other firmware and software that is executed on the computer system" (NIST - National institute of standards and technology, n.d.).

2.3 Bootloader

The bootloader is part of the firmware and is stored in non-volatile memory, such as Read Only Memory (ROM) or EEPROM. It initializes the hardware and loads the operating system. It typically includes hardware initialization, boot device selection and operating system loader execution. It initializes the system memory layout through the memory map management. In case of Unified Extensible Firmware Interface (UEFI) with Secure Boot enforcement, the bootloader verifies the cryptographic signatures of loaded components to prevent unauthorized code execution.

2.3.1 Official bootloader

When speaking of the "official bootloader", this paper specifically means the proprietary bootloader shipped with the RPi, which is developed by the Raspberry Pi Ltd.

2.3.2 U-Boot

Contrary to this, U-Boot is a widely used open-source bootloader, available for RPi among many other (mostly embedded) platforms, however it can only be used as a second-stage bootloader on the RPi, loaded by the official bootloader.

U-Boot can boot the next stage in two different modes: Legacy and UEFI. The "legacy" mode is the classic and more simplistic way to boot embedded devices. It is how almost all RPi 4 Linux distributions are booted.

However, there is also the option to use UEFI on U-Boot which means that U-Boot exposes a simplified UEFI API targeted for embedded devices to the next boot stage. This also gives the option to use Secure Boot as defined by the UEFI specification. (The U-Boot development community, n.d.)

2.3.3 Secure Boot

Secure Boot describes a concept where a platform only boots an image that is signed by a trusted party. The image is signed with a private key, while the corresponding public key is stored securely on the platform so that it cannot be changed by an untrusted party. If the signature of the boot image cannot be verified with the public key on the platform, the boot process will be terminated with an error message.

Although various terms exist for this concept, this paper makes use of the term *Secure Boot*, as it is most widely recognized for this technology, originating in the UEFI specification, and is now supported by nearly all modern personal computers and servers. For example, the RPi bootloader flag to activate Secure Boot is called *Signed Boot* (although the official documentation (Raspberry Pi Ltd, 2023a) also refers to the feature as *Secure Boot*). In the U-Boot bootloader, this concept is called *Verified Boot* (Raspberry Pi Ltd, 2023b).

2.3.4 Measured Boot

The term *Measured Boot* refers to the process of measuring the hash of the code and the configuration data for each subsequent boot stage in the boot process of a system. The hash is typically stored securely in an HSM such as the TPM. This information can e.g. be forwarded to servers to determine whether a computer is allowed to log into a network. This process is known as Remote Attestation. In summary, Measured Boot provides the technological basis for Remote Attestation.

Like Secure Boot, Measured Boot checks the integrity of the system by itself but will not block the boot process in case of unexpected measurement values. That would only be achieved by additionally using Secure Boot.

2.4 Related Work

While all the basic technologies utilized in this paper have been individually explored and implemented before, no prior work has integrated these features into a continuous CoT and demonstrated the feasibility of combining Secure Boot and Measured Boot on the RPi platform.

There is official documentation available from the Raspberry Pi Ltd about how boot security can be implemented on the RPi 4. This includes a whitepaper describing the technology involved in achieving a CoT (Raspberry Pi Ltd, 2023b) as well as a how-to guide for how to use Secure Boot on the RPi 4 (Raspberry Pi Ltd, 2023a).

Important work has been done by Johannes Holland, who shows in his GitHub repository (Johannes Holland, 2022) how to integrate and compile TPM 2.0 support into U-Boot on the RPi 4. This lays the foundation for enabling Measured Boot on the RPi 4, because TPM support is needed to securely store measurement values when loading the subsequent boot stages.

3. Use Cases

The reasons why Measured and Secure Boot on a RPi can be important are best explained by different use cases and why these features offer an advantage for them. It will also be discussed which requirements have to be fulfilled for satisfying these use cases.

3.1 Industrial Use

In the context of Industry 4.0 and Industrial Internet of Things (IIoT), IT networks and thus information security is more important than ever, due to measurement values and control commands being transferred remotely. When these get compromised, this can lead to expensive damage of industrial equipment such as production machinery, possibly stopping production completely or even lead to human injuries. With Measured and Secure Boot, the attack surface can be significantly reduced.

Industrial-grade hardware based on the RPi Compute Module is available, such as the KUNBUS Revolution Pi 4 (KUNBUS GmbH, 2025). The device adapts the Raspberry Pi platform for use in industrial environments and includes an on-board TPM 2.0 which is needed for Measured Boot. Another example for such hardware is the Seeedstudio EdgeBox RPi 200 which is marketed as an *IoT Edge Device* or *Industrial Edge Controller*; however, it does not include a TPM 2.0 (Seeed Technology Co.,Ltd., 2025).

Requirements for industrial use cases are mainly reliability. A system must not shut down due to false positives; its behaviour should be deterministic. Also, performance should not be significantly impacted by security measures, especially not in terms of application software or data transfer. A longer time to boot a system can be acceptable, though.

3.2 Personal Use

The RPi is a commonly used component in DIY projects for smart home, home server and Home Theatre PC (HTPC) setups. Of course, such a central component in a home network has to be trustworthy. Not only can it possibly control devices such as smart door locks, it is also within the boundaries of the user's LAN, behind the firewall of the router. So, if the RPi was compromised, an attacker could use it to access the user's home network and perform Man-in-the-Middle (MitM) attacks to capture login credentials via DNS spoofing, phishing, and similar techniques. Measured and Secure Boot can help mitigate these attacks and make them harder to execute.

4. Threat Model

A threat model is defined to understand possible attack vectors. In the evaluation, it will be examined how well the implemented concept works to mitigate these threats. It is assumed that an attacker possesses the capabilities of the Dolev-Yao adversary, i.e., full control over network communication, including intercepting, modifying, replaying, and delaying messages. While the original Dolev-Yao model focuses on network-level attacks, this work adopts the model for a stronger hardware focus: the attacker can attempt to replace or roll back software and firmware on a device, both at rest and during updates. However, the attacker cannot break standard cryptography or the TPM's protection mechanisms.

4.1 Assets and Trust Anchors

The relevant entities involved in the boot process can be categorized as assets and trust anchors, which have to be analyzed:

- Assets: Second-stage bootloader (U-Boot), U-Boot environment, initramfs, Device Tree Binary (DTB)/overlays, Linux kernel, TPM PCRs and event log (for Linux Integrity Measurement Architecture (IMA)), attestation results.

- Trust anchors: System on Chip (SoC) boot ROM and the official RPi bootloader (EEPROM), OTP-fused hash of the customer public key, TPM 2.0 (including its Platform Configuration Registers (PCRs)), and standard cryptographic primitives.

4.2 Capabilities

This section outlines the main attack vectors as well as assumed capabilities of the attacker:

- Network: Full MITM on all channels; can replay quotes/logs, but cannot forge TPM quotes or signatures.
- Local software: Gains OS-level control (e.g. root), can modify /boot contents, U-Boot environment, initramfs, DTB, Linux kernel, but cannot alter OTP or the official bootloader.
- Physical hardware: brief hands-on access (swap SD card / eMMC, attach to USB/UART ports); no MITM attacks on the RPi bus system, e.g. no interception of messages between software and TPM on the SPI bus. No invasive chip attacks (no decap, microprobing, fault injection).

4.3 Security Goals

This section outlines the security objectives that the provisions in this paper are intended to achieve:

- Prevent execution of unauthorized second-stage bootloaders.
- Produce verifiable measurements for initramfs, DTB/overlays, Linux kernel and other relevant configuration to enable remote attestation.
- Detect (and optionally prevent) rollback to older, vulnerable components.
- Optionally enforce integrity of OS (U-Boot Verified Boot).
- Optionally bind secrets (e.g. LUKS keys) to expected PCR values.
- Optionally measure integrity of OS user-space via Linux IMA.

4.4 Out of Scope

- Invasive physical attacks against OTP/EEPROM/TPM (e.g. decapping, microprobing, fault injection).
- Hardware-based MITM attacks on RPis bus system, e.g., no interception of messages between software and TPM on the SPI bus
- Compromise of vendor signing keys for the official bootloader.
- Runtime attacks: Exploitation of application-layer vulnerabilities beyond Secure Boot and Measured Boot.

5. Concept

As described earlier, the RTM has to be placed as early in the boot process as possible. On the RPi, the earliest stage where this can be implemented is U-Boot, which is loaded directly after the official bootloader. Thus, it can be assumed that U-Boot acts as the RTM, while the TPM provides a secure and shielded location for storing the measurement values. Ideally, the official bootloader would serve as the RTM, as it is placed earlier in the boot process. However, implementing custom features in this proprietary software is not feasible.

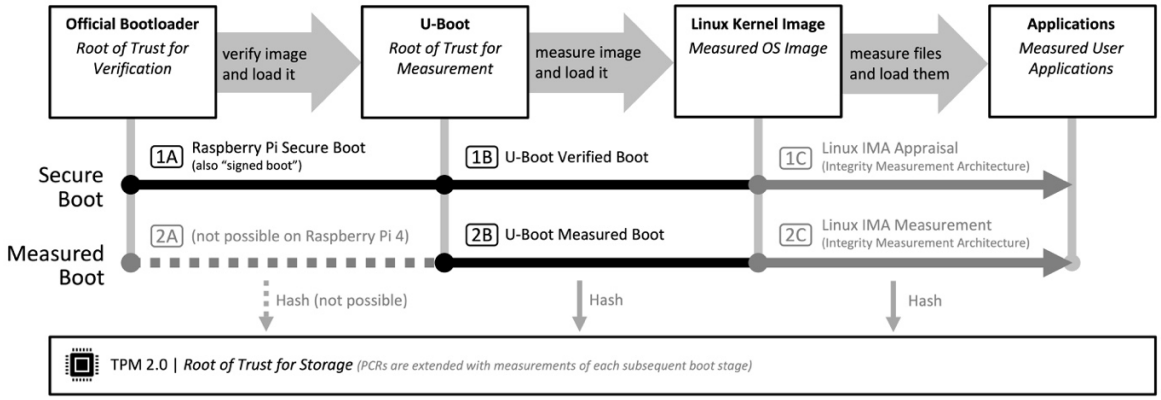


Figure 1: Chain of Trust for the Secure and Measured Boot process on the Raspberry Pi 4

The complete CoT is shown in Figure 1. The boot chain begins with the official bootloader which acts as a root of trust for the system and uses Secure Boot to securely load the signed U-Boot bootloader image.

Subsequently, U-Boot measures the Linux kernel image and other necessary boot data like the DTB and initial ramdisk and extends the measurement values to the TPM 2.0 PCRs as shown in Table 1. Now, U-Boot loads them into the RAM and runs the Linux kernel.

Table 1: Intended use of PCR banks according to the TCG TPM 2.0 Mobile Common Profile (Trusted Computing Group, 2015) compared to the real use by U-Boot legacy Measured Boot mode

PCR	TCG TPM 2.0 Mobile Common Profile	U-Boot (Legacy Mode)
0	Platform firmware code integrated into system board or SoC	U-Boot version string
1	Platform firmware data associated with code measured in PCR0	DTB and environment variables
2	Platform firmware code (including drivers) added by VARs	not in use
3	Platform firmware data associated with code measured in PCR2	not in use
4	Pre-OS diagnostics and OS loader code	not in use
5	Pre-OS diagnostics and OS loader data associated with code measured into PCR4	not in use
6	Platform-specific OS and Secure Boot code	not in use
7	Platform-specific Secure Boot policy data associated with code measured in PCR6	not in use
8	n/a	OS kernel image
9	n/a	initrd (initial ramdisk)
10	n/a	Linux IMA (not implemented here)

Optionally, Secure Boot can also be enabled for this stage, so that only a correctly signed image would be loaded. In the next step, the Linux kernel will load the user space and it is conceivable to use the Linux IMA mechanisms to measure the accessed data. However, the implementation of Linux IMA was not in the scope of this paper.

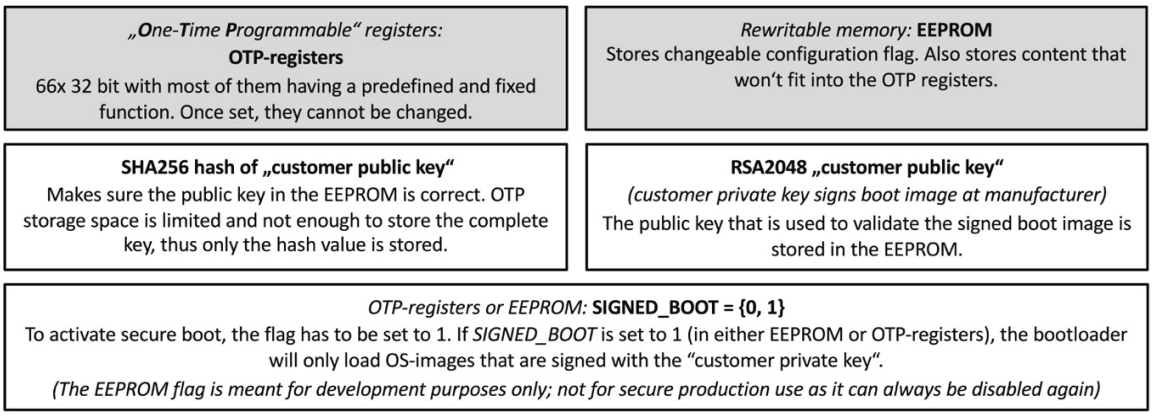


Figure 2: Data stored in OTP registers and EEPROM for Secure Boot on the RPi 4

To save the configuration data and cryptographic keys needed to implement Secure Boot, the RPi 4 uses OTP memory and EEPROM storage. The allocation of the OTP registers is shown in Figure 2. A Secure Boot implementation purely using EEPROM is possible for testing purposes, so that no permanent changes to the platform are persisted. For secure productive use, the OTP registers must be used. Changing the OTP registers is permanent by definition and cannot be undone, which is a security feature by itself. Secure Boot on the RPi 4 requires at least bootloader EEPROM version 2022-01-06. As soon as the SIGNED_BOOT flag in the OTP-registers is set to 1, only bootloader versions that support Secure Boot can be installed, to prevent circumventing the mechanism by simply installing an older bootloader without Secure Boot support. The public key for the signed boot image is stored in the EEPROM and its integrity is confirmed by a hash of it written into the OTP registers. This is done to save storage space in the relatively small OTP memory.

6. Evaluation

The proposed implementation brings a lot of advances in security for the RPi, but it still has some shortcomings that the user has to be aware of.

6.1 Considerations

When using the described mechanisms to secure a RPi, one should consider that there are multiple parties that they need to trust or else the whole boot process would not be trustworthy. It is crucial to recognize the need for trust in multiple parties to ensure the integrity of the boot process. That includes all parties involved, e. g. the Raspberry Pi Ltd as the creator of many of the scripts and tools involved as well as owning the private RSA key for signing the official bootloader. Trust must be placed in their ability to securely store this key and prevent any potential leaks.

Obviously, the manufacturers of the underlying hardware have to be trusted as well, that includes Broadcom as they are responsible for the CPU as well as the TPM manufacturer and others. Furthermore, the U-Boot developers, the implementation of their security features and the source code hosting and build architecture has to be trusted. Vulnerabilities in relied on software and libraries like OpenSSL, which is used to create the keys, also have to be considered.

6.2 Security Achievements

The proposed approach strengthens the security of the RPi platform by establishing a verifiable CoT during the boot process. RPi Signed Boot ensures that only customer-signed images can be executed, while U-Boot (legacy mode) measures critical boot components, including the U-Boot environment, initramfs, DTB/overlays, and the Linux kernel. The resulting measurements stored in the TPM PCRs enable the use of Remote Attestation on the Raspberry Pi platform.

Although not implemented in this work, the established measurement chain provides the foundation for extending integrity verification to the operating system using Linux Integrity Measurement Architecture (IMA) as demonstrated by Jäger, Lorych and Eckel (2022) or for binding secrets, such as LUKS keys, to specific TPM PCR states.

6.3 Limitations

6.3.1 Swap of SD card / eMMC

A physical attacker can always modify the content of the SD card or eMMC offline to alter boot files and software of the RPi. Most of these changes can be detected and a successful boot be prevented. It mostly depends on which specific steps from Figure 1 are implemented. Steps 1A to 1C will stop the system from booting if any of the monitored files are changed. Steps 2A to 2C will at least make unwanted file changes transparent to other systems via Remote Attestation.

That means that if U-Boot Verified Boot is not used, an attacker can still modify the Linux kernel but not the bootloader. With U-Boot Measured Boot in place, this change could still be detected via Remote Attestation.

6.3.2 Early-stage measurement limitation

With the official bootloader not having support for the TPM, the first stage (U-Boot) cannot be measured into the PCRs, so that trust in the context of Remote Attestation only begins in U-Boot.

6.3.3 OTP memory

The OTP memory can be considered being safe against tampering via software, because the data is burned into the hardware. However, they are not necessarily safe against sophisticated physical attacks which can possibly make the content visible or even change the data stored by them. While there are ways for hardware manufacturers to also protect areas like the OTP registers against hardware tampering (e.g. with wire frames to enclose the area of the chip for intrusion detection), it is unlikely that this has been done for the RPi 4 as it is not mentioned in any documentation. In summary, storage in the OTP registers can be considered safe enough for consumer-grade devices, but cannot be trusted in critical equipment that has to be protected against physical attacks from state attackers, which are categorized as Advanced Persistent Threats (APTs).

6.3.4 Leak of private key and downgrade attack

There are two major issues due to hardware limitations imposed by the RPi platform: If the public signing key is compromised, it cannot be replaced by a new one. So, if a private key used for signing valid U-Boot images is leaked, there is no mechanism to revoke it and an attacker could sign their own malicious U-Boot images with the leaked private key.

The same problem applies to the official bootloader: If a specific version of it contains a vulnerability, an attacker could always roll back to that vulnerable version which will always have a valid signature. Unlike other hardware platforms, the RPi does not allow for replacing the public signing key or implementing a minimum version policy. This is an improvement that the platform manufacturer should look into for future revisions of the RPi chipset. With the current limitations, a per-device or per-customer signing key can possibly limit the number of affected devices in some cases.

6.4 Complexity

The effort to set up a system with the proposed Secure and Measured Boot mechanisms is much higher than simply installing a standard Linux distribution on the RPi 4. Apart from that, some of the steps are significantly more complex than others. That especially is the case for step 1B (U-Boot Verified Boot) shown in Figure 1 which requires extensive U-Boot configuration and also introduces some practical problems. One example is the updatability of the Linux kernel, because it is merged into a U-Boot specific Flattened Image Tree (FIT) image which means the kernel cannot simply be updated from package repositories like it is commonly done in most Linux distributions. Generally, even if this problem could be solved, updates still need to be signed by the maintainer, i.e. in most industrial use cases the manufacturer of the device.

7. Conclusion and Future Work

This paper demonstrates that combining Secure Boot and Measured Boot significantly improves the security capabilities of the RPi platform by establishing a continuous CoT from early boot stages to the operating system. While certain limitations remain due to hardware and proprietary components of the platform, the proposed approach enables verifiable integrity and supports security mechanisms such as Remote Attestation.

The presented approach is particularly suitable for industrial use cases, where higher setup complexity is acceptable in exchange for increased trustworthiness. Future work includes evaluating UEFI on U-Boot to improve flexibility and extending the CoT into user space using Linux IMA.

Acknowledgements

This research is directly supported by the German Federal Ministry of Research, Technology and Space in the context of the project TRUSTnet (TRUSTnet Consortium, 2026) (ID: 16KIS1788 – Hochschule Bremen / 16KIS1786 – Fraunhofer SIT). Further, this research work was supported by the National Research Center for Applied Cybersecurity ATHENE (National Research Center for Applied Cybersecurity ATHENE, 2024). ATHENE is funded jointly by the German Federal Ministry of Research, Technology and Space and the Hessian Ministry of Science and Research, Arts and Culture.

Ethics declaration: This research did not involve human participants, animals, or personal data. No ethical approval was required.

AI declaration: AI tools were used during the preparation of this paper exclusively for language refinement, grammar correction, and stylistic improvements. The scientific content, technical concepts, analyses, and conclusions were developed by the authors. All input was reviewed and validated to ensure correctness.

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Disinformation and Trust in Digital Environments: Expert Decision-making, Dismiss or Discuss?

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Abstract: Leveraging a management and organizations sciences perspective, this paper conceptualises AI, security and information warfare practitioner decision-making as a decision to trust or distrust, mediated by intuition. To explore how practitioners navigate trust in digital environments and benchmark to concerns a survey was conducted among 95 expert cyber security AI and information warfare practitioners. Questions explored practitioners' thoughts on sources of trusted material, intuition, and approaches to managing disinformation. Scenarios were included to explore practitioners' thoughts on unusual incidents and help elicit future threats and solutions. Findings highlight variations in decision-making approaches according to age, experience and domain. For trust in intuition, early-stage career and military/ defence individuals were found less likely to rely on intuition than public and private sector peers. When faced with out-of-the-ordinary events practitioners were spilt among four responses, re-checking data (37%), dismissing out-of-the-ordinary events (30%), pausing decision-making (19%), or seeking discussing (13%). Experience levels matter, with mid-career practitioners behaving distinctly from those at early- and late-stage careers. The contribution of this paper have direct implications for policy-makers, including recommendations for personalised stage-appropriate training in decision-making across age groups, and domains. Given the increasing velocity and uncertainty of the current and future threat landscape more precise calibration of practitioner decision-making is urgently needed.

Keywords: Disinformation, Information warfare, Trust, Intuition, Decision-making, Experts, Artificial intelligence, AI, Cyber security

1. Introduction

The 2026 World Economic Forum ranked disinformation (including AI augmented disinformation) as the second most important short-term threat, illustrating the increasing importance of decision-making by security practitioners responsible for managing this threat (WEF, 2026). Yet, although published standards and guidance provide steps in risk management and information security and zero trust architectures (Rose, 2020; NCSC, 2021), detailed knowledge on the processes and drivers for decisions taken by expert security practitioners remains under-explored. In contrast to spotting a gap in the literature, this paper leverages management and organizational studies scholarship and an interpretive approach aims to increase our depth of understanding (Alvesson & Sköldberg. 2009).

Our research questions explore topics of trust in digital environments augmented by AI to examine and benchmark concerns. The findings here concentrate on intuition and decision-making in an out-of-the-ordinary event (scenario). Further material from the larger survey on disinformation and trust has been published separately (Wylde et al., 2026) and the remaining study is in press

Given the complexity of concepts like decision-making, intuition and trust and the realities of experts, for example, fire fighters and paramedics making split-second decisions based on experience and intuition (Klein, 2017) a pragmatic approach was adopted to allow key terms such as decision-making and intuition to be simplified to issues of trust and distrust (Alvesson & Sköldberg, 2018: Weick, 1989).

This paper proceeds by reviewing key literature from management and organization sciences on trust in decision-making and intuition (self-trust). This is followed by a discussion on the methodology setting out the rationale for the selected research approach – which has to be capable of addressing the subjective contexts of trust and practitioner decision-making. To achieve this goal a scenario was included to allow practitioners to explore the current state of a system, potential future disruptions and solutions (Rasmus et al., 2025) Next,

drawing on the findings, important questions of trust are unravelled in contexts of uncertainty. The discussion and conclusion present the contribution and implications for practitioners, policy makers and academics.

1.1 Trust and Decision Making

As a research topic, interest in trust continues to grow, well-established scholarship sets out the processes for trust building (notably, Mayer et al., 1995), with trust defined as based on confident positive expectations of another's behaviour (Lewicki et al., 1998) and a willingness to be vulnerable irrespective of control or monitoring (Mayer et al., 1995). The multiple scales of trust relations have been acknowledged as ranging from inter-personal to inter-organization, institutional (Fulmer, & Gelfand 2012; Zaheer et al., 1998) and beyond, to trust in relations that are non-human (McKnight et al., 2011), and, for example, trust in AI systems.

In this paper decision-making is conceptualised a viewpoint based on whether to trust or distrust a particular individual, organization or factor. One strand of current discussions centres on the framing of the central constructs in trust and distrust with Verhoest et al. (2024) questioning whether these concepts are the opposite ends of the same continuum, arguing that they should be judged by different dimensions, ability, benevolence and integrity, compared to suspiciousness and watchfulness for negative consequences, how this ties with intuition is considered next.

1.2 Intuition and Trust

Significant evidence demonstrates that experts rely on intuition (Medvegy, 2022). In cases of crises where decisions must be made under time and risk constraints, for example, the split-second decisions by fire chiefs in a crisis were founded on intuition, drawing on past-experience and heuristics (Roghanizad et al., 2015).

In considering intuition as it intersects with trust, scholars suggest that although there are times when intuition (gut feeling) must be trusted, it is also important to consider the role of experience (Kahneman & Klein 2010: Klein, 2017). For example, as surgeons deal with some cases regularly, expert intuition is highly relevant. Yet, when unusual problems arise, there may be risks of over confidence. Indeed some experts may go along with their gut while other may draw on hindsights allowing them to trust their intuition (Kahneman & Klein 2010: Klein, 2017). At the same time, some scholars suggest that disinformation and AI augmented disinformation is successful because it contains a grain of truth, suggesting that society should reduce trust (Marco-Franco et al., 2021). Zero trust is discussed next.

1.3 Zero Trust

Zero trust emerged as a cyber security solution in response to the blurring of organizational boundaries and supply chains, and the need to evolve from simple perimeter-based security (Kindervag, 2010). In zero trust thinking, all network architectures are assumed to be breached and therefore hostile and all access requests must be verified (Rose et al., 2020; NCSC, 2021). The four main propositions of zero trust can be specified as features of: trustor disposition; the trustor-trustee relationship; the domain; and the institutional context (Wylde, 2021). In zero trust, the disposition of the trustor to a trustee is viewed as based on non-presumptive trust (zero trust), in other words, verify then trust (Lewicki et al., 1998). The nature of the trustor-trustee relationship consists of the trustor as an assessor (or controller) and a trustee as a user or subject, whether as an individual or a device, or a software application (Rose et al., 2020; NCSC, 2021). The domain-specific concerns involve the network architectures which are assumed to be breached, with the institutional context as one of mandated cybersecurity based on zero trust. On assessment, if an identity is confirmed, trust is earned (Rose et al., 2020; NCSC, 2021). Finally, continuous monitoring of the identity occurs; should any changes or indeed violations occur, trust will be withdrawn. Unlike the assessment of trust (Mayer et al., 1995), the features of zero trust operate in isolation and in parallel (Rose et al., 2020; NCSC, 2021).

1.4 Disinformation

The definition of disinformation draws from the US Cybersecurity and Infrastructure Agency (CISA, Nd) and the European Commission. (2018). Disinformation is defined by the US, CSIA as information "deliberately created to mislead, harm, or manipulate a person, social group or country" (CISA, nd.). The EU, definition considers disinformation as "verifiably false or misleading information that is created, presented and disseminated for economic gain or intentionally to deceive the public and may cause public harm" (European Commission, 2018). Both definitions stress disinformation creates harm through deception and manipulation. The US, scope includes people, social group and country-level (CISA, nd.) while the EU focus is on economic beneficiaries and country-level economics (European Commission, 2018). Disinformation differs from misinformation simply in terms of harm. Marco-Franco et al. (2021) recommend that to address trust in disinformation, as a society we

need to reduce our trust in the internet. Murphy (2023) sums up, arguing that disinformation involves the simultaneous presence of malign actors (with masked identities), the release intentionally harmful or destructive information, with a predetermined political, military, economic or social objective. It is with these conversations in trust, zero trust, intuition and disinformation that this paper seeks to better characterise decision-making under conditions of uncertainty and AI to generate insight and foresight (Hauptman & Steinmüller, 2019).

2. Methodology

The study was conducted among experienced cyber security practitioners focused on decision-making for cyber security and disinformation management based on questionaaries and a scenario to elicit views on current practice and future foresight (Hauptman & Steinmüller, 2019). University ethics were obtained; participants were advised the survey was anonymous, that they could with withdraw their consent at any time before the end of the survey, and, that the findings would be made available.

2.1 The Study

The survey questions were derived from published papers published on the topics of interest, trust, intuition, zero trust and disinformation (Medvegy, 2022; Kahneman, 2013; Rose, 2020; NCSC, 2021): the first questions explored the nature of decision-making.

A purposive sampling approach was used as the study required contact with appropriately experienced, domain experts (Alvesson & Sköldberg, 2018: Alvesson, 2002). The survey was web based survey hosted by Qualtrics XM, released from September 2025 to November 2025.

Participants were contacted and invited to participate directly by the authors via email and LinkedIn. Participants included recognised domain experts, personal contacts and European Conference on Cyber Warfare and Security attendees.

A total of 112 responses were collected, 4 did not consent, 1 was a test and 9 were incomplete; a final response of 95; comprising, male 67.3%, female 21.4% non-binary, prefer not to say and missing 11.3%; the age range was 18-65+; experience ranged from less that 1 year-to more than 15years.

Table 1: Survey questions, main topics

No.	Topics
1	Demographics, age, gender, self-identification, years of experience and domain expertise (sector)
2	Trust
3	Intuition
4	Scenario on an unexpected event
Note.	This paper reports on sections 3, and one scenario the remaining material will be published separately.

2.2 Research and Analysis Approach

This research focused by security practitioners as they managed complex processes of decision-making for cyber security, AI, disinformation and other aspects of digital security. Unlike lab-based experiments that can be studied using hypotheses and statistics, this study demanded a research approach capable of dealing with the messy realities of life, for example, involving people, organizations and learning (Miller& Tsang, 2011). To study the dynamics of decision-making, a simplified framework based on trust was drawn on as a lens through which to study the dynamics and factors involved (Klein, 2017, Weick, 1989). The analysis followed an interpretative approach to allow seeing beyond different levels of meaning and contrasting what the material may mean (Alvesson & Sköldberg, 2018).

An important part of the survey included scenarios. The scenario presented here explored here included an unknown out-of-the-ordinary event designed to help practitioners to explore the current state of the system, potential future disruptions and solutions (Rasmus et al., 2025), In addition the scenario helped provide respondents an opportunity to exercise their imagination and foresight (cf. Hauptman & Steinmüller, 2019: Hiltunen et al., 2025) - outside of any bias implied by zero trust architecture or systems (Rose et al., 2020; NCSC, 2021).

2.3 Findings

Results are from the study of intuition and the scenario are presented below. The analysis sought to integrate the findings through including the participant demographics (age, gender, years of experience and domain), the findings from the questions on intuition and the scenario. The findings were triangulated to increase the depth of understanding (Adams & Sasse, 1999).

2.4 Intuition

The question on intuition asked, "I rely on professional intuition when time is limited". For simplicity results from the Likert scale were aggregated: not at all and very little; slightly/ moderately; quite a bit/ very much/ a great deal.

Table 2: Relationship of relying on intuition under time pressure - to profession

	Intuition; relying on intuition under time pressure		
Profession	**Not at all/ very little**	**Slightly/ moderately**	**Quite a bit/ very much/ a great deal**
Academic/Researcher	32%	41%	27%
Cybersecurity Prof	27%	27%	46%
Military/Defense	50%	25%	25%
Private Sector	17%	33%	50%
Public Sector	0%	50%	50%

The results show that (46%-50%) of cyber security and the private sector professionals place the highest value on relying on intuition under time pressure, while 50% of the military and defense professionals said their reliance on intuition was "not at all or very little".

The reliance on intuition by experience; "very little or not at all" was found to be was the greatest in the less experienced professionals, less that 1yr (0%), 1-3yrs (50%); highly experienced (33%), compared with the mid-level practitioners, 4-7yrs and 8-15yrs who had lower levels (14%) and (26%) respectively.

However, the highest level of reliance of intuition under time pressure was (50%) for less that 1yr of experience (25%); while for 1-3yrs, mid-level practitioners, 4-7yrs and 8-15yrs (43% and 37% respectively); for the highly experienced, 8-15yrs and 15+yrs, the level was (37% and 29% respectively). The results seem to show the highest variance among the least experienced practitioners (less than 1yr, 1-3yrs), with 0% for no reliance, to 50% with a high reliance.

For "using intuition by profession", the public sector scored highest for using intuition (50% relied strongly and 50% relied moderately) along with the private sector and cyber security professionals (50% and 46% agreed strongly, respectively). The results differed for the military, 50% said they did not rely on intuition at all, compared with 25% who relied moderately and 25% relied strongly.

2.5 Scenario

Scenario 3 asked participants to imagine;

> *You have an unusual dream about a major crisis – something like a widespread power outage that disrupts communication and operational systems. The next day, the data at work seem to support what you dreamt. Surprisingly, your colleagues say they had a similar dream and agree with your risk assessment. This strange coincidence makes you question whether people around you – including yourself – are interpreting the situation clearly. You begin to wonder if your team's judgement is being influenced by something other than reliable information, and whether your usual ways of processing information, both digital and analogue, can still be trusted. What is your first reaction to this situation? Please select one of the following choices: re-check the data carefully; pause decision-making until you feel more certain; discuss the situation with someone outside the team; or, dismiss the coincidence as irrelevant.*

The findings from the scenario choices are clustered around cohorts, the largest cohort comprised those who rechecked data 37% followed by 30% who dismissed the scenario.

The next largest cohort, 19% paused further actions until they were clearer, and the final and smallest cohort were those who discussed 13%. One individual indicated they would speak with a leader. The largest % of selections were found in the recheck cohort; 1-3yrs (64%) and 15+ yrs professionals (48%) as compared the mid-career professionals (18% and 16%). The dismiss group; was highest among the mid-career group (8-15 yrs, 47% and 4-7 yrs, 36%) as compared with the lower %'s for the younger (18%) and senior (19%) groups.

A number of respondents selected more than one choice, for a first choice to recheck the data, 45% follow by discussing outside the team; notably, 41% of this cohort had no second response.

Table 3: Response to the scenario event, by years of experience

Years (yrs) of experience	Re-check the data carefully	Pause decision-making until you feel more certain	Discuss the situation with someone outside the team	Dismiss the coincidence as irrelevant
Less than 1; (1) 1-3 yrs; (10)	(7) 64%	0%	(2) 18%	(2) 18%
4-7yrs; (10#)	(2) 18%	(2) 18%	(2) 18%	(4) 36%
8-15 yrs; (19)	(3) 16%	(5) 26%	(2) 11%	(9) 47%
15+ yrs (27)	(13) 48%	(6) 22%	(3) 11%	(5) 19%
Sub-totals	(25) 48%	(13) 19%	(9) 13%	(20) 30%
#Note, 1 respondent indicated they would seek advice from a leader, not included above				

Of those who posted the second choice, to discuss, a third choice to pause further actions was selected (13%).For gender it was found that the majority of males were likely to re-check data (49%) while for females the response was to discuss (36%), only 2 responses were returned for non-binary/ prefer not to say, re-check data and dismiss.

3. Discussion

In examining the intuition findings, more junior professionals are at a learning stage, with limited self-awareness, hence more likely not to trust any intuition, rather preferring to present qualified decisions as compared with to a gut instinct. Mid-years experienced professionals are more likely to possess self trust, validated by their experience (seen it before) tied in with their domain specific knowledge and training (Medvegy, 2022). However, in highly trained personnel, for example, in the military, trusting intuition may seem like cutting corners, taking decisions that are not defensible (Medvegy, 2022), in a similar vein, senior professionals approaching retirement may take a safe bet. In addition, experienced military and security practitioners may operate under conditions of zero trust or AI driven cyber security processes, reducing intuition.

In terms of gender, the %'s presented here reflect the acknowledged over representation of males as found in the industry (ISC2, 2024). Examining differences in gender-related behaviour, an explanation could be provided by issues of socialisation, with males preferring to act alone, while females, represented by smaller numbers (ISC2, 2024), may act more collaboratively, and hence enter into discussions.

Taking a decision to dismiss an unexpected event seems to contrast with those practitioners who rechecked their data or those who discussed or paused actions. Looking at these actions in the context of trust decisions and responses by age, the highest levels of response were by juniors (64%) followed by the senior practitioners (48%), both in favouring re-checking data. As a response related to self-trust, this could indicate juniors exercising caution associated with a lack of self-trust, as compared with seniors favouring further investigation. However, in a crisis situation, both these results are could be seen as reflecting a lack of self-trust, causing a delay in response. The second highest raking response was among the mid-year experienced cohort (4-7yrs and 8-15yrs) both favour dismissing the incident (36% and 47% respectively). This result could be taken to indicate that this cohort are motivate to take decisions, but the numbers of practitioners taking this decision increased with age. This could indicate that the 8-15yrs cohort, who although they have a good deal of

experience, close to half were dismissive. This response, although quick, could indicate a bias related to training in zero trust or over confidence.

The scenario and intuition findings will be incorporated into future studies and help explore observations and responses to systems on work focused on disinformation (Wylde et al., 2026), and the assessment of current and potential future states as well as potential disruptions and solutions (Rasmus et al., 2025). As with all research, limitations are inevitable; notably issues with self-reporting, thinking about an abstract scenario, gender imbalance and the lack of statistical analysis. To overcome the problems with self-reported data, it is recommended that future studies be conducted with practitioners in the workplace during critical incident and/ or crisis management and using AI, this would allow real-time observations of behaviour and decision-making. In thinking through abstract scenarios, future work could observe practitioners during table-top simulations, AI scenarios and science fiction scenarios. For gender, future studies could seek to include more females to redress the balance.

The contribution of the study highlights different responses according to age and experience; leading to three recommendations for policy makers. Firstly, recognition that most security practitioners do not behave the same due to issues including, sector norms and prior levels of experience. Secondly, training should be directed at early stage and later stage career individuals to help build experience and overcome blind spots, respectively. Thirdly, for military and defence personnel, participation should be encouraged in joint operations with the private and public sectors, to allow experience of different aspects of decision-making under different conditions and hierarchies- including AI.

4. Conclusion

Recent fines of big Tech companies illustrate the importance that practitioners demonstrate transparent, compliant and auditable decision-making. This paper argued that although in practice, recognised standards and guidelines are implemented by security professionals, the decision-making steps involved remain under researched. The findings reported here highlight that there are distinct differences in practitioner's decision-making, related to experience and domain, highlighting key questions for future research.

The contribution raises important implications for policy makers, practitioners and scholars. To account for differences in decision-making among security practitioners, it is recommended that training be developed to addresses differing career and experience stages and domain knowledge. For example, in light of differences found across practitioners from the public and private sectors and the military, is is suggested that operations be conducted jointly among these sectors together with AI. This could allow practitioners to experience working in different contexts with different decision hierarchies and among differing levels of experience and training.

Acknowledgements

Thank you to the research participants for taking time from their busy schedules to take part in this study and for the reviewer's comments which have improved the final paper.

Ethics and AI: Ethical approval was obtained, Claude AI was used to help format the first version of the paper.

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NEXUS-HC: A Framework for Technology Foresight in Strategic Communications

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Abstract: Strategic communications teams increasingly operate in an information environment shaped less by what people say to each other and more by what platforms choose to show, boost, or hide. Automation, synthetic media, and faster technology cycles mean influence activity can scale quickly, while decision-makers must still choose what to monitor, test, and prepare for. Many organisations track technology "hype" informally through news and vendor claims, but this often fails to produce clear priorities or explainable trade-offs. This paper introduces NEXUS-HC (Navigational Examination and Understanding System for Hype Cycle Analysis), a decision-oriented framework that adapts the familiar hype-cycle idea for contested, next-generation information environments. NEXUS-HC standardises technology assessment through a lightweight cross-impact rubric to compare likely effects, and links assessment to action through five portfolio postures: Monitor, Pilot, Adopt, Govern/Harden, or Counter. The framework separates (a) maturity and diffusion signals, (b) disruption mechanisms relevant to influence and integrity, and (c) adversarial leverage and governance readiness. We provide practical guidance for running the workflow in a small StratCom team, recording evidence notes and confidence, and setting reassessment triggers. A short three-technology illustration and light-touch retrospective validation—synthetic media, algorithmic Information-Operations (IO), and AI avatars—demonstrate how technologies associated with synthetic saturation, algorithmic contestation, and reality mediation can still lead to different actions depending on leverage and governance. The contribution is a repeatable approach that improves transparency (how judgements were made), comparability (across technologies and time), and briefing value (clearer decisions for leaders). NEXUS-HC is designed to complement, not replace, deeper intelligence assessments and technical evaluation. It is intended primarily for StratCom teams, with cyber or technical specialists contributing when required. It provides a common language for briefings, helps teams avoid over-reacting to short-lived attention spikes, and highlights when governance should start early because standards, labelling practices, and organisational controls often lag behind capability diffusion. When applied on a quarterly cadence, NEXUS-HC produces an auditable decision record that captures evidence, confidence, and triggers for reassessment—supporting learning across cycles and reducing reliance on individual judgement.

Keywords: Strategic communications, Horizon scanning; Technology assessment, Synthetic media, Algorithmic IO, AI avatars; Decision support

1. Introduction

Strategic communications (StratCom) has traditionally focused on crafting messages for human audiences. That remains important, but it is no longer sufficient. Today, what people see is strongly shaped by ranking systems, recommendation engines and automated accounts that amplify or suppress content at scale (Bolt and Lange-Ionatamishvili, 2026).

This shift changes the operational question for StratCom leaders (Chairman of the Joint Chiefs of Staff, 2022). It is not only "what story should we tell?" but also "what system will deliver, distort or drown out that story?". New capabilities such as synthetic media and algorithmically-optimised influence techniques can reduce the cost of manipulation, increase speed and widen reach, while also increasing ambiguity and undermining trust (Wardle and Derakhshan, 2017; Tabassi, 2023).

Technology anticipation is often informal: teams track trends through headlines or vendor pitches, but struggle to compare technologies, explain trade-offs and translate scanning into decisions. NEXUS-HC addresses this by combining maturity signals with disruption mechanisms and governance readiness, producing an action posture that can be briefed and revisited (UK Ministry of Defence, 2021).

2. Background

Hype-cycle models are widely used because they offer an intuitive vocabulary for expectation dynamics. However, stage placement can be opaque and different technologies follow different trajectories, which limits their use for high-stakes decisions (Dedehayir and Steinert, 2016).

Readiness frameworks such as Technology Readiness Levels (TRLs) provide disciplined evidence gates for engineering and acquisition, but they were not designed to capture adversarial leverage, platform incentives or the institutional burden of verification in contested information environments (U.S. Department of Defense, 2005; Defense Acquisition University, n.d.; Mankins, 2009; U.S. Government Accountability Office, 2020).

For StratCom, the practical need is a repeatable way to (a) track maturity and diffusion (adoption and spread) signals, (b) translate technical affordances into mission-relevant disruption, and (c) decide whether to Monitor, Pilot, Adopt, Govern/Harden, or Counter a technology. Across current approaches, the persistent weakness is prioritisation: many methods detect and describe emerging technologies well, but still struggle to convert noisy signals into defensible, decision-relevant recommendations that make trade-offs explicit and can be revisited over time (Australian DSTG, 2016).

3. The NEXUS-HC Framework

Here, the Navigational Examination and Understanding System for Hype Cycle Analysis (NEXUS-HC) is introduced. NEXUS-HC is designed as a navigational decision-support framework that helps organisations prioritise emerging technologies under conditions of uncertainty and adversarial pressure. It adapts the hype-cycle idea into a transparent decision-support rubric for StratCom and information-warfare organisations operating in contested, platform-shaped information environments. Rather than predict exact futures, it structures how a small team can (a) translate an environment scan into comparable disruption dimensions, (b) stage technologies using observable "maturity and diffusion (adoption/spread)" signals, and (c) derive repeatable portfolio actions (Monitor, Pilot, Adopt, Govern/Harden, Counter) supported by evidence notes, confidence, and reassessment triggers (Gordon and Hayward, 1968). Figure 1 provides an overview of NEXUS-HC. The intended primary user is a small StratCom team rather than a full cyber threat-intelligence cell.

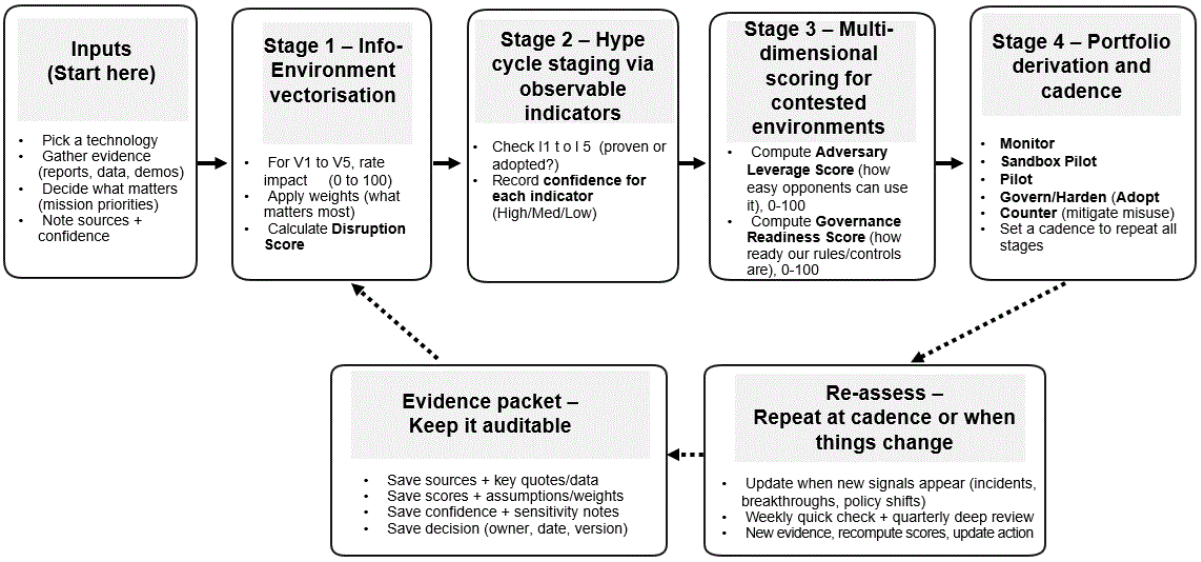


Figure 1: NEXUS-HC framework overview

Stage 1 — Information-environment vectorisation. NEXUS-HC begins with an explicit environmental baseline (here, NATO's Next-Gen Information Environment framing), but the same workflow can be re-run using other baselines (e.g., national strategies, regional architectures, or threat-intelligence scans) to compare how priorities change under different assumptions. The baseline is operationalised into five vectors (Table 1) that represent distinct ways technologies can reshape information dynamics.

Table 1: Next Gen information environment vectors

Vector	Definition
V1: Reality Mediation	Shift from direct information consumption to AI-curated immersive experiences; agents and avatars as reality gatekeepers
V2: Authority Shift	Movement of epistemic authority from institutions (media, academia, government) to technical systems (algorithms, AI assistants, verification infrastructure)
V3: Algorithmic Contestation	Campaigns and counter-campaigns targeting computational systems (recommendation algorithms, training data, model behaviour) rather than solely human audiences
V4: Synthetic Saturation	Scale and indistinguishability of synthetic content (deepfakes, generated text, synthetic audiences) overwhelming detection and verification capacity
V5: Human-Machine Convergence	Neuro-data collection and affective/behavioural modelling enabling finer-grained manipulation; blurring boundaries between human cognition and machine augmentation

Vector scoring is intentionally lightweight. For each technology and each vector, assessors give a Magnitude score, *M* (0–100) that represents the expected size of the technology's impact on that specific vector for the mission setting being analysed (i.e., the organisation's target audiences, platforms, time horizon, and threat model). Next, assessors proceed to apply two small adjustments: Directness, *D* (0.5–1.0) for how directly the technology enables the vector's disruption pathway (e.g., reality mediation, authority shift, algorithmic contestation, synthetic saturation, or human–machine convergence), and Timeframe, *T* (1.0 near-term; 0.75 mid-term; 0.5 long-term) for how soon that vector impact is expected to materialise at operationally relevant scale within that mission setting. Here, $i \in \{1,\ldots,5\}$ indexes the five Next-Gen information environment vectors (V1–V5) defined in Table 1. Let $VectorScore_i$ denote the score for vector V_i. In other words:

$$VectorScore_i = M_i \times D_i \times T_i$$

The overall *Disruption Score* is then a weighted average across the five vectors, where w_i is the organisational weight assigned to V_i:

$$\text{DisruptionScore} = \Sigma_{i=1}^{5}\, w_i \cdot VectorScore_i, \quad \text{with } \Sigma_{i=1}^{5}\, w_i = 1$$

Weights w_i can be set uniformly by default, but should ideally reflect mission priorities; NEXUS-HC makes these weights explicit and auditable, and teams can elicit them quickly using the Analytic Hierarchy Process (AHP) (Saaty, 1980; Saaty, 2008).

Stage 2 — Hype-cycle staging via observable indicators. Instead of relying on vendor-defined, proprietary stage assignments (e.g., the Gartner Hype Cycle), NEXUS-HC stages technologies using the same familiar hype-cycle stages but grounds placement in five observable indicators of adoption, institutionalisation, and adversarial use (Table 2): I1 Attention, I2 Investment, I3 Deployment, I4 Standardisation, and I5 Adversarial Adoption. Each indicator family is assessed on a simple ordinal scale (e.g., Low/Medium/High) with a brief evidence note (and, where useful, an evidence-quality tier), and the combined pattern is used to justify stage placement. Assessors compile "observable signals" (e.g., media/conference volume, funding/procurement signals, production deployments and incidents, standards activity, and documented misuse) and select the hype-cycle stage most consistent with the balance of evidence across the five indicator families (i.e., the stage supported by most indicators and the strongest evidence). Thresholds are transparent starting points: teams are expected to calibrate them to their language/platform ecosystem and record any changes to the default thresholds (and why) for auditability. Where indicators conflict, NEXUS-HC treats disagreement as uncertainty rather than forcing false precision; evidence quality tiers and a confidence level (or a simple stage probability distribution) can be recorded alongside the stage assignment.

Table 2: Five observable indicators of adoption, institutionalisation, and adversarial use

Indicator Family	Measurement Approach*
I1: Attention	Volume and volatility of technical and mainstream media coverage; Google Trends; conference session counts; social media mentions
I2: Investment	Venture funding rounds and amounts; government procurement/contract awards; corporate R&D allocations
I3: Deployment	Evidence of operational use (pilots, production integrations, documented incidents); user adoption metrics where available
I4: Standardisation	Emergence of standards bodies, technical specifications, regulatory frameworks, certification programs, audit methodologies
I5: Adversarial Adoption	Observed misuse in influence operations; red-team findings; threat-intelligence reports; vulnerability disclosures

* Note: I1–I5 are recorded on an ordinal Low/Medium/High scale with brief evidence notes; teams may also record evidence quality and confidence.

Stage 3 — Multi-dimensional scoring for contested environments. Beyond disruption, NEXUS-HC adds two dimensions that often diverge from "maturity" in adversarial settings. *Adversarial Leverage* is scored on a 0–100 scale and is computed as the sum of four 0–25 component scores: (a) access barriers (how hard it is for an adversary to obtain or access the capability), (b) deployment simplicity (how easy it is to operationalise at scale), (c) attribution difficulty (how hard it is to detect, trace, or prove responsibility), and (d) impact asymmetry (how large the effect is relative to the attacker's cost or risk). Because adversaries differ in resources and risk tolerance, teams may score distinct attacker archetypes (e.g., state-linked, criminal, hacktivist) and report either a mission-weighted score, scenario-specific scores, or a conservative min–max range. *Governance Readiness* is

also scored on a 0–100 scale and is computed as the sum of four 0–25 component scores covering (a) technical countermeasures, (b) standards/protocols, (c) regulatory/policy coverage, and (d) organisational capacity to implement controls—so that the overall score reflects the combined availability and maturity of mitigation mechanisms.

Stage 4 — Portfolio action derivation and cadence. NEXUS-HC converts the combined picture into action categories (Table 3) using an all-encompassing two-layer mapping over (a) the indicator profile across I1–I5 recorded on a Low/Medium/High scale and (b) the three scores (*Disruption*, *Adversarial Leverage*, and *Governance Readiness*). First, NEXUS-HC assigns a capability posture—Monitor, Pilot, Adopt, or Govern/Harden—based on *Disruption* and the diffusion-related indicators (especially I2 Investment, I3 Deployment, and I4 Standardisation) together with *Adversarial Leverage* and *Governance Readiness*. Second, it applies a threat overlay: Counter is added whenever I5 Adversarial Adoption and/or *Adversarial Leverage* indicates credible hostile use or high exploitability, particularly when *Governance Readiness* is weak (UK Ministry of Defence, 2023). This two-layer structure ensures that all possible combinations of indicator ratings and scores map to a clear decision posture, while still allowing combined actions (e.g., Pilot+Counter or Govern+Counter) when the capability and threat pictures diverge. Where indicators conflict, NEXUS-HC records uncertainty (evidence quality and confidence tiers) and defaults to the higher-urgency posture when the strongest credible signals justify it.

For cyber-relevant technologies, NEXUS-HC is not intended to replace established cyber risk management processes such as NIST RMF or ISO/IEC 27005. Rather, it gives a StratCom team an upstream prioritisation layer and a common briefing language. Where a technology interacts with attack surfaces or platform control systems, I3 Deployment and I5 Adversarial Adoption can draw on threat-informed inputs such as ATT&CK-mapped TTP reporting, incident reporting, and formal advisories, while Governance Readiness can be cross-checked against existing organisational cyber risk processes (Joint Task Force, 2018; ISO/IEC, 2022; MITRE, 2025).

To reduce scoring burden for small teams, NEXUS-HC can also be applied in a light-touch calibration mode. The aim is consistency rather than false precision: assessors can anchor 0–100 scores around illustrative bands of 20 (low), 50 (medium), and 80 (high); keep Directness at 1.0 unless the pathway is clearly indirect; and use Timeframe only to distinguish near-term, mid-term, and longer-term salience. A filled example for synthetic media is provided in Appendix A.

Dynamic reassessment is built in. Teams record explicit reassessment triggers (e.g., major deployments, regulatory actions, observed attacks, technical breakthroughs) and use scheduled reviews matched to action category (e.g., quarterly for Monitor, monthly for Counter, and event-driven for Pilot and Govern). Automated monitoring of I1–I5 can flag material shifts for expert re-evaluation. To address "leapfrogging" (rapid transitions over weeks), NEXUS-HC recommends a two-speed cadence: (a) a lightweight fast-lane weekly scan that updates only high-velocity indicators (I1 Attention, I2 Investment, and I3 Deployment/misuse signals) and (b) a quarterly full-lane review that refreshes slower-moving baselines (especially I4 Standardisation and I5 Adversarial Adoption) and re-runs weighting/sensitivity checks. The result is a short assessment card per technology that preserves an auditable record of why priorities changed across cycles.

Table 3: Portfolio action categories and trigger conditions

Action category	Complete trigger logic (using I1–I5 on Low/Medium/High scale and 0–100 Scores)	Organisational response
A. Monitor (capability posture)	Assign Monitor if *Disruption* <60 and I3 Deployment is Low and I2 Investment is not High (I1 Attention may be High).	Periodic review; lightweight tracking; knowledge building.
B1. Sandbox Pilot (Sandboxed Discovery)	Else Assign if *Disruption* > 80 and *Governance Readiness* < 50.	Isolated 'safe-to-fail' environment; no live audiences or production systems; objective is governance-building (evidence notes, standards/procedures (I4), countermeasures) with rapid feedback into Stage 3 scoring. Graduate to standard Pilot once Readiness ≥ 50.
B2. Pilot (capability posture)	Else assign Pilot if (I3 is Medium/High or I2 is High) and *Disruption* is 60–80 (or *Disruption* <60 with a defined use case), and *Governance Readiness* is not critically low (≥50).	Controlled experiments; capability assessment; gap analysis.

Action category	Complete trigger logic (using I1–I5 on Low/Medium/High scale and 0–100 Scores)	Organisational response
C. Adopt (capability posture – Resilient integration)	Else assign Adopt if I3 Deployment is High and *Governance Readiness* is High (≥75), and the disruption profile is stable (no recent step-change in *Disruption* Score drivers or diffusion indicators.)	Full operational integration; formal training programs; lifecycle maintenance; transition from "project" to business-as-usual, with conditional reassessment triggers.
D. Govern/Harden (capability posture)	Else assign Govern/Harden (all remaining cases), e.g., *Disruption* >70, or I4 Standardisation is Medium/High, or *Governance Readiness* <60 while I2/I3 indicate emerging adoption.	Standards development; policy formulation; capability acquisition; defensive investment.
E. Counter (threat overlay; may be combined)	Add Counter in addition to the capability posture if any holds: I5 *Adversarial Adoption* is High; or *Adversarial Leverage* >75; or (I5 is Medium and *Governance Readiness* <60).	Active defence; attribution investment; defensive capability development; intelligence collection.

* Note: Apply the capability posture rules (A–D) in order, then add the Counter overlay (E) when triggered. If indicators are mixed or evidence quality varies, record uncertainty (evidence-quality tiers and confidence) and default to the higher-urgency posture supported by the strongest credible signals.

4. Worked Example Determining Action Postures

Table 4 summarises a worked example using three technologies—synthetic media, algorithmic information operations (Algorithmic IO), and AI avatars—to show how NEXUS-HC translates evidence and scores into portfolio actions.

The example is intended to make the action logic inspectable rather than to forecast outcomes. Assessors score disruption vectors (V1–V5) to compute the *Disruption Score*, rate the five indicator families (I1–I5) on a Low/Medium/High scale based on observable signals, and then interpret the combined profile alongside *Adversarial Leverage* and *Governance Readiness* to assign a capability posture (Monitor/Pilot/Adopt/Govern) and, where warranted, a Counter overlay (Bolt and Lange-Ionatamishvili, 2026).

Synthetic media (including deepfakes and other AI-generated or AI-altered audio, images and video) receives a high Disruption score because it scales convincing content production and accelerates synthetic saturation, while also weakening trust and provenance (Table 1, V4). In Table 4, the indicator profile (I1–I3 High; I4 Medium; I5 High) and an elevated Adversarial Leverage score suggest both broad diffusion and active hostile uptake; Governance Readiness is improving but uneven, supporting a combined Govern/Harden + Counter posture focused on coordinated controls, labelling practices, monitoring and resilience measures (Doss et al., 2023; National Security Agency, Federal Bureau of Investigation and Cybersecurity and Infrastructure Security Agency, 2024; European Commission, 2025).

Algorithmic IO targets the computational systems that allocate attention—such as ranking, recommendation and moderation workflows—rather than relying only on direct persuasion. Its high *Disruption* Score reflects system-level leverage over amplification and visibility (Table 1, V3). Table 4 shows a Medium indicator profile (I1–I3 Medium; I4 Low; I5 Medium) paired with high *Adversarial Leverage* and low *Governance Readiness*, indicating exploitability even before strong standardisation or institutional controls emerge. Under NEXUS-HC, this combination supports a Govern/Harden posture, with Counter measures as a closely linked workstream: the priority is to close governance gaps early (policies, monitoring, platform engagement, and organisational controls) while hardening measurement and operational processes against manipulation. Accordingly, the recommended posture emphasises governance-first mitigation—standards and controls where feasible, monitoring and response playbooks, and targeted countermeasures for coordinated manipulation—rather than treating detection alone as sufficient (Bolt and Lange-Ionatamishvili, 2026; Tabassi, 2023).

AI avatars—represented here as interactive digital humans or virtual influencers—score primarily on reality mediation because they insert synthetic spokespeople into quasi-social interactions rather than only modifying isolated artefacts. Current research suggests that audiences can form one-sided audience attachments to virtual influencers comparable to those formed with human influencers, while engagement is shaped by human-likeness and perceived authenticity (Stein, Breves and Anders, 2024; Ju, Kim and Im, 2024). In NEXUS-HC terms, this pattern suggests rising salience and operational potential, but still uneven deployment, standards, and safeguards. For a StratCom team, that combination supports a Pilot posture, paired with governance safeguards around disclosure, provenance, consent, and impersonation risk.

Table 4: Worked example—synthetic media, algorithmic IO and AI avatars produce different action postures under NEXUS-HC

Technology	*Disruption* Score	Indicators (I1–I5)	*Adversarial Leverage* Score	*Governance Readiness* Score	Action
Synthetic media — Synthetic saturation	80	I1: High I2: High I3: High I4: Mid I5: High	75	58	Govern/ Harden +Counter
	High-end-to-end synthetic content at scale, undermining trust/provenance and saturating verification capacity	High attention; mature tools; active misuse	Low-cost, widely accessible tooling that's easy to operationalise and hard to attribute, with outsized impact	Improving, but uneven (policy + platform practice varies)	
Algorithmic IO — Algorithmic contestation	88	I1: Mid I2: Mid I3: Mid I4: Low I5: Mid	82	32	Govern/ Harden
	Directly targets the attention allocation machinery (ranking/recommendation/moderation), amplifying influence effects system-wide	Growing attention; feasible tactics	Highly scalable exploitation of platform dynamics with low barriers, low attribution, and strong impact asymmetry	Low–medium (limited controls and measurement)	
AI avatars — Reality mediation	72	I1: High I2: Mid I3: Mid I4: Low I5: Low	58	55	Pilot
	Synthetic spokespersons and interactive digital humans mediate audience attention and social presence, shifting engagement from direct human communication to avatar-led interaction.	High public visibility; growing vendor ecosystem; meaningful but still uneven deployment.	Moderate barriers to entry, scalable persona creation, and some impersonation potential, but less mature hostile use than synthetic media.	Partial safeguards exist, but disclosure, provenance, consent, and authenticity norms remain uneven across platforms and use cases.	

5. Retrospective Validation Illustration

As a retrospective validation, the three technologies in Table 4 can be compared against their observed trajectories over roughly the last 5–8 years. The purpose is not statistical proof, but to test whether NEXUS-HC would have generated action postures broadly consistent with what later became operationally salient.

On this reading, synthetic media is a plausible Govern/Harden + Counter case: the literature shows falling barriers to realistic manipulations and substantial public vulnerability, while governance responses have accelerated but remain uneven (Doss et al., 2023; European Commission, 2025). Algorithmic IO is a plausible Govern/Harden case because manipulation increasingly targets the systems allocating visibility, and even modest changes in collective behaviour can alter downstream recommendation outcomes (Fredheim and Pamment, 2025; Matias, 2023). AI avatars are a plausible Pilot case: virtual influencers and other digital humans already attract engagement and one-sided audience attachment, but operational norms for disclosure,

authenticity, and impersonation remain unsettled (Stein, Breves and Anders, 2024; Ju, Kim and Im, 2024). Taken together, these cases suggest that NEXUS-HC is most useful not when it predicts exact dates, but when it separates maturity from leverage and governance in a way that produces defensible early action.

6. Discussion

NEXUS-HC is intended to make technology prioritisation easier to justify and easier to revisit. It reduces a common failure mode: treating novelty or maturity as a proxy for urgency. In contested environments, urgency can arise early when adversaries can combine low-cost tools into effective workflows, while governance and standards lag behind diffusion. This complements related work on actor interventions in narrative evolution, which likewise emphasises timing, pathways, and intervention points rather than technology novelty alone (Ng, Zeng and Ponmani, 2026).

The framework also supports balanced mitigation. Counter does not mean only technical detection; it can include resilience measures. Evidence for prebunking and inoculation suggests that technique-based interventions can improve resistance to misinformation, which can complement technical and governance controls (Roozenbeek et al., 2022; Lewandowsky and van der Linden, 2021).

In contested information environments, organisations may encounter a catch-22 where a technology is highly disruptive yet poorly governed: they cannot safely pilot it without controls, yet cannot design effective controls without practical learning. NEXUS-HC therefore distinguishes between a standard Pilot and a Sandbox Pilot (Sandboxed Discovery) for 'leapfrogging' technologies. A Sandbox Pilot is permitted when *Disruption* > 80 and *Governance Readiness* < 50, but it is conducted under strict constraints (e.g., isolated environments, no interaction with live audiences, and no production recommendation engines) and exists primarily to generate the evidence required to raise *Governance Readiness*. Pilot objectives in this state are explicitly governance-building—producing evidence notes for attribution/traceability, drafting internal standards and procedures (contributing to I4 Standardisation), and validating technical countermeasures. Scoring becomes recursive: findings from the Sandbox Pilot feed rapidly back into Stage 3 (e.g., updating *Adversarial Leverage* and *Disruption* mechanisms), while *Governance Readiness* is updated as controls are tested and formalised. Once *Governance Readiness* crosses the 50 threshold, the technology graduates from Sandbox Pilot to a standard Pilot posture; a Counter overlay may still be triggered in parallel if *Adversarial Leverage* is high.

To address potential drift between organisational priorities and the evolving information environment, NEXUS-HC treats vector weights (w_i) as periodically reviewable parameters rather than fixed constants. Organisations should establish a standing review cadence (e.g., quarterly or aligned to major platform or policy shifts) to reassess whether existing weights continue to reflect mission risk. Trigger-based reviews are also recommended following significant ecosystem changes (such as major platform access restrictions or sudden adversarial capability shifts). Where material divergence is identified, weights may be adjusted through a documented governance process, with changes logged alongside technology score updates. This adaptive weighting mechanism preserves comparability over time while ensuring the *Disruption* Score remains aligned with current strategic priorities in contested information environments.

Limitations remain. Scoring involves judgement, signals are uneven across technologies, and some sources are grey literature. In addition, some indicator evidence may be unavailable, delayed, or systematically obscured (e.g., low-visibility deployments, restricted reporting, or capabilities developed in closed settings), which can bias assessments toward what is most observable rather than what is most consequential. NEXUS-HC should be used as a structured aid to judgement, not a mechanical ranking, and teams should document confidence and reasons for disagreement.

7. Conclusion

This paper presented NEXUS-HC, a hype-cycle-informed decision rubric for anticipating emerging technologies in next-generation information environments. By separating maturity signals from disruption mechanisms and governance readiness, it produces clearer portfolio actions and an auditable record of why priorities change over time.

Future work can extend the framework with empirical evaluation (e.g., retrospective back-testing of stage assignments), richer indicator libraries for specific technology families, and integration with measurement pipelines that track adoption and incident signals. These extensions would further strengthen the ability of StratCom organisations to manage the algorithmic burden of proof as new capabilities emerge.

Ethics Declaration: This paper is conceptual and did not involve human participants, personal data collection or activities requiring ethical clearance.

AI Declaration: AI tools were used to assist with language refinement and editing. The author reviewed all changes and is responsible for the final content.

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Appendix A: Light-touch Assessment Card (Synthetic Media)

Table A1 provides a filled example of the light-touch calibration approach for synthetic media. It is intentionally illustrative rather than normative, and is included to show how a small StratCom team can document scores, evidence notes and the resulting posture without over-engineering the process.

Table A1: Filled light-touch assessment card for synthetic media

Field	Illustrative value	Rationale / evidence note
Mission setting	Public-facing StratCom monitoring across major social and video platforms	Assumes a team concerned with audience exposure, trust effects and response options.
Dominant vector	V4: Synthetic Saturation	Synthetic media most directly increases scale and indistinguishability of manipulated content.
Magnitude (0–100)	80	High potential effect on trust, verification workload and content volume.
Directness (0.5–1.0)	1.0	The technology directly produces the artefact that creates the disruption.
Timeframe	1.0 (near-term)	Operational salience is already present in current platforms and workflows.
I1 Attention	High	Sustained public, policy and platform attention.
I2 Investment	High	Mature tooling ecosystem and continued vendor/platform investment.
I3 Deployment	High	Widespread legitimate and malicious use.
I4 Standardisation	Medium	Labelling, provenance and policy responses are advancing, but unevenly.
I5 Adversarial Adoption	High	Active misuse and deception risks are already evident.
Adversarial Leverage	75	Low-cost tooling, scale, attribution difficulty and outsized effect.
Governance Readiness	58	Improving, but uneven across organisations and platforms.
Recommended posture	Govern/Harden + Counter	Governance and resilience measures are needed alongside active defensive monitoring.

PhD Research Papers

Systematically Integrating Cyber Threat Intelligence into Resilient Space-Cyber Architectures

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Abstract: Space systems are undergoing unprecedented commercialisation, increased autonomy and expanded connectivity, bringing both operational efficiency and heightened exposure to evolving cyber threats. These systems underpin critical services such as communication, navigation and Earth observation, yet their cybersecurity practices remain inconsistent across the global space ecosystem. Although frameworks such as NIST SP 800-160, NASA-STD-1006, ECSS-Q-ST-80C and MITRE's Cyber Resiliency Engineering Framework (CREF) provide guidance for secure engineering, they lack mechanisms for the systematic integration of Cyber Threat Intelligence (CTI). This paper examines current CTI integration practices and the organisational, technical, and regulatory barriers that hinder CTI-informed resilience in space-cyber architectures. Drawing upon an extensive review of academic and industry literature, the study maps how CTI is currently applied across space-system lifecycles and identifies critical impediments to broader adoption. The findings reveal that CTI is primarily leveraged in an ad hoc, reactive manner for patching and advisory processes, with minimal integration into design or operations. Identified barriers include fragmented standards, limited automation in threat-intelligence consumption, cultural resistance to information sharing and divergent regulatory frameworks across jurisdictions. The paper concludes with analytical insights into how these findings can inform future policy and research directions aimed at improving intelligence-driven resilience within the space sector.

Keywords: Cyber threat intelligence, Space-cyber architecture

1. Introduction

As space operations expand to support defence, communications, and scientific missions; the cyber threat landscape surrounding them has become increasingly complex. The convergence of terrestrial networks with orbital assets introduces additional vulnerabilities through shared infrastructure, COTS components and cloud-integrated mission systems (Falco, 2019; Bradbury et al., 2020). Although many national agencies and commercial operators implement baseline controls aligned to NIST, ECSS or NASA standards, few operationalise CTI as part of system design or mission assurance.

This paper addresses two central questions.

What are the current practices for integrating CTI into the cybersecurity of space systems?

What organisational, technical and regulatory barriers impede CTI-informed resilience in space cyber architectures?

Through addressing these questions, the paper aims proposes a pathway for transforming CTI from a predominantly reactive function into a proactive design and governance instrument for the space sector.

2. Space Architecture Overview

Space system architecture consists of a tightly interconnected ecosystem spanning the ground, link, space, user, and integration domains. Each domain contains distinct components, services and operational functions that collectively contribute mission assurance. The architectural model, as illustrated in the referenced diagram produced by the IEEE P3536 - Space System Cybersecurity Design Standard Working Group demonstrates that cyber risk in space systems emerges not from isolated components but from the interactions and dependencies among these domains (Willbold et al., 2023, Bradbury et al., 2020).

The ground segment includes mission control centres, launch operations, science data systems and the ground security operations centre (GSOC). Key functions include telemetry and telecommand (TM/TC) operations, payload tasking, mission scheduling, data processing, intrusion detection and vulnerability management. Ground stations and associated network services act as the operational anchor for space assets, creating a high-value target for adversaries due to their central role in command and control (Peled et al., 2023).

The link segment encompasses all communication pathways between ground and space components, including RF links, optical links, data uplinks and downlinks, modulation and demodulation functions, radio resource management and error correcting protocols. This segment represents a critical attack surface, as adversaries may exploit weak authentication, unencrypted channels, or disruption techniques such as jamming and spoofing

(Tedeschi, 2022). Link-level monitoring and anomaly detection are increasingly recognised as essential resilience measures.

The space segment consists of the satellite bus and payload. The bus includes subsystems such as CDHS, cryptographic services, ADCS/GNCS, propulsion, power systems, data storage and communication modules. These components support satellite health, stability, and communication. The payload provides mission-specific capabilities such as scientific instruments or imaging systems and inter satellite links. The space segment is resource constrained, physically inaccessible post launch and therefore highly sensitive to pre-launch supply chain risks and firmware integrity failures (Varadharajan & Suri, 2022).

The user segment includes components such as VSAT terminals, GNSS receivers, PNT systems, anomaly detection tools for user-space threats, and encryption/decryption services used by downstream consumers. User terminals often form the outermost and least controlled attack surface, introducing risks through social engineering, misconfiguration, weak authentication or exploitation of unpatched end user equipment (Casaril, F. et al. 2024; CISC, 2024).

The integration layer spans the cross cutting functions that link all segments together, including key management, PKI, intrusion and anomaly detection, software testing and emulation, threat intelligence, supply chain management, and system wide situational awareness. This layer is essential for cyber resilience, as it governs the consistency and coherence of security practices across the entire architecture (Falco et al., 2024).

Taken together, this architectural model highlights the multidimensional attack surface across space systems. It shows that cyber threats do not target components in isolation. Rather, adversaries exploit interdependencies between ground stations and satellites, link protocols and bus subsystems, and user devices and payload data flows. These interactions emphasise the need for a holistic understanding of space architecture to inform CTI integration and resilience planning.

3. Space Infrastructure and Criticality

Space infrastructure underpins a broad array of terrestrial and orbital services, spanning communications, remote sensing, meteorology, navigation, scientific experimentation, financial-timing and national security functions. The criticality of these services extends far beyond the space sector itself, embedding orbital systems deeply into the operational fabric of modern societies (Plotnek, J. J., & Slay, J. (2022; Bradbury et al., 2020). As a result, the resilience of space systems is no longer a specialised engineering concern but a strategic national priority.

Sectors such as aviation, maritime logistics, agriculture, emergency services and financial markets rely on satellite-enabled Positioning, Navigation and Timing (PNT), GNSS integrity, continuous communications, and Earth observation data. Interruptions to these services can lead to cascading failures across essential national systems. This interdependence elevates space systems from mission-specific platforms to indispensable components of national critical infrastructure ecosystems.

The strategic value of space infrastructure is amplified by increasing geopolitical contestation. Satellites now function as both military enablers and potential strategic targets, providing reconnaissance, missile warning, secure communications, and situational awareness (Tedeschi et al., 2022). In this context, cyber threats become attractive because they offer a means to disrupt, degrade, or manipulate services without the visibility or escalation risk of kinetic attacks. This geopolitical environment intensifies the need for intelligence-driven cyber resilience.

While countries such as Australia, the United Kingdom and several in the European Union have begun to explicitly recognise space services as critical infrastructure, others including the United States have not fully codified space within CI legislation, instead emphasising sector-specific voluntary guidance (Vasquez, 2024). The absence of a harmonised global classification framework leads to inconsistent baseline security requirements, non-uniform reporting obligations, and uneven incentives for CTI sharing. This fragmentation inhibits collective threat awareness and slows incident coordination.

The NewSpace environment, characterised by rapid growth in commercial operators, launch providers, subsystem vendors, and downstream service integrators, has expanded the global supply chain significantly (Vollmer, 2021). Commercial operators often enter the market with limited cybersecurity maturity and minimal regulatory oversight. As a result,

- Heterogeneous supply chains create opportunities for covert manipulation of firmware, components and software.
- Varied security practices across integrators increase systemic exposure
- Dependency on commercial ground stations and cloud integrated architectures expands the threat surface (Varadharajan & Suri, 2022)

These supply chain interdependencies mean that vulnerabilities in one noncritical component can exploited and propagate across mission systems or even across operator networks, reinforcing the need for sector-wide CTI coordination.

Unlike terrestrial systems, space assets suffer unique fragility. Once launched, hardware cannot be physically accessed, components cannot be replaced, and compromise events, whether via malicious telecommands, payload manipulation or firmware tampering may be irreversible (Peled et al., 2023). This amplifies the importance of early threat awareness, supply chain assurance, and mission-specific intelligence, making CTI indispensable at design, integration and ground operations phases. The 2022 cyberattack against Viasat's KA-SAT network during the onset of the Russia-Ukraine conflict illustrates this fragility vividly. Destructive interference against ground side modems cascaded into widespread service disruption across Europe, demonstrating how targeted cyber operations can produce rapid, large-scale, and operationally irreversible impacts on satellite-enabled services (Boschetti et al., 2023)

These factors collectively show that space systems occupy a unique position within global critical infrastructure. Their geopolitical sensitivity, operational irreversibility, commercial heterogeneity and multi-sectoral dependencies demand a more structured and intelligence-driven approach to cyber resilience. CTI becomes essential not merely for operational monitoring but for informing architecture decisions, prioritising vulnerabilities, contextualising adversary intent, and aligning cross-operator understanding of cyber risks. Recognising space as critical infrastructure, formally and practically, is therefore a foundational step toward enabling effective CTI-informed resilience.

4. Security Posture and Trends

Space assets are exposed to a diverse threat set, including RF jamming, spoofing, supply-chain tampering, and software exploitation (Tedeschi et al., 2022). The emergence of NewSpace has introduced thousands of small satellites built with commercial components, expanding the potential attack surface (Vollmer, 2021). While COTS adoption accelerates innovation, it imports known vulnerabilities into orbit (Varadharajan & Suri, 2022). Post-launch patching limitations make preemptive, CTI-driven hardening indispensable. Frameworks such as IEEE P3349 seek to codify baseline controls but stop short of defining CTI workflows (Falco et al., 2024).

The security posture of contemporary space systems reflects a convergence of legacy assumptions, rapidly evolving threat-actor capabilities, and structural changes in how space services are designed, launched, and operated. Historically, satellite systems were engineered under the implicit assumption of isolation and physical security; orbital distance and specialised protocols were believed to offer inherent protection (Livingstone & Lewis, 2016). These assumptions no longer hold in the NewSpace era, where increased interconnectivity, commercialisation, software-defined architectures, and cloud-integrated mission systems have expanded the exposure of space infrastructure to cyber threats.

Nation-state and state-aligned groups increasingly view space infrastructure as a strategic cyber target due to its geopolitical significance and the potential for creating widespread disruption without kinetic escalation (Tedeschi et al., 2022). Operations attributed to groups such as Russian state APT demonstrate that satellite-enabled services including broadband connectivity, military communications, and critical civilian infrastructure are viable and attractive targets. This shift has demonstrated the real-world consequences of targeting space-reliant networks, including the potential for widespread service disruption, operational degradation and downstream impacts on civilian and military systems.

The proliferation of small satellites, CubeSat constellations, private launch providers, and space-as-a-service models has diversified the operational landscape. Commercial entrants often lack the longstanding cybersecurity culture found in national space agencies (Pavur & Martinovic, 2022). Variability in vendor maturity creates uneven security baselines across the supply chain, from firmware development to ground operations. This heterogeneity presents systemic risks; the compromise of a single insecure commercial subsystem can propagate across integrated mission environments.

The increasing reliance on commercial off-the-shelf (COTS) components, virtualised ground stations, and cloud-based mission management platforms accelerates innovation and development but introduces familiar IT vulnerabilities into space systems (Varadharajan & Suri, 2022). Publicly documented architectures and firmware interfaces allow threat actors to discover, replicate, and weaponise vulnerabilities pre-launch. Once deployed, patching constraints such as limited uplink bandwidth, operational risks, and strict mission schedules make remediation slow and resource intensive.

Modern satellites increasingly rely on software-defined radios (SDRs), reprogrammable payloads, and flexible bus architectures that can be updated or reconfigured on orbit. While these capabilities enhance mission agility, they also widen the attack surface. Vulnerabilities in update mechanisms, command authentication, or cryptographic key management can enable adversaries to alter payload behaviour or interfere with mission data (Saha et al., 2019).

Ground stations, satellite operations centres, cloud-based TT&C pipelines, and data distribution platforms now form essential components of end-to-end mission architecture (Peled et al., 2023). This creates shared dependencies between terrestrial and orbital systems, making ground nodes attractive targets for attackers seeking scalable impacts. The KA-SAT incident again illustrates how ground-side compromise can cascade into large-scale space service disruption.

The Internet of Space Things (IoST), where satellites, sensors, user devices, and terrestrial systems interact, creates a distributed cyber-physical ecosystem with multiple entry points (Falco, 2019). The growing volume of inter-satellite links, automated crosslink routing, and mesh style constellations increases the complexity of securing communications, trust boundaries, and identity management.

These trends highlight a widening gap between threat-actor capabilities and the current maturity of space cybersecurity practices. The increasingly contested and interconnected nature of the space environment demands not just stronger controls but the ability to continuously update assumptions, detect novel behaviours, and understand adversary motivations. CTI becomes critical to bridging this gap by providing the contextual, adaptive insight needed to interpret evolving attack patterns, prioritise risks, and respond proactively.

5. Cybersecurity Standards and CTI Relevance

Cybersecurity guidance for space systems is shaped largely by terrestrial security engineering frameworks that have been adapted, sometimes only partially, to the unique constraints of orbital environments. While these standards provide essential foundations for secure design, assurance, and operational governance, they vary considerably in scope, maturity, and applicability to space architectures. Importantly, none of the major frameworks currently offer explicit mechanisms for the systematic integration of Cyber Threat Intelligence (CTI), leaving operators to independently interpret how intelligence should inform their engineering, monitoring, and incident-response processes.

A review of existing standards highlights several systemic themes that shape their effectiveness and limitations in supporting intelligence-informed resilience.

- Space operators often adopt a blend of NASA, ESA/ECSS, NIST, or defence-specific overlays depending on contractual obligations, launch location, or vendor preferences. This leads to inconsistent baselines and divergent interpretations of security requirements, complicating cross-operator CTI sharing and coordinated defence activities (Falco et al., 2024) creating a fragmentation of security expectations across jurisdictions and mission types.
- Most standards focus on secure design, testing, and verification, but provide limited guidance on how evolving adversary behaviours should influence ongoing risk assessments, threat modelling, or detection engineering. This is particularly problematic given the dynamic nature of threats against space systems (Kavallieratos & Katsikas, 2023).
- While frameworks outline high-level requirements for monitoring and incident response, they provide limited guidance on how CTI should shape operational telemetry design, anomaly detection logic, cross-segment correlation, and mission-specific threat prioritisation. This lack of integration mechanisms results in reactive rather than intelligence-led security postures.

Against this backdrop, the following table summarises how major space and cybersecurity standards address CTI, or fail to, and highlights the gaps that continue to limit intelligence-informed resilience across the sector.

Table 1: Summary of major space and cybersecurity standards address CTI

Standard / Framework	Primary Focus	CTI Inclusion	Key Gaps
NASA-STD-1006	Space system protection from physical and cyber threats	Absent	No mechanism for threat data ingestion or intelligence-led control design
ECSS-Q-ST-80C	Software product assurance	Absent	Static assurance lacking adaptive intelligence feedback
NIST SP 800-160	Systems security engineering	Partial	Lacks space-specific tailoring and CTI implementation detail
MITRE CREF	Cyber resiliency for critical systems	Implicit	Limited guidance on CTI integration and telemetry mapping
IEEE P3349	Space system cybersecurity trustworthiness	Emerging	Focused on component hardening, minimal CTI automation guidance

6. Literature Synthesis: Threats and CTI Use in Space

The literature shows that cyber threats to space systems arise from a combination of architectural complexity, evolving adversary sophistication, and the persistent integration of terrestrial technologies into orbital environments. Unlike traditional IT systems, space systems involve interdependent segments: ground, link, space, user, and integration layers. Each with distinct threat vectors but also tightly coupled behaviours. The literature consistently highlights three overarching realities:

- Adversaries increasingly target cross-segment dependencies
- Vulnerabilities are frequently introduced long before launch through the supply chain, and
- CTI remains underutilised despite its potential to inform both design and operational defence.

The literature consistently structures threats across control, component, and interface layers, reflecting how adversaries exploit weaknesses not in isolation but along pathways that traverse multiple architectural boundaries.

Research documents Control Layer Threats involving manipulation of telecommands, uplink interference, unauthorised tasking, and degradation of command authority (Bradbury et al., 2020). Attacks at this layer can cause loss of mission control, orbital manoeuvre disruption, or payload misuse. These threats often stem from insufficient authentication, outdated cryptographic implementations, or misconfigured TC interfaces.

Vulnerabilities within satellite buses, payload firmware, and subsystems have been revealed through empirical studies, including experimental security analyses of in-orbit satellites (Willbold et al., 2023). Supply-chain compromise, hardware Trojans, and unauthorised firmware modifications remain critical vectors. The literature emphasises that these Component Layer Threats often originate pre-launch through inadequate assurance processes or opaque vendor components (Varadharajan & Suri, 2022).

Weaknesses in TM/TC links, inter-satellite links, ground-station networks, and cloud-based mission architectures expose systems to Interface Layer Threats such as jamming, spoofing, replay attacks, network intrusion and session hijacking (Peled et al., 2023). With increasing reliance on standardised IP based protocols, attackers are able to adapt known terrestrial attack patterns to space-ground interfaces.

Across all layers, the attack surface has expanded due to IoST, mesh constellations, and software-defined architectures, allowing adversaries to exploit vulnerabilities dynamically across segments.

The following visual threat taxonomy table consolidates threats across architectural layers, synthesising insights from Bradbury et al. (2020), Willbold et al. (2023), Varadharajan & Suri (2022), and Peled et al. (2023). It provides a structured basis for comparing adversary behaviours and identifying CTI-relevant intelligence requirements.

Table 2: Threat Taxonomy Across Architectural Layers

Architectural Layer	Threat Category	Description	Representative Adversary Techniques	CTI-Relevant Intelligence
Control Layer	Telecommand Manipulation	Injection or modification of TC frames to alter spacecraft state or payload activity	Replay attacks, brute-force TC guessing, protocol exploitation	Actor TTPs targeting TM/TC paths; protocol abuse cases; command-set intelligence
Control Layer	Uplink/Downlink Interference	Jamming, spoofing, or signal distortion affecting mission operations	RF jamming, GNSS spoofing, downlink noise flooding	RF threat signatures; geolocation of repeat interference events
Component Layer	Firmware/Payload Tampering	Modification of bus or payload firmware pre- or post-launch	Supply-chain compromise, malicious firmware injection	Supplier intelligence; SBOM-linked CVEs; firmware behavioural baselines
Component Layer	Hardware Trojans	Embedded malicious logic in chips/subsystems	Rogue chip activation, side-channel manipulation	Supply-chain provenance intel; vendor risk profiles
Interface Layer	Ground–Space Link Exploitation	Attacks against TM/TC links, inter-satellite links, or ground–cloud interfaces	Session hijacking, protocol downgrade, MITM attacks	Network-level IoCs; link-layer anomaly indicators
Interface Layer	Ground Segment Intrusion	Compromise of GS networks, SOC systems, cloud mission pipelines	Credential theft, lateral movement, privilege escalation	Campaign intelligence; intrusion-set profiles
User Layer	Terminal Exploitation	Abuse of end-user devices (e.g., VSATs, GNSS units) to degrade or manipulate mission outputs	Modem compromise, user-equipment spoofing	IoT/VSAT threat intel; malware signatures
Integration Layer	PKI/Key Management Compromise	Abuse or leakage of cryptographic keys used across segments	Key extraction, certificate forgery	Crypto-related CTI; key-compromise reports
Integration Layer	Supply-Chain Subversion	Manipulation of components, software, or services during development/production	Counterfeit parts, malicious dependencies	Upstream vendor intelligence; ecosystem monitoring

The literature also identifies a spectrum of adversaries, nation-states, state proxies, criminal groups, hacktivists, and insiders, each motivated by espionage, disruption, competitive advantage, coercion, or opportunism (Maple et al., 2020). Threat actors are also shifting toward campaign-based operations, using long-term intrusion life cycles (Hutchins et al., 2011). These campaigns frequently involve,

- supply-chain infiltration
- credential harvesting across vendor networks
- lateral movement through ground segment infrastructure
- manipulation of command paths or space-ground interfaces

The literature warns that persistent access to any one segment, particularly the integration segment, can allow threat actors to stage complex, multi-step attacks affecting orbital assets.

Despite the breadth of threats, the role of CTI in space cybersecurity remains limited and inconsistent. Current CTI use can be grouped into three domains:

- Design-Time CTI Use: CTI is informally used to identify high-risk components, known vulnerabilities, and adversary TTPs relevant to system architecture. However, there is little evidence of structured processes that integrate CTI directly into threat modelling, requirements engineering, or interface design (Falco et al., 2024). Most CTI inputs occur at late design stages, reducing their value.
- Run-Time CTI Use: Operators primarily use CTI in the form of advisories, IoCs, and vulnerability alerts for patching and defensive monitoring. There is minimal automation linking CTI to detection logic, telemetry schemas, or satellite-specific anomaly-detection baselines (Kavallieratos & Katsikas, 2023). Cloud-integrated ground operations offer more opportunities for CTI-driven detection, but adoption remains inconsistent.
- Governance and Sharing: Space ISACs and cross-agency intelligence exchanges exist but face constraints due to classification regimes, liability concerns, and uneven maturity across participants (Plotnek, J. J., & Slay, J. 2022). These cultural and structural barriers restrict intelligence flow, undermining the collective situational awareness required for resilience.

Across literature, several recurring gaps emerge:

- Lack of structured CTI intake methods for system engineering, interface hardening, or requirements validation.
- Absence of space-specific threat taxonomies that organise adversary behaviours, attack vectors, and segment-specific vulnerabilities.
- Limited integration of CTI into threat modelling tools and architectural patterns used by operators.
- Operational silos limiting intelligence sharing, particularly between commercial and government operators.
- Insufficient automation linking CTI ingestion to configuration updates, detection logic or anomaly models.

Overall, the literature points to a widening gap between the speed and sophistication of space-targeting adversaries and the static, highly manual nature of CTI use in the sector. Although CTI has the potential to significantly strengthen resilience by anticipating adversary behaviour, informing architectural decisions, and enhancing anomaly detection. It is not yet embedded into space system lifecycles in a systematic or measurable manner. This synthesis highlights the need for deeper investigation into CTI integration practices and the barriers currently limiting intelligence-informed resilience.

7. Current Practices

Across the literature and industry reporting, current CTI integration practices in space systems remain fragmented, uneven, and primarily reactive. While operators increasingly acknowledge the value of intelligence-informed defence, the practical application of CTI differs substantially across mission types, organisational structures, and maturity levels. Several themes recur across empirical studies and technical analyses, highlighting how CTI is currently used and where gaps persist.

Most operators employ CTI to support patching cycles, vulnerability scanning, and exposure assessments. Intelligence feeds (e.g., CVEs, vendor bulletins, ISAC alerts) assist in identifying weaknesses in ground infrastructure, cloud platforms, commercial software, and third-party services (Ettinger, 2019; Borges Amaro et al., 2022). However, CTI is rarely embedded into requirements engineering, design reviews, interface assessments, or system-level hazard analyses. As noted by Falco et al. (2024), this results in CTI influencing operational posture but seldom shaping architectural decisions prior to deployment.

National space agencies and defence missions often benefit from classified threat intelligence, geopolitical analyses, and upstream supply chain reporting that offer high-fidelity insights into adversary activity (Bradbury et al., 2020). Commercial NewSpace operators, by contrast, rely heavily on OSINT, commercial feeds or vendor-supplied advisories. This asymmetry is significant, as state actors often possess superior threat visibility compared to the organisations operating high-value orbital assets, particularly in communications, imaging, and IoT-integrated constellations (Maple et al., 2024).

CTI ingestion remains largely manual. Operators rarely automate CTI correlation with telemetry, configuration states, or detection rules. Ground segment SOCs often employ generic SIEM and EDR tools lacking satellite-specific context, leading to gaps in anomaly detection and mission-aware analysis (Varadharajan & Suri, 2022). As a result, CTI seldom informs detection engineering, attack-path evaluation or mission impact modelling, contributing to slow identification of ground side intrusions and incomplete visibility across segments.

Current CTI use is heavily concentrated on terrestrial infrastructure, malware alerts, credential-theft campaigns, and intrusion-set profiling reflecting where most adversary activity is detectable (Peled et al., 2023). However, CTI is infrequently applied to orbital-specific risks such as payload manipulation, inter-satellite link exploitation, onboard firmware anomalies, or telecommand authentication weaknesses. Literature consistently notes that the orbital domain remains underrepresented in intelligence-led planning (Willbold et al., 2023).

Space ISACs, cross-agency groups and vendor led forums have emerged to facilitate CTI exchange but participation is inconsistent and heavily influenced by cultural and legal constraints. Liability concerns, classification regimes and reputational risk reduce transparency particularly among commercial operators and international partners (Plotnek, J. J., & Slay, J. 2022; Vasquez, 2024). Consequently, shared intelligence often consists of high-level advisories rather than actionable indicators or behavioural insights.

A small number of operators are beginning to adopt more advanced CTI practices, including:

- Monitoring adversary interest in specific missions, sectors, or payload types
- Integrating CTI into supplier assurance and supply chain vetting
- Using CTI to forecast targeting likelihood during geopolitical escalation (Tedeschi, 2022)
- Incorporating CTI into pre-launch red team scenarios and validation exercises.

These practices remain exceptions but reflect early movement toward a more strategic use of intelligence.

Commercial NewSpace operators are disproportionately reliant on opensource and commercially available CTI, resulting in a broader but less curated threat picture. In contrast, traditional agencies benefit from high confidence classified intelligence but face integration and dissemination constraints. This divergence creates fundamentally different challenges in operationalising CTI for resilience.

Table 3: CTI Consumption Models. Traditional vs NewSpace

Dimension	Traditional Agencies	Commercial NewSpace
CTI Sources	Classified intel, government sharing	OSINT, commercial feeds, vendor intel
Timeliness	Often delayed but high fidelity	Near real time but variable quality
Integration	Structured, policy-driven	Ad hoc, tool driven
Security Posture	Risk-averse, compliance-heavy	Agile, speed to market focused
Automation	Limited due to classification constraints	Increasing but immature
Threat Coverage	Nation-state focused	Broader cybercrime, supply chain, opportunistic attackers

Overall, CTI use in space systems remains predominantly reactive, ground centric and reliant on manual workflows. Few operators leverage CTI to anticipate adversary behaviour, drive architectural decisions, or develop mission-specific detection logic. These limitations reinforce the sector's reactive posture and directly inform the barriers examined in the next section.

8. Barriers to CTI-Informed Resilience

Barriers to the systematic integration of Cyber Threat Intelligence (CTI) into space system security and resilience emerge across organisational, technical, and regulatory dimensions. These obstacles collectively contribute to the fragmented, reactive posture observed across the current space-cybersecurity landscape.

8.1 Organisational Barriers

Space missions traditionally separate disciplines into engineering, operations, mission assurance, and cybersecurity silos. This division creates misalignment around CTI ownership, interpretation, and operational use. In many organisations, no single role or team is responsible for translating intelligence into engineering or operational decisions, resulting in CTI being consumed passively rather than operationalised (Ahmad et al., 2023).

Moreover, CTI often competes with mission priorities such as launch schedules, payload performance, and cost efficiency. For commercial operators, time-to-market pressures and resource constraints further reduce incentives for integrating CTI into early design phases. The literature also highlights **workforce limitations**, particularly the shortage of personnel who understand both space mission architecture and intelligence-led cybersecurity (Kavallieratos & Katsikas, 2023). This skills gap makes it difficult to maintain continuous CTI analysis or embed intelligence into engineering reviews.

Trust barriers also play a role. Within multinational missions or consortia, partner organisations may hesitate to share sensitive intelligence due to reputational or liability risks, even when that intelligence would enhance collective resilience (Falco et al., 2024). This constrains situational awareness across the ecosystem.

8.2 Technical Barriers

Technical constraints significantly hinder the operationalisation of CTI across space systems. Most space operators rely on manual review of advisories and threat reports. Few possess systems that automatically correlate CTI with telemetry, system configurations, or known attack vectors. This limits the ability to rapidly detect emerging threats or adapt defences in real time (Borges Amaro et al., 2022).

Space systems typically incorporate diverse subsystems, proprietary protocols, and custom interfaces sourced from multiple vendors across long supply chains. This results in inconsistent security baselines and complicates the integration of standardised CTI-driven controls. As observed in recent experimental research, even satellites using widely adopted COTS components exhibit inconsistent firmware protections and update mechanisms (Willbold et al., 2023).

Onboard computing and power availability limit the deployment of advanced telemetry collection, real-time analytics, or autonomous CTI-driven defensive actions. Satellites also operate under strict bandwidth restrictions, meaning that CTI-relevant data (e.g., anomaly traces, system logs) may not be transmitted to the ground at the fidelity needed for threat analysis (Varadharajan & Suri, 2022).

Space architectures rely on dynamic, interdependent interactions between ground facilities, satellites, user terminals, cloud-based mission systems, and commercial communication networks. The absence of unified monitoring mechanisms prevents CTI-informed correlation across segments, making it difficult to detect attacks that traverse boundaries, such as ground-to-orbit exploitation or compromised user terminals influencing mission operations.

8.3 Regulatory and Policy Barriers

CTI integration also depends heavily on broader governance structures and legal frameworks. Several key issues arise.

Different jurisdictions vary in whether they classify space systems as critical infrastructure. Countries such as Australia and the UK recognise space as critical infrastructure, whereas the United States has historically avoided formal designation (Bradbury et al., 2020; Vasquez, 2024). These inconsistencies create mismatched obligations for reporting, incident disclosure, and CTI sharing.

International Traffic in Arms Regulations (ITAR), national security classifications, and commercial confidentiality all limit how much intelligence can be shared between partners. Such restrictions can prevent operators from accessing high-fidelity intelligence about threats that directly target their own systems (Jakhu & Pelton, 2017).

While initiatives such as IEEE P3349 and guidance from CISA aim to increase consistency, they remain voluntary or fragmented across agencies. Without mandatory CTI-sharing requirements or standardised exchange formats, intelligence dissemination remains informal and uneven (CISA, 2024).

Operators may hesitate to share detailed incident data because doing so could imply security deficiencies, trigger regulatory scrutiny, or expose them to contractual penalties. The absence of legal safe-harbour provisions for space-related CTI sharing exacerbates this reluctance.

Collectively, these barriers demonstrate that CTI integration depends as much on organisational culture and international governance as on technological capability. Overcoming them will require coordinated evolution in policy, engineering practices, information-sharing norms, and investment in mission-aware intelligence processes. The effectiveness of CTI-informed resilience is therefore contingent not only on better data, but also on the ecosystem's ability to translate that intelligence into consistent, shared and actionable security practice.

9. Discussion and Implications

The analysis demonstrates that effective CTI integration demands embedding intelligence as part of systems engineering rather than post-incident analysis. The implications extend beyond technology, requiring governance realignment, international trust frameworks, and sustained investment in CTI automation. Continuous CTI-fed resilience engineering can shift organisations from reactive patching to predictive defence.

Trade-offs emerge around autonomy, bandwidth, and data classification. Balancing these against resilience goals requires risk informed decision-making, and cross sector collaboration (Tedeschi, 2022). For policy makers, CTI integration highlights the urgency of harmonised standards and reciprocal disclosure agreements.

10. Conclusion and Proposed Research Agenda

This study examined two central questions: how CTI is currently used within space system security and what organisational, technical and regulatory barriers limit CTI-informed resilience. The analysis demonstrates that CTI adoption in the space sector remains fragmented and uneven, with most applications concentrated in terrestrial infrastructure and post disclosure vulnerability management. Intelligence rarely influences architectural decision making, interface assurance or mission specific detection logic, leaving a persistent gap between strategic awareness and operational practice.

Barriers across organisational structures, technical constraints and regulatory environments further limit the systematic integration of CTI. These obstacles reinforce a predominantly reactive security posture at a time when threat actors, geopolitical tensions and rapid commercial expansion are accelerating cyber risk across the space domain.

By synthesising trends across the existing literature, this paper establishes a foundation for understanding the role CTI should play in shaping resilient space systems. To support this transition, this paper introduces the **Operational Resilience through Behavioural Intelligence and Threat Integration (ORBIT)** framework as a conceptual workflow for operationalising CTI into adaptive, mission aware security processes.

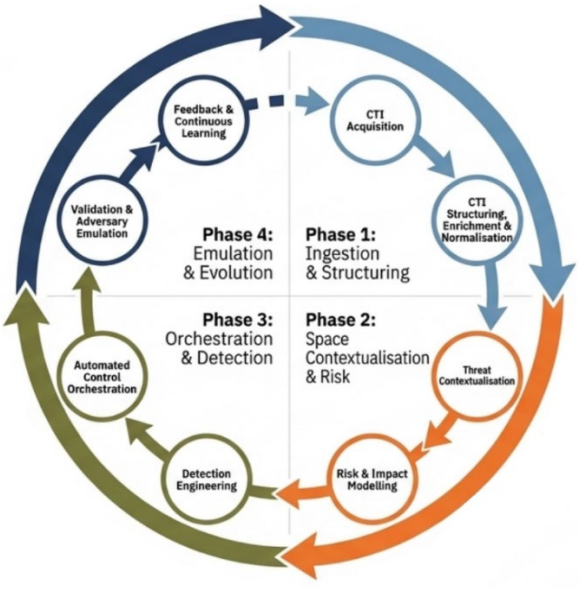


Figure 1: ORBIT Workflow Phases

Building on this foundation, addressing the identified gaps requires a structured research agenda focused on advancing the automated translation of CTI into detection and response controls, developing space specific threat modelling approaches that contextualise intelligence across ground, space and communication segments and extending existing frameworks to better reflect space system behaviours. Further research is needed to establish trust and validation mechanisms for automation in safety critical environments, enable effective integration of diverse intelligence sources and define measurable resilience metrics such as detection coverage and the latency between CTI ingestion and control deployment.

Taken together, these findings highlight the necessity of treating CTI not as an adjunct capability, but as a core architectural input to securing the space domain. Advancing this field will require a shift from reactive, manually

driven practices towards adaptive, intelligence-led resilience capable of evolving alongside both the threat landscape and the critical services that space systems underpin.

Ethics Declaration: Ethical clearance was not required for this research in accordance with institutional and national guidelines, as the study did not involve human or animal subjects, nor the collection of personal or sensitive data.

AI Declaration: AI assisted technologies were used only for proofreading and language refinement. They did not contribute to the conceptual development, methodological design, data analysis, or interpretation of results. The author retains full responsibility for the accuracy and integrity of the work.

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‘What’s in a Name?’: How Does the UK Government and Media Construct Cyber Actors?

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Abstract: Understanding how cyber actors are labelled is important to effectively respond to cyber threats. It has been suggested that cyber is becoming increasingly connected to national security concerns, a process called securitisation. This research sought to take a first step towards understanding if securitisation is occurring through examining the evolving conceptualisation of cyber actors in the UK. The research reviewed cybercrime reporting from the UK Government and three UK media websites between 2019-2023, taking a mixed methods approach using thematic analysis to group cyber actors, and content and statistical analysis to detect shifts in these categorisations. The research identified six primary categories used to conceptualise cyber actors: Attackers, Companies, Criminals, White Hats, Hacktivists, and Nation States. The research identified significant changes in multiple subcategories between 2019-2023, influenced by events such as COVID-19, the 2021 Colonial Pipeline ransomware attack, and the changing geopolitical landscape. Notably, there was an increased tendency to associate cyber actors with nation states, particularly evident following the Colonial Pipeline attack which correlated with a shift towards linking cybercrime groups to states, and the 2023 TikTok ban on government devices which saw an increase in companies conceptualised as state influenced. The results also suggested the type of act does not always determine the perception of cyber actors, instead geopolitics appears to have greater influence on conceptualisations. The research additionally found that terms for cyber actors (such as Hackers) are often used loosely and interchangeably. Furthermore, the categories of actors formed a spectrum, especially blurring distinctions between state and criminals. The research recommends organisations consider language around cyber actors more carefully. Further study is recommended to understand if the results found are evidence of securitisation of cyber actors or a consequence of increased state cyber activity.

Keywords: Cybercrime, Securitisation, Fear discourse, Cyber actors

1. Introduction and Background

In Shakespeare’s Romeo and Juliet, Juliet famously asked “What's in a name? That which we call a rose by any other name would smell as sweet”. To contradict Juliet, distinct and well-defined names are important. Varying names for threats can lead to confusion and being unclear on how to respond (Furnell, 2021). In understanding cybercrime an important step is attribution, identifying or naming the actors responsible for specific acts, helping to defend against future incidents by understanding the motivation and tactics of specific actors (DiMaggio, 2022). Attribution is also needed to ensure correct societal responses, yet terms for cyber actors are often used interchangeably (for example, terrorist and criminal) risking disproportionate legal responses (Cap, 2017). Continuing the Shakespeare analogy; not only is a rose being called by multiple names, but other flowers are being called a rose.

When a term or label has no universal definition, it can function as a boundary object; acquiring different meanings across various social groups while maintaining enough commonality for it be used between the groups (Bowker & Star, 2008). One such boundary object is the term National Security, traditionally used in the military context, to defend against an existential threat to the state, it has been expanded to include a wider range of threats (for example, to the economy, environment and society); a process called securitisation (Buzan, Waever and Wilde, 1998). This can set a dangerous precedent as defining something a national security threat legitimises responding with emergency measures, which can take place outside of established political oversight mechanisms (Buzan, Waever and Wilde, 1998). It has been argued there is an increase in the media portraying cyber incidents as a security concern (Boholm, 2021; Zeffiro et al., 2022), with the process of progressively framing cyber issues as an extreme security concern is a known method of securitisation in cyberspace (Hansen & Nissenbaum, 2009).

This paper does not seek to determine if securitisation of cyber actors is occurring in the UK, but to explore if the conceptualisation of cyber actors has shifted, which might be an indication of securitisation. The paper seeks to understand how the UK views cyber actors, if this changed between 2019 to 2023 (a period with a number of events that could be seen as existential threats to the UK) and what factors might have influenced those changes. The paper puts forward a typology for actors, developed from UK perceptions of actors, laying a foundation for further research.

1.1 How are Cyber Actors Viewed?

The predominant portrayal of a cyber actor is of a hacker, often viewed as a lone, young, male, computer genius (Yar and Steinmetz, 2019). The term hacker is often viewed negatively, frequently used interchangeably with criminal and terrorist (Cap, 2017). Sometimes hackers are presented as either *Black Hat* ("bad"), *White Hat* ("good") or *Grey Hat* (somewhere in-between) (Yar and Steinmetz, 2019) whilst allowing for more nuance than only a negative view, it is an oversimplification.

1.2 How are Cyber Actors Categorised?

One of the most common approaches to categorising cyber actors is through a cybersecurity lens. Commercial threat intelligence companies group the Tactics, Techniques and Procedures (TTPs) from incidents into named cyber groups (DiMaggio, 2022). These companies often have their own naming conventions with different attribution frameworks that may not align with each other (Lemay et al., 2018). Additionally, the information used to categorise is often from confidential sources which can create validation issues (Lemay et al., 2018). Grouping actors by TTPs may be useful for clients of specific threat intelligence companies, however doing so creates issues comparing cyber actors between companies and in independently validating the cyber actor groupings.

Another common approach to categorisation in cyberspace is through motivation. Yet motivation can be multifaceted and differ between what society and what actors themselves say the motivation is (Yar and Steinmetz, 2019). Prevalent motivations can also change, Furnell (2021) noted financial and political motivations have become dominant since 2001. Concentrating on motivation also fails to capture the complexity of the actor, such as states undertaking financially motivated attacks (DiMaggio, 2022).

Rather than broad typographies, academic discussion around categorising cyber actors tends to focus on discrete terms. However, within the terms there is disagreement over definitions. For example, for the term Organised Crime there is debate around the extent cybercriminal groups online can be considered "organised" (Lavorgna & Sergi, 2016), and Hacktivism is subjective to the person categorising the activity, deciding if it is hacktivism or terrorism (Yar & Steinmetz, 2019).

Even if there were universally agreed upon terms for cyber actors, it requires an understanding of who performed an incident to be able to apply a term to an act. Attributing cyber incidents is imprecise, with high levels of uncertainty (DiMaggio, 2022). Beyond the technical challenges, the decision to publicly attribute, and framing of cyber actors behind incidents, is a political tool (Egloff, 2022). The state is often attributed a level of responsibility for cyber actors within their jurisdiction (Healey, 2012) and others frame cyber actors in terms of their proximity to the state (Egloff, 2022). This creates the potential for multiple interpretations of cyber actors; who *undertook* the act, and who is *responsible* for the act.

Ultimately, there are multiple perspectives for understanding cyber actors depending on the needs of the person undertaking the typology. More fundamentally, there are challenges in attributing level of responsibility to actors.

2. Methodology

The research applied a mixed methods approach, taking an exploratory sequential design. First, thematic analysis was undertaken to understand the conceptualisation of cyber actors. Quantitative content analysis was then applied to the categories derived from the thematic analysis, to identify if changes had occurred between 2019-2023.

Sources from both government and media were used to capture a range of dialogues. Media reporting was taken from the top three news brands in the UK by engagement; BBC News, Mail Online and The Guardian (Majid, 2023). His Majesty's Government (HMG) reporting was taken from the 'News and Communications' section of the Gov.UK website for the topics 'cyber security', and 'crime, justice and law'. For the latter, as there was no sub-topic for cybercrime, a filter for the specific terms ('cyber', 'computer' or 'online') was applied. Reports were then filtered to remove articles that were not relevant (such as not alluding to a cyber actor in the article).

Reporting was taken from 01 April 2019–31 March 2023, selected to include a timeframe before COVID-19 impacted the UK as it has been observed that some forms of cybercrime have changed since COVID-19 (Wall, 2021). Furthermore, it encompasses multiple geopolitical events which may have influenced the perception of cyber threats, such as the 2022 Russian invasion of Ukraine and heightened tensions in the Indo-Pacific region (Cabinet Office, 2023).

Theoretical thematic analysis, inductively coded for latent themes, was undertaken to develop the categories of cyber actors. The thematic analysis following the six stages put forward by Braun and Clarke (2006). Results from the analysis were used to create categorisations of the cyber actors, with the same data re-analysed using quantitative content analysis. Trend graphs were created from the content analysis to visually identify trends. Specific events were identified through observing spikes in frequency or changes in trends. Articles around these time periods were reviewed for mention of events that may have generated the change.

Table 1: Summary of the six stages of thematic analysis. Edited from Braun and Clarke (2006)

Stage	Description
Data familiarisation	Reading and re-reading, noting initial ideas to gain an in-depth understanding of the data.
Initial code generation	Systematic coding of the data, identifying pertinent features.
Searching for themes	Collation of codes into themes.
Reviewing themes	Refining the themes, checking for internal homogeneity within each theme and external heterogeneity between themes.
Defining and naming themes	Developing analysis for each theme, understanding the 'story' it tells. Generating definitions and names for the themes.
Producing the report	Integrating the analysis with research questions and literature, selecting compelling data extracts.

3. Results

The analysis suggests that HMG and the UK media conceptualise cyber actors in six broad categories: Attackers, Companies, Criminals, White Hats, Hacktivists, and Nation States, with each category having further sub-categories (Table 1). Whilst each category was distinct, categories were frequently associated with each other. For example, in articles with actors categorised as *Nation State-Criminal State*, 32% also mentioned *Nation State-Hacking Groups* and 24% mentioned *Criminals-State Approved*. Likewise, in 20% of the articles referencing *Companies-State Influenced*, *Nation State-Hostile State* were also discussed.

There is a variety of terms used to refer to the same actor, six of the articles reviewed used eight different terms for a single actor within the article. Despite this range of terms, hacker appears as the prevalent term for cyber actors, found in 46% of articles, and used in all categories except for the sub-category of Sexual Perpetrators.

Table 2: Categories of cyber actors

Category	Sub-category	Description
Attackers	Vandals	Individuals or groups who undertake petty or nuisance acts
	Immature	Individuals or groups not understanding the impact of their actions. Usually in reference to teenage boys.
	Personal Malicious	Individuals with personal motivations beyond financial, often with reference to revenge, bullying, or hate crimes.
	Ideological Malicious	Political or ideologically motivated, but not portrayed as activists
	Sexual Perpetrators	Individual sexual perpetrators. Includes judgements about their behaviour being predatory, repulsive, or abusive.
Companies	Mercenary	Private companies acting as mercenaries, providing Nation States with sophisticated cyber tools and/or weapons.
	Amoral	Companies that facilitate criminal activity through inaction or negligence. Often in reference to 'Tech Giants'.
	State Influenced	Companies that are heavily influenced by, or beholden to, a Nation State.
Criminals	State Approved	Organised groups of professional and experienced criminals with links to a Nation State. Often unscrupulous in targeting of their victims.
	Syndicate	Network of criminals that work together. Implies or refers to 'Crime as a Business' and professionalisation.
	Opportunistic Predatory Gangs	Opportunistic and predatory criminal gangs. Able to exploit vulnerabilities in technology or use advanced technology. Unscrupulous and devious, preying on or exploiting victims.

Category	Sub-category	Description
	Sophisticated Gangs	Serious and organised criminal gangs, undertaking sophisticated hacks.
	Cyber Thieves	Individual or multiple people undertaking, usually money or cryptocurrency, heists. Referred to as sophisticated criminal masterminds.
	Lavish Playboys	Individuals showing off their ill-gotten gains. Overt displays of excessive wealth.
	Amateur	Amateur criminals, using unsophisticated techniques or are seen as being incompetent (such as not planning how to evade detection).
	Underground Hackers	Nefarious underground hackers, operating in the shadows. Anonymously operating as individuals or as a community.
White Hats	Ethical Hackers	Hackers working ethically, helping find vulnerabilities for the challenge or the greater good.
	Treasure Hunters	Financially motivated hackers working to help people.
Hacktivists	Vigilantes	Individual activists or vigilantes.
	Political Collectives	Group of hackers working together for a cause.
Nation State	Cyber Warriors	Friendly nations undertaking legal and responsible operations or offensives to hunt the 'bad guys'.
	Hacking Groups	Highly skilled and sophisticated hacking groups directly connected to a nation state.
	Hostile State	Referring to the state itself as an irresponsible and hostile cyber power. Perceived as a national security threat.
	Contracted Hackers	Proxies acting on behalf of a state, contracted or mercenary actors.
	Criminal State	States undertaking crime or using criminal actors to undertake criminal acts.
	Unethical State	States using cyber for perceived unethical reasons, such as hiring mercenary companies to spy on dissidents or spreading general disinformation.

The conceptualisations of cyber actors changed noticeably between 2019-2023 (Figure 1). A brief description of the categories, and significant changes within the larger categories are outlined below.

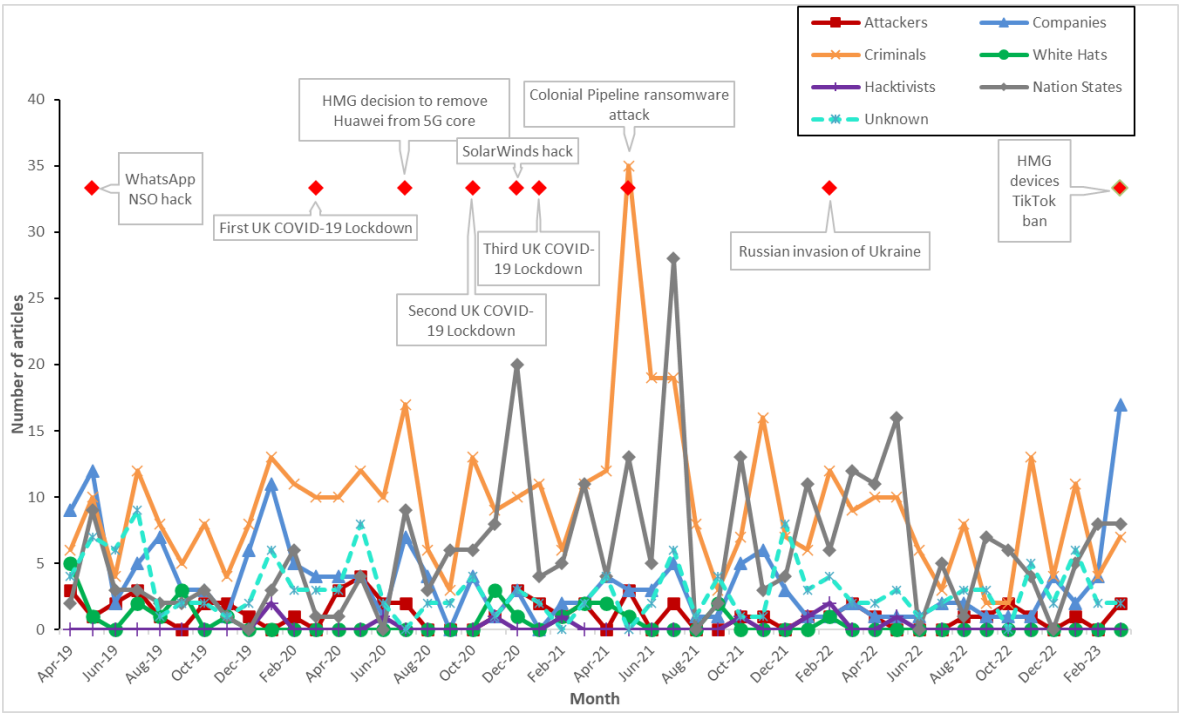


Figure 1: Frequency of articles coded with main categories of cyber actor between April 2019 to March 2023

3.1 Attackers

The Attackers category is predominantly driven by non-financial motives. This category is the most amorphic, more clearly defined by what it is not; they are not financially motivated, nation states, activists, or part of a

collective. Attackers are seen as individual or small groups who are not part of a wider community. They are often referred to by terms such as perpetrator, attacker, or offender, rather than criminal or hacker. Attackers are usually identified as an individual, supplemented with information on their career or education.

3.2 Companies

Companies are seen as being nefarious by the nature of their business (Mercenary), by their actions (Amoral), or that they are unable to be trusted by their provenance (State Influenced). Companies are referred to as an entity in themselves rather than individuals within it. Frequently, articles about companies are accompanied by debates on law and regulation, often looking to tighten rules or introduce new restrictions. Mercenary and State Influenced companies are often seen as proxies for nation states, with most criticism leveraged against the controlling nation. Whereas, for Amoral companies the blame is laid on them, often implying the company was negligent.

All three sub-categories of Companies were found to have significantly changed between 2019-2023. A spike in the portrayal of State Influenced companies correlated with HMG's ban on TikTok (a Chinese company) on its devices. This spike is particularly notable when compared to the similar reporting on HMG's July 2020 decision to remove Huawei (another Chinese company) from the 5G core.

3.3 Criminals

Criminals is the largest category (represented in 46% of the articles), with the actors being construed as criminal. These actors are referred to by multiple terms (for example, hacker, criminals, attackers, fraudsters), with each sub-category having between six (for Amateur) to 33 (State Approved) terms used to refer to actors within it.

Criminal conceptualisations of Generic Group and Sophisticated Gang peaked at the time as the Colonial Pipeline attack, giving rise to State Approved group conceptualisations shortly after. The Colonial Pipeline attack also correlated with changes in how criminal groups are conceptualised, shifting from Generic Groups towards Sophisticated Gangs and State Approved. References to Opportunistic Predatory peaked around the first COVID-19 lockdown but maintained frequent smaller spikes until the summer of 2022 after which its usage declined.

3.4 White Hats and Hacktivists

White Hats and Hacktivists are similar groups, their activities are not seen as criminal (although, this does not mean they are not breaking the law) or as working for a nation state. White Hats are viewed as performing legal hacks to help people (Ethical Hackers) or for financial gain (Treasure Hunters). They are often described as professional and experts, with Ethical Hackers frequently referred to as Security Researchers. Hacktivists are seen as acting unlawfully but with their actions being morally guided, they are not seen as receiving any personal gain. Vigilantes are identified as individuals acting from a perceived injustice, while Political Collectives are closer to the original idea of Hacktivists being political activists and are viewed as a group of hackers acting together for a perceived just cause.

3.5 Nation State

Nation States are viewed as powerful actors in cyberspace, HMG aligns states as being responsible (Cyber Warriors) or irresponsible cyber powers. States are often referred to as being 'prolific' in their hacking and 'sophisticated' in their techniques, performing hacks that civilian companies are unable to defend against. The state is frequently referred separately from the employees (Hacking Groups) or proxies hired (Contracted Hackers) to undertake the hacking. Unethical States are often associated with Companies-Mercenary and are accused of spying on their own people or dissidents living abroad. Criminal States are accused of hacking for monetary gain, often linked with bypassing financial sanctions or passing intellectual property to their own companies. Hostile States are seen as aggressive and enemies of the UK, conducting espionage or destructive attacks, often threatening critical infrastructure.

4. Discussion

The results suggest that there is no clearly defined terminology used to refer to cyber actors, supporting earlier findings that terms are being used interchangeably and indiscriminately (Cap, 2016). Whilst hacker was the prevailing term used; it was still only used in less than half (46%) of the articles. However, the prevalence of the term hacker across multiple categories (found in all sub-categories except Sexual Perpetrator), suggest it has become a boundary object for the categories (Bowker and Star, 2008) having multiple interpretations but retaining the common identity of a cyber actor.

Whilst distinct categories can be seen in the categorisation of cyber actors, there are blurred boundaries between actors. The lack of distinction is especially prevalent where there is a state-criminal nexus or proxy actors. This was seen in the reporting of the Colonial Pipeline attack; Nation State sub-categories of Hacking Group and Contracted Hackers spiked alongside Criminals-State Approved. These categories can be viewed as being on a spectrum of delegation from a state: Hacking Groups directly employed, Contracted Hackers under active direction but with looser ties, and Criminals-State Approved receiving passive sanctioning of their activities. The three categories spiking simultaneously suggests articles conceptualised the attack differently, potentially deciding on different points along the spectrum to report them. This finding may also suggest different conceptualisations of who is *responsible* for the act (i.e. determining state responsibility (Healey, (2012) versus the criminals who undertook the act). Further research is required to determine why these differences in conceptualisation occur.

The type of cyber act perpetrated did not bear directly onto the conceptualisation of the cyber actor. In news reports, for example, ransomware incidents were categorised as being performed by a variety of Criminals and Nation States sub-categories, likewise multiple types of Criminals were accused of fraud or scams. These changes may be reflective of the shifting perceptions of who the cyber actors are that are undertaking different acts, for example the rising tensions with Russia between 2019 to 2023 (Cabinet Office, 2023) may have influenced perceptions of ransomware groups. This suggests TTP based typologies, which focus on technical elements such as the tactics used, may not be useful to understand how we conceptualise threat actors.

Changes in geopolitics impacting the UK (Cabinet Office, 2023) were reflected throughout the articles. Criminals shifted from being referred to as Generic Groups to increasingly labelled as State Approved; for example, in referring to the ransomware group Sodinokibi (also known as REvil) The Guardian referred to the group in January 2020 as simply a "*ransomware gang*" (Jones, 2020) however in June 2021 described them as "*…a flourishing, aggressive group of primarily Russian native speakers based in a former Soviet state and enjoys protection by Russian intelligence or the Russian government*." (Hern & Villarreal, 2021). This changing perception was also evident in the category of Companies. The reporting around the 2023 HMG ban of TikTok on government devices saw almost triple the portrayal of Companies-State Influenced compared with the 2020 ban of Huawei in UK's 5G Core, reflecting the changing language on Chinese influence (Cabinet Office, 2023). Whilst these may be an indication of securitisation, progressively framing events as security concerns (Hansen & Nissenbaum, 2009), it may also be reflective of an increase in nation state cyber activity.

5. Conclusion

To respond to Juliet's question 'What's in a name'; there is a complex interaction between geopolitical events, technological and political considerations with attribution, securitising speech acts, and blurring distinctions in a name. A name is not static. Between 2021-2023, HMG and the UK media constructed cyber actors under six broad categories: Attackers, Companies, Criminals, White Hats, Hacktivists, and Nation States, and presented a changing narrative in their depictions of cyber actors, influenced by events including COVID-19 and the changing geopolitical landscape.

Geopolitics had a strong influence on perceptions of cyber actors in the UK, the articles during key events often blurred the distinctions between state and criminals or companies, which may suggest securitisation is occurring to the conceptualisation of cyber actors, or it may reflect the changing threat landscape. Further research should be undertaken to understand what areas, if any, securitisation has occurred.

The results suggest the common depiction of cyber actors as hackers remains, although multiple terms for cyber actors are used, often loosely and interchangeably. The lack of a common terminology is compounded by reporting using different categorisations of actor for the same event, or for the same actor in different events. Varying names for threats can lead to confusion (Furnell, 2021), and use of ambiguity and terms with negative connotations may cause anxiety (Boholm, 2021). Organisations should decide on specific terms to use for cyber actors and carefully consider connotations with the terms used.

By identifying how the UK views cyber actors this research has provided a typology to categorise and track further changes in reporting on cyber actors. Understanding the changes in representation of cyber actors between 2019 and 2023 indicate a shift in perceptions, laying a foundation for further research to identify why these changing perceptions have occurred.

Ethics declaration: Ethical clearance was not required for the research.

AI declaration: AI tools were not used in the creation of this paper

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Beyond Obscurity: Developing CubeSat Cybersecurity

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Abstract: As modern space systems, particularly CubeSat constellations, are increasingly embedded in defence, industrial, and civilian operations, fulfilling an increasingly vital role in telecommunications, earth observation, and national security, their vulnerabilities to cyberattacks continue to grow. Despite the advantages of CubeSats; cost-effectiveness, scalability, and enhanced coverage; as satellite providers attempt to maximise payload capabilities, these systems are fundamentally constrained by Size, Weight, and Power (SWaP), imposing significant design trade-offs that limit onboard security. This has contributed to emerging U.S. national security requirements for commercial satellites supporting defence missions to implement real-time on-board intrusion detection and prevention systems forcing cybersecurity for satellite vendors to no longer merely be a desirable design feature, but an explicit mission-assurance and acquisition requirement for space systems used to support national security. This paper examines the growing cybersecurity risks faced by CubeSat constellations, focusing primarily on multi-stage attacks—complex sequences of interrelated behaviours that may appear individually benign but are collectively malicious. Where existing terrestrial intrusion detection systems have succeeded, they lack the distinctive dynamics of satellite networks, and publicly available satellite-oriented datasets to achieve the same success in the space domain. This necessitates the development of bespoke, packet-level datasets for effective cybersecurity modelling. To address the immediate need for enhanced resilience while bespoke datasets are developed, Through the review of existing cybersecurity measures and the integration of machine learning-based solutions, we propose a preliminary cybersecurity framework based on self-supervised learning. This approach uses contrastive learning to produce a nominal operational profile of the satellite's systems. This profile serves as a baseline for an onboard anomaly detection system, aiming to identify deviations that could indicate a cyberattack. By developing adaptive intrusion detection systems (IDS) that prioritise resource conservation, we aim to enhance CubeSat security in future space missions, ensuring both operational integrity and data confidentiality. Furthermore, we propose the development of a minimum cyber resilience capability checklist, accompanied by a standardised testbench. This testbench would provide analogous testing to vacuum and vibration tests common in satellite engineering, covering core, low-cost, high-reward attack vectors such as authentication and encryption vulnerabilities, fuzzing, replay attacks, and Denial of Service (DoS). The results would be delivered to the satellite owner or producer in a simple pass/fail format, identifying which tests failed and recommending standard methods to mitigate the identified vulnerabilities. This framework aims to establish a foundational and verifiable level of cyber resilience for CubeSat missions.

Keywords: Space system cybersecurity, Satellite cybersecurity, On-board intrusion detection systems, Self-supervised learning, CubeSat constellations

1. Introduction

The rapid expansion of the space sector, often termed "New Space", has seen a significant shift from large governmental projects to the small satellite domain, where industry and academia exist as principal drivers. This proliferation is largely driven by CubeSats: compact satellites, typically nanosatellites, comprising modular 10cm³ (1U) units leveraging commercial off-the-shelf (COTS) components, such as Field-Programmable Gate Arrays (FPGAs) and Software-Defined Radios (SDRs). These small, comparatively cost-effective satellites are often deployed in Low Earth Orbit (LEO) constellations, allowing for global coverage and seamless data collection across vast geographical areas (Sweeting, 2018). CubeSats are affordable for academia, offering high sensing resolutions and low latencies, and when designed to be homogeneous; sharing common hardware, software, and mission objectives, constellations, provide industry with greater geographical coverage and redundancy at a cost comparable to larger satellites. This evolving space ecosystem enables CubeSats to be used in a variety of applications critical to national infrastructure, including positioning, navigation, and timing (PNT), for GPS and financial tracking, earth observation for agricultural and climate monitoring, communications for global internet access, and scientific research (Manulis et al., 2021). From the critical services outlined, this makes satellite systems an integral part of critical infrastructure even if only as an enabler.

Despite their growing prominence, CubeSats are inherently vulnerable to cyberattacks that could compromise their functionality, leading to significant risks to the integrity of space missions and national security. The surge

in satellite deployments has inadvertently increased the attack surface of the space domain, making it an increasingly attractive target for cyber adversaries. Of particular concern is the rise of sophisticated multi-stage cyberattacks. These attacks involve an ensemble of attack steps, often chaining multiple single-stage attacks into complex sequences of interrelated behaviours. These steps may appear individually benign and are difficult to detect in resource-rich terrestrial environments, let alone in the resource-constrained, physically inaccessible, and radiation-battered environment of space. With limited power budgets where critical sensors and payloads take precedence, CubeSats are often deployed with limited defence capabilities due to perceived security through obscurity and physical inaccessibility, resulting in an attack surface collectively representative of enterprise networks without the power and processing to match. These attacks are harder to detect than single-stage attacks, as each step may seem innocuous on its own, but forms part of a larger operationally or physically destructive sequence (Gupta & Mishra, 2020), asymmetric to conventional warfare. Furthermore, CubeSats operate in highly resource-constrained environments, with limited computational power, storage, and energy due to their strict Size, Weight, and Power (SWaP) limitations (Weston *et al.*, 2025). These constraints make it difficult to implement traditional cybersecurity defences designed for more powerful systems, necessitating a new approach to CubeSat security. For example, the recent cyber attack on ViaSat's satellite network started with the exploitation of a virtual private network (VPN) vulnerability of several Gateway Earth Stations in ViaSat's ground segment (Boschetti et al, 2022). The adversary penetrated the demilitarised zone (DMZ) and then tunnelled through the trusted management network to the end users' modems. In the final stage of the attack, the deployment of a wiper malware disabled approximately 40,000 modems across multiple countries. This spillover effect outside of Ukraine, whether by mistake or through the selection of intersecting geographic zones, also resulted in one fifth (5,800) of Germany's wind turbines defective for control intervention. This has finally led to the U.S. (Committee on National Security Systems, 2025) requirement that cybersecurity be fully integrated across the lifecycle of space systems used to support national security missions, with real-time on-board intrusion detection and prevention forming part of the minimum defensive capability expected of such platforms. As a result, intrusion detection should be viewed not simply as an optional safeguard, but as a core requirement for mission assurance in security-sensitive satellite systems.

2. Analysis

2.1 Cybersecurity Risks in CubeSat Constellations

Although CubeSats offer many advantages, they are not immune to cybersecurity risks. These risks include traditional cyber threats such as data breaches, denial-of-service (DoS) attacks, and unauthorised access, but more critically, CubeSats are vulnerable to advanced cyberattacks, including multi-stage attacks. A significant aspect of CubeSat cybersecurity concerns the interconnectivity between satellites in a constellation. Although this interconnectedness allows for enhanced system performance, it also means that compromising one satellite can lead to cascading failures across the entire constellation (Martin et al, 2018). For example, in the event of a compromised satellite, the attacker may use it as a launchpad to manipulate communication protocols, inject false data into the system, or disrupt operational capabilities (Pavur et al, 2021).

Ground and user segments typically have a mixture of specialised and general-purpose equipment. "Security through obscurity" refers to the assumption, implemented in some kind of technical practice, that obscured interfaces of specialised equipment deter attackers. In reality, whether for general interest, notoriety or malicious intent, closed undocumented systems are routinely reverse-engineered and the resultant findings circulated. As an example, a voltage fault injection (or "glitching") using a custom modification chip ("mod-chip" for short) was demonstrated on a Starlink User Terminal from SpaceX (Wouters, 2022). There existed a glitching pattern that allowed an attacker to bypass signature verification and subsequently run arbitrary code on the terminal, further bridging the gap between the space and user segment for adversaries. For larger profit margins, vendors of embedded devices often economise on security mechanisms, hard-coding access credentials, using weak cryptographic schemes and failing to patch identified vulnerabilities in a timely manner, if at all (Manulis et al., 2021). Knowing this, attackers often find resource- constrained devices attractive targets. It follows that the ground segment must be locked down, and based on the principles of zero trust, the space segment should operate without any intrinsic trust of the ground and user segments. Furthermore, as illuminated by the Viasat attack where freedom of lateral movement and trust that the ground segment is secure provided the vector necessary for the attack, the principles of defence in depth mandate the space segment to have additional security measures or cyber defences independent of its neighbouring segments.

2.2 Multi-stage Intrusion Detection

Multi-stage attack detection is comparable to classic signature and anomaly-based techniques, albeit with differing terminology and priorities. The primary distinctions are to connect consecutive actions into potential, evolving and current attacks. As shown in (Navarro et al, 2018), multi-stage detection techniques can be classified as similarity-based, causal correlation, structural-based, case-based and mixed approaches. In summary of this research:

Similarity-based: Determine the degree of similarity between alerts to construct the attack scenarios. Following the premise that similar alerts are tied to the same root cause, when sorted by field, such as host IP address, they can be appended, clustered or compared to nominal traffic to detect multi-stage attacks.

Causal correlation: Where causal connections between actions may arise as a result of the latter, causal correlation methods use this as the key to detecting attacks. By establishing which steps facilitate future actions, it is possible to construct attack scenarios and forecast future steps from the causality of the current, allowing a more targeted defence effort.

Structural-based: Working backwards in comparison to prior approaches, structural-based methods utilise known vulnerabilities of the allied system and project current network traffic to construct potential attack paths that would exploit these weaknesses.

Case-based: For well-known and characterised attack scenarios, similar to traditional signature detection, case-based methods compare current network traffic to a database of attack signatures, determining when a specific sequence of network events occur.

Mixed or hybrid: Used to incorporate two or more of the above methods in an attempt to maximise the detection performance while mitigating the drawbacks encountered by differing techniques.

Our research is motivated by the need for space-segment cyber defences that can detect and mitigate multi-stage attacks, which represent a significant threat to the operational integrity of CubeSat constellations and are anticipated to gain command and control of satellite systems (Falco et al., 2021).

2.3 Challenges in CubeSat Cybersecurity

One of the key challenges in securing CubeSat constellations is the resource limitations inherent in these small satellites. CubeSats have limited computational resources, power, and memory, which means that traditional security solutions, such as firewalls, antivirus software, or full intrusion detection systems, cannot be deployed in their entirety. This presents a fundamental challenge for cybersecurity, as it limits the types of defences that can be applied without exhausting the satellite's limited energy supply or reducing its operational efficiency (Manulis et al., 2021). Furthermore, CubeSats operate in a harsh environment that presents additional challenges. These satellites are exposed to space radiation, which can cause hardware malfunctions and data corruption (Ecoffet, 2013). The lack of physical access to CubeSats further complicates security efforts; once a satellite is launched, it cannot be easily repaired or updated in response to emerging threats (Falco, 2020). These factors demand that any cybersecurity solutions be lightweight, adaptive, and capable of functioning in an environment where physical access is not possible. The need for resource efficient solutions is paramount in CubeSat security. For example, CubeSats rely on solar panels for power, and excessive computational tasks may quickly deplete their energy supply, leading to mission failure (Manulis et al., 2021). As such, any cybersecurity mechanisms need to minimise computational overhead and optimise energy consumption without sacrificing the effectiveness of intrusion detection, response, recovery and retaliation.

3. Emerging strategies for CubeSat Resilience

3.1 Machine Learning for Cyber Threat Detection

In response to the unique cybersecurity challenges posed by CubeSats, researchers have increasingly turned to machine learning (ML) techniques for intrusion detection and threat mitigation. ML algorithms have the ability to learn from vast amounts of system data and identify patterns of behaviour that indicate a potential attack (Tedeschi et al, 2022). Anomaly-based intrusion detection systems (IDS), for instance, are capable of flagging irregular behaviour that may indicate the presence of a multi-stage attack. Such attacks often involve subtle changes to system behaviour over time, which can be difficult for traditional IDSs to detect. Supervised learning methods are commonly used for intrusion detection in CubeSats, as they are trained on labelled datasets to identify known attack patterns. However, the lack of labelled data for space-based cyberattacks can be a significant limitation (Li et al., 2020). As a result, unsupervised and semi-supervised learning

techniques are gaining traction. These methods do not require large, labelled datasets, making them particularly useful for detecting novel threats in a dynamic space environment. Another promising approach is the use of deep learning, specifically convolutional neural networks (CNNs), which can learn complex patterns and provide high accuracy in detecting attacks (Fourati and Alouini, 2021) Moreover, CNNs can be designed to operate efficiently in low-resource environments, addressing one of the key challenges faced by CubeSat systems. The ability of deep learning algorithms to process large amounts of telemetry data and identify subtle anomalies makes them a strong candidate for improving CubeSat cybersecurity.

3.2 Data Challenges

The development of effective IDS has historically relied on the availability of comprehensive and realistic datasets. Seminal datasets like KDD99, and its successor NSL-KDD, provided a foundation for much of the early research in the field (Tavallaee et al., 2009). More contemporary datasets, such as UNSW-NB15 (Moustafa & Slay, 2015) and CIC-IDS2017 (Sharafaldin et al., 2018), were created to reflect more modern network traffic and attack vectors. However, a common critique, as noted by Moustafa and Slay, is that the patterns in older datasets like KDD99 are vastly different from those in current network environments, which motivated the creation of UNSW-NB15 (Moustafa & Slay, 2015). This evolutionary trend highlights a core problem: datasets are products of their specific network environments. The traffic characteristics, protocols, and attack surfaces of a corporate LAN are fundamentally different from those of a CubeSat constellation or other LEO satellite constellation such as Starlink, rendering terrestrial datasets a poor proxy for the space domain. Our major challenges therefore include the lack of suitable datasets to develop ML based controls. Where terrestrial security datasets have garnered notable success with a range of machine learning techniques, they lack the distinctive dynamics inherent to satellite networks. These datasets fail to encapsulate the unique dynamics and communication protocols of space systems, such as limited access windows, increased data loss, and latency. Even the recent satellite-oriented STIN dataset (Li et al., 2020) is only publicly released as a flow-level subset (TER20/SAT20) of the original dataset with no nominal satellite traffic available. As a result, there remains a lack of realistic data for on-board intrusion detection systems for space-segment networks. Furthermore, there is a significant class imbalance in existing datasets between benign/single-stage attacks. Central to the methodology of our future work is a data-centric AI process: iterative dataset engineering through scenario-based digital twin simulations, domain-specific feature encapsulation, and data augmentation. This integrated approach preserves theoretical rigor and objectivity while systematically refining data representations to enhance the validity and applicability of intrusion detection models in homogeneous satellite constellations. Though while this area is developed, a preliminary solution is proposed using semi and self-supervised learning.

3.3 Semi-supervised and Self-supervised Learning

While supervised learning has shown great promise in cybersecurity applications, CubeSat systems as mentioned often lack sufficient labelled data for training. To overcome this challenge, semi-supervised learning has been proposed as a viable solution. Existing between supervised and unsupervised learning, as an umbrella term, weakly-supervised learning works with data that may be incorrect (inaccurate supervision), coarsely labelled (inexact supervision) and or partially labelled (incomplete supervision) (Zhou, 2018). Semi-supervised learning, a form of incomplete supervision, is a popular technique utilised to implicitly improve the performance of few explicitly labelled data points through a greater sum of unlabelled data (Song et al., 2023). In semi-supervised learning, the model is trained on partially labelled data, allowing it to make predictions based on incomplete or noisy information (Yang, 2024). Semi-supervised learning works on the principle that similar data yields similar results and it is the purpose of the unlabelled data to aid in discerning which data is similar (Zhou, 2018). This approach is particularly useful for space systems, where attack datasets are scarce and difficult to obtain, and could aid space scenarios where aforementioned data is partially labelled at best.

For example, pseudo-labelling works by taking a small amount of labelled data and a large sum of unlabelled data. The labelled data is used to produce pseudo labels for the unlabelled data and those with a high confidence prediction are treated as ground truth and added to the network [119]. A subsequent neural network can then be trained or fine-tuned using the updated dataset [126] in a supervised manner.

Self-supervised learning, a form of unsupervised learning, is also gaining popularity in CubeSat cybersecurity. Self-supervised learning algorithms generate their own training labels from the data itself, enabling them to learn meaningful representations without relying on external supervision (Yang, 2024). This technique has shown promise in detecting complex, multi-stage attacks that involve multiple phases of exploitation and lateral movement within the system.

Our work preliminarily explores self-supervised contrastive learning, a similarity-based technique, to produce a nominal operational profile for a CubeSat (Liu et al., 2022). This approach creates a baseline of normal behaviour against which telemetry and network traffic can be compared to detect anomalies. Contrastive cosine pair learning can be adapted for satellite cyber security by treating each spacecraft, subsystem, or communication endpoint as part of an attributed network in which normal behaviour is defined by the expected agreement between a node and its local neighbourhood rather than by explicit attack labels. (Liu et al., 2022) argue that normal instances exhibit a consistent matching pattern with neighbouring structure, whereas anomalies emerge when attributes and structure become mismatched. In a satellite setting, this idea can be reframed with cosine similarity by maximising similarity between nominal instance pairs whose embeddings point in similar directions in feature space, while reduced similarity indicates deviation from expected operational state. Such nominal embeddings could be learned from pre-launch validation data and refined during the first few orbital epochs, allowing the system to characterise mission-specific baseline behaviour without requiring explicit attack labels. In this formulation, both system faults and cyberattacks are expected to manifest as lower cosine agreement with the learned nominal state, yielding a continuous measure of system normality rather than a hard class label.

Moreover, the approach could later be fine-tuned for supervised cyber resilience testing by introducing known attack behaviours as deliberately contrasting or opposing pairs, thereby supporting both anomaly detection and downstream attack classification. However, this preliminary method has a core assumption/limitation. It places a heavy reliance on trusted physical and software supply chains to ensure the initial profile is not built on a compromised or malicious foundation. Hence this approach is being proposed as an initial solution to the real-time onboards IDS problem while bespoke space domain datasets continue to mature.

3.4 Defence-in-depth and Zero-trust Architectures

The concept of defence-in-depth has long been a cornerstone of cybersecurity, particularly in complex systems. In a CubeSat constellation, this approach involves implementing multiple layers of security, ensuring that if one layer is breached, others remain intact. Examples of defence-in-depth measures include the use of firewalls, encryption, intrusion detection systems, and secure communication protocols. These layers work together to form a multi-faceted security posture, making it more difficult for an attacker to compromise the entire system. Zero-trust architectures, which operate under the principle of “never trust, always verify,” are also being increasingly applied in CubeSat security. In a zero-trust model, every request for access is authenticated and authorised, regardless of its source. This model assumes that any user or device within the network could be compromised, and as such, access to resources is restricted until the user or device has been properly verified (Kumar & Chatterjee, 2021). Implementing zero-trust principles in CubeSat constellations can significantly reduce the likelihood of lateral movement by attackers, preventing them from exploiting one compromised satellite to launch attacks on others.

3.5 A framework for Verifiable Cyber Resilience

To standardise security practices, we propose the creation of a minimum cyber resilience capability checklist. This checklist would provide a concrete set of security controls and best practices that CubeSat developers and operators should implement (Plotnek, 2022). In line with defence-in-depth principles, this checklist should not rely on any single safeguard, but instead require multiple complementary layers of protection, such as authentication controls, encryption, intrusion detection systems, secure communication protocols, and other mechanisms that ensure if one layer is breached, others remain intact. In parallel, zero-trust principles should also be incorporated, operating under the assumption of “never trust, always verify,” such that every request for access is authenticated and authorised regardless of its source. In a CubeSat constellation, where any user, device, subsystem, or satellite may be compromised, this reduces the likelihood of lateral movement and helps prevent one compromised satellite from being used to launch attacks on others.

In time, this would be accompanied by a testbench for conducting tests analogous to the vacuum and vibration testing performed during hardware qualification. This testbench would include components to cover core low-cost, high-reward attack vectors, with capabilities to test for vulnerabilities in authentication, encryption, fuzzing, replay attacks, and Denial of Service (DoS) scenarios for example. The results of the testbench would be delivered back to the owner or producer in a straightforward pass/fail method, clearly indicating which tests have failed and referencing standard methods to ensure these vulnerabilities are covered. This provides a verifiable and repeatable process for ensuring a baseline of cyber resilience.

Ideally, this process would adhere to the resilience framework taxonomy defined by Plotnek (2022), not only by supporting the detection of threats, but by enabling systems to *react* to threats detected, *survive* adverse effects, *sustain* minimal operational capacity, *recover* to nominal system state, and *adapt* from information gathered. In this sense, the proposed checklist and testbench are not merely mechanisms for identifying vulnerabilities prior to launch, but an initial framework for demonstrating that a system can maintain and restore mission-relevant functionality under adverse cyber conditions. This would provide a foundation to the U.S. requirements through a standardised cyber detection threshold prior to the launch of military or dual use satellites.

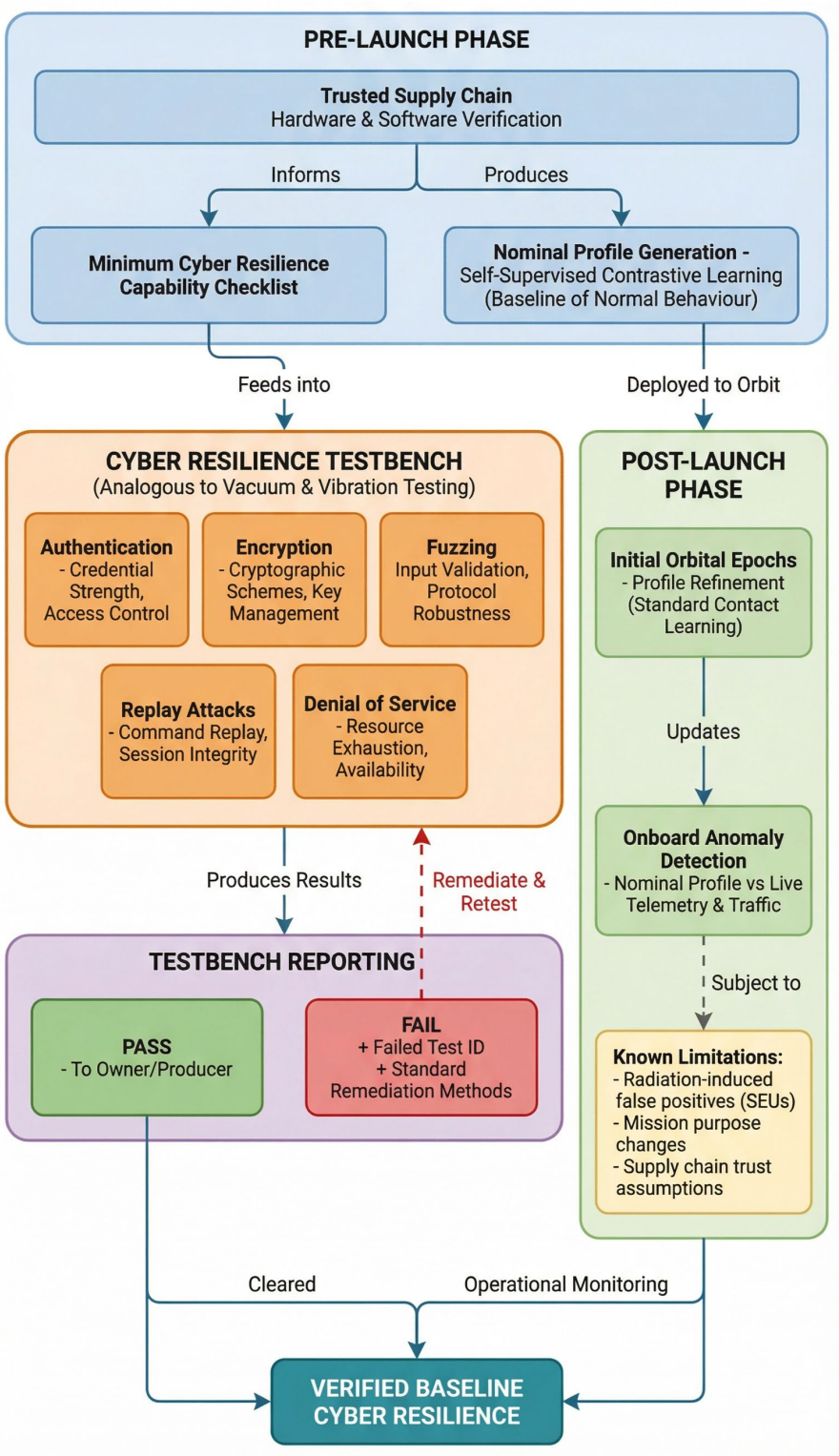


Figure 1: Minimum cyber resilience framework

4. Conclusion

CubeSat constellations are becoming increasingly important, offering low-cost, scalable solutions for global coverage in both civilian and military applications. However, their inherent constraints regarding Size, Weight, and Power (SWaP), combined with the harsh space environment and growing interconnectivity of constellation architectures, make them highly vulnerable to cyberattacks. To address these challenges, this work proposes a framework that combines self-supervised learning for nominal profiling with a structured approach to verifiable cyber resilience. By using contrastive learning to establish a baseline of normal operations, we aim to enable lightweight, onboard anomaly detection as an initial intrusion detection capability suited to resource-constrained platforms. While acknowledging the limitations of this approach, including its reliance on supply chain integrity and the potential for false positives, we propose post-launch refinement of the nominal profile alongside the development of bespoke, space domain-specific cyber datasets. This is complemented by a proposed minimum cyber resilience capability checklist and an accompanying testbench to standardise and verify security postures against common attack vectors, supporting a resilience process that can initially detect threats, supporting future downstream segments to react to adverse conditions, sustain minimal operational capacity, recover toward a nominal system state, and adapt from information gathered. There is not yet a widely applicable IDS solution that can be used across vendors and equipment; accordingly, this work represents a preliminary step toward a standardised cyber resilience requirement for detection and verification. In doing so, it aligns with emerging U.S. national security expectations that cybersecurity be integrated across the full lifecycle of relevant space systems, including the implementation of real-time onboard intrusion detection and prevention capabilities, and may help inform both downstream system design and operator understanding of cyber posture before and after launch.

Ethics Declaration: This research did not involve human participants, human data, or animal subjects. Ethical clearance was therefore not required for this study.

Artificial intelligence Declaration: Generative artificial intelligence tools (ChatGPT, Claude) were used in a limited capacity to assist with language refinement, structural editing, and clarity of expression. All technical content, analysis, interpretations, references and conclusions were developed by the author/s, who retain full responsibility for the accuracy, originality, and integrity of the work.

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Zero-Day Vulnerabilities, Cartography, and Quantification Initiative

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Abstract: Zero-day vulnerabilities have become a critical concern across security teams. Despite their growing frequency, they remain a largely uncharted domain: there is currently no consolidated information, statistical visibility, or cartography describing the true scale of the problem. Organisations lack metrics that would enable them to understand how zero-days are distributed among products or technological ecosystems, limiting their ability to anticipate, detect, and accurately assess the risks associated with these vulnerabilities. In the absence of a structural understanding of the phenomenon, organisations rely on linear, product-centred approaches inherited from traditional vulnerability management and built around indicators such as CVE identifiers, CVSS scores, or patch availability. Although these indicators are essential, they do not capture the multidimensional relationships and ecosystem-level dependencies that shape zero-day behaviour. Consequently, analyses remain confined to individual vulnerabilities rather than the structures that connect them, leaving organisations without models capable of describing how zero-days emerge, cluster, or propagate across technologies. To address this gap, this work begins with an in-depth *a posteriori* phase aimed at establishing the first consolidated inventory of past zero-days. This fundamental effort is intended to establish an initial structural basis that will enable further long-term research into the systemic characteristics of zero-day vulnerabilities. Afterwards, this study seeks to reveal "domino effects", clusters of technological weakness, and cross-product propagation paths that remain invisible in traditional analytical frameworks. The goal is to provide a new visualisation to support not only future predictive models and improved detection strategies, but also more informed and contextualised risk assessments. By moving beyond linear scoring systems and embracing a structural, graph-driven perspective, this work lays the groundwork for a more proactive, comprehensive understanding of zero-day vulnerabilities and the technological ecosystems they inhabit.

Keywords: Vulnerability, Zero-day, Cartography, Graph

1. Introduction

A zero-day is a vulnerability that has not been publicly disclosed and for which there is no known fix. The existence of such a flaw in a product means that there is no protection, either temporary or permanent. They are more dangerous than traditional vulnerabilities because they emerge in a space of total asymmetry: no patch or mitigation measure exists at the time of their discovery, leaving defences structurally behind. In a context where disclosure and remediation cycles generally provide a framework for managing known vulnerabilities, zero-days impose a total break, especially when their number keeps increasing (Figure 1). They reveal not only the absence of immediate protection but also the limitations of our analysis models, which are designed to react to existing threats rather than anticipate the mechanisms that promote the emergence of these invisible vulnerabilities. The potential damage from them can be substantial and their challenge lies in our limited understanding of them. We still do not have consolidated metrics, models, or frameworks that tell us how zero-days behave as a group. We know how to handle a vulnerability once it becomes public, but we do not fully understand the conditions that lead to its emergence. This brings the central problem of this paper into focus: For years, our industry has depended on the same indicators, CVE identifiers (Common Vulnerabilities and Exposures), CVSS scores (Common Vulnerability Scoring System), and patch availability. These indicators are vital, but they are inherently reactive. They show us what has already happened, not what is happening structurally beneath. When we talk about zero-days, the problem becomes even clearer: a zero-day is, by definition, discovered too late. Rather than asking ourselves how we can correct them more quickly, we should ask ourselves whether we could anticipate their future occurrence through better understanding. We used to analyse zero-days as a singularity, but we never established a correlation between the different conditions that lead to their discovery and exploitation. We may wonder whether there are similar patterns, common mechanisms for their emergence, that we can model and highlight. The idea is not to predict the exact next zero-day but to identify where it is more likely to appear and how. By analysing connections between vulnerabilities, shared components, recurring exploit primitives, or historical sequences of related weaknesses, we can start building a structural understanding that does not exist today. This structural understanding, in turn, can guide organisations in prioritising monitoring, testing, and hardening efforts, not based only on CVSS, but based on the actual dynamics of their vulnerability ecosystem.

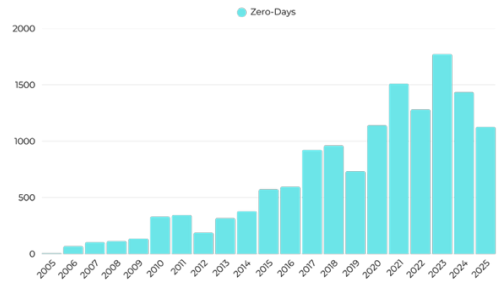


Figure 1: Number of zero-day vulnerabilities per year (Zero Day Initiative)

2. Related Work

Empirical studies on zero-day vulnerabilities have mainly focused on measuring the lifecycle and dynamics of patches. Bilge and Dumitras conducted the first large-scale field study on zero-day attacks, identifying 18 vulnerabilities exploited before public disclosure on 11 million real hosts and showing that a typical zero-day vulnerability persists for an average of 312 days. Ablon and Bogart characterised the zero-day ecosystem in more detail from a strategic perspective, estimating that approximately 5.7% of stockpiled vulnerabilities are independently discovered by others within a year. More recently, Roumani applied survival analysis to 4,897 ZDI vulnerabilities to model patch release times, while Shet and Alsmadi analysed ZDI disclosures from 2024 using a machine learning-based severity classification. Although this work provides valuable statistical insights, it describes vulnerability attributes in isolation and does not capture the relational structures that link vulnerabilities across products, weakness types, and exploitation contexts. Yin et al. introduced a compact vulnerability knowledge graph oriented toward risk assessment. However, none of these approaches are tailored to zero-day vulnerabilities specifically, nor do they incorporate community detection to reveal latent structural groupings. The present work addresses this gap by constructing a heterogeneous graph dedicated to zero-days and applying the Leiden algorithm and UMAP to uncover structural communities and visualise their organisation beyond what conventional metrics such as CVSS or EPSS can capture.

3. Dataset Creation

The primary challenge with zero-day vulnerabilities lies in the fact that we must wait for their exploitation to become aware of their existence. Consequently, we are limited to studying the past rather than predicting the future. This necessitates conducting an *a posteriori* analysis by examining their characteristics. As explained in the introduction, what makes a zero-day vulnerability particularly dangerous is that no one is aware of its existence until an exploit is deployed in real-world situations. (Figure 2).

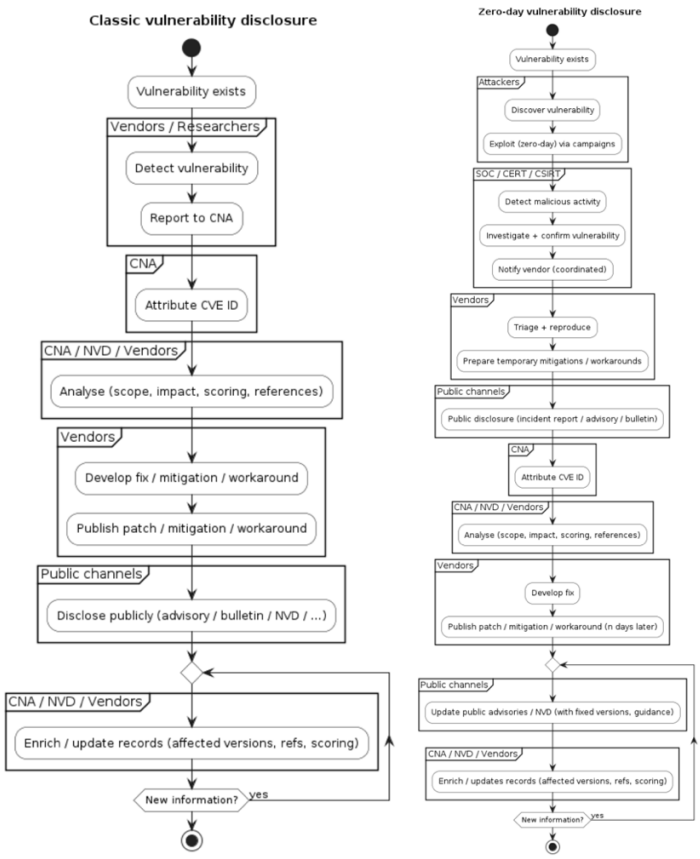


Figure 2: Vulnerability lifecycle

To better understand zero-days, we need to analyse the different patterns that make them zero-day vulnerabilities. The advantage of identifying them like other vulnerabilities is that we have access to the same data about them, all recorded under a single CVE identifier. However, since all zero-days are recorded as CVEs without any distinction, no official source, such as MITRE, NVD, CISA, etc., currently allows zero-days to be isolated, categorised, or quantified accurately. In practice, they disappear statistically "into the mass" of CVEs, which prevents us from obtaining a consolidated view of their volume, their distribution by publisher, product, or technology sector, or even their evolution over time. In the absence of formal recognition in official databases, monitoring of zero-days therefore relies, at the time of writing, on non-institutional inventories maintained by researchers, threat intelligence teams, or certain cybersecurity companies, which attempt to record every known case. These sources, although valuable, remain heterogeneous, non-standardised, and biased, which makes it even more difficult to build a comprehensive and methodologically robust understanding of the zero-day phenomenon.

This is why this initial research phase will draw on Trend Micro's Zero Day Initiative (ZDI) database, as did the authors cited above, to evaluate the results of this initial approach. This choice will enable us to analyse the relevance of the method in a controlled environment, pending the enrichment and refinement of the zero-day dataset in future work. Each zero-day vulnerability identified by ZDI was retrieved either under a CVE ID, if it was associated with one, or under a ZDI ID if it was not, in the form ZDI-YY-XXX. We enriched each with different metrics from open-source data:

- CVSS Score, which measures the severity of the vulnerability;
- CPE (Common Platform Enumeration), which specifies the products and versions concerned;
- EPSS Score (Exploit Prediction Scoring System), which measures the probability that a vulnerability will be exploited within 30 days of its publication;
- KEV affiliation (Known Exploited Vulnerabilities), catalogue that lists vulnerabilities confirmed as being actively exploited;
- CWE (Common Weakness Enumeration), which provides details about the type of vulnerability exploited;

- CAPEC (Common Attack Pattern Enumeration and Classification), which characterises the typical attack patterns and exploitation strategies associated with the vulnerability;
- ATT&CK Technique, which maps the vulnerability to concrete adversarial behaviours and operational techniques used in real-world attacks;
- Threat Actors, known to exploit specific CVE.

The generated dataset comprises 12,342 CVEs between 2005 and 2025.

4. Graph Approach

This section presents the first methodological phase of this work devoted to modelling zero-day vulnerabilities. The goal is to identify latent structures and recurring threat profiles.

4.1 Construction

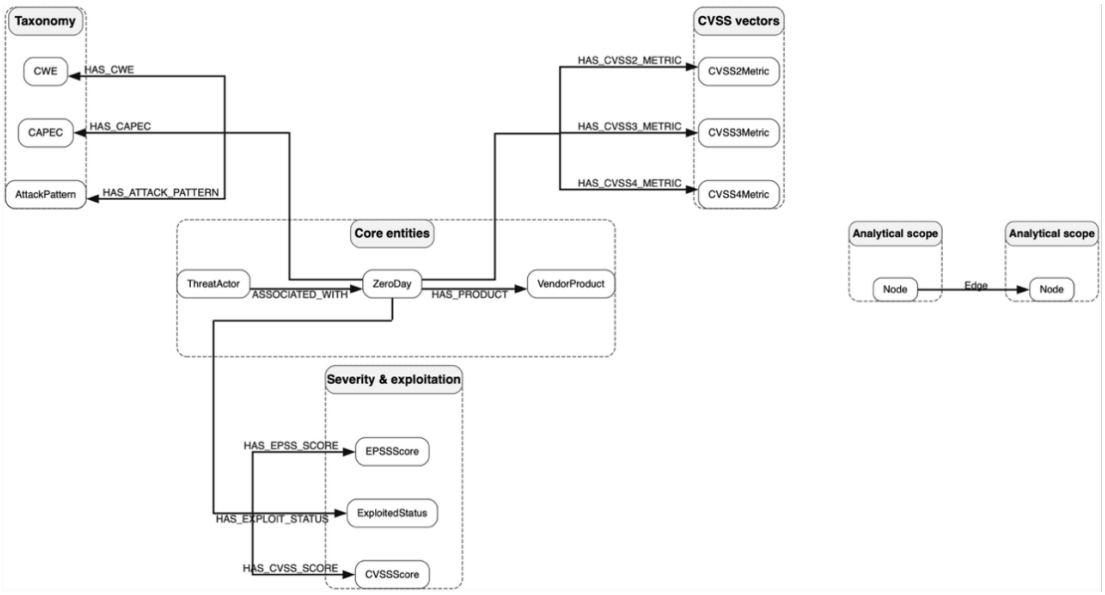


Figure 3: Pseudo-graph structure

The graph is constructed using the database generated in the previous section. It is a heterogeneous oriented graph $G = (V, E)$ where the set of nodes is partitioned into subsets. Each node $v \in V$ is associated with a type $\tau(v)$ belonging to a finite set of types and a vector of attributes. The set of edges $E \subseteq V \times V$ is also typed, with each relationship has a specific meaning, such as “affects”, “exploits”, “is associated with”, etc.

4.2 Matrix Projection

To enable algorithmic exploitation of the graph, we project the relational structure into a matrix space. The first projection is based on the construction of a direct context matrix $B \in \mathbb{R}^{|Z| \times |C|}$, where Z denotes the set of zero-day nodes and C the set of context nodes. A context node corresponds to all entities directly linked to a zero-day by a semantic edge. Formally, for a zero-day $z_i \in Z$ and a context node $c_j \in C$, the coefficient B_{ij} is 1 if and only if there is an oriented edge $(z_i, c_j) \in E$ or 0 otherwise. This matrix is deliberately binary to capture the presence or absence of relationships regardless of their frequency. The result is a matrix where each row corresponds to a zero-day and each column to an element of its context.

4.3 TF-IDF Weighting

In a second step, a weighting stage is carried out to reassess the relative importance of contexts based on their overall rarity. To do this, matrix B is transformed using TF-IDF (Term Frequency-Inverse Document Frequency) weighting, commonly used to reinforce discriminating dimensions. Here, each zero-day is equivalent to a document and each context node to a term describing that document. Since the matrix B is binary, the term frequency $\mathrm{tf}(z_i, c_j)$ is defined as 1 if $B_{ij} = 1$ and 0 otherwise. The document frequency $\mathrm{df}(c_j)$ corresponds to the number of zero-days associated with context c_j. Based on this quantity, we define a weight of importance inversely proportional to the overall frequency of the context: the more frequent a context is, the less informative it is for distinguishing zero-days. In this work, we adopt an adapted version of the weighting factor defined by:

$$\mathrm{idf}(c_j) = \log\left(\frac{1+|\,Z\,|}{1+\mathrm{df}(c_j)}\right) + 1.$$

The $+1$ in the numerator and denominator avoids degenerate cases when $\mathrm{df}(c_j) = 0$. The $+1$ added after the logarithm prevents contexts present in the zero-day set from being completely cancelled out by IDF weighting. These contexts thus retain a strictly positive weight, which guarantees a complete and stable representation of the context space. The weighted matrix $B^{\mathrm{tfidf}} \in \mathbb{R}^{|Z|\times|C|}$ is then obtained by applying the weighting factor column by column, according to:

$$B_{ij}^{\mathrm{tfidf}} = \mathrm{tf}(z_i, c_j) \cdot \mathrm{idf}(c_j).$$

To make representations comparable between zero-days regardless of their degree of connectivity, L_2 normalisation is then applied line by line. This normalisation consists of dividing each row by its Euclidean norm: for a zero-day z, if we denote x_z as the corresponding row vector in B^{tfidf}, we get $\hat{\mathrm{x}}_z = \frac{\mathrm{x}_z}{\|\mathrm{x}_z\|_2}$. This operation reduces the influence of the degree of a zero-day and emphasises the direction of the vector.

4.4 Community Detection

4.4.1 Cosine similarity

The next step is to identify vulnerability groups with similar contextual profiles by constructing a similarity graph between zero-days and applying a community detection algorithm. We start with the matrix $B^{\mathrm{tfidf}} \in \mathbb{R}^{|Z|\times|C|}$ obtained previously. From each normalised representation, we define a measure of similarity between two zero-days z_i and z_j using cosine similarity:

$$s_{ij} = \cos\left(\hat{\mathbf{x}}_i, \hat{\mathbf{x}}_j\right) = \frac{\hat{\mathbf{x}}_i \cdot \hat{\mathbf{x}}_j}{\|\,\hat{\mathbf{x}}_i\,\|_2 . \|\,\hat{\mathbf{x}}_j\,\|_2} = \hat{\mathbf{x}}_i^{\top}\hat{\mathbf{x}}_j, \quad s_{ij} \in [0;1]$$

We choose the cosine similarity measure because an Euclidean norm-based method would favour the most connected zero-days. Here, cosine similarity applied to vectors normalised in L_2 depends only on their normalised scalar product. This makes it possible to compare zero-days based on the relative composition of their context, regardless of their degree.

4.4.2 KNN

To avoid the quadratic cost of exhaustive pair-by-pair similarity calculations for all nodes in the graph, a k-nearest neighbours (kNN) graph is constructed, where each node z_i is connected to its k most similar neighbours, provided that this similarity exceeds a minimum threshold θ. θ acts as a filtering mechanism to eliminate weak similarity links that are more likely to introduce noise. This gives us a non-oriented and non-redundant graph $G_{\mathrm{sim}} = (Z, E_{\mathrm{knn}})$, whose edges are weighted by similarity s_{ij}. The hyperparameters of the similarity graph were selected empirically based on a comparative analysis of several pairs (k, θ). The aim is to limit excessive fragmentation of the graph, to ensure the existence of a dominant connected component (DCC) and to preserve sufficient contrast between zero-days. A DCC enables the propagation of local similarity information on a global scale and community detection guided by the intrinsic structure of the data rather than by induced fragmentation. Experimental results show that the configuration $k = 35$ and $\theta = 0.05$ provides the best trade-off between connectivity and discrimination. This setting produces a graph without isolated nodes, a DCC covering approximately 99% of the zero-day corpus, and a limited number of connected components overall. At the same time, the distribution of similarity weights remains sufficiently spread out, thus preserving significant contrasts between vulnerabilities. This balance ensures that the similarity graph is both globally connected and locally informative.

4.4.3 Leiden

Community detection is performed using the Leiden algorithm by partitioning the similarity graph so that the nodes that are most strongly connected to each other relative to the rest of the graph form a community. This algorithm optimises an objective function that evaluates the quality of the partitioning by comparing the observed density of intra-community links with that expected in a null model, where the graph structure is random while maintaining the degree of each node. A community will be considered relevant when it has an excess of internal connections relative to the degrees alone. The function introduces a resolution parameter γ that serves as a scale: the smaller it is, the more it will favour large communities, and vice versa. To avoid an

arbitrary choice of the resolution parameter, a sensitivity analysis was conducted by varying γ over a grid of values $\gamma \in \{0.5,0.75,1.0,1.25,1.5,2.0,2.25,2.5,2.75,3.0\}$. For each value of γ, community detection was repeated for several seeds to assess the robustness of the results with respect to the randomness of the algorithm. The choice of the γ parameter is based on several complementary criteria:

- total number of communities detected
- distribution of community sizes
- relative size of the dominant community
- proportion of very small communities
- stability of the results with respect to the choice of random seed

The results obtained are generally stable for the seed considered, both in terms of the number of communities and the distribution of sizes. To assess the robustness of the detected communities, we also measured the stability of the partitions obtained using the Adjusted Rand Index (ARI). ARI assesses the concordance between partitions obtained with different random seeds by correcting for chance: values close to 1 indicate almost identical groupings, while values close to 0 indicate concordance that is no better than chance. Consistently high ARI values (≈ 0.93) indicate that the community structure is very stable and largely independent of random initialisation. Therefore, a fixed seed (seed = 42) is used for the final partition to ensure full reproducibility of the results. A monotonic evolution of partitioning is observed as γ increases: the number of communities gradually increases, while the size of the dominant community decreases. The value $\gamma = 2.5$ was chosen because it represents the best compromise between these two extremes. This value therefore, provides a good level of interpretable and stable resolution without introducing artificial fragmentation. This leaves us with 71 communities.

4.5 Profiling

Finally, to make each community interpretable, three different types of profiling are performed.

4.5.1 Coverage

Based on the partitioning obtained by Leiden, we consider for each community k the set of zero-days that compose it, Z_k. For each context c_j defined within the binary matrix B, we calculate its number of occurrences in the community and then normalise it by the size of the community to account for its coverage within the latter:

$$\mathrm{cov}(c_j, k) = \frac{1}{|\, Z_k \,|} \sum_{z_i \in Z_k} B_{ij}.$$

Coverage therefore represents the proportion of zero-days that share the same context within the community. The higher the coverage of a context, the more it can be considered structuring. This initial profiling highlights the most common contexts within each community but does not target more specific ones.

4.5.2 TF-IDF importance

With this second profiling, we want to incorporate the notion of weighted importance for each context. We therefore use the TF-IDF matrix: within each community k, we calculate the average TF-IDF weights for each context c_j:

$$\mu_{\mathrm{tfidf}}(c_j, k) = \frac{1}{|\, Z_k \,|} \sum_{z_i \in Z_k} B_{ij}^{\mathrm{tfidf}}.$$

This quantity measures the average importance of each context within a community. The higher the average, the more prevalent it will be among several members of the community and the more relatively rare it will be on the global scale of the graph. Unlike different profiling, this type of profiling penalises overly generic contexts to highlight those that specifically characterise each community.

4.5.3 Lift

The final profiling step consists of comparing the frequency of a context within its community to its overall frequency within the corpus. To do this, we calculate the ratio between the coverage of a context within its community $\mathrm{cov}(c_j, k)$ and its overall coverage $\mathrm{COV}(c_j)$, defined by:

$$COV(c_j) = \frac{1}{N}\sum_{i=1}^{N} B_{ij}\,,$$

where N denotes the total number of zero-days. The lift (over-representation factor) is then defined as:

$$\text{lift}(c_j, k) = \frac{cov(c_j, k)}{COV(c_j)}.$$

A lift greater than 1 indicates that the context is overrepresented in the community compared to the rest of the corpus and is therefore a distinctive marker of the group. Conversely, a lift less than 1 indicates that the context is underrepresented. A lift close to 1 indicates a generic context whose presence is not specific to a given community. This profiling thus makes it possible to identify the truly discriminating attributes of each community, regardless of their absolute frequency.

5. Results

5.1 Global Community Structure of Zero-day Vulnerabilities

Overall, the communities generated are neither trivial product-based groupings nor purely taxonomic groupings. Rather, they emerge from the interaction between CWE, affected technology ecosystems, exploitability indicators, severity measures and, in a very limited number of cases, explicit associations with malicious actors. From a macroscopic perspective, the partitioning highlights a clear distinction between large cross-cutting communities and more specialised clusters. The largest communities are characterised by generic vulnerability patterns associated with a wide dispersion of affected products with characteristics similar to those identified in the previous section. In contrast, smaller communities tend to exhibit greater internal consistency, often driven by specific software ecosystems and attack patterns. The various profiling strategies applied to communities have brought to light more specific and structured information for each community, providing a different perspective on traditional coverage analysis. Communities are structured around a small number of dominant technical signals, generally a combination of vulnerability weakness and technological products, while exploitability and severity measures act as modulators rather than the main drivers of grouping. In particular, there is a strong emphasis on high CVSS contexts and low or moderate EPSS scores. Some communities show signs of exploitation by threat actors, but this context never appears to be a determining factor, but rather a secondary one. Let us introduce a few communities selected for certain characteristics:

- Community 0 (n=555): This community constitutes the largest group identified in the graph and can be interpreted as the structural backbone of the zero-day corpus. It includes a significant proportion of vulnerabilities that are not publicly observed as exploited and are mainly associated with low EPSS scores, although they have high severity levels according to CVSS v3. It is dominated by weaknesses related to memory management across a diverse range of software products and platforms. However, profiling based on lift reveals a more nuanced picture. Although no single product dominates the community, there is a clear overrepresentation of technologies related to industrial software, virtualisation environments and network infrastructure components.
- Community 13 (n=300): It forms a very coherent group focused on injection-type vulnerabilities. This is reflected in the CAPEC and ATT&CK layers, which are almost “saturated” in terms of coverage (almost 100%). From a risk perspective, the community is dominated by High or Critical vulnerabilities, while the probability of exploitation remains mainly low with a small high fraction and a limited portion exploited in the wild, suggesting selective and likely opportunistic operational exploitation. Coverage mainly highlights Ivanti and TrendMicro products and OT-oriented components. At the same time, there is a low presence of several threat actors, which shows the attackers' interest in security technologies.
- Community 51 (n=92): It corresponds to a server-side cluster and enterprise infrastructure, largely shaped by weaknesses in resource management and isolation, particularly accentuated by very high lift values. Technologically, the community relies on management and collaboration ecosystems and infrastructure and industrial components. The community is primarily classified as CVSS v3.X High/Critical and strongly aligned with remotely exploitable conditions, while still associated with low to moderate EPSS classes and only a small fraction is observed to be exploited in the wild. Finally, although several malicious actor nodes appear in the coverage and lift, their individual support remains low and none dominate, suggesting opportunistic behaviour.

The global analysis highlights dominant contexts characterised by low or moderate EPSS scores and a majority of vulnerabilities not publicly observed as exploited. Nevertheless, these contexts constrain us in the evaluation of structural patterns of zero-days known to be exploited. To better identify them, we apply the same methodology to a reduced corpus composed exclusively of zero-day vulnerabilities known to be exploited in nature, as referenced in the CISA KEV catalogue. This filtering step significantly reduces the corpus size from 12,342 to 678 vulnerabilities and leads to 23 communities. We choose here $k = 15$, $\theta = 0.05$, and $\gamma = 3.0$.

5.2 Community Analysis of Exploited Zero-day Vulnerabilities

Three major community archetypes can be identified at a macro level. First, several large and medium-sized communities are structured around generic exploitation primitives, such as input validation failures, injection vectors, or even authentication and access control workarounds. These clusters tend to have a high dispersion between products and suppliers, suggesting that they represent reusable attacker techniques rather than ecosystem-specific weaknesses. Secondly, a set of communities is primarily structured around specific technology ecosystems, notably Microsoft Windows, Apple's platforms, Google Chrome, or Qualcomm firmware. In these cases, the product signal dominates the community structure, with high elevation values on specific OS versions or software branches. Finally, a third class of communities is primarily actor- or technique-focused, where no single product dominates.

- Community 9 (n=29): it aggregates zero-days that are actively exploited and highly severe, dominated by authentication and access control flaws (CWE-287 and CWE-284), exploitable remotely without interaction and with high impacts. Discriminants and lifts converge towards identity abuse, account manipulation and methods of bypassing access mechanisms. Targeted products remain scattered, indicating a community defined by attack techniques rather than a supplier ecosystem.
- Community 6 (n=37): it captures a coherent family of browser-centric exploitation chains dominated by use-after-free and lifecycle errors (CWE-416**,** CWE-825). Although Google Chrome is the primary anchor, the community also includes Linux distributions that propagate the same vulnerable components. The exploitation pattern combines remote attack vectors, low complexity, and frequent user interaction, forming a well-defined "web exploitation" cluster with strong technical homogeneity and high operational impact.
- Community 17 (n=20): it groups exclusively exploited zero-days characterised by high-severity impacts and attack paths requiring no user interaction. The community is structured around flaws affecting execution ordering, resource synchronisation and control-flow enforcement, which are leveraged to reliably escalate privileges in post-compromise scenarios. These vulnerabilities typically require a precise execution context and exploit subtle timing or logic weaknesses rather than broad, opportunistic vectors. Multiple attacker groups recur within the community, indicating sustained and coordinated interest rather than isolated incidents. A notable aspect is the prevalence of low EPSS scores despite confirmed exploitation, suggesting that these technically demanding attack chains tend to be underestimated by probabilistic models. Targeted products remain dispersed, reinforcing the interpretation of a technique-driven community rather than one centred on a specific technology ecosystem.

5.3 UMAP Projection

To compare the community structure obtained from the graph-based modelling with the original contextual representation of the dataset, we project zero-day vulnerabilities using UMAP (Uniform Manifold Approximation and Projection). This visualisation aims to assess whether vulnerabilities sharing similar contextual attributes naturally form clusters and how this organisation relates to the communities identified by the Leiden algorithm. UMAP is a nonlinear dimension reduction method that projects high-dimensional data into a lower-dimensional space while preserving the topological structure of the data.

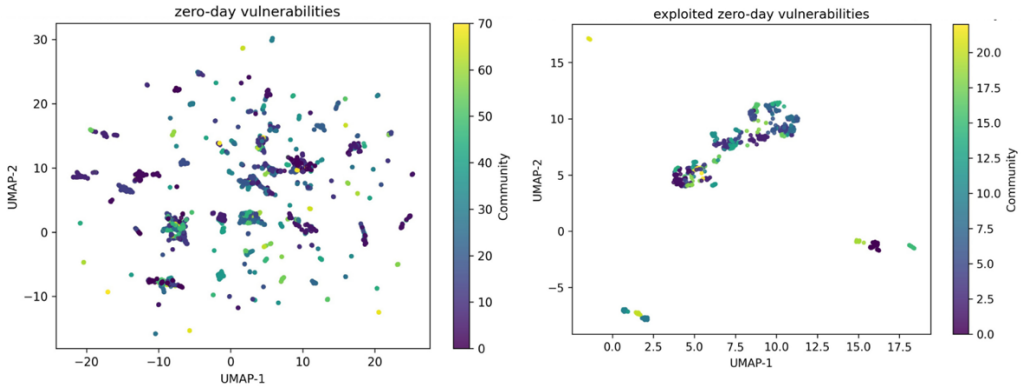


Figure 4: UMAP projection of the raw contextual matrix of exploited zero-day vulnerabilities, coloured by Leiden

These projections (Figure 5) highlight the fact that sharing similar contextual attributes does not necessarily lead to coherent clusters of zero-day vulnerabilities. Local clusters in the raw context space often contain vulnerabilities from multiple communities, illustrating the limitations of similarity based solely on contexts. In contrast, the graph-based community detection approach captured higher-order structural patterns, enabling the identification of meaningful zero-day clusters that are not directly observable in the original context space.

6. Conclusion

This paper introduced a graph-based methodology to analyse and contextualise zero-day vulnerabilities beyond traditional severity-centric approaches. By modelling zero-days as nodes embedded in a heterogeneous graph, we demonstrated that meaningful structural communities emerge without relying on a priori taxonomies or vendor-centric assumptions. The results show that zero-day vulnerabilities do not organise themselves around a single dominant dimension. Instead, communities arise from the interaction between technical weaknesses, exploitation mechanisms and ecosystem contexts, with severity and exploitability scores acting as modulators rather than primary drivers. In particular, high CVSS scores frequently coexist with low or moderate EPSS values, even in communities where exploitation is confirmed, highlighting a systematic mismatch between probabilistic exploitability models and real-world attacker behaviour. The comparison between the full zero-day corpus and the subset of vulnerabilities known to be exploited in the wild further emphasises this gap. While the global corpus is dominated by non-exploited vulnerabilities with generic technical characteristics, the exploited-only graph reveals a fragmented and heterogeneous landscape structured around distinct exploitation logics. Graph-based representations provide a complementary perspective, enabling the identification of latent risk structures, operationally relevant clusters and under-estimated attack chains, particularly in the context of zero-day vulnerabilities. From an operational standpoint, this approach opens new perspectives for vulnerability management, threat-informed prioritisation and risk modelling: By shifting the focus from individual vulnerabilities to communities of related weaknesses, exploitation patterns or technology ecosystems relevant to a given operational context, defenders can better anticipate attacker behaviour and allocate remediation efforts more effectively. Future work will focus on extending this methodology through dynamic and temporal graph representations, not limited to zero-day vulnerabilities, as well as through predictive modelling based on graph learning techniques. Integrating additional threat intelligence sources and evaluating the approach in industrial and cloud environments will further strengthen its applicability to real-world vulnerability management workflows.

Ethics and AI Statement: This research did not require ethical approval. AI-based tools were used solely to facilitate linguistic and editorial improvements; all scientific content, analyses, and conclusions are the sole responsibility of the author.

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Masters Research Papers

Warfare in the Gray Zone: The Need for a Western Paradigm Shift

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Abstract: This paper examines how China's historical strategic culture informs the development of its information warfare doctrine and identifies the changes required for the United States to adapt. China's contemporary approach to warfare extends beyond the traditional battlefield, integrating information, cognitive, and influence operations as central components of strategic competition. China's strategic culture draws on classical and modern foundations, including Sun Tzu's emphasis on deception (Sawyer, 1994), Mao Zedong's theory of protracted conflict (Mao, 1938), and the concept of Unrestricted Warfare (Qiao & Wang, 1999). This study traces the institutionalization of the Three Warfares doctrine and the establishment of the Strategic Support Force, illustrating their application through case analysis in the South China Sea and Pacific Islands. The findings highlight key U.S. strategic vulnerabilities, particularly the continued treatment of information operations as peripheral rather than central to national strategy.

Keywords: Unrestricted warfare, Gray zone conflict, Cognitive and information warfare, Non-kinetic deterrence, China, Three warfares, Strategic culture, U.S. doctrine

1. Introduction

This paper analyzes the historical and doctrinal foundations of China's approach to modern conflict, emphasizing its expansion beyond the conventional battlefield into the information domain. The People's Republic of China (PRC) has conducted sustained information and influence operations that blur the distinction between peace and war. In contrast, the United States employs information operations primarily in support of military objectives rather than as a central element of strategy. The strategic objective of China is to "win without fighting" to accomplish strategic purposes without having to fight. As a result, U.S. doctrine remains vulnerable, as it conceptualizes information operations as peripheral rather than foundational to strategic competition.

2. Problem

The central problem is that U.S. strategic planning continues to prioritize kinetic warfare and technological superiority, while China emphasizes information dominance and gray-zone competition. Chinese strategy treats war and peace as a continuum, enabling persistent competition through influence, legal warfare, cyber operations, and economic pressure.

The United States often responds slowly due to bureaucratic fragmentation, legal constraints, and doctrinal separation between military and civilian instruments of power. These structural gaps create exploitable seams that allow competitors to shape the operational environment prior to kinetic conflict. The United States needs a comprehensive system which connects information warfare activities with its national defense plans, because without this system, the nation will lose its strategic advantage during extended competition.

3. Purpose

This paper examines the influence of China's historical strategic culture on its information warfare doctrine and identifies changes needed in U.S. strategy. It traces the development of Chinese strategic thought from classical Chinese philosophy through to contemporary Chinese doctrine to show how China integrates its information, political, and military means into a unified whole to compete with other nations.

This paper is meant to provide a conceptual basis for understanding U.S.-China information warfare rather than serving as an operational plan. Ultimately, this paper will assist policymakers and military planners in determining how to adapt their strategies, improve agency coordination, and build societal resilience necessary for competing effectively in the information realm.

4. Literature Review

Numerous academic fields, including military history, political science, strategic studies, and communication theory, have produced scholarly works on China's information warfare and strategic culture. This review highlights the gaps this study fills, identifies important debates, and places the current paper within that corpus of work.

The basic intellectual foundation for most of the existing literature on information warfare in China is Sun Tzu's The Art of War, read in terms of its implications for strategic competition in the post-Cold War era. Both Sawyer (1994) and Ota (2014) suggest that Sun Tzu's emphasis on deception, psychological preparation, and winning before the war begins reflects not merely ancient philosophy, but rather an enduring logic of war that continues to influence PLA doctrine. Sawyer's work expands this basic argument in The Art of War, arguing that the basic idea of shi, or shaping rather than using force, which is part of traditional Chinese philosophy derived from Taoism, underpins Chinese military thought from ancient times down to the twentieth century. This basic argument is crucial to understanding why China's approach to information warfare is so different from that of the West, which has traditionally conceived of information operations primarily in terms of their support role to kinetic force.

The contemporary doctrinal literature uses Qiao and Wang's Unrestricted Warfare (1999) as its main reference source. The authors who served as PLA colonels after the Gulf War established their text to demonstrate that Western military power could be defeated through simultaneous attacks on all non-combat areas of an enemy nation which included its financial systems and media and legal and diplomatic and cyber operations. Mulvenon (1999) provides useful context for reading Unrestricted Warfare as a direct institutional response to China's observation of American precision-guided warfare in Iraq, noting that the PLA interpreted the Gulf War not as a lesson to emulate but as a vulnerability to exploit. Martin and Głodek and Behrendt (2022) show that the Three Warfares doctrine which includes public opinion warfare and psychological warfare and legal warfare reached formal establishment in 2003 because it had been embedded into PLA political work regulations which protected the doctrine from experimental status and provided institutional backing for its implementation.

Over recent years, research into how China applies certain strategies in distinct regions has expanded noticeably. Examining Beijing's efforts throughout the Pacific Islands and wider Indo-Pacific area, Brady (2017) along with Lee (2022) highlight control over Chinese-language news outlets, gaining leverage over key decision-makers, alongside funding large construction projects as tools tied to strategic pressure campaigns. Focusing on Taiwan, Cole's (2020) analysis suggests authorities there face more than just traditional security threats instead of becoming a testing ground where psychological tactics are refined. Meanwhile, investigations by the Stanford Internet Observatory including studies led by DiResta (2020) and Tiffert (2020) reveal concrete evidence of coordinated messaging guided by state interests spreading through online networks, showing how extensive such activities have become worldwide.

A lasting structural issue appears in U.S. analyses. Not according to Friedman (2023), but because the Joint Force still sees information operations as support, not strategy this sets up a core clash with China's way of thinking. Seen through Brands (2022), the difference fits a longer timeline; comparisons emerge with Cold War rivalry, though today's U.S. effort lacks the unified government-wide coordination once used against Moscow. Into that space step Lawrence (2024) and Murray (2021), pointing at broken oversight across agencies, along with no standing authority to act before crises hit.

Recent studies about cognitive warfare are shaping the leading edge of research. While focusing on China, Beauchamp-Mustafaga (2023) along with Gadzala Tirziu (2024) explore how artificial intelligence merges with insights from neuroscience within psychological strategies. These analysts suggest upcoming military information efforts may go beyond altering views aiming instead at the mental mechanisms behind decision-making itself. From another angle, Fazio and colleagues (2015) offer foundational work in social psychology showing that frequent contact with false information can still sway knowledgeable people. This insight becomes crucial when measuring how well China's campaigns influence mass perception.

Even though much has been written, key shortcomings still exist. While most research focuses on either Chinese military thinking alone or only American reactions, linking these frameworks remains rare. Some claim today's Chinese strategy grows directly from ancient ideas, yet proof through careful study of texts and institutions tends to be missing. Connecting deep intellectual roots with modern practice could offer clarity where assumptions now stand. By following how Chinese concepts evolved alongside official teachings about information warfare, contrast becomes visible when set beside U.S. approaches. Where differences are sharpest reveals space for refinement. Instead of treating doctrines as isolated traditions, examining them together shows what change might require.

5. Methodology

This study employs a qualitative comparative doctrinal analysis to examine the relationship between strategic culture, institutional doctrine, and operational behavior. A qualitative approach is appropriate given that

strategic culture and doctrinal evolution are not directly measurable and require interpretive analysis of primary texts and institutional practices. Strategic culture, doctrinal evolution, and cognitive influence are phenomena that are better understood through interpretive analysis of primary documents and the synthesis of secondary scholarly literature because they are not amenable to quantitative measurement.

Primary sources include classical texts (i.e., Sun Tzu), revolutionary doctrine (e.g., Mao), and modern PLA writings (Qiao & Wang; AMS 2020), which are analyzed alongside U.S. doctrinal publications such as Joint Publication 3-13. A key piece comes from Mao, written during 1938, titled "On Protracted War." Then there is the 1999 book by Qiao and Wang that speaks beyond traditional battle lines. Another source appears late military thinking from China's Academy updated in 2020. Each one shapes how today's People's Liberation Army sees conflict. Their main ideas surface repeatedly in real-world military actions. From America's side, a guide on information operations offers contrast. This document, published under joint command rules, outlines official thinking about digital-era warfighting. It becomes the point of comparison when measuring strategic differences.

Secondary sources include peer-reviewed scholarship, RAND reports, and policy analyses focused on Chinese information warfare and gray-zone competition. Preference went to recent outputs that clearly explained their methods while incorporating original texts or doctrine issued in Mandarin.

The analysis compares Chinese and U.S. doctrinal approaches across three dimensions: conceptual foundations, institutional organization, and operational application. Where differences surface, they shape the suggestions offered later in Section 6. Though separate in origin, these doctrines reveal contrasts that matter.

Limitations include reliance on publicly available sources and the absence of classified PLA materials; however, triangulation across doctrinal texts and observed behavior mitigates these constraints. Access to confidential Chinese military plans remains impossible, so examination draws instead on public doctrinal material alongside unclassified evaluations of field practices sources that might miss parts of real PLA capacity or aims. The work centers on ideas, not hands-on evaluation, nor does it aim to deliver secret-level findings. A key point made that today's Chinese strategic thinking links to long-standing beliefs is one some scholar's challenge; while the article enters that discussion, closure lies beyond its reach.

6. Analysis and Background: Historical Foundations, Doctrinal Development, and Case Studies

6.1 Classical Foundations: Sun Tzu, Shi, and the Logic of Pre-emptive Shaping

Chinese strategic thought emerged in the fifth century BCE with emphasis on subtle tactics, mental readiness, and merging war with governance. Rather than emphasizing winning wars against armies, Sun Tzu's The Art of War establishes strategies on winning situations, where outcomes are evident even before war is engaged. The often-quoted passage winning without fighting best encapsulates an approach where knowledge is supreme, with success not being determined by physical prowess but by molding beliefs, decisions, and environments (Sawyer, 1994). Even though ancient, it is evident that there was an early comprehension of control of knowledge.

What is at the core of all this is shi both in terms of arrangement and in terms of energy. When a leader is good at arranging conditions in this way, opposition dissolves even before conflict begins, dissolving in both mind and body. Influencing perception, shaping how an opponent makes decisions, pushing on cracks in their allies, building pressure until defeat is inevitable all of these contribute. Unlike in Western thought, which is centered around clear battles and building strength as key elements, this approach does not see these elements as supportive. For Chinese thought, they are the central act (Ota, 2014; Sawyer, 2007).

Looking at this in another way, this dichotomy is the basis for the way in which the Chinese approach conflict and peace. Rather than having delineated moments of conflict, the struggle is one that continues over time in ancient Eastern philosophy. Rather than waiting for the open conflict to begin, the tactics of misinformation and mental strain continue unabated. The delineations that are made in conflict and peace appear to be artificial in this approach. In this way, the approach that the Chinese take in the digital influence campaigns makes more sense. The approach that the United States takes in conflict appears to be one that is based on delineated moments of conflict.

6.2 Mao Zedong and the People's War: Turning Everyone Into Political Actors

From within the turmoil of civil conflict and foreign invasion, Mao Zedong shaped a strategic outlook rooted in endurance and influence rather than brute strength. Instead of matching firepower, he emphasized persistence

through popular engagement, framing struggle as much about belief as territory. His 1938 essay "On Protracted War" proposed that prolonged resistance could erode even dominant foes when their will to fight faded under mounting strain. Success came not just from combat but from shaping how events were seen at home and abroad. Each clash served broader aims strengthening unity among allies, lifting spirits in villages, shifting global opinion. Victory unfolded slowly, fed by patience, messaging, and unrelenting pressure. What mattered most was not who won battles, but who held support when exhaustion set in.

Durable strength, Mao saw, comes not just from force but from weaving together party structure, armed might, and alliances with others. Because of this view, power was never only about battles; it also meant shaping perceptions, building legitimacy, and managing narratives. One result? A military where political guidance runs through each layer, tied directly into command decisions. That setup persists today in the form of commissars placed throughout the PLA hierarchy. Rather than treating politics and warfare as separate realms, they operate as fused elements within one framework. Modern strategies focusing on media, law, and perception echo earlier ideas once championed by Mao himself. What began as revolutionary insight now underpins long-standing institutional practice inside China's armed forces.

6.3 Unrestricted Warfare Meets the Three Warfares

Published in 1999, Unrestricted Warfare by PLA officers Qiao Liang and Wang Xiangsui offered a structured view of how China might engage in strategic rivalry without relying on force. Following closely after the U.S. airstrikes in Kosovo and informed by earlier events like the Gulf War the book proposed bypassing American military strength altogether. Instead of matching firepower, it suggested shifting conflict into areas like finance, law, information networks, global bodies, and news environments. Victory, in this framework, did not require winning battles but undermining confidence, cohesion, or credibility through coordinated non-military actions. Rather than confronting power head-on, influence could be reshaped across less visible arenas. Though written decades ago, its perspective continues to inform discussions about modern forms of state competition.

In 2003, the Central Military Commission updated the People's Liberation Army's political guidelines, marking a turning point this change formally adopted the Three Warfares (San Zhong Zhanfa) into its strategic framework. Shaping how events are seen at home and abroad becomes possible through public opinion warfare (yulun zhan), which relies on media narratives, diplomatic statements, along with coordinated information release. Instead of physical force, psychological warfare (xinli zhan) works by unsettling enemy leaders, weakening their unity, influencing choices under pressure. Where law appears neutral, it can still be shaped legal warfare (fālǜ zhan) exploits national and global legal systems to justify China's moves while pressuring opponents to defend their own positions. Sources such as Martin (2021) and Głodek & Behrendt (2022) trace these methods across recent decades.

Beyond moments of open hostilities, the Three Warfares persist without pause. Activation does not hinge on formal warfare announcements or troop movements. Instead, they unfold steadily during periods commonly labeled peace. Their influence weaves through diplomatic, informational, and psychological channels. Over time, these efforts tilt conditions ahead of potential clashes. Even when no fighting occurs, their presence alters how events are perceived. Strategic advantage builds quietly, long before any battlefield emerges.

6.4 The Strategic Support Force: Combining Cyber, Space, and Electronic Warfare

Born in 2015, the PLA Strategic Support Force brought together threads long developing within Chinese military thought. Under one roof now sit cyber efforts, electronic interference, orbital missions, along with influence campaigns not as isolated tools, but pieces of a larger design. What was once treated separately now operates as connected layers of a shared struggle for control over data flows. From Beijing's view, information does more than stand on its own; it shapes how battles unfold everywhere else. Whether on solid ground, beneath waves, through skies, or beyond atmosphere, access to knowledge shifts advantage. This idea appears clearly in recent strategic writings approved by top defense scholars. Power over signals, networks, and perception is seen not just as another front, but as the foundation shaping every other move made. While earlier doctrines kept these realms apart, today's framework treats them as interwoven forces feeding into one system.

What stands out is how China built an information warfare system meant for use during peace, able to run complex actions in various areas at once, while avoiding lines that might prompt American military pushback. Found within Chinese strategic thinking is a calculated approach: staying beneath the level where conflict becomes officially acknowledged, which gives the gray-zone idea its essential value in analysis.

6.5 South China Sea Case Study

China demonstrates its use of the Three Warfares through its actions in the South China Sea. China maintained its nine-dash-line claim to historical rights over the area despite the Permanent Court of Arbitration issuing a 2016 denial of its rights to the region. China rejected the arbitration court's jurisdiction and proceeded with ongoing territorial development and military expansion in the disputed region. The United States and its allies faced a critical decision between two options which required them to choose between fighting a nuclear power or accepting Chinese territorial claims. Chinese media depicted US naval operations as aggressive while they described Chinese activities on artificial islands as non-threatening. The message to Southeast Asian nations including Vietnam and the Philippines and Malaysia combined economic incentives with punitive measures. The region experienced a gradual acceptance of Chinese dominance which occurred without any official military aggression.

7. Findings and Discussion

The findings demonstrate that Chinese and U.S. information warfare strategies are grounded in fundamentally different conceptual frameworks that shape doctrine, organization, and execution. China employs an integrated approach that synchronizes military, informational, economic, and legal instruments of power within a unified strategic framework. The analysis demonstrates that China develops its international relations through an approach which unifies all elements of its operations while maintaining ongoing efforts to establish international partnerships. The Three Warfares doctrine establishes state policy to conduct continuous public opinion and psychological and legal competition across military, diplomatic, and economic and media sectors through a unified strategic framework. The Strategic Support Force functions as the institutional framework which enables organizations to align their cyber and space and electronic warfare capabilities with the operational needs of the entire information system. China establishes an operational framework which enables all national power elements to create information dominance while maintaining strategic control over the distinction between peacetime competition and wartime conflict.

In contrast, the United States continues to treat information operations as supporting functions rather than as a central domain of continuous competition. Instead of viewing them broadly, Joint Publication 3-13 ties these efforts tightly to battlefield goals, offering little direction on how agencies might work together outside active combat. Such thinking mirrors a mindset long focused on clear boundaries between wartime and calm holding back powerful responses until open conflict begins. Yet in the blurred space China actively exploits, this line becomes a weakness: allowing Beijing room to push narratives, evaluate laws, and apply pressure without provoking America's full countermove.

The analysis yields four key implications:

- military deterrence alone is insufficient,
- cognitive resilience is underdeveloped,
- economic and legal tools must be integrated into deterrence, and
- alliance cohesion is a critical center of gravity.

While keeping strong military defenses matters, relying on them alone does not work. To avoid sudden shifts by China in places like Taiwan or the South China Sea, having troops ready and visible across the Indo-Pacific makes sense; efforts by the U.S. and partners to train together, position units ahead of time, and build fast-moving capabilities align with this need. Still, depending only on armed strength ignores subtler moves already changing the landscape before open conflict arises. When confidence in elected governments weakens, cooperation among allies' frays, and local decisions shift due to long-term pressure from Beijing, even well-prepared militaries may operate under worse conditions than expected.

It begins with cognition: defense here remains oddly neglected despite growing importance. Rather than just shifting opinions, Chinese information tactics aim deeper undermining mental frameworks and organizational resilience needed to resist collectively. Evidence shows repetition sways judgment; familiar falsehoods feel truer over time, per Fazio et al. (2015), even when people know better. This effect signals a need not urgent, yet unavoidable for strengthening how citizens process media. Awareness efforts must rise, matched by systems able to detect manipulative patterns quickly within fast-moving online spaces.

One way to respond involves weaving economics and law more carefully into strategies meant to discourage unwanted actions. Because China turns shared markets, loans for major projects, and money movements into tools for gaining influence, traditional defenses like troop readiness or media campaigns fall short. Instead,

penalties aimed at specific actors, restrictions on technology exports, efforts to strengthen production networks, alongside rules built through global agreement can form part of a broader approach. When an international tribunal ruled against Beijing's sweeping maritime claim in 2016, it showed how legal paths might draw sharp lines — yet also revealed their weakness when there is no way to force compliance. That moment confirmed that laws without power behind them may stand as principles but fail as shields.

What makes U.S. power distinct in the region is not just military reach its web of partnerships does more than any weapon system could. Though China lacks equivalent bilateral leverage, it works relentlessly behind the scenes to weaken those ties. Countries like Japan, Australia, South Korea, and the Philippines are bound by decades-old agreements; still, their unity faces quiet erosion through trade pressures and domestic political shifts shaped by external influence. Instead of treating cooperation as automatic, renewed attention must go toward aligning responses to subtle aggression below the threshold of war. Shared messaging, synchronized intelligence practices, and common methods for tracing covert interference become tools just as vital as hardware. Experience during tense global standoffs shows that trust among allies' frays without deliberate upkeep even when treaties remain signed and unchanged on paper.

8. Recommendations

To operationalize the Inverse Unrestricted Warfare framework, deterrence must be translated from conceptual alignment into coordinated, whole-of-government action. The discussion above shows that the PRC is actively engaged in gray zone activities across military, informational, economic, legal, and diplomatic areas, while the US response is scattered among different agencies, commands, and legal authorities. The following recommendations align with the five lines of effort in the Inverse Unrestricted Warfare framework. They aim to strengthen deterrence before a crisis escalates. Each recommendation points out areas the PRC is currently taking advantage of like bureaucratic confusion, gaps in understanding, cognitive weaknesses, or issues in alliance coordination — and suggests changes to fix these problems. To make this work, it is not enough to just add new activities to what we already have; the US needs to rethink its approach to competition, how it combines its tools of power, and how it collaborates with allies to impose costs and prevent gains overall. The objective is to establish a proactive, continuous, and integrated deterrence posture that operates across all domains of competition.

1. Integrate Non-Military Warfare into National Strategy: The United States should view non-military operations as integral parts of national security. This would involve the integrated application of intelligence, diplomacy, and private sector expertise. Similar reforms to the Goldwater-Nichols Act, which enforced the concept of jointness among the various military services, are necessary to achieve true interagency integration in the information domain.
2. Develop Cognitive Defense Capabilities: Investment in the monitoring of information flows, counter-narratives, and societal resilience also needs to be a priority. Public awareness campaigns and media literacy may help alleviate the consequences of disinformation. The relevance of the Fazio et al. (2015) study on the phenomenon of illusory truth also highlights the need to develop such capacities before the consequences of disinformation campaigns are already established in the minds of the public.
3. Employ Strategic Ambiguity Carefully: Adaptive signaling and response are needed to deter competitors that are below traditional conflict thresholds. The United States must develop a body of doctrine and authorities that allow for proportionate and prompt responses to gray-zone actions without a political declaration of armed conflict.
4. Revise Information Operations Doctrine: The U.S. doctrine should place greater emphasis on perception management and influence in strategic planning. Joint Publication 3-13 should be revised to make information operations a continuous peacetime activity rather than a wartime enabler.
5. Improve Cultural and Language Competence: An understanding of Chinese strategic culture, language, and doctrinal literature can improve analysis and foresight capabilities across the entire intelligence, diplomatic, and military communities. Investment in this competency is a long-term strategic asset currently in a state of underdevelopment.
6. Strengthen Alliances: The coordination of the Allied efforts in the sharing of intelligence and the conduct of counter-influence operations is vital in building resilience. It is imperative for the United States to establish common frameworks with the Indo-Pacific nations in the identification of Chinese operations in the gray zone and the response to such operations, with the cohesion of the Alliance being a strategic imperative that demands constant and active investment.
7. Pursue Structural Reform: Similar institutional reforms to the Goldwater-Nichols Act could also enhance the integration of the national instruments of power in the information domain. However,

without institutional reform, the fragmentation of the interagency response will continue to create the response delays that the Chinese doctrine in the gray zone was specifically designed to take advantage of.

9. Conclusion

China's information warfare strategy reflects a deliberate integration of historical philosophy and modern military doctrine. Information operations are central—not peripheral—to China's conception of national power. China uses its ability to control information and spread its narratives through technological methods to create conditions that exist between peace and war.

The United States must adapt by integrating information operations into national strategy, strengthening societal resilience, and improving interagency and allied coordination. Future competition will be determined as much by perception and influence as by kinetic force, requiring a fundamental shift in strategic mindset and doctrine. Competition needs an innovative approach because the existing mindset and doctrine do not work for handling ongoing gray-zone conflicts.

Ethics Declaration: Ethical clearance was not required for this research.

AI Declaration: Open-source artificial intelligence tools were used solely for proofreading and citation formatting. All analysis, arguments, and conclusions presented in this paper are the original work of the authors or are derived from appropriately cited sources.

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Banking Resilience: Building Cyber Incident Response in the Finnish Financial Sector

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Abstract: Cybersecurity incidents in the financial sector pose systemic risks to economic stability and societal continuity. Despite extensive regulatory oversight and generally high cybersecurity maturity, recent incidents in Finland have revealed persistent weaknesses in incident response and recovery. Using a recent incident at the Nordic bank Nordea as a descriptive case, the study examines governance structures, role allocation and skills coordination during cybersecurity incidents at the sectoral level. The research data consist of document analysis of public incident-related material and six semi-structured interviews with cybersecurity professionals experienced in the financial sector. The analysis is informed by established cybersecurity governance and incident response frameworks. The data were analysed using thematic analysis to identify key patterns and gaps in incident response practices. The findings indicate that while preventive controls in the Finnish financial sector are well-developed, effective incident response is constrained by rigid structures, fragmented accountability, and limited application of skill-based roles. Incident response is frequently managed within functional silos, reducing shared situational awareness and slowing adaptive decision-making. The study contributes to cybersecurity and crisis management literature by contextualising the European Cybersecurity Skills Framework within financial-sector incident response and highlighting the importance of continuous learning, clear role coordination, and flexible governance mechanisms.

Keywords: Cybersecurity incident response, Financial sector, Organisational resilience, Cybersecurity governance, European cybersecurity skills framework

1. Introduction

Cyber security and cyber resilience are increasingly important in the operating environment of contemporary organisations. The financial sector is part of critical infrastructure, which makes it an especially attractive target for cyberattacks (Didenko, 2020). For this reason, the industry operates under heavy regulatory oversight from both international and national bodies, which enforce security and resilience measures. The European Union Agency for Cybersecurity (ENISA) provides coordination, threat intelligence, and support for implementing EU-wide directives such as DORA (Digital Operational Resilience Act).

Nationally, Finland's cybersecurity landscape in the financial sector is shaped by Traficom's National Cyber Security Centre and Financial Supervisory Authority (FIN-FSA), which guide, assist, and supervise organisations with implementing cybersecurity best practices in the industry. In Finland, the financial sector has previously been reported to be the third most advanced industry in terms of cybersecurity, after telecommunications and ICT and software (Huoltovarmuuskeskus, 2022). However, the pressure on the already targeted industry has grown. Internationally, cybersecurity attacks, especially denial-of-service (DoS) attacks, have increased both in size and volume over the past few years (de Neira et al, 2023). National Cybersecurity Centre of Finland has reported that the number of denial-of-service attacks has grown in Finland; however prolonged attacks disruptive to organisations are still rare (Kyberturvallisuuskeskus, 2024).

This paper analyses the regulatory and best practice landscape of the Finnish financial sector and uses the prolonged DoS attacks against the finance company Nordea in 2024 as an illustrative case. The paper aims to answer the question: How could the European Cybersecurity Skills Framework be used to identify and address skills gaps in incident response? The paper reports the results of a Master's thesis written by the first author.

2. Incident Response and Skills Coordination

2.1 Incident Response and Cyber Resilience

Cyber resilience refers to the ability of an organisation to absorb, adapt to, and recover from cyber disruptions while maintaining continuity of critical functions (Dupont, 2019; Petrenko, 2019). Unlike traditional cybersecurity, which prioritises prevention, resilience acknowledges that not all incidents can be avoided and emphasises response, recovery, and organisational learning (Björck et al, 2015).

In the financial sector, resilience is particularly important due to systemic interdependencies and the potential cascading effects of localised incidents (Carilo, 2023). Cyber disruptions may result not only in operational downtime but also in reputational damage and broader economic instability (Varga et al, 2021). Consequently,

incident response must extend beyond technical containment to coordinated organisational action across multiple functions.

Most standards structure incident response around detection, response, and recovery processes; however, some argue that formalised procedures alone do not guarantee adaptive performance during real incidents (Adetunji & Chinonso, 2025). Effective response requires situational awareness, flexible decision-making, and the capacity to integrate lessons learned into future preparedness (Petrenko, 2019).

Resilience therefore depends on dynamic organisational capabilities rather than static compliance mechanisms. The ability to reconfigure roles, maintain coordinated communication, and institutionalise post-incident learning distinguishes resilient organisations from those relying solely on formal controls (Uddin et al, 2020).

2.2 Governance and Role Clarity

Cybersecurity governance encompasses the structures, policies, and decision-making processes through which cybersecurity activities are directed and monitored (Cortez & Dekker, 2022). In the financial sector, governance is shaped by extensive regulatory oversight, including requirements that emphasise management accountability for cybersecurity risks (Calliess & Baumgarten, 2020). Despite formal structures, governance deficiencies may emerge in fragmented accountability and unclear role definitions. During disruptive incidents, ambiguity regarding decision authority and escalation pathways can delay coordinated response efforts (Akinsulire & Ohakawa, 2024). This suggests that governance effectiveness depends not only on regulatory compliance but also on operational clarity.

Research further indicates that compliance-driven cybersecurity cultures may prioritise audit readiness over adaptive capability (Peihani, 2022). Although institutions may satisfy formal requirements, coordination challenges can persist in practice, particularly when responsibilities are distributed across technical teams, management, communication units, and external stakeholders (Varga et al, 2021). Moreover, governance mechanisms are embedded within organisational culture and behavioural norms (Weickert et al, 2023). Without shared understanding and clearly articulated responsibilities, even well-designed governance frameworks may fail to translate into effective incident coordination. Strengthening incident response therefore requires aligning governance structures with real-time operational demands and clarifying roles across hierarchical and functional boundaries.

2.3 The European Cybersecurity Skills Framework

While governance structures define accountability, effective incident response also depends on clearly articulated competencies. The European Cybersecurity Skills Framework (ECSF), developed by ENISA, provides a structured taxonomy of cybersecurity professional roles and associated knowledge, skills, and competences (European Union Agency for Cybersecurity, 2022a). It aims to harmonise role definitions across Europe and support workforce development within cybersecurity functions (European Union Agency for Cybersecurity, 2022b). However, competence frameworks are often implemented primarily as human resource instruments rather than as integrated elements of cybersecurity governance (Olutimehin, 2025).

Incident response requires multidisciplinary coordination, including technical expertise, crisis communication, risk assessment, and leadership capabilities (Varga et al, 2021). If roles are ambiguously defined or competencies misaligned with operational demands, response effectiveness may be compromised. Structured role frameworks can therefore support clearer allocation of responsibilities and identification of capability gaps.

Although existing research emphasises governance and technical controls in financial cybersecurity (Didenko, 2020; Uddin et al, 2020), limited attention has been paid to the integration of structured skills frameworks into incident response governance. Connecting ECSF-defined competencies with governance mechanisms may strengthen situational awareness, clarify escalation responsibilities, and support adaptive recovery processes. This integration provides a conceptual foundation for examining how skills coordination contributes to resilient incident response.

3. Research Design and Method

This study seeks to generate analytical and actionable insights to improve incident response capabilities from literature, documentary sources, and empirical material. The pragmatist approach of the study accommodates both the descriptive aim to depict how incident response is organised, and the prescriptive aim to identify how it could be improved (Farjoun et al, 2015; Goldkuhl, 2012). Document data, such as standards, media articles, and public reports, provide insight into official narratives, institutional framing, and sector-level expectations,

while expert interviews reveal practitioners' situated interpretations, reasoning, and tacit knowledge that are often absent from formal documentation (Eriksson & Kovalainen, 2008; Puusa et al, 2020; Yin, 2018).

Document analysis is used to examine the incident response of the financial sector through news articles, standards, and public reports for the descriptive case study. In total, 99 documents were included in the analysis. The document dataset consists primarily of publicly available news articles as well as public reports and decisions by FIN-FSA. A key inclusion criterion was the potential of the document to provide insight into the Nordea incident and related incident response practices. Table 1 shows examples of thematic coding linked to the documents.

Table 1: Document analysis coding example

Main Theme	Subtheme	Example Codes	Frequency
Leadership and the role of management	Leadership taking responsibility	Leadership visibility during crisis, communication roles	15
Skills and ECSF Roles	Competence management	Unclear division of responsibilities, need for specific skills	5
Organisational resilience and incident response	Evolving operational environment	Increased number of attacks	10
	Recovery from service disruptions	Lessons learned and improvement actions	20

In this paper the thematic coding of the document data presented in Table 1 is not very strongly visible due to space constraints. Individual materials from the data are used as example sources in the findings, but they represent findings from a larger pool of articles as seen in the table.

Semi-structured interviews were selected as another data collection method to complement the document data and enable an in-depth exploration of expert perspectives on incident response practices in the financial sector. Recommendations by Hair (2023) and Flick (2021) for forming interview questions that guide the discussion but remain open to interpretation were considered. In total, six experts with varying backgrounds and experience were interviewed in this study. Providing themes in advance to the interviewees was considered beneficial for directing attention to specific areas within the broad scope of incident response, while withholding detailed questions preserved the spontaneity and authenticity of the discussion (Puusa et al, 2020). The interviewees are given the identifiers I1, I2, I3, I4, I5 and I6 in the findings section of this paper. The thematic analysis of the interviews is shown in table 2.

Table 2: Interview analysis example

Raw Excerpt	Initial Code	Subtheme	Main Theme
"Companies must have crisis management plans in place in case, for example a cloud service provider experiences security issues"	Third-party risk identification	Outsourcing management and third-party coordination	Organisational resilience and incident response
"It does not make sense to keep forensic experts in-house, as they have work once or twice a year, and their skills need to be maintained"	Balancing outsourcing Cost-benefit of external expertise	Balancing in-house and outsourced capability decisions	Skills

The data were analysed with a thematic analysis process guided by the research questions (Braun, 2022). Qualitative interpretation is inevitably shaped by the researcher's prior understanding and assumptions (Patton, 2023). Therefore, reflexive notetaking and journaling were used to document analytical decisions. Thematic coding was conducted from the interviews by combining codes and sub-themes as illustrated in Table 2. The interview questions were based on the document analysis, but this type of coding was made to ensure as much independence between the analyses of the datasets as possible.

4. Findings

4.1 Incident Response and Cyber Resilience

Document data revealed mixed perceptions of Nordea's resilience and incident response capabilities. Experts questioned the technical explanations given publicly, and many noted that Nordea had experienced recurring mobile and online banking disruptions on most days over several weeks (Oukanen, 2024). At the same time, Nordea consistently framed its response as evidence of resilience, repeatedly emphasising ongoing investment in defence capabilities and the iterative strengthening of systems as attacks evolve (Nordea, 2025a).

The disruptions affected not only online banking but also Nordea's authentication application (Suutari, 2025). Because bank credentials are the dominant method of strong authentication in Finland, customers were temporarily unable to access unrelated essential services such as government platforms. From a resilience perspective, this reflected a system-level single point of failure rather than a Nordea-specific technical limitation. Document data highlighted that authentication via the Mobile Certificate requires prior activation using bank credentials, making it unusable as an alternative once the disruption began, and unavailable to many users due to operator constraints. Customer support channels were also impaired, as chat services required online-bank authentication (Mäntylä, 2024). This highlights the dependencies that are created within systems over time and emphasises the role of banks as a critical part of the entire digital society in Finland.

Nordea and external commentators framed the incident as a catalyst for strengthening resilience. Nordea highlighted defence mechanisms becoming "even more robust" (Oxvig, 2024), and even critical voices acknowledged the potential of the event to improve defences (Linnake, 2024). Nordea stated that thousands of updates and modifications are deployed annually, most invisible to customers, and that large-scale changes may occasionally require interruptions (Kärkkäinen, 2024). Nonetheless, documents also noted that service disruptions continued after the attack period, suggesting that the incident occurred amid broader infrastructural strain.

Although several major Nordic banks, including SEB, Danske Bank, Swedbank, and OP, were targeted during the same campaign, Nordea experienced the most prolonged and visible disruptions. Document data suggested contrasting interpretations. Nordea attributed the differential impact to its position as the largest Nordic bank and therefore the most attractive target (Oxvig, 2024), while some experts questioned whether Nordea's existing system fragilities amplified the effects. The observation that the strongest attacks were reported in Sweden, despite lower public attention than in Finland, reinforces the need to evaluate resilience not solely through media visibility but through structural preparedness and recovery capability across institutions (Raeste, 2024). Cybersecurity experts also cautioned that it is inherently difficult to assess an organisation's resilience from the outside. They noted that given the volume of attacks targeting Finnish entities, the relative scarcity of large-scale disruptions indicates strong baseline resilience in the country (Raeste, 2024). However, Nordea faced recurring issues throughout 2024 and early 2025 (Pietiläinen, 2024; Suutari, 2025), which may have shaped public perceptions and heightened scrutiny during the autumn incident.

4.2 Governance and Role Clarity

Both the document data and interviews suggest that incident response governance in the Finnish financial sector is generally well structured and closely aligned with regulatory expectations. In the Nordea case, governance was publicly framed through visible engagement with authorities and cross-institutional coordination, indicating that the incident was managed as a matter of national relevance rather than a purely technical disruption (STT-YLE, 2024). Nordea's interactions with authorities and the broader institutional attention given to the incident reflect a high level of formal coordination within the sector's governance ecosystem, involving key supervisors and national cybersecurity actors.

At the same time, the document data indicate that from a legal and supervisory perspective, the Nordea incident did not necessarily reveal a failure of governance as such, but rather the limits of what regulation can achieve. Public commentary and supervisory framing emphasised that oversight primarily evaluates whether required processes and controls exist and whether obligations are met, rather than how effectively practices function in real time under rapidly evolving conditions (Valkama, 2024). This creates a gap between formal compliance and experienced resilience, a phenomenon that has been previously documented in literature (He et al, 2022). Governance structures may appear sufficient from a regulatory standpoint, while stakeholders affected by disruptions may interpret the response as inadequate or unclear.

The interviews reinforce the view that Finnish financial institutions maintain mature and rehearsed governance processes and roles for incident response. Respondents described governance structures as formalised, role-based, and supported by pre-defined escalation pathways (I3). These structures were described as well-established and practised, supporting the broader perception of high cybersecurity maturity in the sector (I5).

However, the analysis also suggests that rigid governance does not automatically translate into adaptive incident response. Interviewees highlighted that real-world incidents often inspire unpredictability and require cross-unit coordination and prioritisation decisions that cannot fully be scripted. While governance structures support accountability and role clarity, the increasing specificity of obligations can also introduce complexity and additional workload during an active incident (I3). In practice, this may divert resources from operational response tasks to reporting and coordination routines. Even when these routines are necessary for compliance this may not be the optimal use of resources during the incident (I4).

Both datasets point to a visibility and trust challenge in the sector. Even where governance processes and roles exist and are exercised sector-wide, their effectiveness may not be evident to external stakeholders such as customers during service disruptions. Interviewees emphasised that stakeholder trust is fragile and that communication decisions carry reputational consequences, particularly if customers perceive responses as vague or unaccountable (I2). Unlike the interviews, the document data indicate that the clarity of governance roles was not consistently reflected in public communication during the Nordea incident. Updates to customers were described in media coverage as ambiguous, limited, and scattered around channels (Kärkkäinen, 2024). This contrast suggests that internally coherent governance structures do not automatically translate into externally coherent processes. In practice, role clarity within organisations may remain invisible to stakeholders if processes are not sufficiently integrated into incident response governance.

4.3 The European Cybersecurity Skills Framework

While Nordea describes structured training programs and internal coordination models (Nordea, 2025b, 2023), there was little evidence of systematic alignment with the European Cybersecurity Skills Framework (ECSF) or comparable competence models found in the document analysis. This gap may hinder efforts to clearly assign, develop, and evaluate the roles involved in incident response. The lack of competence models might also hamper communication and reduce trust when organisational communication is inconsistent and ambiguous.

The Nordea case illustrates the multidisciplinary nature of incident response competencies. Media coverage revealed that individuals without explicit technical expertise responded to detailed questions about attack methods and defensive measures (Herrala, 2024; Linnake, 2024), which increased distrust and critique (Linnake, 2024). The absence of cybersecurity leadership in media contradicts with the ECSF's distinction between operational, communication, and strategic cybersecurity roles. This does not necessarily indicate a lack of expertise, but rather a potential misalignment between competence structures and their external enactment.

Broader public discussion during the incident further highlighted concerns about cybersecurity competencies within Finnish organisations, particularly regarding human error and cybersecurity awareness (Nyman, 2024). This reflects the ECSF's emphasis on defined competence areas across both technical and organisational domains.

Interview data confirm that financial institutions maintain strong technical capabilities, including internal SOC and CERT functions, while highly specialised expertise is often outsourced due to its infrequent use (I4, I5). Respondents emphasised that effective incident response requires not only deep technical knowledge but also communication and leadership competencies (I4, I5). Training was described as continuous and responsive to identified gaps (I5, I6). However, these practices appear to operate without explicit integration of structured competence frameworks such as the ECSF into governance mechanisms. The findings suggest that while the Finnish financial sector demonstrates high levels of cybersecurity expertise, competence management remains practice-driven rather than framework-integrated. This gap highlights the potential value of linking ECSF-defined competencies more systematically with incident response governance to enhance role clarity, situational awareness, and adaptive recovery.

5. Discussion and Conclusions

The comparison between the empirical findings and literature reveals that Finnish financial institutions largely adhere to the spirit of international best practices in but may fall short of implementing them in the systematic and accountable manner into governance processes. While interviewees consistently emphasised that DORA does not change anything substantial because the sector largely already follows international best practices, the

document data demonstrates that the practical application of these standards remains uneven, especially in accountability and post-incident learning. This gap invites a critical reflection on whether adherence to formal frameworks equates to genuine resilience in practice, or whether resilience depends on how incident response capabilities are used in real incidents.

Effective incident response encompasses preparation, detection, analysis, containment, eradication, recovery, and post-incident activity (ISO/IEC 27035, 2016; National Institute of Standards and Technology, 2024). Evidence from both datasets shows that Finnish financial institutions perform strongly in the preventive and detection phases. Interview data emphasised extensive monitoring capabilities, active participation in national exercises, and integration of threat intelligence into routine operations. These findings support previous research suggesting that Nordic financial entities demonstrate advanced detection maturity and inter-organisational cooperation (European Union Agency for Cybersecurity, 2025). However, the later stages of the incident response life cycle, particularly response, recovery, and post-incident learning, appear less consistent with the frameworks' intent, which raises the question of whether compliance-driven maturity adequately translates into agile and effective incident response (Computer Security Division, 2024) when confronted with complex incidents.

From a theoretical perspective, the findings both confirm and extend prior studies on the relationship between institutional maturity and adaptive response. Consistent with He et al (2022), the data suggests that high technical preparedness can coexist with limited strategic flexibility and lack of agility in incident response processes. However, this study extends the discussion by providing sector-specific evidence from Finland that even when frameworks are embedded at the policy level, their interpretive application varies depending on organisational culture and perceived reputational risk.

The European Cybersecurity Skills Framework (ECSF) provides a comprehensive structure for defining cybersecurity roles and competencies across organisations. Although it has not yet been widely adopted in the Finnish financial sector, the findings suggest that it could serve as a valuable tool for clarifying responsibilities, managing outsourcing relationships, and improving communication and accountability in incident response. Both document and interview data indicate that roles in the Finnish financial sector are currently defined through standards and regulations rather than through the ECSF. This observation aligns with assessment of ECSF (Polemi & Kioskli, 2023), which note that the frameworks' uptake has been limited across sectors despite its potential to harmonise competence requirements.

Across both datasets, ECSF was not explicitly recognised as a guiding structure. Interview data revealed that incident response roles are already well established within financial institutions, typically reflecting regulatory expectations and industry best practices. During the Nordea incident, several executives commented publicly on the situation, yet technical experts or the CISO did not take a visible role. This pattern contradicts the ECSF's approach, which emphasises clear role definition and accountability chains extending from technical experts to strategic management. This further contradicts with the interviewees' stance that the CISO often has a communicative role. However, the ECSF does not precisely define the communicative role and responsibility for stakeholder communication (European Union Agency for Cybersecurity, 2022a), which can be considered a major limitation especially in terms of its utilisation in incidents like the one in this study. Clarifying these responsibilities could directly strengthen communication as an incident response capability.

This study contributes to cybersecurity governance literature by contextualising the European Cybersecurity Skills Framework (ECSF) within financial-sector incident response and by highlighting the importance of integrating structured competence frameworks into governance mechanisms. Practically, the findings suggest that financial institutions and regulators should prioritise escalation clarity, cross-functional coordination, and systematic learning processes alongside regulatory compliance.

The study is limited by its reliance on publicly available documents and a relatively small interview sample, which may not fully capture internal organisational dynamics. Future research could examine longitudinal incident response development, compare multiple institutions, or explore how competence frameworks such as the ECSF can be operationalised in crisis communication and leadership practices.

Ethics Declaration: The research adhered to the ethical review guidelines of the home institution and did not require formal ethical clearance from an institutional ethics committee.

AI Declaration: AI tools were not used in writing of this paper.

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AI Warfare

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Abstract: Artificial intelligence (AI) is rapidly transforming military strategy, yet the idea of AI warfare remains loosely defined. This paper introduces a structured framework that views AI warfare as a form of strategic competition centred on algorithms, training datasets, AI-as-a-Service (AIaaS), and AI-generated content (AIGC). These technological instruments are used to influence adversaries' decision-making and cognitive processes, while simultaneously undermining their defensive and command capacities. The analysis begins with the vulnerabilities of layered architecture of AI ecosystem—infrastructure, algorithm-data, foundation models, and applications—each containing vulnerabilities that can cascade through the system. AI systems also carry inherent limitations, such as unclear problem contexts, lack of creativity or emotional understanding, disembodiment, and weak collaboration between models. These traits distinguish AI warfare from conventional cyber operations and highlight why traditional cybersecurity measures often fall short. The proposed framework operates across three interlinked components: technological infrastructure—semiconductors, high-performance computing, and high-speed networks—sets the capability and flexibility of AI systems, while an opaque algorithm-data core becomes a frontline where adversarial manipulations threaten reliability. At the operational level, AI is deployed through AIGC campaigns and AIaaS platforms, with feedback loops among these components driving continuous escalation and adaptation in AI warfare. Five critical focus areas emerge: (1) proprietary algorithms functioning as opaque "black boxes," examined through a new Wargaming Design (WD) model using iterative red-blue team challenges; (2) vulnerable training datasets, tested for integrity via WD model's consistency checks; (3) AIaaS platforms demanding security-by-design safeguards like role-based access and auditing; (4) AIGC as both an effective offensive tool and a potential source of self-sabotage; and (5) quantitative audience analysis to assess cognitive and behavioural outcomes. Defensive strategies include blockchain-based distributed architectures for resilience, secure interaction design, AI-native firewalls, interdisciplinary user/audience research drawing on sociology and psychology, and global governance structures akin to non-proliferation treaties. Through this approach, the paper explains why conventional defences fail against AI-specific threats. Future work will experimentally apply the WD model to existing AI systems, measuring its effectiveness in identifying algorithmic weaknesses and improving AI security. Ultimately, policymakers must balance the power of AI with the preservation of strategic stability and human agency.

Keywords: AI warfare, Cyber warfare, Cybersecurity, AIaaS, AIGC, Algorithm defence

1. Structural Vulnerabilities of AI Ecosystem

As discussed by Blunden and Cheung (2014), Dyer-Witheford and Matviyenko (2019), Mehan (2014), Carvalho and da Silva (2006), the artificial intelligence (AI) ecosystem can be understood as a set of interdependent layers that together shape how AI systems are developed and deployed.

At its foundation is the infrastructure layer, which includes semiconductors, computing power centres, and high-speed networks; this layer determines computational capacity, scalability, and even geopolitical influence over AI competitions. Built on top of this is the algorithm-data co-evolution layer, where algorithms and training datasets interact continuously to improve model performance. The foundation model layer then provides large, pre-trained models that serve as adaptable bases, allowing developers to reuse general capabilities across tasks while reducing time and cost. These models are further refined in the specialization layer, where fine-tuning, domain-specific data, and retrieval systems produce both general-purpose products and highly specialized services, often applied by sensitive sectors such as government, military and finance. The application layer represents the point of deployment, where AI is integrated into real-world environments and will generate economic, social, or strategic effects.

Across all these layers, governance and security concerns act as a cross-cutting force, shaping how data is accessed, how services are deployed, and how infrastructure is controlled, while also influencing risk, accountability, and competitive dynamics.

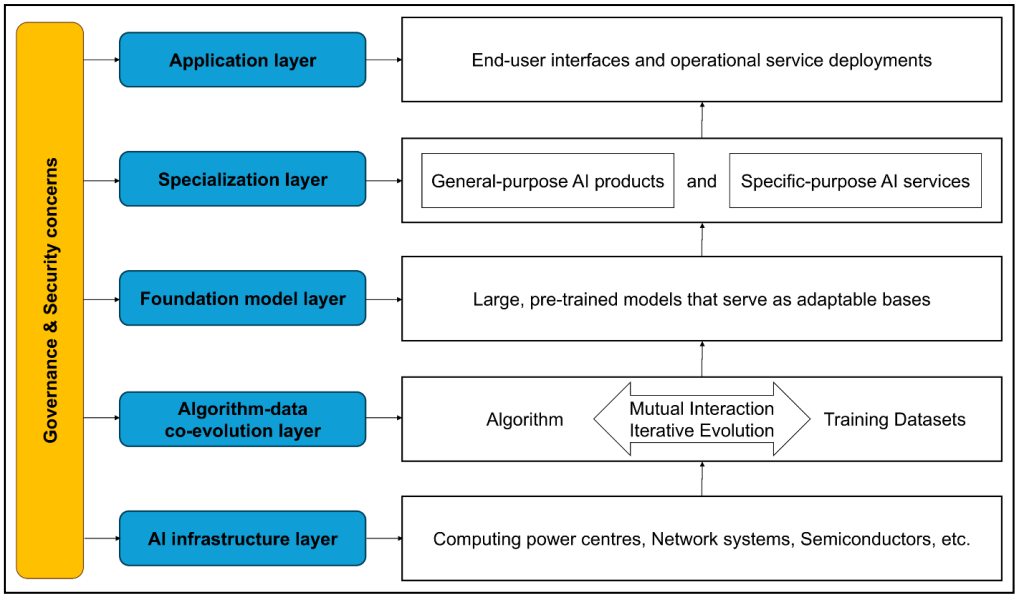


Figure 1: The structural layers of AI ecosystem

However, this stratified architecture creates cascading vulnerabilities where compromise at lower levels propagates upward, undermining algorithmic integrity, model reliability, and operational security.

1.1 Infrastructure Vulnerability

The biggest vulnerability in the AI infrastructure layer is geopolitics, particularly supply chain disruptions from export controls and the risk of kinetic attacks on data centres. U.S. restrictions on advanced AI chips since 2023 have created global dependencies, limiting access to critical hardware like NVIDIA H100 GPUs and amplifying competition with China. Recent 2026 incident, Iranian drone strikes on Gulf data centres, underscore the physical fragility of these facilities amid rising tensions. Technical challenges persist, but geopolitical factors pose the most acute threat to AI capability and scalability.

1.2 Vulnerability of Algorithm and Data

The main vulnerabilities in the algorithm-data co-evolution layer are the black-box nature of algorithms and opaque training datasets quality. Data poisoning attacks pose the greatest risk, as attackers insert malicious samples into datasets, causing models to learn flawed patterns that persist after deployment. Souly, A. et al. (2025) found that just 100-500 poisoned examples can compromise large-scale models, especially in federated learning where detection is difficult. These attacks exploit the iterative algorithm-data feedback loop, creating persistent threats and risks.

1.3 Foundation Model's Vulnerability

The typical vulnerabilities in the foundation model layer are prompt injection and jailbreaking. Attackers craft inputs to override safety alignments, forcing models to produce harmful outputs like malware code or misinformation. Anthropic (2026) detected industrial-scale distillation attacks by DeepSeek, Moonshot AI, and MiniMax, which created ~24,000 fake accounts to systematically extract Claude's reasoning and tool-use capabilities via structured queries.

This threat is critical because foundation models underpin specialized applications across sectors, amplifying systemic risks when guardrails fail. Industry analysis shows these models form chokepoints where a single exploit cascades downstream, unlike narrower attacks on specific adaptations.

1.4 Vulnerability at Specialization Layer

In the specialization layer, AI-generated content (AIGC) and AI-as-a-Service (AIaaS) form key risk surfaces for general-purpose products and specific-purpose services. AIGC introduces vulnerabilities like insecure code generation, Veracode (2025) found that AI-generated code introduced exploitable security vulnerabilities in 45% of tested development tasks across more than 100 large language models, expanding attack surfaces at scale. AIaaS exposes risks through API weaknesses and prompt injections; Cycode (2026) highlights CVE-2025-53773,

where hidden injections in GitHub Copilot enabled remote code execution (CVSS 9.6). These amplify in specialized military or financial systems, where flawed outputs or hijacked workflows cascade to critical failures.

1.5 Application Layer Vulnerability

In the application layer, cognitive manipulation emerges as the primary vulnerability for end-users, where AI subtly influences opinions and behaviours through personalized disinformation. In Ireland's 2025 presidential election, AI-generated deepfakes falsely depicted a leading candidate withdrawing from the race and the election being cancelled, prompting authorities and platforms to remove the content as election-related disinformation. Canadian Centre for Cyber Security (2024) warned that AI-driven narratives erode trust, with chatbots echoing manipulated content from poisoned sources. These risks extend beyond technical flaws, threatening democratic integrity as users increasingly rely on AI for information.

2. Weaponized Vulnerabilities: Why is the Analysis of AI Warfare Needed?

AI is rapidly emerging as a transformative force across economic, social, and security domains. Its speed, scalability, and convenience encourage widespread adoption, often leading users to trade autonomy and control for efficiency. At the same time, it is important to recognize the substantial gap between narrow AI systems and human-level general intelligence. Several structural constraints limit the effectiveness of current AI in military contexts, including the inability to handle undefined problem spaces, lack of genuine insight and creativity, dependence on limited sensory inputs, absence of emotional understanding, and weak cross-system integration. These constraints affect how AI can be deployed, trusted, and countered in operational settings.

In addition to these fundamental gaps, the previously discussed vulnerabilities of AI may also increase the potential for AI weaponization. This can occur through algorithms, training datasets, AIaaS, and AIGC, thereby introducing new attack surfaces and reshaping strategic interactions in conflict environments. These developments demand systematic analysis and the advancement of theoretical frameworks tailored to AI from a warfare perspective.

2.1 Algorithm Weaponization

Algorithm weaponization denotes the intentional design or manipulation of algorithms to produce adverse cognitive and operational effects in conflict environments. In AI warfare context, Lange, L. (2024) described an "algorithmic cognitive warfare" framework, in which AI-driven recommendation systems and social-media algorithms are repurposed to microtarget users with tailored narratives, aiming to polarize public opinion, erode trust in institutions, and fragment collective decision-making under information overload. In particular, Chinese-linked military and security discourse explicitly frames these algorithmic tools as instruments for influencing foreign populations along political, ethnic, and ideological lines. In practice, this can resemble algorithm-driven bursts of misleading content timed to elections or crises, although the specific mechanisms are still being mapped in the literature.

2.2 Data Weaponization

Strategic poisoning, distortion, or exploitation of datasets used to train or operate AI systems is a powerful weapon in warfare. In AI-driven conflicts, adversaries manipulate datasets to degrade reliability, mislead targeting systems, or create synthetic "ground truths" that align with their narrative. Liebgold (2025) researched on U.S. military AI scenarios and highlighted how data poisoning can be used as a covert cyber capability to undermine adversary intelligence, surveillance, and reconnaissance systems without triggering conventional warfare thresholds This case demonstrates that control over data integrity is central to AI warfare, because corrupted or biased inputs systematically warp the outputs of even technically robust models.

2.3 AIGC Weaponization

AIGC weaponization designates the deployment of generative models to produce synthetic audio, video, and text for cognitive-targeting purposes. During the 2026 Israel–Iran hostilities, Brookings Institution (2026) observed that Iranian asymmetric campaigns employed AIGC deepfakes to simulate military leaders' pronouncements and false battlefield footage, which were disseminated through semi-official channels to amplify doubt and reduce coalition cohesion. Guess et al. (2023) conducted empirical studies of synthetic media in information operations show that AIGC disinformation can significantly increase perceived credibility among test audiences, especially when aligned with local cultural or linguistic cues. These dynamics transform content creation into a scalable, adaptive layer of AI warfare rather than a one-off propaganda tactic.

2.4 AIaaS Weaponization

AIaaS weaponization captures how AI services and APIs enable adversaries or non-state actors to execute sophisticated information operations without in-house expertise. In AI warfare, adversaries rent AI services for text generation, voice synthesis, and behavioural prediction, then integrate them into automated attack chains.

Nobles, C. (2024) studied on the weaponization of AI in cybersecurity highlights that AIaaS platforms lower the skill barrier for creating malware-generation tools, sentiment-analysis pipelines, and fake-network-traffic simulators, thereby enabling rapid experimentation and adaptation of offensive toolkits. Consequently, AIaaS weaponization reframes AI warfare as an ecosystem-level problem, where the same commercial platforms used for benign automation become vectors for scalable cognitive attack.

In conclusion, given these multiple, mutually reinforcing layers of AI weaponization, a systematic analysis of AI warfare is essential to anticipate, mitigate, and regulate emerging threats. Without tailored theoretical and operational frameworks, states and other entities risk adopting AI-enabled capabilities reactively, while adversaries exploit structural gaps and cognitive vulnerabilities at scale. Understanding AI warfare is therefore not merely an academic exercise but a strategic necessity.

3. Conceptual Framework of AI Warfare

This section builds on the earlier analysis of the AI ecosystem, its vulnerabilities, and how those weaknesses can be weaponized in warfare, including real-world examples. It will focus on a core question: what is AI warfare? First, we review and evaluate existing definitions. Then, we explain the key components that make up AI warfare and propose a practical definition that can be used for analysis. Finally, we apply this definition to a case study to show how it helps interpret a real-world warfare scenario.

3.1 Literature Review

Since 2020, academic and policy discourse on AI warfare has evolved from a narrow, technology-centric view toward a broader, systemic understanding of cognition, information, and operational speed. Early work treated AI warfare as AI-augmented conventional warfare, focusing on target-recognition systems, predictive logistics, and autonomous platforms.

Around 2022–2023, scholars such as Rickli and Mantellassi (2023) began explicitly framing AI warfare through military uses and international security implications, linking AI-driven capabilities to arms-control, escalation risk, and alliance-level strategic competition. Johnson (2022)'s work on the "AI commander problem" added a strong ethical and psychological dimension, redefining AI warfare as a domain where human–machine interaction creates dilemmas in responsibility, control, and trust.

Around 2024, policy-oriented scholarship emphasized AI's role in information warfare and influence operations, with Hunter et al. (2024) showing how major powers deploy AI for narrative-level contestation, deepfakes, and algorithmic targeting, thereby shifting definitions toward cognitive and information-centric warfare. Mallick (2024) and Nobles (2024) treated AI warfare as a meta-domain that reshapes military capability, doctrine, and national-security thinking, encompassing kinetic autonomy, cyber-information operations, and AI-driven decision-making at scale.

From 2025 onward, conceptualizations have become more systemic, with studies further sharpening definitions of AI warfare by emphasizing AI's role across kinetic, cognitive, and systemic-level conflict. Sticher (2025) framed AI warfare as a domain that reshapes not only weapons and operations but also alliance structures, risk-assessment, and governance. Gallitelli (2025) highlighted AI-driven military decision-making as a core pillar of AI-enabled warfare, underscoring speed, autonomy, and human–machine interaction as defining features of the emerging paradigm.

Table 1: Existing approaches to defining AI warfare

Existing approaches to defining AI warfare		
Definitional basis	Core claim	Main limitation
Technical enablement	AI enhances military effectiveness	Treats AI as tool, obscures strategy
Warfare paradigm	New form of warfare after mechanization, informatization	Underestimates transformation of military organization

Existing approaches to defining AI warfare		
Algorithm-centric	Competition for algorithmic superiority and cognitive dominance	Ignores data dependencies and bias issues
Decision-making support	AI accelerates OODA (Observe-Orient-Decide-Act) cycle	Ignores social/cognitive domains
Hybrid operations	Integration of cyber, kinetic, and information operations under AI coordination	Underspecifies AI's unique contribution

While the literature agrees that AI accelerates military processes and enhances operational effectiveness, it remains divided over whether the concept should be defined narrowly in relation to combat or broadly as a cross-domain transformation of warfare. A key gap in the literature is the lack of a unified, interoperable definition that explicitly integrates kinetic, cognitive, and information-operations dimensions, with most authors focusing on only one or two of these layers.

3.2 Components of Understanding AI Warfare

Understanding AI warfare can be structured around three interrelated components: the technological infrastructure that enables AI systems, the algorithm-data core that generates their behaviour, and the operational practices that deploy AI in conflict. Together they clarify how AI reshapes the speed, scale, and cognitive dimensions of contemporary warfare.

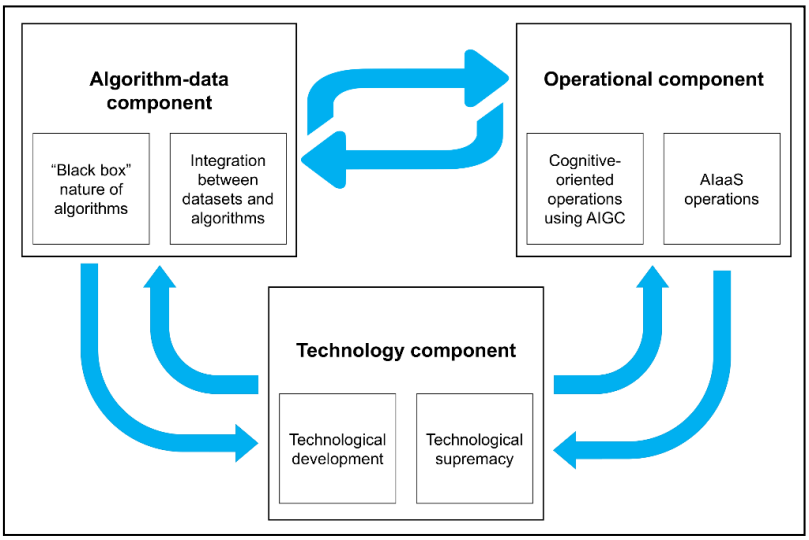


Figure 2: The interdependent components of understanding AI warfare

The technology component rests on semiconductors, high-performance computing, and high-speed networks, which do not decide battles but shape the speed, scale, and adaptability of military operations.

The algorithm-data component reflects the opaque, data-driven logic of AI, where tightly coupled models and datasets make adversarial manipulations difficult to detect and correct. Data-poisoning, model-substitution, and stealthy prompt-based exploitation blur the boundary between normal operation and attack, so the algorithm-data domain has become a critical frontline in AI warfare, where control over data quality and model integrity directly affects system reliability.

The operational component captures how AI is used in practice, mainly through cognitive-oriented and service-oriented operations. Cognitive-oriented operations use AIGC to influence perception, belief, and decision-making, including disinformation and deepfakes. Service-oriented operations apply AIaaS to execution and coordination, such as autonomous systems, swarm tactics, and real-time decision support.

The three components are interdependent. Technological infrastructure provides the foundation that enables algorithmic development, while algorithm–data interactions shape the effectiveness and reliability of operational applications. In turn, operational demands drive the evolution of both algorithms and underlying technologies. This dynamic interplay means that weaknesses at any single component can propagate across the

entire system. Therefore, understanding AI warfare requires a holistic perspective that considers how these levels interact rather than analysing them in isolation.

3.3 Definition of AI Warfare

Based on the preceding discussion, we propose a new conceptual definition of AI warfare：

AI warfare is the conduct of strategic competition through the deliberate manipulation of algorithms, datasets, AIGC or AIaaS to influence the decision-making processes, command-and-control functions, operational behaviours, and cognitive states of target populations (including strategic elites, military organizations, opinion leaders and general publics), thereby advancing the attacker's strategic and tactical objectives while potentially degrading the defender's strategic judgment and operational effectiveness.

This definition emphasizes the intentional character of AI warfare, the multidimensional nature of its effects, and the critical role of human decision-making as both means and target.

3.4 Case Study: China's Spam AIGC Campaign on X.com

In late January 2026, Nikita Bier, X.com's head of product, publicly accused China of deploying 5-10 million fake accounts on the platform. He claimed these accounts flooded Chinese-language searches with pornographic spam during periods of China’s political unrest. This tactic buried dissenting voices and made real-time information nearly impossible to access. The case aligns directly with the proposed AI warfare definition and its analysing framework:

- The technology component formed the backbone of this operation. Attackers relied on scalable computing infrastructure to create and manage millions of accounts rapidly. Cloud services or botnets provided the necessary speed and volume. Such resources ensured the spam campaign could operate undetected at scale. China's heavy investments in computing power made this feasible with minimal cost.
- In the algorithm-data component, AIGC played a key role. Algorithms trained on X.com's user patterns produced realistic spam contents that evaded detection filters. Datasets hoarded from prior activity allowed accounts to mimic authentic behaviour. The black-box nature of these AI systems hid manipulations from platform defences. Bier noted pre-existing account pools, built before X.com tightened signup rules, which added resilience.
- Operationally, the campaign focused on cognitive effects. Spam distorted perceptions among Chinese users, elites, and the general public seeking news on unrest. It overwhelmed searches for sensitive terms, eroding collective judgment at critical moments. Coordination hints at AIaaS too, as bots timed floods to outpace platform algorithms. This advanced Beijing's goals of narrative control and dissent suppression.

These components proved interdependent. Technological scale enabled algorithmic stealth, while data sophistication drove operational impact. Together, they warped user decisions and eroded trust in X.com. Attackers achieved strategic aims by manipulating algorithms, datasets, and AIGC to influence cognition and operations, just as the definition predicts. This degraded defenders' effectiveness in real time.

4. Critical Research Questions on AI Warfare

Effective analysis of concrete AI warfare scenarios requires a systematic framework. We propose five interconnected focus areas that collectively enable comprehensive assessment of AI warfare cases.

4.1 How to Disclose the Black box of Algorithms?

Algorithm is a systematic problem-solving methodological procedure for analysing, modelling, and acting on complex environments. AI infrastructure provides the means to execute algorithms; AIGC and AIaaS represent their observable manifestations in the military and strategy domains.

Due to their strategic value, core algorithms of leading AI providers remain proprietary black boxes. Techniques such as model distillation and exhaustive input-output probing can infer partial behavioural patterns but cannot fully reconstruct underlying design choices.

To address this concern, Dong (2026) proposed the Wargaming Design (WD) model as a viable solution for approximate algorithm transparency.

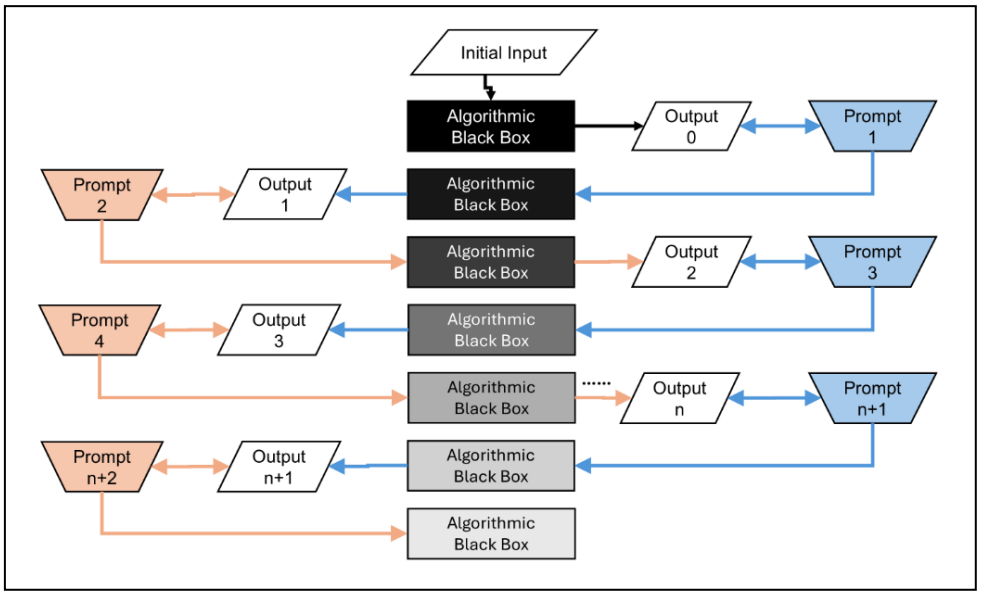


Figure 3: The revised workflow diagram of Wargaming Design model

The core insight of this model applies adversarial reasoning and game theory to algorithm interrogation:

- Blue team proposes input prompts and receives outputs from the target algorithm.
- Red team challenges these outputs through adversarial counter-arguments, alternative interpretations, and critical questioning.
- Through iterative refinement—each team responding to the other's critiques—the algorithm is pressed toward internal logical consistency.
- The critical moment: A black-box algorithm forced to reconcile contradictory outputs while maintaining internal coherence must partially expose its underlying assumptions and constraints.

Rather than achieving perfect transparency, the WD model creates pressure for logical self-consistency that reveals operational characteristics sufficient for strategic assessment. This approach recognizes that perfect transparency may be unattainable but that iterative adversarial dialogue can approximate understanding through forced coherence.

4.2 Why are Training Datasets the Primary Attack Surface?

Thinking of algorithms as the architectural blueprint, datasets provide the building materials through which algorithms learn patterns, correlations, and decision rules. These datasets—whether public, proprietary, real-world, or synthetic—are continuously updated and remain the key constraint on AI performance.

However, they also introduce critical vulnerabilities as discussed. Research shows that data poisoning can implant backdoors using only a small number of malicious samples, making such attacks highly cost-effective regardless of model size. Existing defences rely on pre-training data vetting, but this becomes infeasible at the scale of modern datasets.

We propose applying the idea of WD model for data integrity verification. Instead of exhaustive pre-screening, datasets are iteratively tested for internal consistency using the model itself, allowing unreliable or harmful inputs to be identified and excluded.

4.3 Why is AIaaS a Security-critical Architecture?

Syed et al. (2025) and Lewicki et al. (2023) state that AIaaS serves as the interface between algorithms and end users, acting as the primary channel through which external actors interact with AI systems. Current designs inherit the search-engine model of a single, minimalist input box, which reduces user friction but shifts most security responsibility onto algorithms and training datasets.

As prompt-based interaction remains the dominant communication mode, AIaaS has become a key attack surface, vulnerable to prompt injection, jailbreaking, and context manipulation. To improve resilience, specialized or military AIaaS should embed security into interface design, including role-based access, multi-step

verification workflows, explicit risk acknowledgment, and comprehensive interaction auditing. Although these measures reduce usability, the trade-off is justified in high-stakes and security-sensitive contexts.

4.4 What is the Double-edged Character of AIGC?

AIGC has a fundamentally double-edged character in AI warfare. As an offensive tool, high-quality AIGC enables scalable information operations, psychological campaigns, and ideological influence, especially when integrated into coherent long-term strategies. It can systematically shape public opinion and elite perceptions.

However, AIGC also creates defensive liabilities. Hallucinations, factual errors, and manipulative framing can mislead decision-makers and undermine credibility if exposed. Poorly executed campaigns risk backlash, amplifying negative effects.

This duality highlights a critical principle: public media literacy must keep pace with AIGC capabilities. Widespread access to powerful generative tools without sufficient critical thinking skills is both strategically counterproductive and ethically problematic. Effective defence therefore requires layered responses, including narrative resilience, content verification, and rapid psychological countermeasures.

4.5 Why Quantify AI Warfare Effects?

Quantifying AI warfare effects is essential for assessing both offensive and defensive capabilities. Measuring AI influence requires evaluating how AIaaS and AIGC shape cognitive and behavioural outcomes across different audiences, including decision-makers, operators, and the broader public. Key dimensions include shifts in perception, belief formation, decision processes, and public opinion dynamics.

A robust questionnaire framework must integrate long-term monitoring, targeted analysis, and thematic investigation to capture both persistent and situational effects. This involves tracking audience acceptance of AIaaS, their ability to identify AIGC, changes in issue-specific cognition, and levels of AI security awareness.

Such quantification provides the empirical foundation for designing, calibrating, and validating AI warfare strategies, ensuring that influence operations and defensive measures are both effective and accountable.

5. AI Warfare Defence Strategies

Beyond developing indigenous AI capabilities, states and entities must build resilient, forward-looking defence architectures to address AI-related threats:

- Distributed computing architectures. Reducing reliance on centralized data centres can mitigate single points of failure. While centralized systems maximize computational efficiency, they are vulnerable to disruption if critical nodes are compromised. Distributed architectures—potentially leveraging blockchain—offer enhanced resilience, privacy protection, and traceability, despite current limitations in scalability and coordination. In high-stakes domains such as national defence and finance, these trade-offs may be justified.
- Security-by-design. Prompt-based interaction remains the primary attack vector, yet current AI interfaces inherit the minimalist design of search engines, externalizing security risks. AI systems, especially specialized AIaaS, should embed security into interaction design through structured workflows and explicit thresholds. Although this reduces usability, it significantly strengthens system security.
- AI-native security models. Emerging threats resemble “AI viruses,” which both exploit technical vulnerabilities and manipulate user authorization and cognition. These threats blur the boundary between technical and social attack surfaces. Frameworks such as the WD model illustrate the need for AI-era defences, including advanced firewalls and adaptive security systems.
- Audience-centred research. AI influence extends beyond direct users, shaping cognition and public opinion through pervasive AIGC exposure. Defence strategies must therefore incorporate insights from communication studies, sociology, and psychology to monitor and understand these effects.
- International governance. The weaponization of AI raises urgent legal and ethical challenges, including technological supremacy, privacy, sovereignty, and autonomous weapons control. International frameworks analogous to arms control treaties are needed, alongside long-term national strategies to avoid technological dependence.

6. In Conclusion

AI represents a transformative technology with profound implications for military competition, strategic stability, and international security. Unlike cyber warfare, which operates through traditional networks and exploits system vulnerabilities, AI Warfare operates through algorithms, datasets, and human cognition itself.

In this paper, we have proposed a multidimensional definition of AI warfare emphasizing the integration of technical, operational, and cognitive dimensions. This framework enables systematic analysis of how AI can be weaponized to achieve strategic objectives.

In this study, we identified the key questions that require attention in AI warfare, and we also provide some macro-level solutions for defending against AI warfare. Future research should extend the solutional framework to specific military domains (intelligence analysis, targeting, command-and-control, force protection), examine case studies of AI warfare (actual and hypothetical), and develop defensive doctrine appropriate to military organizations.

The challenge before strategists and policymakers is significant: to harness AI's strategic potential while managing its risks to international stability and human autonomy. This challenge requires sustained investment in research, development of robust defensive capabilities, international coordination, and wisdom to recognize both the power and the limits of AI as a strategic instrument.

Ethics Declaration: This research did not require ethical approval.

AI Declaration: No AI tools were used in the development of this paper.

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Non Academic Papers

Building Cyber Defenders of the Future: Curriculum Design for Emerging Roles

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Abstract: Creating and maintaining curriculum for emerging cybersecurity work roles is a significant challenge for organizations. Training is expensive, and quality curriculum requires careful curation and sustained effort. Such curriculum typically combines cognitive learning with a considerable amount of applied, hands-on practice. Data is currency, both for emerging cybersecurity work roles and for instrumenting the curriculum itself. We are developing courses for emerging work roles on Cyber Protection Teams (CPTs), specifically for the positions of Analytic Support Officer (ASO) and Data Engineer (DE). Analytic Support Officers learn to ingest cyber threat intelligence, analyze cybersecurity datasets, map enemy courses of action, develop analytics, and provide expert assessments in support of operational decision-making. Data Engineers learn to explore cybersecurity datasets, implement effective data models, collect information from key data sources, transform data for usability, and store data for future analysis. We take a learning engineering approach that incorporates instrumentation, data collection, and behavioral analysis to support curriculum development while maximizing the use of open-source tools and open standards. The effort also includes integrating hands-on virtual environments, competency frameworks, and open standards such as Experience API (xAPI) and Computer Managed Instruction (cmi5) to track training effectiveness and ensure alignment with training goals. This paper discusses the technical and organizational challenges of developing cognitive and hands-on content, aligning instruction with learner motivations and competency frameworks, and applying learning engineering methods and open standards to support modern cyber workforce development.

Keywords: Cybersecurity curriculum development, Cyber threat intelligence, Emerging work roles, Learning engineering, Data-driven warfighting

1. Introduction: The Cyber Workforce Readiness Gap

Cyber Protection Teams operate in high-tempo, evolving threat environments where adversary tactics shift rapidly and unpredictably. Their Mission Essential Task Lists (METLs) for cyber hunts, incident response, and reinforcement to Defensive Cyberspace Operations (DCO) define core functions required for mission success. Executing these tasks demands more than familiarity with tools and platforms; it requires personnel who can apply technical expertise in realistic operational conditions.

Despite clear mission requirements, the Cyber Mission Force (CMF) continues to face personnel shortfalls and uneven capability development across the Joint Force. Many training approaches remain course-centric and event-based, emphasizing completion and certification rather than validated mission performance. These training models provide limited fidelity in measuring readiness because completing instruction does not demonstrate the ability to perform METL-driven tasks in applied environments. Reliance on Temporary Duty (TDY) training also introduces cost and operational inefficiencies without consistently improving capability.

These challenges are becoming more important as data-centric roles grow within CPTs. Analytic Support Officers and Data Engineers work with threat intelligence, data flows, analytics, and decision support aligned with the Joint Cyber Warfighting Architecture (JCWA). Preparing personnel for these responsibilities calls for more than small updates to legacy curriculum. It benefits from an approach that builds strong cognitive foundations, includes sustained hands-on practice, aligns outcomes with Knowledge, Skills, and Abilities (KSAs), Measurable Samples of Behavior (MSBs), and Joint Qualification Requirements (JQRs), and captures learner performance over time.

This paper presents that approach: a learning-engineered curriculum supported by a content-as-code architecture and instrumented, standards-based training environments built on open frameworks like xAPI and cmi5. By embedding measurement into applied learning, this strengthens the link between education, analytics, and warfighting capability in modern Defensive Cyber Operations.

2. Emerging Work Roles in Defensive Cyberspace Operations

Within CPTs, the Analytic Support Officer and Data Engineer ensure data is available, structured, and turned into actionable insight. Together, they enable effective decision-making and mission execution in complex environments.

2.1 Analytic Support Officer

ASOs are force multipliers. They contribute to the Commander's decision-making process by collecting, analyzing, and responding to network data using mathematics, programming, and domain knowledge to enable the unit to efficiently gain and exploit situational awareness. They are subject matter experts for the analytic function at each echelon. The ASO ensures analytic readiness, conducts analytic planning, executes analysis, and grows analytic capabilities. The ASO creates the Analytical Scheme of Maneuver (ASOM), refined by threat intelligence and available data sources. In practice, this means providing valuable insight into the Tactics, Techniques, and Procedures (TTPs) used by threat actors and the vulnerabilities they may target, ensuring analytic readiness, conducting analytic planning, executing analysis, and growing analytic capabilities in support of defensive cyber operations.

2.2 Data Engineer

Where the ASO focuses on the analysis of creating and weaponizing the ASOM, the DE is responsible for ensuring the data to support the ASOM in the hunt for Malicious Cyber Activity (MCA) is in the right format, structure, and location for analysis or ingestion. CPTs cannot find what they cannot see. Ensuring the requisite data is available to identify each TTP is the responsibility of the DE. When the storage environment is complex, the DE ensures optimal placement of data to provide parallel or stream processing capabilities, makes modifications to tune capabilities for different environments, and automates data collection and processing through extract, transform, and load (ETL) pipelines. Data Engineers provide scalable analytics across mission environments, assisting ASOs in exploratory data analysis and visualizations and making them an essential enabler of the analytic function.

2.3 Why These Roles Matter

Cyber operations are at the heart of modern military strategy. Together, these two roles reflect a shift in how defensive cyber operations are conducted, prioritizing data-driven warfighting. Advanced analytics are indispensable in maintaining information dominance, and data is operational currency. The ability to ingest, filter, analyze, and act on cyber terrain data at speed is central to mission success. The ASO and DE work roles formalize that capability within the Joint Force structure, establishing dedicated personnel whose primary function is to ensure that data flows are purpose built, and analytics are actionable to ensure commanders have the insights they need to make decisions in time-sensitive environments.

3. Curriculum Design Philosophy: Learning Engineering at Scale

Here we outline our instructional approach used to design and deliver the curriculum. We begin with learning engineering as the foundation, guiding how content is developed, evaluated, and refined. Then, we describe the content-as-code model used to build and deploy training at scale, followed by the balance of cognitive and applied instruction.

3.1 Learning Engineering as the Foundation

Developing curriculum for emerging cybersecurity work roles is not just a matter of content selection and course structure. It also means creating training in a way that can be refined over time based on learner needs and instructional results. Goodell and Kolodner (2022) describe learning engineering as a "process and practice that applies the learning sciences using human-centered design methodologies and data-informed decision-making to support learners and their development." Put simply, it helps bring research-informed practices into real-world training environments.

For the curriculum described in this paper, learning engineering serves not only as a guiding perspective but also as a practical framework for design. Decisions about content sequencing, assessment design, and instructional support are informed by learning science principles and revisited over time based on learner performance. The curriculum is therefore not treated as fixed or final. Instead, it is designed to be refined as evidence accumulates about where learners struggle, where instruction is effective, and where gaps remain between cognitive understanding and applied performance. (Goodell, Kessler, Kurzweil, Greenwald, & Craig, 2022)

3.2 Content-as-Code Model

To support curriculum development at scale, the program uses a content-as-code model. Lessons, labs, scenarios, and assessments are maintained as structured files in GitLab, where they can be versioned, reviewed, updated, and reused in a controlled way. This approach reduces dependence on static course files, makes changes easier to manage across modules, and supports consistent delivery over time. Each module includes

instructional content, hands-on activities, and assessments, and is built using open-source tools and open standards such as xAPI and cmi5 to improve portability and interoperability across training environments.

When a content-as-code release is tagged, it triggers a Continuous Integration and Continuous Delivery (CI/CD) workflow that builds the deployable course package automatically, running automated checks on structure, formatting, and configuration before the final artifact is produced. The resulting package is a cmi5-compliant artifact that bundles instructional content, applied hands-on practice, assessments, and the backend infrastructure needed to deliver them – essentially a self-contained learning environment. A human review step follows, where the package is uploaded to a Learning Management System (LMS) for post-validation and functional testing before distribution to learners. This step functions much like a production approval gate in a software release pipeline. illustrates how this pipeline operates across a single module, from content authoring through validation and deployment. How this architecture supports the measurement of learner performance and training effectiveness is discussed in detail in Measuring What Matters: Instrumentation and Validation.

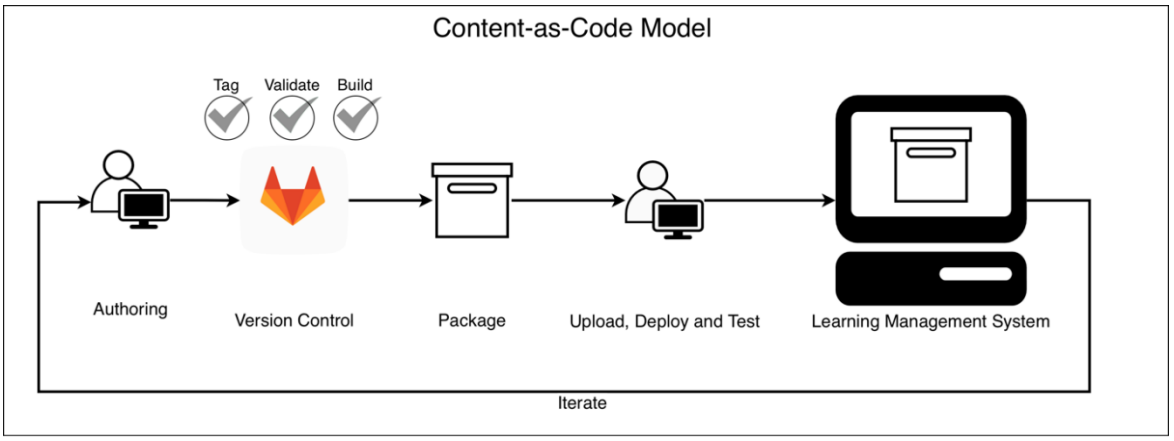


Figure 1: Content-as-Code Model

3.3 Cognitive and Applied Balance

The curriculum uses two complementary layers of instruction: cognitive content and applied practice. Cognitive content establishes the conceptual and theoretical foundations for each work role. Applied, hands-on practice then gives learners the opportunity to apply those foundations under realistic conditions, reinforcing and deepening understanding through execution. Each layer includes its own assessment. Quizzes, knowledge checks, and exams evaluate cognitive mastery, while performance-based assessments and labs measure applied proficiency by requiring learners to execute tasks rather than describe them. All modules map to competency frameworks, KSAs, MSBs, and JQRs, ensuring each unit of instruction aligns with operational standards.

The curriculum intentionally weights the majority of instructional time toward applied instruction, where learners work through hands-on practice mirroring real mission conditions, requiring them to make decisions, execute technical tasks, and adapt to unexpected outcomes. These scenarios are deployed within a persistent cyber range infrastructure that provides sufficient fidelity for meaningful applied learning. Specifics are addressed in Technical Architecture and Standards Integration.

Notably, the curriculum culminates in a capstone experience. In the capstone, learners complete advanced scenarios that draw on competencies from all modules and apply their full range of knowledge and skills in an integrated mission context. The course structure, module organization, and capstone design for both ASO and DE curriculum are examined in greater detail in Course Structure and Modular Design.

4. Technical Architecture and Standards Integration

This section describes the technical and standards-based foundation that supports training and performance measurement. It covers how open standards and environments enable tracking of learner activity, how training systems integrate within the Joint Cyber Warfighting Architecture (JCWA), and how learner behavior is captured. It also presents the competency frameworks used to map, measure, and validate performance against operational requirements.

4.1 Open Standards and Tooling

This section describes how xAPI enables consistent tracking of learning experiences, how an LRS stores and retrieves that data, and how cmi5 defines how content launches, tracks, and reports within the LMS. When used together, these components create an interoperable architecture that supports performance measurement, analytics, and consistent data exchange across systems.

4.1.1 xAPI

Tracking activity across learners and environments provides insight into evaluating assumptions, learning pipelines, and outcomes. IEEE Learning Technology Standards Committee (LTSC) defines standards to support this capability, called xAPI. xAPI serves as an interoperability standard (language) for capturing and sharing data about learning experiences across platforms.

xAPI records learner actions in a consistent *actor-verb-object* format, enabling detailed tracking of activity such as opening modules, viewing content, and completing labs or assessments. This data supports both performance measurement and analytics, allowing instructors to identify learner progress, detect struggles, and adjust instruction. It also allows verified skills to transfer across xAPI-enabled environments.

An xAPI profile defines how activities are tracked. It is a constrained set of rules for implementing xAPI within a specific domain. It describes vocabulary, statement templates, and data patterns to ensure consistent use. Profiles standardize how organizations structure and share data, allowing systems to use a common language. They also organize xAPI statements within a Learning Record Store (LRS) for consistent tracking and analysis.

4.1.2 Learning Record Store

An LRS is a database that stores and retrieves xAPI statements. It receives statements from Learning Record Providers (like a quiz, module, or lab) which send data using standard, RESTful HTTP web requests (PUT, POST, GET, DELETE). Learning Record Consumers (dashboards or analytical tools) use GET requests to retrieve the data. The LRS also strictly checks the structure of the data to ensure it does not receive malformed JSON. The LRS, though, is not instructed to understand the semantics of an xAPI statement according to the IEEE LRS standards. The statement could contain a verb like “sing” to be accompanied by “math equation” to create “the student sang to complete the math equation.” The LRS would accept this statement if the correct syntax was followed. To counter this, tooling can be placed before the LRS to adhere to IEEE standards by allowing the LRS just to store statements.

4.1.3 Computer managed instruction

These standards capture behavioral data within a module or course by combining xAPI with cmi5. While xAPI provides the flexibility to track activity anywhere, cmi5 defines how that data communicates with the LMS. As an xAPI profile, cmi5 uses xAPI to store behavioral data in an LRS and establishes rules for content launching, tracking, and reporting.

Developers package content as courses composed of Assignable Units (AUs), which contain the learning content and generate xAPI data. cmi5 defines a strict set of required verbs for session management between the AU and the LMS, including Launched, Initialized, Completed, Passed, Failed, Terminated, and Abandoned. These “cmi5 defined” statements standardize core interactions, while “cmi5 allowed” statements support additional custom tracking. Once enrolled, learners launch AUs through the LMS and generate data as they interact with the content.

4.2 Persistent Cyber Training Environment

4.2.1 Integration with joint cyber warfighting architecture

The Joint Cyber Warfighting Architecture established a shared platform for training with cyber systems, tools, and sensors. Within that environment, cmi5 supports data exchange between the learning management system (LMS) and the learning record store (LRS), while a common xAPI profile captures more detailed learner performance data. This creates a more consistent structure for sharing learner data across services while still allowing each service to tailor implementation to its needs.

4.2.2 Range-based applied learning

Classroom-based learning from presentations and textbooks is a sound foundation for cyber security capacity. Applying the lessons, however, is best in a high-fidelity simulated environment such as a cyber range. These

cyber ranges allow participants to perform live exercises launched through an LMS in PCTE and tracked by xAPI statements. The xAPI statements help instructors understand a participant's thought process within the nonlinear learning path of a cyber range. The cmi5 standard records when the range is launched within the LMS and if it is completed.

4.2.3 Instrumented learner behaviors

Capturing participant interactions in the LMS and cyber range provides evidence of learning outcomes. Measuring how a learner navigates the range helps determine whether they are guessing or acting with precision. Observing tool usage shows whether they rely on established tools or create their own. It also confirms that they follow the rules of engagement and avoid disrupting (accidentally or otherwise) systems marked as production in the simulated environment. With xAPI, these actions can be tracked in real time, enabling adaptive learning and assessment based on performance rather than knowledge alone.

4.3 Competency Mapping Framework

4.3.1 Knowledge, skills and abilities

KSAs are specific attributes, qualifications and traits required to perform a job effectively. They can be measured in course work and captured using xAPI statements. By storing the statements into an LRS, KSAs can be mapped, identified, and attributed to a learner and aggregated in a learner profile throughout a career.

4.3.2 Measurable samples of behavior

MSBs are specific, observable actions quantified to track progress. Representative samples are identified, reflecting the desired learning objectives connected to the instructional goals. It is important that there are sufficient samples to assert consistent learned behaviors. MSBs are categorized as: outcomes, processing, and errors. Outcomes show whether the participant learned the objective. Processing shows whether the participant followed the correct methodology. Errors identify what mistakes the learner made and whether they are critical or non-critical.

4.3.3 Joint cyberspace training and certification standards

Joint Cyberspace Training and Certification Standards (JCT&CS) are specific tasks mapped to work roles in the Department of War Cyber Workforce Framework (DCWF). The tasks are closely aligned with KSAs but are distinct. A task is an activity an employee regularly performs to fulfill job responsibilities. The JCT&CS identifies certain tasks and KSAs as Core, highlighting them as critical for successful performance within a given work role. Others are considered additional and are not required for success in the work role.

4.3.4 Joint qualification requirements

Joint Qualification Requirements (JQRs) define the skills required for a learner to obtain a specific job. They are the checklists of tasks and competencies a learner must master to qualify for an operational work role. To complete a JQR, the learner demonstrates each task with proficiency to a qualified evaluator. JQRs set the course standard and determine what participants must do to meet professional requirements.

5. Course Structure and Modular Design

The design philosophy and technical architecture established in Learning Engineering at Scale and Technical Architecture and Standards Integration are integrated in the two courses built for the ASO and DE work roles. The modular architecture introduced in Learning Engineering at Scale organizes content at the lesson level. Modules build sequentially from introductory concepts and tools to the operational competencies each work role requires. This hierarchy makes the curriculum maintainable through the content-as-code pipeline. It also enables granular instrumentation with the xAPI and cmi5 architecture described in Technical Architecture and Standards Integration.

5.1 ASO Curriculum

The ASO curriculum offers a fast-track bootcamp comprised of fourteen modules and forty-eight lessons. The curriculum is a mix of approximately 70% applied and 30% cognitive instruction. The delivery is scaffolded: modules progress from foundational domains like cyber terrain, programming, development and data operations, mathematics, and statistics to applied data skills like data processing and visualization. Finally, it moves into operational training, covering Joint Cyber Hunt Kit (JCHK) familiarization and Joint Cyber Warfighting Architecture Common Runtime Stack for Data (JCRS-D) architecture and operations. Later modules focus on

critical thinking, analytic planning, SIEM and BDP operations, and machine learning, building end-to-end analytic workflow expected in a mission environment.

5.2 DE Curriculum

The DE curriculum follows the same delivery and applied-to-cognitive ratio, fourteen-module structure across forty-three lessons. Where the ASO curriculum is oriented toward analytic development and execution, the DE curriculum is built around the data engineering fundamentals and infrastructure that makes network hunt cyber data analysis possible. Modules progress from the cyber terrain and programming foundations through machine learning, data management, data storage architectures, data ingestion through batch and stream processing, data staging, and ETL pipeline development. Later modules address data visualization, JCHK familiarization, SIEM operations including log managements, content development and alerting, and JCRS-D architecture, operations, and data capture, preparing the DE to integrate data sources, manage pipelines, and support analytic development across mission environments.

5.3 Capstone as Readiness Validation

Both courses culminate in a capstone, presenting learners with a comprehensive set of mission-representative scenarios requiring them to apply the full range of competencies developed across the preceding modules. All objectives map directly to MSBs established throughout the course, making the capstone the primary point at which demonstrated readiness is formally assessed and where the instrumentation layer, described in Section 4, produces its most fulsome learner behavior assertion, which is examined in the next section.

6. Measuring What Matters: Instrumentation and Validation

This section focuses on measuring readiness using performance data instead of completion metrics. It outlines how learner behavior supports readiness modeling and highlights key organizational challenges.

6.1 From Completion to Capability

A persistent problem in cybersecurity training is that traditional LMS metrics do not result in mission readiness. Knowing a learner opened a module, spent 40 minutes on it, and passed a multiple-choice quiz at the end says very little about whether that learner can execute the associated tasks when it counts. Completion is not capability. Unvalidated readiness has real operational consequences. Commanders need to know: “Can this operator perform this mission task?”

The instrumented curriculum described in this paper takes a different approach. Rather than relying on whether a learner answered correctly or completed a task, the curriculum captures behavioral evidence across cognitive and hands-on instruction. Cognitive assessments contribute structured data about conceptual understanding, while applied hands-on practice generates a richer and more operationally meaningful record of how learners perform under realistic conditions. As described in Persistent Cyber Training Environment, a central xAPI profile defines which actions and tasks are captured throughout the hands-on environment, producing evidence that reflects demonstrated performance rather than recalled knowledge.

6.2 Behavioral Data and Readiness Modelling

Collecting behavioral data is only meaningful if it is realistic, mapped to learning objectives and outcomes, actionable, and actioned. As learners move through the curriculum, the xAPI statements generated across both cognitive and applied hands-on practice build a cumulative record of how individuals engage with the material, which tasks they complete successfully, where they struggle, and how their performance evolves over time. Mapping those actions to the operational tasks each work role demands is what transforms raw activity data into a meaningful picture of readiness, one that reflects demonstrated performance rather than assumed competency.

Over time and across participants, this accumulated evidence creates the conditions for a more predictive approach to readiness assessment. By understanding which learning behaviors and performance patterns are most strongly associated with successful outcomes, instructors and curriculum developers can begin to identify early indicators of readiness gaps and adjust their instruction, accordingly, getting ahead of capability shortfalls rather than reacting to them after the fact.

6.3 Overcoming Organizational Challenges

Realizing the full potential of an instrumented curriculum requires solving organizational and technical challenges. Cross-service interoperability demands not just technical compatibility but also wider adoption of

shared frameworks and a common data language across the Joint Force. The cross-service xAPI profile being developed within JCWA, referenced in Technical Architecture and Standards Integration, is an active effort toward addressing that gap.

Tempo is also a constraint. The distinction between "Ready Qualified" and "Ready Trained" is a real one, and the TDY model of pulling personnel away from primary responsibilities to achieve the latter is expensive and operationally inefficient. Finally, integration with existing platforms across joint environments remains an ongoing challenge, and the deliberate choice to build the curriculum around open-source tooling and established standards is a practical response to that reality, designed to work within those constraints rather than depend on resolving them first.

7. Organizational and Cultural Implications

This section presents the organizational impact of our approach. It identifies key stakeholders, outlines the shift from course completion/certification to capability-based training, and highlights how our model enables long-term relevance.

7.1 Stakeholders

The curriculum described in this paper serves a broad set of stakeholders, balancing requirements throughout development and delivery. Schoolhouses and training commands are responsible for course execution, while CPTs, National Mission Forces, and Joint Service personnel are the operational end users whose readiness ultimately determines whether training is successful. Leadership and decision-makers at the command level depend on the readiness insights the instrumented curriculum produces to make informed judgments about force capability.

7.2 Shifting from Course-Centric to Capability-Centric

Adopting this approach to training and mission readiness requires more than a technical change. It requires an organizational shift in how training success is defined, moving away from disparate training events measured by completion and certification toward continuous capability pipelines measured by demonstrated behavioral performance. Compliance metrics are a low bar for a high-stakes domain and sustaining this shift requires institutional commitment to treating curriculum as a living system rather than a product delivered and accomplished. From training completion checklist to behavioral validation of human and squadron performance capabilities.

7.3 Workforce Sustainability

Sustainability depends on building training infrastructure that does not require constant reinvestment to remain relevant. The open-source tooling, standards-based architecture, and content-as-code pipeline are designed with that goal in mind, reducing dependency on proprietary systems and enabling curriculum to evolve alongside the mission. Portable learner records further support sustainability by ensuring that the evidence of a learner's demonstrated proficiency travels with them across environments and assignments rather stored in siloed and proprietary systems.

8. Lessons Learned and Future Directions

This section evaluates the current state of the approach. It highlights what is working, identifies remaining gaps, and outlines areas for future research and development.

8.1 What's Working

The content-as-code pipeline, from authoring through automated validation and CI/CD packaging to LMS deployment, has been tested and functions as designed, demonstrating that a software-style release workflow is a viable and practical approach to curriculum development and delivery. The integration of cmi5 and xAPI ecosystem is operational, confirming that open-source tools and standards can serve as a reliable foundation for tracking and communicating learner activity across training environments. Together these foundational elements validate the core tenants of the approach. A learning-engineered, standards-based curriculum can be built, delivered, and instrumented at scale within the constraints of Joint Force training environments.

8.2 Remaining Gaps

Several meaningful challenges remain unresolved as this work continues to develop. Variance in cross-service weapons systems complicates joint practice as the tools, platforms, and data environments differ across

services. This makes a single standardized course difficult to execute uniformly. Training to capabilities and critical thinking rather than tool centric helps ameliorate to some extent. The TDY burden, while addressed in the curriculum's design philosophy, has not been fully eliminated, and the organizational and logistical structures that have historically supported TDY-based training do not change quickly. Integration with existing joint platforms also remains incomplete, and until the connections between the curriculum's instrumentation layer and broader joint infrastructure are fully established, the behavioral evidence the curriculum is designed to produce cannot yet flow to and be aggregated in the places where it would be most useful.

8.3 Research Agenda

This curriculum establishes a foundation for research that the field of cybersecurity training has not yet fully explored. The behavioral data generated as learners move through cognitive and applied hands-on practice represents a largely untapped resource for understanding how cyber operators develop proficiency over time, and future work will focus on developing the analytical methods needed to make that data actionable at scale. Predictive readiness modeling, using accumulated behavioral patterns to identify capability gaps before they become operational problems, is a particularly high-value direction that this learning architecture is designed to support as the data matures. More broadly, the application of learning engineering principles to cyber operations training remains a target rich environment, and the approach described here is intended both as an invitation for others to build on as it is a record of what has been built.

9. Conclusion

The challenge of building capable cyber defenders, let alone cyber defenders of the future, is not resolved simply by more training. It is solved by better training, training that is engineered, instrumented, and continuously refined in response to evidence of how learners in the cyber domain perform. The ASO and DE curricula described in this paper represent a deliberate effort to narrow the gap between a training approach of course completion and mission readiness by embedding learning engineering principles, open standards, and behavioral measurement into each component of the instructional design. This is not without its challenges, as the discussed organizational, infrastructure, and interoperability gaps make clear. But there is inertia, the foundation is in place, and the path forward toward predictive readiness modeling, scalable instrumentation, and a genuinely capability-centric training culture is one this work has begun to establish. There is also a network effect as increased adoption will provide additional impact and inertia. The use of learning engineering methodologies, instrumentation, and data collection in cybersecurity curriculum development is an area where much work is still to be done in support of advancing the practice. Hopefully, this will inspire other practitioners for the betterment of cybersecurity training, tooling and learners, data-driven mission ready warfighters. Advancing cybersecurity curriculum requires intentional integration of behavioral science, instrumentation, and open standards to support modern data-driven cyber workforce development.

10. Acknowledgements

Carnegie Mellon University 2026

This material is based upon work funded and supported by the Department of War under Air Force Contract Nos. FA8702-15-D-0002, and FA870225DB003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

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DM26-0283

Ethics Declaration: Ethical clearance was not required for the research.

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Work in Progress Papers

Towards a Resilience Framework for Securing ADS-B Surveillance Systems in Air Traffic Management

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Abstract: Automatic Dependent Surveillance–Broadcast (ADS-B) has become a cornerstone of modern air traffic surveillance, enabling real-time aircraft tracking and supporting enhanced situational awareness within Air Traffic Management (ATM) systems. However, the open and unauthenticated nature of ADS-B transmissions introduces significant cybersecurity vulnerabilities, including spoofing, jamming, and data injection attacks. These threats pose risks not only to surveillance integrity but also to operational trust and decision-making in safety-critical environments. This paper presents a resilience-based cybersecurity framework for securing ADS-B systems within ATM environments, with particular consideration of resource-constrained and evolving airspace environments. The proposed framework integrates technical detection mechanisms, operational response strategies, and governance principles to enhance system robustness against cyber-physical threats. A scenario-based approach is adopted to illustrate how the framework supports the detection and management of anomalous ADS-B behaviour, while maintaining continuity of surveillance services. The contribution of this work lies in bridging the gap between theoretical vulnerability analysis and practical resilience design in aviation surveillance systems. The framework provides a structured foundation for enhancing cybersecurity posture in ADS-B-enabled environments and supports ongoing research into resilient and trustworthy air traffic systems.

Keywords: ADS-B, Aviation cybersecurity, Air traffic management, Resilience, Surveillance systems, Decision-making

1. Introduction

The increasing reliance on digital surveillance technologies has fundamentally reshaped the operational landscape of Air Traffic Management (ATM). Among these technologies, Automatic Dependent Surveillance–Broadcast (ADS-B) has emerged as a critical enabler of real-time aircraft tracking, supporting enhanced situational awareness, improved airspace efficiency, and the transition toward data-driven air traffic operations. By broadcasting aircraft position, velocity, and identification data, ADS-B enables more dynamic and responsive decision-making within increasingly complex airspace environments.

However, despite its operational advantages, ADS-B was not designed with security as a foundational requirement. The system's open and unauthenticated broadcast architecture introduces inherent vulnerabilities, including spoofing, jamming, and message injection attacks. These vulnerabilities are no longer theoretical; they represent a growing class of cyber-physical risks capable of compromising surveillance integrity and, more critically, undermining trust in the data upon which operational decisions are made.

This shift introduces a fundamental challenge for modern ATM systems. Surveillance is no longer simply about data availability, but about **data trustworthiness under contested conditions**. In safety-critical environments, where decisions must be made in real time, the presence of unreliable or manipulated surveillance data can have cascading operational consequences, including degraded situational awareness, incorrect controller actions, and reduced safety margins.

While existing research has extensively examined the technical vulnerabilities of ADS-B systems, much of this work remains focused on isolated attack scenarios or detection mechanisms. Less attention has been given to how these vulnerabilities translate into operational risk, and how ATM systems can maintain continuity, stability, and trusted decision-making in the presence of cyber threats. This gap highlights the need for a broader perspective that moves beyond vulnerability identification toward system-level resilience.

This paper addresses this gap by proposing a resilience-oriented cybersecurity framework for ADS-B surveillance systems within ATM environments. The framework integrates technical detection mechanisms, operational response strategies, and governance considerations to support the maintenance of surveillance integrity and continuity under adverse conditions. A scenario-based approach is used to illustrate how ADS-B anomalies can be detected, interpreted, and managed within real-world operational contexts.

The contribution of this work lies in reframing ADS-B cybersecurity as a **systemic resilience challenge**, rather than a purely technical problem. By linking vulnerabilities to operational decision-making and governance structures, the proposed framework provides a structured foundation for enhancing trust, robustness, and adaptability in next-generation air traffic surveillance systems.

2. Background and Literature Review

The evolution of surveillance technologies in aviation has been driven by the need for improved situational awareness, increased airspace capacity, and enhanced operational efficiency. Traditional radar-based systems, including Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR), have historically formed the backbone of air traffic surveillance. However, these systems are associated with high infrastructure and maintenance costs, as well as limitations in coverage, particularly in remote or oceanic airspace.

The introduction of Automatic Dependent Surveillance–Broadcast (ADS-B) represents a significant shift towards cooperative and satellite-enabled surveillance, enabling more precise and cost-effective tracking of aircraft. ADS-B operates by broadcasting aircraft-derived data, including position, velocity, and identification, to ground stations and other aircraft, supporting real-time tracking and advanced Air Traffic Management (ATM) concepts such as trajectory-based operations.

Despite these advantages, ADS-B was designed with a focus on interoperability and efficiency rather than security. As a result, transmissions are neither encrypted nor authenticated, making them inherently vulnerable to cyber threats. Existing literature has demonstrated the feasibility of spoofing attacks, jamming, and message injection (Costin and Francillon, 2012; Strohmeier et al., 2015), all of which can compromise surveillance accuracy and mislead operational decision-making.

While these studies provide valuable insights into technical vulnerabilities, they often focus on isolated attack scenarios. More recent research has explored mitigation strategies such as multilateration, cryptographic enhancements, and anomaly detection (Leonardi et al., 2017; Illiashenko et al., 2023). However, practical implementation remains constrained by interoperability requirements, legacy systems, and regulatory limitations, particularly in resource-constrained environments.

3. Research Problem and Gap

Despite extensive research into ADS-B vulnerabilities and mitigation techniques, a critical gap remains in understanding how these vulnerabilities impact operational decision-making within real-world ATM environments. Existing approaches primarily focus on detection and prevention at a technical level (Dave et al., 2022; Ukwandu et al., 2022), with limited integration of operational and governance considerations.

In practice, air traffic systems must continue to function under conditions of uncertainty, degraded data integrity, and potential cyber interference. The challenge is therefore not only to detect anomalies, but to ensure that operational decisions remain safe, reliable, and informed even when surveillance data cannot be fully trusted.

This highlights a fundamental shift from a vulnerability-centric perspective to a resilience-oriented perspective, where the focus extends beyond preventing attacks to maintaining continuity of operations and trust in decision-making processes.

4. Research Methodology

This study adopts a qualitative, scenario-based research approach, supported by a structured review of existing literature (Illiashenko et al., 2023) on ADS-B vulnerabilities and mitigation strategies.

Three representative cyber threat scenarios are considered:

- ADS-B spoofing (injection of false aircraft data)
- Trajectory manipulation (alteration of aircraft movement patterns)
- Signal degradation or jamming

These scenarios are used to analyse the impact of cyber threats on surveillance integrity and operational decision-making.

In addition, preliminary practitioner insights are incorporated through survey-based input from aviation and cybersecurity professionals. While not statistically representative, these insights provide contextual grounding and highlight practical challenges faced in operational environments.

5. Findings and Analysis

5.1 Technical Vulnerabilities

ADS-B systems remain susceptible to spoofing, jamming, and message injection (Costin and Francillon, 2012; Strohmeier et al., 2015) due to the lack of authentication and encryption. These vulnerabilities allow attackers to introduce false data or disrupt signal reception.

5.2 Operational Impact

The presence of unreliable or manipulated data can degrade situational awareness, leading to incorrect or delayed decision-making by air traffic controllers. This introduces safety risks, particularly in high-density or complex airspace environments.

5.3 Governance and System Gaps

Current approaches do not sufficiently integrate cybersecurity into operational procedures and decision-making frameworks. There is a lack of structured mechanisms for responding to degraded surveillance conditions and maintaining operational continuity.

6. Discussion

The findings highlight the limitations of purely technical approaches to ADS-B cybersecurity. While detection mechanisms are essential, they are insufficient in isolation. Operational environments require integrated approaches that combine detection, validation, response, and governance (Illiashenko et al., 2023; Dave et al., 2022).

The challenge lies in ensuring that ATM systems can continue to operate safely even when data integrity is compromised. This requires a shift toward resilience thinking, where systems are designed not only to prevent failures but to adapt and recover from them (Ojo-Oba, 2025; ICAO, 2019).

7. Proposed Resilience Framework

This paper proposes a resilience-oriented framework structured around five key domains:

- Threat Awareness and Monitoring
- Information Validation and Decision Support
- Operational Response and Control
- System Resilience and Continuity
- Governance and Implementation

The framework integrates technical, operational, and organisational elements to support robust and adaptive responses to cyber-physical threats in ADS-B systems.

8. Conclusion

ADS-B cybersecurity represents a critical challenge for modern Air Traffic Management systems. While vulnerabilities are well documented, there is a need to move beyond detection-focused approaches toward resilience-based strategies that support operational continuity and trusted decision-making.

This paper contributes by proposing a structured framework that integrates technical and operational considerations, providing a foundation for enhancing cybersecurity resilience in ADS-B-enabled environments.

Future research will focus on validating the framework through empirical studies and expanding its application within broader ATM and critical infrastructure contexts.

Ethics Declaration: This research involved preliminary practitioner insights collected through voluntary professional participation. The study does not disclose personal or organisationally identifiable information. Ethical considerations relating to confidentiality, professional sensitivity, and responsible research conduct were observed throughout the study.

AI Declaration: AI-assisted tools were used in a limited supporting capacity for language refinement, structural editing, and drafting support. All technical analysis, research interpretation, framework development, and final academic content validation were performed and reviewed by the author.

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AI Safety Under Uncertainty: Hallucinations and Unpredictable Failures

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Abstract: With the rise of AI-supported tools across mission-critical workflows in medicine, finance, commerce, education, and cybersecurity, their errors and incorrect decisions can pose safety risks. In our broader study of safety challenges in AI applications, we identify and analyze various safety concerns related to AI-supported tools, including hidden dangers in AI-generated content, the misuse of AI-supported tools for cyberattacks, and their societal impacts. In this particular work-in-progress paper, we focus on our analyses of unpredictable failures and hallucinations in AI-supported systems. We analyze how generative AI models can produce fluent, convincing, yet misleading results, and how they can contaminate mission-critical applications, such as healthcare/medical decision-making, software development, cybersecurity, privacy/data governance, and workflows with agentic AI-supported systems. We survey use cases across domains to articulate the vulnerabilities. We discuss how agentic AI-supported workflows can amplify small errors into significant damage by automatically feeding erroneous outputs and actions. We also propose practical countermeasures to minimize the hallucinations and unpredictable failures with continuous monitoring and evaluation. In our future work, we will integrate this analysis with other areas of AI safety to develop a comprehensive framework and strategies.

Keywords: AI safety, AI risk analysis, AI governance

1. Introduction

Today, Artificial intelligence (AI) technologies are influencing decision-making in various applications, including the financial services sector, educational platforms, predictive algorithms for cybercrime detection, and other productivity enhancements (Park, 2025a; Park, 2025b). However, as machine-learning-derived systems settle into positions within workflows rather than coexisting as advisory systems in the background, hallucination errors may pose a critical issue rather than a simple technical failure, with a broader potential for influence, including safety, equity, privacy, organizational stability, and public confidence. AI hallucination is defined as responses returned by an AI system that are convincingly incorrect, inconsistent, inaccurate, or other facts misaligned with the context of the situation. AI safety may shift from a theoretical concern to a practical impact in responsible use-case scenarios across sectors, where erroneous output could ripple effect into material threat vectors. AI-driven safety risks can arise from numerous sources, such as unpredictable system behavior, misleading or incorrect outputs, misuse of AI for breaches and intrusions, privacy and ethical violations, and others.

This work-in-progress paper addresses a primary type of safety risks caused by AI's unpredictable hallucinations in AI-enabled applications. We discuss the unpredictability of AI failure modes and hallucinations, the reasons for their emergence, and their impacts in safety-critical settings. By analyzing technical vulnerabilities to real-world implications, we aim to support system developers, organizational decision-makers, and end users. We believe this study can help minimize potential risks through effective safeguards, policy expectations, and proper operations.

2. Related Work

Researchers define hallucinations as instances in which an advanced language model returns factually inaccurate results and demonstrates similarities to human cognitive errors, and address predictive mechanisms that both the model and its results share, making it prone to mistakes (Tripathi et al., 2024). They classify the AI's hallucination types, considering input-conflicting, context-conflicting, and fact-conflicting, and examine their implications through industry examples, particularly focusing on healthcare and life sciences. Both studies provide evidence of unpredictable failures and risk breakdowns in AI-enabled systems generating content. Some researchers concerned with the physical and digital safety in AI-enabled systems take a more skeptical perspective, arguing that AI will remain a disruptive technology. They further emphasize that advances in deep learning, particularly multi-layer neural networks, computer vision, and anomaly detection, have driven significant performance gains in health monitoring, public safety, and cybersecurity (Simmons & Park, 2024). More researchers emphasize the urgent need to develop AI-enabled systems that effectively control safety throughout data collection, model training, and deployment (Salhab et al., 2024). They also

identify critical safety concerns, including explainability, interpretability, robustness, reliability, bias, and adversarial attacks, and present the need to establish a comprehensive AI safety framework.

3. Unpredictable AI Failures and Hallucinations

AI-enabled systems may fail in unpredictable, unreproducible, and unexplainable ways in safety-critical and high-stakes environments. Hallucination is one of the most common ways such failure arises. Hallucinations are especially dangerous because we may simply accept a well-written claim that sounds confident and polished, even when it is false or unverified. Modern generative AI models are likely trained and optimized to continue a prompt that sounds contextually appropriate, rather than to verify the relations between claims and corresponding evidence. Therefore, when the input is incomplete, ambiguous, or even internally inconsistent, the AI models may "fill in" the missing content that seems related to the expected results. From a systems assurance perspective, this may create a more serious problem, especially in mission-critical systems (Farahmand, 2023). A major source of uncertainty is the gap between how a generative model is trained and how it is actually used in the system environment. Models typically inherit blind spots from their training data, and the AI-enabled system can make critical errors at runtime due to them. Sometimes, ordinary changes, such as new user types, workflow shifts, or different operating environments, may trigger unexpected problems. Malicious users can provide adversarial inputs or crafted prompts that can lead the model to produce hallucinations or unsafe actions (Majeed & Hwang, 2023). People often treat AI output as a time-saving substitute for careful review, especially when it looks polished on the surface. As a result, small errors or shaky assumptions can transmit faster and farther than they would in a purely human workflow.

For instance, in healthcare AI-enabled systems, analyses of hallucinated outputs have found recurring patterns that consist of confident claims about biomarkers or treatments with no solid support, inaccurate summaries of clinical details, and even polished, "guideline-like" recommendations that look professional but aren't reliably grounded in evidence (Aditya, 2024; Verma et al., 2025). In software engineering, a generative AI might produce flawed code, unsafe configurations, or misleading vulnerability descriptions that seem professional and correct. This might be benign in normal situations, but under adversarial conditions, with crafted inputs or exploit attempts, the same code can break in dangerous ways or provide attackers with advantages. Furthermore, AI-supported cybersecurity management can increase risk by insecure patterns, such as weak authentication procedures, insecure parsing, or improper cryptographic usage. It can also deliver security advice with unverified confidence (Gupta et al., 2023; Bhuiyan & Park, 2025). AI-supported intrusion detection systems (IDS) and monitoring can also fail in unpredictable ways, and when they do, the fallout can be serious. The damage from a persuasive hallucination is not only bad information, but also bad process, such as misdirected decisions, misplaced priorities, and poor allocation of defensive resources (Dhanushkodi & Thejas, 2024). A poor configuration or inaccurate filtering of a vulnerability can rapidly spread across teams, tools, and systems, leading to correlated vulnerabilities and a growing attack surface.

Another concern about hallucinations is how they interact with governance and privacy. When a generative AI confidently, but incorrectly, interprets what counts as private data, how long data can be retained, or what information can be shared with others, it can unintentionally guide an organization into policy violations or legally questionable practices. Researchers address that AI's ability to profile, reason, and process data at scale raises privacy concerns, and that misleading AI guidance about what is safe/acceptable can substantially amplify those concerns. From a more practical perspective, the concern is that an AI tool can provide a highly convincing narrative that falsely reassures people about governance and privacy.

Finally, as AI-supported systems become more agentic, where multiple AI agents work in a chained workflow (i.e., outputs from one step become inputs to other steps) and more deeply embedded in mission-critical environments, hallucinations can cause greater damage by amplifying actions rather than simply spreading misinformation. Systems that flow model outputs into plans, decisions, actions, and feedback loops can escalate the potential damage caused by even small mistakes. A single hallucinated assumption about system state, constraints, decisions, or interdependencies can cascade through subsequent steps in the workflow and become integrated with real operational processes. For instance, an informational error in an agentic AI-supported system can quickly escalate into an operational failure with serious consequences (Xenos & Serpanos, 2025).

4. Conclusions and Future Strategies

In our broader study of safety challenges in AI applications, we identify and analyze additional safety concerns with AI-supported tools, including hidden dangers in AI-generated content, the misuse of AI-supported tools

for cyberattacks, and their broader societal impacts. In this particular work-in-progress paper, we focused on our analyses of unpredictable failures and hallucinations in AI-supported systems, including their types, causes, and impacts on workflows, especially in mission-critical applications. We characterized how generative AI models can produce fluent, convincing, yet misleading results, and contaminate mission-critical applications, such as healthcare/medical decision-making, software development, cybersecurity, privacy/data governance, and workflows involving agentic AI-supported systems. In our future work, we will integrate this analysis with other areas related to AI safety to develop and introduce a comprehensive framework and strategies for AI safety.

In more reliable AI-supported systems, especially for mission-critical applications, layered assurance at the technical level should provide comprehensive validation and context-aware evaluation embedded at all stages, including data collection, curation, training, pre-deployment validation, and post-deployment monitoring. Evaluation and verification should consider the measures of real operational failures and runtime uncertainty, in addition to reference accuracy. In mission-critical applications, human oversight and workflow controls are necessary. Human-in-the-loop review should be mandatory when incorporated as a workflow decision point for high-consequence decisions, such as clinical recommendations. In cybersecurity fallbacks, baseline assumptions should be that AI-generated artifacts (e.g., code, playbooks, threat summaries) are unverified and require systematic review prior to acceptance for operational use, thereby minimizing exploitable opportunities for undetected vulnerabilities, false positives/negatives, or recommendations. Ultimately, AI safety rests on more than technical safeguards. It also depends on strong governance, clear accountability aligned with regulations, proper operation, and ongoing training. To prevent privacy violations and compliance gaps, organizations should implement principles into daily practice through training and continuous monitoring of connected components.

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Compliant Cyber Threat Intelligence Sharing in Hospitals: Evaluating the Data Anonymisation Tool

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Abstract: Healthcare organisations face an unprecedented surge of cyberattacks targeting patient data, clinical systems, and connected medical devices. This study examines two ransomware and data breach cases in the United Kingdom and Finland over the past eight years. Both incidents reveal common weaknesses that could have been mitigated through robust Cyber Threat Intelligence (CTI). Despite its benefits, CTI sharing among hospitals remains rare due to privacy concerns, fear of regulatory violations, and limited institutional trust. Under the General Data Protection Regulation (GDPR) and the emerging EU Cyber Resilience Act (CRA), CTI often includes personal or sensitive system data requiring strict protection and traceability, creating tension between collaboration and compliance. This research evaluates whether the Data Anonymisation Tool (DAT) can enable secure, auditable, and GDPR-compliant CTI sharing. The methodology combines a systematic literature review, regulatory mapping of GDPR and CRA obligations, and a functional assessment of DAT's anonymisation and audit capabilities. Simulated CTI-sharing scenarios test how anonymised threat data can flow between healthcare organisations without exposing identifiable information. Findings indicate that DAT integrates technical, legal, and governance safeguards into a single process. It delivers GDPR-compliant anonymisation, preserves CTI utility, and ensures full traceability through verifiable audit logs, addressing CRA requirements for accountability and resilience. While governance challenges persist, particularly around trust models and sector-specific standards, DAT demonstrates strong potential to transform compliance barriers into enablers of collaboration. Privacy-preserving CTI sharing is feasible when supported by structured anonymisation and auditing mechanisms. DAT offers a viable pathway to enhance healthcare cyber resilience and aligns with European efforts to promote secure data sharing in critical sectors.

Keywords: Cyber Threat Intelligence (CTI), Data anonymisation, Cyber Resilience Act (CRA), Healthcare cybersecurity, Privacy-preserving collaboration

1. Introduction

Cyberattacks targeting the Healthcare sector have increased significantly over the past decade, affecting hospitals, clinics, laboratories, and medical device networks. Ransomware, phishing, and exploitation of vulnerabilities in Internet of Medical Things (IoMT) systems routinely disrupt clinical operations and compromise patient safety. Cyber Threat Intelligence (CTI) sharing has emerged as a critical capability for strengthening collective cyber defence. By exchanging information on indicators of compromise, attack patterns, and emerging threats, hospitals could detect incidents earlier and respond more effectively.

Hospitals often refrain from collaborating due to concerns about privacy, data sensitivity, and regulatory compliance, especially under the General Data Protection Regulation (GDPR) and the recently introduced Cyber Resilience Act (CRA). CTI datasets frequently contain personal or system-identifying information that must be protected, traceable, and processed according to strict legal requirements. Real-world incidents analysed in this study, specifically ransomware and data breach cases in the United Kingdom and Finland, illustrate how insufficient patching practices and the absence of CTI sharing amplify the operational and security impacts faced by healthcare organisations.

Hospitals lack a clear and compliant mechanism for exchanging incident information without risking exposure of sensitive data. This research addresses that gap by focusing on the potential of the Data Anonymisation Tool (DAT) to enable secure and regulation-aligned CTI sharing under the EU's evolving cybersecurity framework.

The research question of this study is:

- How can the DAT support secure and compliant CTI sharing among hospitals under the EU CRA?

The rest of the paper is organised into four chapters. Chapter 2 presents a literature review pertinent to this study and outlines the document's scope. Chapter 3 offers both theoretical and practical backgrounds. Chapter 4 outlines the findings, and Chapter 5 provides the conclusions of the study.

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2. Literature

The increasing complexity of cyber threats in the healthcare sector has generated a growing interest in cyber threat intelligence (CTI) sharing as a collective defence mechanism (Fischer, 2023). Research consistently shows that CTI sharing faces substantial barriers. (Skopik et al., 2016) highlight issues of low inter-organisational trust, fragmented governance structures, and unclear responsibilities regarding incident information exchange. A key barrier identified in the literature concerns the sensitivity and identifiability embedded in CTI datasets. (Weber et al., 2023) demonstrate that log files, indicators of compromise, and incident reports often contain personal data, system configuration details, or operational metadata that can reveal internal processes. Organisations operating under GDPR face pressure to ensure that any transferred data remains compliant, minimising the risk of unlawful disclosure (Casarosa, 2023).

(Gadotti et al., 2024) show that anonymisation can enable privacy-preserving collaboration but emphasise the absence of standardised approaches tailored to specific domains such as healthcare. Existing tools such as ARX, Amnesia, and various pseudonymization frameworks provide partial solutions but frequently lack auditability, sector-specific configuration, or full alignment with regulatory principles such as accountability, data protection by design, and secure processing.

The regulatory landscape further complicates CTI sharing. Under GDPR, personal data must be processed lawfully, transparently, and with minimisation principles. CRA places additional obligations on organisations managing digital products and services, demanding traceability, security-by-design, and demonstrable accountability across the product lifecycle (European Parliament and of the Council, 2024). The coexistence of GDPR and CRA creates uncertainty for organisations regarding how to share operational security data while maintaining compliance.

The Horizon Europe DYNAMO project proposes an integrated approach that combines CTI, Business Continuity Management (BCM), and data anonymisation processes (DYNAMO project, 2024; Tikanmäki et al., 2025). The Data Anonymisation Tool (DAT) is designed to support compliant CTI exchange by embedding technical anonymisation, governance controls, and audit features within a single framework. Academic analysis of such tools remains limited, and few studies examine their alignment with emerging EU regulatory expectations.

3. Method

This study employed a multi-stage methodology combining a systematic literature review, regulatory mapping, functional analysis, and scenario-based evaluation of the Data Anonymisation Tool (DAT). The aim was to determine whether DAT can support secure and compliant CTI sharing under GDPR and the EU Cyber Resilience Act (CRA).

A systematic literature review was conducted using academic databases and policy repositories. Twelve key sources published between 2016 and 2024 were selected based on relevance to three thematic areas: CTI sharing barriers and trust challenges; anonymisation techniques and privacy-enhancing technologies; and EU regulatory frameworks shaping cybersecurity and data protection obligations. A regulatory mapping analysis was performed to evaluate how DAT aligns with GDPR and CRA principles. GDPR mandates data protection by design, secure processing, and appropriate technical safeguards. A functional assessment of DAT was conducted to analyse its anonymisation workflow, audit-trail mechanisms, and integration within DYNAMO's combined CTI and Business Continuity Management (BCM) framework (DYNAMO project, 2023). Simulated CTI-sharing scenarios were examined to assess how anonymised incident data could be exchanged between healthcare organisations while preserving analytical value.

The methodology included a brief analysis of two real-world healthcare cyber incidents: a major ransomware attack affecting hospital services in the United Kingdom (The National Audit Office, 2018) and a large-scale patient data breach in Finland (Office of the Data Protection Ombudsman, 2021). These cases were selected due to their public documentation and relevance to CTI failures. Case studies served to contextualise how CTI sharing, if supported by anonymisation and compliance mechanisms, could have reduced the severity or impact of these attacks.

4. Results

The analysis identifies the regulatory, organisational, and trust-related barriers (Bak et al., 2023) that currently limit CTI sharing across healthcare organisations. The evaluation examines how the DAT addresses these barriers through its anonymisation workflow, governance controls, and audit-trail mechanisms. The research assesses

DAT's alignment with GDPR and CRA requirements and evaluates its performance in simulated CTI-sharing scenarios to determine whether anonymised threat intelligence remains operationally useful. These findings provide a comprehensive understanding of both the challenges faced by hospitals and the potential of DAT to support compliant and privacy-preserving CTI collaboration.

Healthcare organisations face systemic cybersecurity risks, yet CTI sharing remains uncommon due to regulatory uncertainty, data sensitivity, and limited institutional trust. CTI logs often contain identifiable information, creating ambiguity about lawful processing under GDPR. Existing anonymisation tools lack sector-specific guides and audit trails, preventing hospitals from demonstrating compliance. These findings highlight the need for a unified tool that can operationalise privacy and accountability.

In both the UK and Finnish incidents, attackers exploited unpatched systems and weak security monitoring capabilities, demonstrating the operational consequences of insufficient CTI utilisation. Relevant threat indicators had been observed in other regions before the attack, but were not shared or acted upon locally due to regulatory uncertainty, negligence and limited trust between organisations.

DAT integrates anonymisation and audit logging within DYNAMO's combined CTI and BCM ecosystem. DAT removes sensitive attributes while preserving operational utility and generates verifiable audit logs that support accountability and regulatory compliance. This operationalises GDPR and CRA principles directly into the CTI workflow, converting compliance requirements into enablers of collaboration.

Simulated CTI-sharing scenarios confirmed that anonymised data retained its analytical value. Mapping DAT's processes to GDPR and CRA requirements demonstrated strong alignment with data protection by design, secure processing, and traceability expectations. Remaining challenges relate to governance models, trust frameworks, and sector-specific standardisation, suggesting paths for future refinement.

5. Discussion and Conclusions

The findings demonstrate that DAT offers a viable and practical approach to privacy-preserving CTI sharing. By integrating technical, legal, and organisational safeguards, the tool directly addresses the core barriers preventing healthcare organisations from collaborating. The study also supports EU policy objectives such as those in the CRA and the European Health Data Space by providing evidence of how regulatory principles can be transformed into operational mechanisms.

However, governance remains a critical factor. Adoption of DAT will require standardised CTI policies, sector-wide trust frameworks, and training to support consistent use. Although DAT provides strong technical and legal alignment, long-term success will depend on how well healthcare institutions embed these practices within their cybersecurity operations.

This study examined whether DAT could support secure and compliant CTI sharing among hospitals. The analysis shows that DAT effectively removes sensitive information, maintains analytical value, and ensures accountability through audit trails. Its alignment with GDPR and CRA principles demonstrates that privacy-preserving CTI sharing is feasible.

Future work should focus on real-world pilot testing, governance model development, and wider integration of DAT into healthcare cybersecurity practices. Despite remaining challenges, DAT represents a promising step toward collective cyber resilience in the healthcare sector.

Acknowledgements

This study has received funding from the European Union project DYNAMO, the European Union's Horizon 2020 research and innovation programme under the grant agreement no. 101069601 and The Cybersecurity in Everyday Work in the Social and Healthcare Sector (KyberSoTe) project. The views expressed are those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Ethics declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI declaration: Keenious was used for literature exploration, and ChatGPT 5.1 for drafting and refinement. Human authors verified all content.

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Enhancing Cybersecurity in Water Plant Infrastructure with SecureAI

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Abstract: Water plant industries are a critical infrastructure that relies on legacy Supervisory Control and Data Acquisition (SCADA) systems, which were not designed to address modern cyber threats. Attackers utilise these vulnerabilities to create significant risks to the industries. As an example, recent incidents such as the attack on the Demin water plant and the Oldsmar water facility, where attackers gained unauthorised remote access to these water plants' systems. This emphasises the urgency of strengthening cybersecurity in this sector. This study investigates SecureAI, an AI-driven cybersecurity tool developed through the Dynamo project. SecureAI provides real-time anomaly detection, recommends isolating protocols to contain threats early, and generates post-incident training materials to improve operator readiness. To ensure that SecureAI implemented into critical infrastructure cannot become autonomous, the EU AI Act requires mandatory human oversight for all high-risk systems. The study includes an evaluation of SecureAI's strengths, weaknesses, and ethical safeguards that align with the EU AI Act, the NIS2 Directive, and the NIST Cybersecurity Framework. Mock-up data on attack scenarios, best practices for the deployment of SecureAI, and an incident response script designed for operator use based on SecureAI alerts. This study bridges the gap between technical detection and regulatory compliance and extends the body of knowledge on AI-enabled cybersecurity measures in water plants. Moreover, SecureAI offers a scalable, operator-centric solution that strengthens resilience while ensuring transparency, compliance and human accountability.

Keywords: SCADA, Water plant infrastructure, Human oversight, Compliance artifacts, Dynamo project

1. Introduction

Water treatment plants rely heavily on SCADA systems to ensure the safe and continuous delivery of clean water. Many of these systems, however, are based on legacy technologies that were not designed to withstand modern cyber threats. The increasing use of remote access for monitoring and maintenance has further expanded their attack surface, making water infrastructure an attractive target for threat actors (Swathika et al., 2024).

Recent incidents have demonstrated that even brief unauthorised access to control systems can pose serious risks to public health and safety. These events highlight the need for improved monitoring and stronger support for human operators, who often must find mitigation strategies during such periods.

This work-in-progress paper presents SecureAI, an operator-centred cybersecurity tool that combines real-time anomaly detection with guided response and training support. By aligning technical detection capabilities with regulatory frameworks such as the EU AI Act, NIST and NIS2, this work explores how AI-based tools can enhance the security and operational resilience of water treatment infrastructure.

This study enhances the academic literature on critical infrastructure cybersecurity. This analysis provides a systematic approach to ensuring that AI-based detection and actionable intelligence comply with the EU AI Act, the NIS2 Directive, and the NIST CSF when operating in a water SCADA/OT environment.

The rest of the paper is organised into five chapters. Chapter 2 presents a literature review, and Chapter 3 offers the method. Chapter 4 outlines the results, Chapter 5 includes a discussion, and finally, Chapter 6 offers the conclusions of the study.

2. Literature

Water treatment plants are critical infrastructure which rely on Supervisory Control and Data Acquisition (SCADA) systems for monitoring and control. Many of these installations operate on outdated or legacy operating systems, which makes them highly vulnerable to cyberattacks (Alanazi et al., 2023; Shewale, 2025) . The reliance on remote access pathways further compounds these risks, as attackers can exploit unsecured connections to bypass traditional safeguards and gain unauthorised control of plant operations.

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Recent incidents highlight the urgency of addressing these vulnerabilities. In the Demin Water Plant attack, attackers exploited a remote maintenance support link to gain unauthorised access, demonstrating how weak remote access pathways can undermine security controls. The Oldsmar Water Plant attack revealed that attackers remotely accessed SCADA systems and attempted to increase sodium hydroxide levels to 100 times the normal amount. Fortunately, an alert operator noticed and reversed the change before any harm occurred (America's Cyber Defence Agency, 2021).

Both cases illustrate the risks posed by legacy SCADA systems when remote access is not properly monitored. Existing literature highlights the importance of resilience in critical infrastructure but often focuses on technical performance rather than operator usability or compliance integration. This project builds on those findings by proposing SecureAI, a tool developed by the DYNAMO project to help operators detect real-time anomalies, provide mitigation strategies and post-incident training response (DYNAMO project, 2024). This research aims to bridge the gap between technical detection and legal compliance in water plant infrastructure by aligning SecureAI with regulatory compliance, such as the EU AI Act (European Parliament, 2025), NIS2 Directive (European Parliament and Council, 2022) and NIST Cybersecurity Framework (NIST, 2024),

3. Method

The research methodology combines desktop research, technical literature review and regulatory analysis to identify gaps between technical detection and legal compliance. Building on these findings, the study proposes a mapping framework that translates SecureAI outputs, such as alerts, logs, and incident timelines, into an audit draft compliance artifact aligned with NIS2. The study used a six-phase approach over three months to investigate the integration of SecureAI into water utility SCADA environments for water plants.

The work progressed through stages:

1. Planning: The project scope, objectives, timeline, roles, and responsibilities are outlined and defined.
2. Case Study Analysis: The Demin and Oldsmar water plant attacks are reviewed and studied to understand vulnerabilities and impacts.
3. Attack Vector Investigation: Common attack vectors, particularly remote access pathways and simulated scenarios to refine SecureAI's detection parameters, are identified.
4. SecureAI Evaluation: Assess strengths, limitations and ethical safeguards of the tool.
5. Response Design: Create an incident response script reflecting oversight and responsible AI deployment
6. Documentation: Compile findings into a final report, including scripts, case study analysis and recommendations

The methodology is guided by compliance with three major frameworks: the EU AI Act, which mandates transparency, accountability, and human oversight for high-risk AI systems, the NIS2 Directive, which regulates common cybersecurity standards across EU critical entities, and the NIST Cybersecurity Framework, which provides a structured model for identifying, protecting, responding to and recovering from cyber incidents.

Structured model data based on the Demin and Oldsmar cases is used in the study, as SecureAI is not yet publicly available. The evaluation framework involves scenario-based detection testing, human-centred instruction clarity assessment, and validation of compliance mapping.

4. Results

SecureAI used the regulatory-aligned guidelines that stressed human oversight to generate containment recommendations. SecureAI is a specialised DYNAMO AI cybersecurity tool designed to identify risk, threats, and abnormalities across different data sources in water plant SCADA environments (DYNAMO project, 2024). SecureAI's architecture is closely aligned with the five pillars of the NIST Cybersecurity Framework. It can identify vulnerabilities within legacy SCADA systems and monitor remote access points, protecting assets by suggesting isolation protocols and detecting anomalies in real time through AI-driven pattern recognition. When threats are detected, SecureAI provides guided containment strategies to support a timely response, while recovery is facilitated through operator training materials and comprehensive documentation.

In addition to technical functionality, SecureAI integrates compliance mechanisms based on the EU AI Act. The system enforces strict human-in-the-loop controls, ensuring that operators retain full authority over all critical actions. It is explicitly designed not to autonomously execute irreversible decisions, thereby prioritising human

oversight and accountability. SecureAI also maintains a transparent audit trail of all actions and decisions, which is essential for post-incident review and regulatory compliance.

Deliverables from this work include a detailed evaluation report assessing SecureAI's strengths, limitations, and ethical safeguards, an incident response script tailored for operator use based on SecureAI alerts and mock-up data on attack scenarios to demonstrate optimal deployment locations. Together, these outputs demonstrate how SecureAI bridges technical detection with regulatory requirements, offering a scalable and operator-centric solution for enhancing resilience in water infrastructure.

5. Discussion

Through literature-based scenarios and compliance mapping, this work establishes SecureAI as an empirically validated product. The objective is to emphasise the social-technical requirements for operating processes and governance techniques. A primary consideration for SecureAI's success is its user interface. The tool must be intuitive and user-friendly to ensure operators can act quickly and correctly during critical incidents. Ease of use is not only a practical requirement but also an ethical one, since credibility and accountability depend on operators' ability to interact with the system effectively. The ethical implications of AI-driven decisions are significant. SecureAI's human-centric design means responsibility for authorising critical actions lies with individuals, yet audits following major incidents may target company protocols and the AI system itself. This reinforces the importance of maintaining a transparent audit trail and compliance framework.

It must be noted that SecureAI is not publicly available. Accordingly, the current analysis is based on theoretical data derived from existing information. The absence of real-world deployment data limits the ability to evaluate SecureAI's benefits compared to other AI-based security tools. Furthermore, technical details regarding installation in test environments are omitted due to a lack of direct access, requiring assumptions about deployment processes.

Despite these limitations, SecureAI demonstrates potential as an advanced Security Information and Event Management (SIEM) system with proprietary algorithms. Its strength lies in leveraging AI for pattern-based detection, enabling it to flag anomalies more quickly and reliably than human operators. While not intended to function as a traditional antivirus program, SecureAI's ability to identify subtle, emerging threats through complex pattern recognition makes it a valuable tool for enhancing resilience in water plant infrastructure.

6. Conclusions

This study addresses the urgent need to protect vulnerable SCADA systems within infrastructure. Water treatment plants are among the most essential services in modern society, yet their reliance on legacy SCADA platforms exposes them to significant cyberattack risks. Incidents such as those at Demin and Oldsmar have demonstrated how easily attackers can exploit unsecured remote access pathways to manipulate critical processes. Against this backdrop, SecureAI emerges as a timely and necessary solution, designed to strengthen resilience, reduce response times and empower operators to manage threats with confidence.

This project's success lies in its deliberate integration of technical innovation with regulatory and ethical safeguards. SecureAI is not simply a detection tool; it is a fully integrated AI-driven system that automates anomaly identification, guides containment strategies, and supports recovery through operator training and documentation. By aligning its design with the EU AI Act, the NIS2 Directive, and the NIST Cybersecurity Framework, SecureAI ensures that its deployment is not only technically effective but also legally compliant and ethically sound. This dual emphasis on innovation and compliance reflects the growing need for cybersecurity solutions to bridge the gap between technical detection and governance requirements.

Finally, this project demonstrates that SecureAI offers a scalable, operator-centric solution that safeguards water infrastructure against evolving cyber risks. By combining advanced AI capabilities with strict regulatory alignment and ethical responsibility, SecureAI helps ensure the operational continuity of essential services. The importance of these results lies not only in the technical achievements but also in the broader impact; a model for how AI can be responsibly integrated into critical infrastructure to enhance resilience, transparency, and human accountability.

Future research should focus on building a functional prototype of SecureAI and testing its detection accuracy and false-positive rates in a simulated water-utility environment. Longitudinal investigations are required to examine the impact of AI-supported case processing on the results of regulatory inspections under NIS2 and the EU AI Act.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Declaration: Keenious was used for literature exploration, and ChatGPT for drafting and refinement. Human authors verified all content.

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Privacy-preserving Cyber Threat Intelligence Sharing in Healthcare: Automated Anonymisation Under EU Regulations.

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ABSTRACT: Healthcare organisations face increasing cyber threats, making cyber threat intelligence (CTI) sharing an essential component of resilience. CTI sharing from hospitals often contains highly sensitive information such as patient identifiers, internal domains or IP addresses that can lead to re-identification if shared without proper protection. When this information is shared without protection, it can allow for re-identification or system mapping, exposing healthcare organisations to additional cyber and privacy risks. Under the emerging EU Cyber Resilience Act, ensuring secure and privacy-preserving cyber threat intelligence exchange becomes critical, requiring tools and processes that safeguard personal and organisational data while maintaining the analytical utility needed for threat detection. This study provides a theoretical framework for evaluating automated anonymisation in the sharing of healthcare cyber threat intelligence (CTI). It explains how to utilise tools such as ARX and DAT to execute privacy-preserving CTI exchange that is compliant with the EU Resilience Act (CRA) and the NIS2 Directive. The framework establishes evaluation criteria that balance anonymisation risk and analytical utility using synthetic CTI data (such as MISP feeds). The evaluation is intended to evaluate the efficiency of anonymisation by using re-identification risk metrics and retained CTI utility (such as Indicator of Compromise, IOC correlation). The model proposed follows European privacy and resilience rules and establishes the foundation for practical and compliant sharing of CTI in healthcare ecosystems.

Keywords: Cyber threat intelligence, Healthcare cybersecurity, Data anonymisation, EU Cyber resilience act, Privacy and data utility, NIS2

1. Introduction

Healthcare organisations are increasingly targeted by sophisticated cyberattacks, making effective cyber threat intelligence (CTI) sharing a critical element of organisational resilience. CTI shared by hospitals often includes highly sensitive data that can enable re-identification or system mapping if distributed without adequate protection. This creates a tension between the need for timely threat information exchange and the obligation to safeguard both personal and organisational data. Legal uncertainties, the caution of organisational culture and the fear of reputational damage are often perceived as obstacles to information sharing in healthcare organisations. These factors slow down cooperation between cyber actors and highlight the importance of anonymisation as an enabler of trust in CTI exchanges (Brilingaitė et al., 2022; ENISA, 2017).

The EU Cyber Resilience Act (CRA) and the obligations under NIS2 mandate create strong expectations and obligations for privacy-preserving mechanisms for sharing cyber threat intelligence (European Parliament and of the Council, 2024). Methods such as differential privacy can lower re-identification risks while still preserving key data patterns when configured correctly (Dankar & El Emam, 2013). Anonymisation should not remove indicator-level technical information such as hashes or IOC chain structures, as these elements are critical in the correlation and identification of threats (Conti et al., 2018). CTI sharing depends on good governance, clear process, and continuous monitoring of privacy and security risks. Anonymisation must be combined with broader cybersecurity practices to remain effective (Bonomi et al., 2023). Without continuous updating work, rule-based controls and anonymisation methods quickly become obsolete, which can reduce the quality and safety level of anonymisation (Modi et al., 2023).

Automated anonymisation techniques present a promising approach to balancing utility and privacy. This study investigates whether such techniques can enable hospitals to share analytically useful cyber threat intelligence while complying with European privacy and cybersecurity regulations. The research question guiding this work is:

- How can automatic anonymisation preserve the usefulness of cyber threat intelligence data while adequately reducing re-identification risk in healthcare organisations?

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The rest of the paper is organised into five chapters. After this Introduction chapter, Chapter 2 presents a literature review, and Chapter 3 offers a theoretical background. Chapter 4 outlines the findings, and Chapter 5 provides a discussion and the conclusions of the study.

2. Cyberthreats in Healthcare

The cybersecurity threat landscape in healthcare is escalating rapidly with increasingly sophisticated attacks and growing regulatory pressures. The healthcare sector now faces "rapidly sophisticated threats", while ransomware remains one of the most disruptive attack types (Rubrik, 2026). ENISA's analysis shows that healthcare organisations are particularly vulnerable to cyberattacks, and most reported cases in the sector are currently related to ransomware attacks, which highlights the need for strong threat intelligence sharing (ENISA, 2023b). Healthcare providers represent a significant share of threat targets in critical infrastructure, and CTI cooperation between organisations remains lacking due to data protection risks and legal uncertainty (ENISA, 2023b, 2023a). The widespread use of MedTech and IoT devices in healthcare significantly increases the attack surface. Many hospital devices run on outdated operating systems and without strong segmentation, increasing the vulnerability of the systems and highlighting the need for anonymised technical threat intelligence sharing (ECSO, 2025).

3. Method

The purpose of this study is to develop an assessment framework for sharing privacy-preserving cyber threat intelligence (CTI) in healthcare using both structured literature-based and conceptual modelling approaches. The objective is to achieve methodological transparency and theoretical rigour, not empirical generalisation.

A systematic literature search was conducted between January 2025 and February 2026 using Scopus, Web of Science, IEEE Xplore, ACM Digital Library, Google Scholar, and official ENISA and EU institutional sources. The searches were conducted using Boolean logic. Search terms that would yield relevant results include ("cyber threat intelligence" OR CTI) AND ("anonymisation or pseudonymisation" OR "privacy-preserving") AND (healthcare OR hospital) AND (EU OR GDPR OR NIS2 OR "Cyber Resilience Act"). Predefined inclusion and exclusion criteria (Table 1) were used to screen titles and abstracts, and search terms were refined iteratively.

Table 1*:* Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Published between 2013 and 2025	Published outside the defined time window
Written in English	Non-English publications
Peer-reviewed articles or authoritative reports (e.g. ENISA, EU bodies)	Opinion pieces or non-authoritative blog content
Addresses CTI sharing, anonymisation/pseudonymisation, or re-identification risk	Focuses on anonymisation without cybersecurity or CTI relevance
Relevant to healthcare or critical infrastructure contexts	Healthcare privacy studies without a cybersecurity dimension

Peer-reviewed studies and authoritative policy documents that directly address anonymisation, re-identification risk, or regulatory compliance were chosen as the top choice for cybersecurity selection. The Anonymisation and Pseudonymisation Guidelines from ENISA 2021 were implemented across three analytical dimensions (ENISA, 2021). The first step was to categorise CTI attributes into direct identifiers, quasi-identifiers, and non-identifying technical indicators to guide anonymisation strategies. The second step was to transform ENISA's risk-based approach to commonly used assessment metrics, which included anonymity and conceptual re-identification probability under reasonable attacker assumptions. To ensure reproducibility, the anonymisation steps, parameter choices, and assessment criteria were clearly documented. The framework is presented using synthetic CTI scenarios that are inspired by MISP-like inputs, emphasising two dimensions: minimising privacy risk and maintaining analytical efficiency.

4. Results

The results are focused on identifying privacy risks, analysing anonymisation effects, and developing an evaluation framework that does not rely on empirical measurement. There are three categories for Healthcare

CTI's recurring identification structure that have clear privacy implications. The risk of re-identification is high when direct identifiers (like usernames or explicit personal references) are used, but they are not common in mature CTI feeds. If they are present, they need to be blocked strictly or anonymised in a way that cannot be reversed.

The primary privacy risk is associated with quasi-identifiers, such as internal IP ranges, hostnames, timestamps, and organisational metadata. Infrastructure mapping and indirect attribution can be achieved through the combination of these elements, although they are not harmful on their own. According to the conceptual assessment, quasi-identifiers are the main cause of the residual identification risk in anonymised CTI, not explicit personal data. The use of non-identifying technical indicators, including file hashes, malware families, and common tactics, techniques, and procedures, poses minimal privacy risks while providing high analytical value. These indicators are crucial for analysing threats and should not be greatly impacted by anonymisation.

The systematic trade-off between privacy and utility is revealed when anonymisation techniques are applied to these identifier constructs. The use of extensive suppression-based anonymisation is advantageous for privacy protection, but it also significantly reduces CTI's utility by disrupting indicator chains and correlation potential. The risk of re-identification can be reduced by using generalisation (including IP address aggregation and timestamp coarsening) and controlled pseudonymization, while still maintaining structural context. The results indicate that there is a range of anonymisation outcomes: risk-aware configurations that reasonably retain significantly more analytical value than maximum anonymisation, while still meeting reasonable privacy expectations.

The ENISA anonymisation guidelines being operationally translated into a CTI-specific evaluation sequence is the primary outcome. When applied to CTI datasets, the ENISA criteria function as operational controls by identifying identifiers, selecting a relative anonymisation strategy, and assessing conceptual residual risk. It utilises metrics such as k-anonymity and the likelihood of re-identification with reasonable attacker assumptions.

From the synthesis of these results, the study derives a two-dimensional evaluation framework that evaluates anonymised CTI from the perspective of privacy protection and analytical utility. Privacy is measured by how much identifiers are exposed and residual risk, while utility is measured by how well indicator relationships are preserved and correlational capacity. By using the framework, transparency can be achieved in justifying the trade-offs of anonymisation, and a structured basis can be established for future empirical validation. Table 2 summarises the resulting evaluation framework.

Table 2*:* Dimensions, privacy and utility focus

Dimension	Privacy focus	Utility focus
Identifier type	Direct / Quasi / Technical	Indicator semantics
Technique	Suppression / Generalisation	Pseudonymisation
Metric	k-anonymity	IOC correlation
Outcome	Risk reduction	Analytical continuity

This study's main outcome is a structured means to evaluate anonymisation's outcomes across privacy protection and CTI utility dimensions, which is provided by the resulting framework.

5. Discussion and Conclusions

The results show that automated anonymisation can support safer CTI sharing in healthcare. Rule-based and statistical methods were able to remove sensitive identifiers while keeping most of the information that analysts need. Findings confirm that there is no perfect balance: when anonymisation settings are too strict, some technical details become less useful for detecting or comparing threats.

The study indicates that anonymisation tools like ARX and DAT can help healthcare organisations meet the privacy expectations created by the EU CRA and NIS2. These regulations require that any shared threat information be protected so that individuals and system details cannot be easily identified (European Parliament and of the Council, 2024). By reducing sensitive fields before the data leaves the organisation, anonymisation supports compliance and lowers the risk of privacy breaches.

The results suggest that hospitals could integrate anonymisation into their existing cybersecurity workflows with limited effort. Anonymisation steps could be applied automatically before CTI is shared with national or EU-level

partners. This could improve both the speed and the safety of information exchange. Automatic anonymisation seems to be a realistic way to increase secure CTI sharing in healthcare, but it must be carefully configured and regularly reviewed. The EU CRA and the NIS2 Directive require the protection of sensitive personal and operational data in information security cooperation between organisations. Automatic anonymisation offers a concrete way to strengthen the overall resilience of healthcare by enabling safer and more confidential participation in national and EU-level CTI networks.

Research shows that anonymisation alone is not enough. Its effectiveness depends heavily on the organisation's governance models, maintaining up-to-date classification rules and threat models, and how well anonymisation is integrated into existing cybersecurity processes. Settings that are too strict can reduce the usefulness of the CTI data being shared, while settings that are too lenient can leave identification risks behind. This study refers to anonymisation as an umbrella term, recognising that a lot of CTI use cases rely on strong pseudonymization instead of irreversible anonymisation. Anonymisation profiles optimised for the healthcare sector are needed to balance data protection and analytical benefits. Such research would support more mature, reliable and privacy-preserving cyber defence cooperation in Europe's healthcare systems. Future work should examine how anonymised CTI performs in larger, real-world sharing environments and how hospitals can standardise their anonymisation practices to ensure consistent quality.

Acknowledgements

This study has received funding from the European Union project DYNAMO, the European Union's Horizon 2020 research and innovation programme under the grant agreement no. 101069601 and The Cybersecurity in Everyday Work in the Social and Healthcare Sector (KyberSoTe) project. The views expressed are those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Ethics declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI declaration: Keenious was used for literature exploration, and ChatGPT 5.1 for drafting and refinement. Human authors verified all content.

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The Future of Authentication: Not as Simple as Providing a Secure Solution

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Abstract: In recent years, the number of online and digital accounts have grown, with the average user needing over 100 passwords. With so many passwords, users often struggle, and therefore, there are many password authentication alternatives on the market, including password managers, biometrics, passkeys, and multifactor authentication (MFA) to add security to passwords. All of these solutions have their pros and cons, and if the user manages them well, they are a secure means to authenticate without relying on multiple passwords and the issues that passwords bring to authentication. For several years, the technology and cybersecurity industries have been calling for the death of passwords, and yet they are still among us. Previous research has identified reasons why password alternatives and solutions are not widely accepted by users. These include users' trust, new technology usage and acceptance, perceptions of privacy, financial cost, and misguided security perceptions. With the introduction of newer and more convenient technologies such as passkeys, it is hoped that passwords will finally die. However, from initial interviews, those working in the technology and cybersecurity industries are reporting resistance from users. This study aims to examine users' perceptions of authentication methods, and their intentions for improving the security of their digital lives in the future. A mixed-method approach will conduct questionnaires, measuring user perceptions and attitudes towards authentication methods, their motivations for securing their own and organizational digital services, as well as demographic data that could indicate any interaction effect. Furthermore, interviews will be conducted to delve deeper into participants' responses. The results will shed light on factors that are influencing the uptake of secure authentication solutions, and will have several implications establishing a comprehensive view of different user factors that influence authentication decision-making that could ultimately shape the future of the authentication solution industry.

Keywords: Authentication, User behaviour, Cyber security, Security motivations

1. Introduction

Passwords remain the most common way people secure multiple accounts, but managing numerous credentials is a persistent challenge. As a result, alternatives such as password managers, biometrics, passkeys, and multifactor authentication have emerged to strengthen or replace traditional passwords. Each option brings advantages and trade-offs, yet passwords persist. Previous research points to several barriers to broader adoption of these alternatives, including trust issues, reluctance to adopt new technologies, privacy concerns, cost, and misconceptions about security (Matzen et al. 2025; Siddique et al. 2017; Wang et al. 2025; Woods & Siponen 2025). Although newer, more convenient solutions like passkeys promise to phase out passwords, user resistance continues to slow that transition (Daffalla et al. 2025; Matzen et al. 2025). Ten years ago, the promise of biometrics taking over and replacing passwords did not come to fruition, this begs the question of whether newer alternatives will really end the use of passwords? And what would it take from the users' perspective?

The objective of this study is to draw upon psychology and decision science to understand the user's influence on future authentication. It will examine users' perceptions of authentication methods, and their intentions for improving the security of their digital lives in the future. With the aim of highlighting the challenges the cybersecurity industry face when providing users with a secure means to authenticate, we aim to answer these research questions: What are the key issues that lead to users' use or reluctance to use different authentication methods? Are there common factors across all authentication methods? What will make authentication solutions usable for users in the future?

2. Overview: Current Authentication Solutions

Passwords are the most common mechanism. Their strengths include cost-effectiveness, easily deployed across multiple systems, and strong if created well. Password weaknesses arise due to multiple accounts, the users' discipline, and cognitive abilities. This can lead to weak passwords, as users struggle to remember complex passwords, which can result in password reuse (Woods & Siponen 2025). Previous research has examined the security, user behaviours, and usability issues with the aim of improving their security (Woods & Siponen 2025).

Password Managers allow users to store their passwords behind one master password or key securely. The advantages include improved security and usability of multiple passwords. The disadvantages can include cross-

device usage limitations, vulnerable to phishing, and loss or theft of the physical device (Siddique et al. 2017). Password managers were thought to answer the password memorability and security problems, however, their uptake has been low (Woods & Siponen 2025). Previous research notes that many users prefer to memorize their passwords instead of using password managers (Das et al., 2014), due to distrust (perceptions off vulnerability to attacks and trust their own memory) (Woods & Siponen 2025).

Biometrics include physical and behavioural attributes (inc. users' fingerprint, iris, face recognition, keystroke, etc.). They are convenient and strong (Siddique et al. 2017). Unfortunately, there are weaknesses including vulnerability to spoofing, privacy concerns, cost, poor accuracy, and unusable by some users. Furthermore, breaches of biometric databases are concerning as credentials cannot be revoked (Wang et al. 2025).

Token-based methods include, USB, passkeys, mobile and authenticator apps, have several advantages, such as providing higher security and reduce the need to memorize information (except for a PIN). However, their disadvantages can include inconvenience, fear of loss of physical tokens, impractical if they need to be revoked and reissued, as well as limitations in cross-device usage (Siddique et al. 2017). The uptake of these devices is mixed, as users' perceptions are influenced by ease of use, compatibility, technical support, and challenges need to be addressed for wider adoption, e.g., easier setup processes (Nanda et al. 2024).

Passkeys are considered a secure, automatic authentication method based on public-key cryptography where the user authenticates using a device and the user's biometrics or a PIN (Lassak et al. 2024; Matzen et al. 2025). However, there challenges include a lack of standardized recovery mechanisms for lost or damaged devices, compatibility issues, privacy concerns, and phishing risks to backup processes and mechanisms. There are user challenges too, such as mistrust, set-up difficulties, privacy concerns, fear of devices being damaged, and denial of services (Daffalla et al. 2025; Matzen et al. 2025; Nanda et al. 2024).

Multifactor Authentication (MFA) (inc. Two-factor Authentication (2FA)) enhances the security of authentication by requiring multiple verification factors (e.g., biometrics, tokens) (Das et al. 2019). The advantages include adding a strong security layer beyond passwords and reducing the risk of unauthorized access (Wang et al. 2025). Despite its security benefits, MFA has its challenges including, complex enrolment and backup processes, inconvenient, complex, and frustrating authentication processes (Das et al. 2019; Klivan et al. 2023; Wang et al. 2025).

3. Is History Going to Repeat Itself? Motivations for Proposed Study

Previous research has noted that user perceptions are critical for accepting authentication schemes (Zimmermann & Gerber 2020), and low adoption can be due to for example, the difference between users' objectivity and subjectivity when considering new authentication methods, influencing their familiarity, trust, ease of use, and perceptions of complexity, reliability, and costs (Klivan et al. 2023; Wang et al. 2025). Furthermore, usability problems discourage adoption leading to choosing less secure options (Das, et al. 2019).

New authentication solutions like passkeys have the potential to revolutionize authentication systems, but also face significant challenges in user perceptions, technical implementation, and usability (Daffalla et al. 2025; Matzen et al. 2025). Preliminary interviews of experts working in the cybersecurity industry have reported resistance from users in using MFA and passkeys. As seen with password managers, users feel that removing their input out of the authentication process justifies distrust and feeling of a lack of control over their security. This suggests that hoping these solutions will replace passwords may be short lived. Therefore, we need to understand and identify what it would take for users to accept a secure solution to authenticate, this can bring to light key factors underlying the future uptake of authentication solutions.

4. Proposed Research Methods: Mixed Method Study

A mixed-method approach will conduct questionnaires measuring users' perceptions and attitudes towards authentication methods using items from the Human Aspects of Information Security Questionnaire (HAIS-Q) (Parsons et al. 2017). Further items evaluating protection motivation (PMT) towards participants' own digital security and the security of their organizations will measure perceived vulnerability, severity, self-efficacy, response efficacy, and response costs (Moody & Siponen 2018). Semi-structured interviews will be conducted using established guidelines (Myers 2013). We will delve deeper into participants' questionnaire responses and discuss their perceptions towards using different authentication methods. The interview data will be transcribed and coded by two coders who are guided by verified data analysis methods (Myers 2013). The participants will be recruited from various organizations within different industries where employees are required to

authenticate using different methods. Due to this mixed-methods study taking a more qualitative approach, we will aim to recruit 15-25 participants (or more until saturation has been reached) (Myers 2013).

Ethical considerations will be taken into account, and ethical clearance from the institution's ethical committee will be sought. Participants' consent will be obtained, information including privacy policies will be provided to the participants, and data collected will be kept confidential and coded.

5. Conclusion

Over twenty years ago, Bill Gates said that passwords were dead and that biometrics would take over. The misconception that biometrics would completely replace passwords as the ultimate authentication method has set digital security especially password security, back considerably, in terms of suppressing password research and industry developments (Herley & van Oorschot 2011; Siddique et al. 2017). Even with all the digital advances, this prediction has not come true, and password authentication remains very much unchanged. In more recent times, there have been developments in authentication, bringing new secure methods to the market, with a lot of promise to finally end passwords. However, many users continue to prefer passwords and are reluctant in using other authentication methods. Getting rid of passwords is enticing, but practically it opens up several issues and difficulties. To replace passwords several concerns need to be addressed. This study proposes a mixed-method approach to fully understand these issues, specifically from the perspective of the user. The results will shed light on factors that are influencing the uptake of secure authentication solutions, and will have several implications establishing a comprehensive view of different user factors that influence authentication decision-making that could ultimately shape the future of the authentication solution industry.

Ethics declaration:Ethical clearance from the institution's ethical committee will be sought before the study commences.

AI declaration: AI tools were not used in the development of this paper.

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No Rules: Can Removing Password Creation Rules Improve Password Memorability and Security?

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Abstract: Many users have significant issues in remembering all their passwords. There are several authentication technologies available on the market to help with these issues, for instance, password managers. However, many users still choose to rely solely on their memory. Creating and recalling multiple strong passwords often leads many users to adopt insecure password practices, such as, creating weak passwords and writing passwords down. Insecure behaviours result in substantial security breaches and financial losses. Therefore, password creation requirements imposing complexity (e.g., X number of higher and lower case letters, numbers and special characters), and length (e.g., X number of characters) are implemented to ensure that users create passwords with a standard or minimum level of strength. Previous research has examined password memory and security issues, suggesting various ways to improve memorability. Furthermore, previous research has also examined users' perceptions and interactions when attempting to meet password creation requirements, and the impact they have on users' password management. Previous results suggest that users struggle to meet password creation rules and often circumvent security by, for instance, reusing the same password or modifying passwords for multiple accounts, which is a significant security issue unto itself. In this study, we will examine whether removing the complexity password creation rules will have beneficial effects on memorability and security. Using a mixed-method study, we will examine password creation and recall, using an online laboratory study, observing the strength of the passwords, and whether focusing solely on creating and not meeting rules will improve password memorability. Follow-up questionnaires will measure user perceptions and attitudes, and interviews will be conducted to deeper examine motivations for digital security while not imposing rules. The results will have important implications for research and practice, and especially for professionals who make recommendations and guidance for password management. This is because, improving password memorability and security could reduce insecure password behaviours and reduce financial losses associated with passwords.

Keywords: Passwords, Password creation requirements, Password behaviour, Memorability, Authentication

1. Introduction

Passwords are the most common authentication mechanism. Even with several security issues pertaining to them, they remain prevalent due to their low cost and how easily they are implemented into systems (Bošnjak & Brumen 2019; Güven et al., 2022; Wang et al. 2025). Over recent years, with a significant increase in digital accounts, users are now expected to have on average, over 100 passwords (Woods & Siponen 2025). Multiple password usage is leading many users to struggle as they attempt to create strong and easy to remember passwords, of which they then often adopt insecure password behaviours such as writing passwords down and reusing passwords to cope with these issues (Das et al., 2014; Woods & Siponen, 2018; 2025; Zimmermann and Gerber, 2020). These insecure behaviours are leading to substantial security breaches, with organizations losing hundreds of thousands of dollars per breach (Merdenyan & Petrie, 2022; Woods & Siponen 2025). In response to the password problem, new authentication solutions have entered the market, including password managers to help keep passwords secure, and multifactor authentication (MFA) solutions to add additional security factors to the authentication process (Daffalla et al. 2025; Das et al. 2019). Yet, passwords are still preferred by many users, and therefore researchers attempt to provide ways to improve the users' password security behaviour, and password memorability (Bošnjak & Brumen 2019; Güven et al., 2022; Siddique et al. 2017).

This paper proposes a study, applying an interdisciplinary approach and drawing upon psychology and cybersecurity to understand how password creation rules affect password memorability and security. It highlights how imposing password rules may be counterintuitive, and examines users' security motivations and implications if users were allowed to be autonomous.

In this proposed study, we suggest that removing complex password creation rules will not only improve password memorability but may also improve their overall security, and will aim to answer these research questions: to what extent does removing password creation requirements improve password memorability? Do users create strong passwords with password creation requirements removed?

2. Password Memorability, Security and Imposing Password Creation Policies

Previous research examining the password problem has often focused on how human memory shapes password related behaviour. Studies have explored factors that influence memorability (e.g., Woods & Siponen, 2018;

2025), the role of perceived importance of information in password creation (Grawemeyer & Johnson, 2011), the impact of password policies on user choices (Campbell et al., 2011; Rodriguez et al., 2022; Shay et al., 2016), and broader patterns in password security practices. Many studies have explored how to improve password memorability by drawing on what is known about human memory — how people learn, store, and retrieve information. This work has been applied across the full password lifecycle, including how users create, learn, and recall passwords, as well as how memory techniques or technological aids might support these stages (e.g., Woods & Siponen, 2018; 2019).

There are two facets of password security, which are interrelated. The first being that users should create strong passwords, by following password creation policies. These password policies are based on NIST SP 800–63 guidelines, to impose a minimal level of strength (minimum number of characters, upper and lower characters, numbers, special characters, etc.) (Campbell et al., 2011; Güven et al., 2022; Rodriguez et al., 2022; Shay et al., 2016). Although these policies have been updated in NIST SP 800–63B (Grassi et al., 2024), with no requirements for complexity; older policies requiring complexity are still imposed on many popular websites and within organizations (Woods & Siponen, 2025). The second facet of password security is the users' behaviour with respect to managing their passwords. Struggling with password memorability can lead to insecure behaviours including reusing and modifying passwords (Grawemeyer & Johnson, 2011; Merdenyan & Petrie, 2022). Many users reuse their passwords, as they believe that it will help them remember their multiple passwords (Das et al., 2014; Zimmermann and Gerber, 2020). When users are prevented from reusing passwords due to varying password policies, they often resort to predictable patterns or small modifications to their existing passwords (Das et al., 2014; Woods & Siponen, 2025). Research suggests that many users believe these minor changes enhance their security, without realizing that such patterns are easily exploitable (Das et al., 2014; Merdenyan & Petrie, 2022).

The purpose of password policies are to encourage users to increase their password strength, with users being required to find the time and mental energy to create and learn passwords that comply with these policies (Marquardson, 2012; Woods & Siponen, 2019). However, human memory has limitations in learning, which are not taken into account in the password creation process, as security policies encourage users to create longer and longer passwords to increase security (Campbell et al., 2011; Marquardson, 2012; Woods & Siponen, 2019). Often, users face the trade-off between password memorability and security due to password composition policies, which results in users choosing to meet the bare minimum due to these constraints (Bošnjak & Brumen 2019; Marquardson, 2012).

3. Rules vs. no Rules: Study Motivation

Technology has been developed that eliminates the need to memorize and recall passwords. One example is, password manager technology which appears to offer a strong solution to the challenges of password memorability and security (Bošnjak & Brumen 2019; Merdenyan & Petrie, 2022). However, they have not achieved widespread adoption despite being available for decades. Research suggests that many users still prefer to memorize their passwords rather than rely on a password manager, and even when encouraged to adopt one, a significant number continue to resist (Das et al., 2014; Wang et al., 2025; Woods & Siponen 2025). Because users largely want to retain personal responsibility for remembering their passwords, finding ways to improve password creation and recall remains essential (Bošnjak & Brumen 2019; Siddique et al. 2017).

During a pilot password study, participants were required to create and recall passwords that met typical password creation policy requirements. The initial results suggested that users were focusing on meeting the password creation rules and not on learning their passwords, which in turn affected their memorability. Therefore, in the proposed study, we will examine whether removing the complexity password creation requirements will have positive effects on memorability as well as overall security, as users will be able to focus on the learning process.

4. Proposed Research Methods: Mixed Method Study

Using a mixed-method approach, we will examine password creation and recall, using a longitudinal online laboratory study (Woods & Siponen, 2018; 2025). Over 200 participants will be recruited from various organizations where several systems and services require password authentication. The participants will be allocated into two groups and will create and recall multiple passwords over several weeks through an online password system, specifically designed for this study. One group will create passwords with password creation rules imposed that include complexity and length requirements, and the second group will have only length requirements imposed while creating their passwords. Password memorability will be measured between both

groups. Additionally, strength will be observed and measured using zxcvbn (a heuristic-based password strength estimator) (Kagnici et al. 2025), to examine whether participants will create complex and long passwords without the requirements in place. Follow-up questionnaires will measure user perceptions and attitudes towards their experience of creating and recalling passwords that meet password creation requirements, and further interviews will be conducted to deeper examine motivations for digital security while not imposing rules.

Ethical approval will be obtained from the institution's ethics committee, and all ethical considerations will be fully observed. Participants will provide informed consent, receive clear information about the study and its privacy practices, and all collected data will be coded and kept confidential.

5. Conclusion

Many users experience persistent difficulty remembering the numerous passwords required across their accounts (Woods & Siponen, 2025). Although a range of authentication technologies has been developed to try to mitigate these challenges, a substantial proportion of users choose to continue to rely exclusively on their own memory (Das et al., 2014; Wang et al. 2025). The demands of creating and recalling multiple strong passwords frequently lead to insecure practices, including the use of weak passwords and writing them down. Such behaviours contribute to significant security incidents and financial losses (Woods & Siponen, 2018). In response, stricter password policies are imposed, with organisations commonly enforcing password creation policies that mandate increased complexity and increased length to ensure password strength. However, these policies can have the opposite effect as users' memories are limited, resulting in a trade-off between password memorability and security (Bošnjak & Brumen 2019; Campbell et al., 2011; Rodriguez et al., 2022; Shay et al., 2016). Therefore, this study proposes examining the effects of removing password complexity requirements on memorability and security to understand whether focusing solely on creating and not meeting rules will improve password memorability.

The findings are expected to offer meaningful implications for both research and professional practice, particularly for those responsible for developing password management guidance. Enhancing the memorability and security of passwords has the potential to reduce insecure user behaviours and, in turn, lessen the financial losses associated with password related security incidents.

Ethics Declaration: Ethical clearance from the institution's ethical committee will be obtained before the study commences.

AI Declaration: AI tools were not used in the development of this paper.

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Late Submissions

Securing the Decentralized Edge: An Integrated Approach to Endpoint Security Monitoring and Threat Detection

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Abstract Modern IT infrastructure is undergoing a significant transformation, becoming increasingly complex and decentralized as organizations move away from centralized on premise data centers toward hybrid, multicloud, and edge computing models. This is a shift driven by the demand for higher resilience, lower latency, and the specialized requirements of modern AI workloads running on the edge. While this shift improves operational efficiency, it introduces significant challenges including limited visibility, legacy network bottlenecks, operational complexity, and a broadened attack surface as a result of the decentralized edge based infrastructure requiring new security approaches that go beyond traditional perimeter security. Adversaries increasingly exploit these decentralized environments for ransomware, espionage, or coscripting devices into botnets for large scale attacks. The resulting breaches carry severe consequences including financial loss, penalties from regulators, non-compliance and irreparable reputational damage. To address the aforementioned challenges, this paper proposes a zero Trust Architecture integrated with Wazuh. Using Wazuh's comprehensive monitoring and incident response capabilities, organizations can implement a "never trust, always verify" framework that protects the decentralized edge against modern threat vectors. This paper provides practical guidance for IT professionals and students seeking to implement modern endpoint security and defend infrastructure against evolving cyber threats.

Keywords: Wazuh, Malware, Threats, Detection, Response, Cybersecurity training

1. Introduction

As the threat landscape continues to evolve alongside emerging technological trends, organizations must continue to upgrade their IT infrastructure to remain competitive and efficient. However, many organizations prioritize infrastructure upgrades with little consideration for security, often treating it as an afterthought. These changes tend to introduce vulnerabilities into the environment, and without proper logging and monitoring of system activities, these vulnerabilities can create significant security risks, which could potentially lead to substantial losses if exploited by adversaries.

The absence of robust monitoring and detection capabilities creates major challenges for detection and response teams, making it extremely difficult to identify and mitigate sophisticated threats such as advanced persistent threats(APTs). A Security Information and Event Management (SIEM) system becomes essential in this situation. A SIEM provides real-time visibility into the organization's security posture regardless of whether your operations are on cloud or on premise, automates analysis of security events, and robust reporting to ensure the organization maintains compliance requirements and well covered during forensic investigations in the event of an incident.

Modern Security Information and Event Management (SIEM) solutions generally fall into two categories: high cost commercial platforms and flexible open-source tools. Although industry leaders such as Splunk, FortiSIEM, and IBM QRadar offer sophisticated automated capabilities as shown on Table 1, they carry significant licensing fees that often create a security gap for small-to-medium enterprises (SMEs). These organizations often operate without centralized monitoring, leaving them acutely vulnerable to cyber threats.

On the other hand, open source SIEM solutions provide robust functionalities for $0 in licensing. However, they typically require extensive time resources through manual configuration and specialized expertise to integrate it into existing IT infrastructures. In this paper, we explore Wazuh, an all in one open source security platform that bridges this gap by unifying Extended Detection and Response (XDR) with traditional SIEM capabilities. It provides enterprise grade features, including configuration assessment, malware detection, File Integrity Monitoring (FIM), and automated vulnerability & threat detection and response. Architecturally, the platform comprises the Wazuh Indexer, Server, Dashboard, and Agent, supporting modern deployment via Docker, Kubernetes, Ansible, and Puppet.

Wazuh also allows integration with various threat intelligence sources such as VirusTotal, YARA, CDB Lists, and AbuseIPDB which ensures realtime detection of threats with an element of automated response to the detected

threats, ensuring that your security team is always one step ahead of adversaries. This paper aims to show the deployment of Wazuh anIT infrastructure and the necessary configurations that can be made to the tool for malware detection , file integrity monitoring, threat and detection and response to suspect bruteforce attack attempts.

Table1: Comparative analysis of SIEM platforms

Platform	Architecture	Key Strength
Microsoft Sentinel	Cloud Native	Ecosystem Synergy: Near-zero configuration for Microsoft 365, Defender, and Entra ID logs
Splunk ES	Hybrid/Cloud	Data Maturity: Powerful search (SPL) and the ability to correlate almost any data source
IBM QRadar	On-Prem/ Cloud	Out-of-the-Box Rules: Excellent for compliance with stable, pretuned correlation engines
FortiSIEM	Physical/Virtual appliance	Unified NOC/SOC: Combines asset discovery (CMDB), performance monitoring, and security
Wazuh	Open-source (On-Prem/Cloud)	The Endpoint Edge: Native File Integrity Monitoring (FIM) and EDR-like capabilities for $0 licensing

2. Objective

The main objective of this paper is to show how to integrate Wazuh in an IT infrastructure environment, identify the recommended key configurations required for threat detection, monitoring endpoints, and automated incident response in the event of an attack. Our key focus will highlight the deployment of this critical tool and the necessary configurations that will enable your organization to stay ahead of adversaries, providing blue teams with more time to focus on actual threats, minimizing alert fatigue or danger of false negatives while at the same time saving the organization running costs that would have been incurred in the option of using the commercial tools.

3. Related Work

Endpoint protection plays a critical role as the first line of defense against cyber-attacks and remains a key priority in safeguarding an organization's assets from threats. Various efforts have been put to address and improve endpoint security. We see the work of A. Al Siam et al. (2025), where they developed a threat detection and response solution solely meant for Linux endpoints, unlike in our approach where we show how Wazuh caters not only for Linux endpoints but also endpoints running MacOS and Windows operating systems, which ensures a centralized approach to monitoring all endpoints. Recent comparative analyses emphasize the superiority of Wazuh among open source SIEM solutions (such as ELK and OSSIM) precisely due to this cross platform compatibility, along with its integrated File Integrity Monitoring (FIM) and native active response capabilities R. Amami et al.(2024).

We also see A. Al Siam et al.(2025) focusing on Extended Detection and Responses (EDRs) as a malware detection solution, which highlights some of the capabilities to consider for an EDR for effective detection and response to malware. This is indeed a great insight for organizations when sourcing an EDR, and they also go ahead to provide a list of available enterprise EDRs. In our approach with Wazuh, we highlight its Extended Detection and Response capabilities such as disrupting an ongoing brute force, slowing down the attacker, and providing the security team with an alert for investigation. This is actively supported by recent research demonstrating the effectiveness of Wazuh in instantly mitigating brute force attacks by deploying automated firewall drop actions to block offending IPs after a configured threshold of failed logins as shown by K. Z. Htet et al(2025). Furthermore, Wazuh drastically improves incident response times by allowing integration with messaging

platforms such as Telegram, ensuring that security teams receive automated, real time alerts for high severity threats through an experiment by C. Dhefanni et al.(2025).

Wazuh comes with out-of-the-box rules, the flexibility to create custom rules, and integration with threat intelligence platforms such as VirusTotal, YARA, and CDB lists, which increase the probability of detecting zero-day attacks and responding to them automatically based on your configurations. The integration of live threat intelligence feeds, such as VirusTotal and AbuseIPDB, into Wazuh's event pipeline has been empirically shown to achieve threat detection rates of 95.0% and high alert precision with very low mitigation delays (averaging 2.8 seconds) via dynamic Indicator of Compromise (IOC) querying. Beyond reactive threat detection, Wazuh also offers proactive endpoint defense using its Security Configuration Assessment (SCA) module to continuously validate OS system hardening and ensure compliance with CIS benchmarks (R. Doynov et al, 2025). All of this is available for free, offering a highly capable alternative compared to other commercial SIEMS, EDRs and XDRs such as Crowdstrike, Microsoft Sentinel, Splunk ES, IBM QRadar, FortiSIEM etc

4. Methodology

We deployed the Wazuh server on Google Cloud as a docker container. We then configured Wazuh for FIM, threat detection, and response as will be shown in the paper. We then deployed the agents on our endpoints which comprised a Windows OS, MacOS and Linux operating system. We then centralized our configurations to the respective OS type, which enabled us to create, modify, and push changes to our endpoints without the need to physically do so for each machine. This enabled us to get logs from agents for analysis, detection, and response in real time.

4.1 Wazuh Architecture

For this paper, we deployed Wazuh through the docker deployment option as a single-node stack, suitable for small organizations compared to the multi-node stack that offers scalability for large sized organizations. Our setup included Wazuh docker image on a Google Cloud Ubuntu 22.04 server instance, Cloudflare for our proxy, and Wazuh agent installed on three endpoints running Windows OS, MacOS and Linux respectively. These agents act as the first line of defense Host-Based Intrusion Detection system by detecting threats and forwarding the alerts to Wazuh server, which runs another check against the configured rules before it can determine if the detected threat is indeed positive and then apply the configured actions accordingly to contain it. Figure 1 shows the Wazuh docker deployment architecture on Google Cloud and how the various components of Wazuh come into play to enable it to monitor endpoints and detect malicious activities in real time.

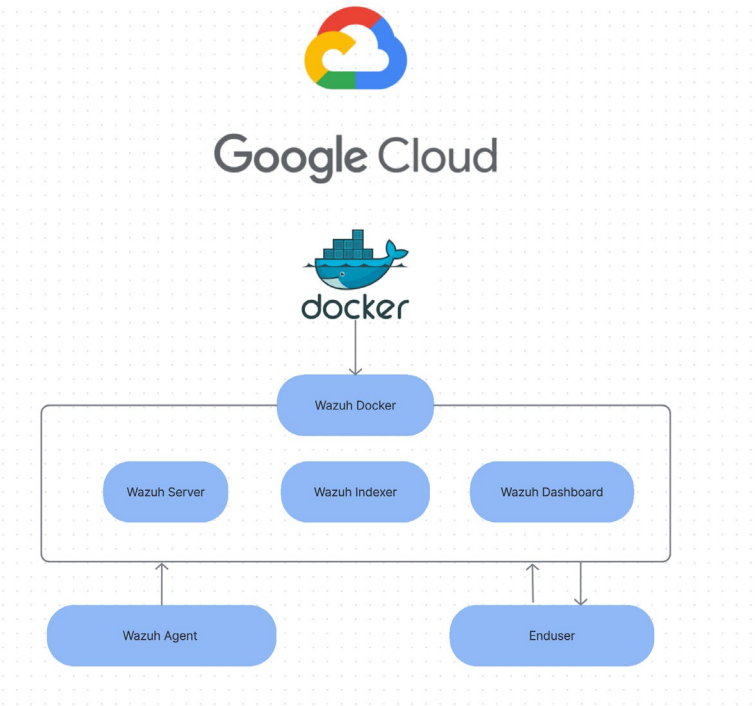


Figure 1: Wazuh docker deployment architecture on Google Cloud showing the various components that communicate with each other to make the platform work

4.2 How Wazuh Works

1. The Wazuh agents installed on endpoints in IT infrastructure collect logs from their respective endpoints and send the logs to the Wazuh server.
2. The Wazuh server parses the logs, decodes, and applies the configured rules to determine if there is any data from the decoded information that matches the rules and if any exists, an alert is raised with an id that specifies the kind of malicious activity detected for security analysts to review and analyze further to confirm if indeed there was a compromise.
3. Wazuh comes with out of the box default rules that are continuously updated and maintained by the Wazuh team to address emerging threats and ensure effectiveness of its detection capabilities which cover a wide range of security events and log sources, providing a great baseline for detecting common security threats. Wazuh also provides an advantage of flexibility through custom rules, either by creating new custom rules or modifying the default rules, which enable users to tailor Wazuh to meet their unique IT infrastructure's needs, greatly enhancing its capabilities and effectiveness.
4. Over time, Wazuh collects information from the alerts received, endpoints, and environments being monitored, and represents this information in dashboards and reports for review by security teams providing an overview of the security posture of your organization.

4.3 File Integrity Monitoring

Malware frequently targets the Windows Registry to achieve malicious objectives, such as establishing persistence and performing other malicious actions. The Wazuh file integrity monitoring module includes Windows Registry monitoring that monitors commonly targeted registry paths to detect modifications. VirusTotal integration uses the VirusTotal API to detect malicious content within files and directories monitored by the Wazuh file integrity monitoring capability. Wazuh allows users to define directories of interest that contain critical files such as system files and confidential information. Any changes made to files or directories of interest will create an alert as shown in Figure 2, where a new suspicious file, suspicious-file.exe, has been added to the monitored directory, Wazuh-test.

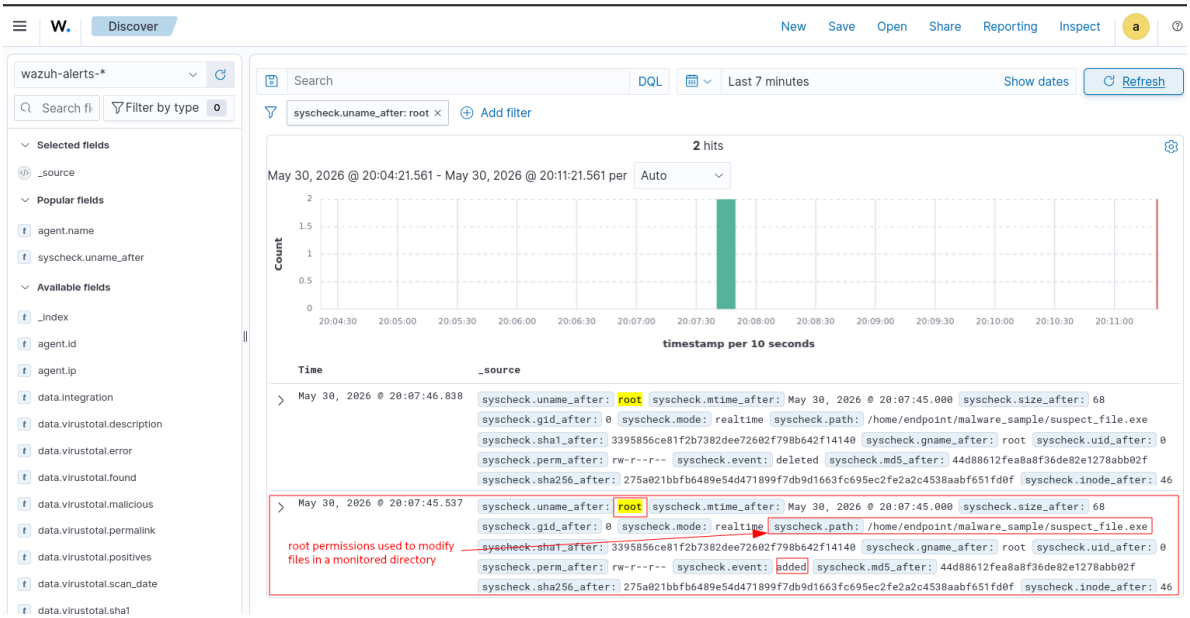


Figure 2: A suspicious file added to the monitored directories is detected by the FIM module

4.4 Threat Detection and Response

Wazuh uses the active response module to run scripts or executables on a monitored endpoint, acting on certain triggers. The data flow for threat detection and response is provided in Figure 3. In our use case, we simulated an ssh brute force attack against an Ubuntu endpoint and configured the active response module on the Wazuh server to block the IP address of the attacker endpoint. The main objective was to prevent brute force attacks from ssh. The active response module executed a script that blocked the IP address of the attacker when Rule 5763-sshd brute force trying to get access to the system got triggered.



Figure 4: Sample of Wazuh Manager configuration that disconnects connection to victim machine

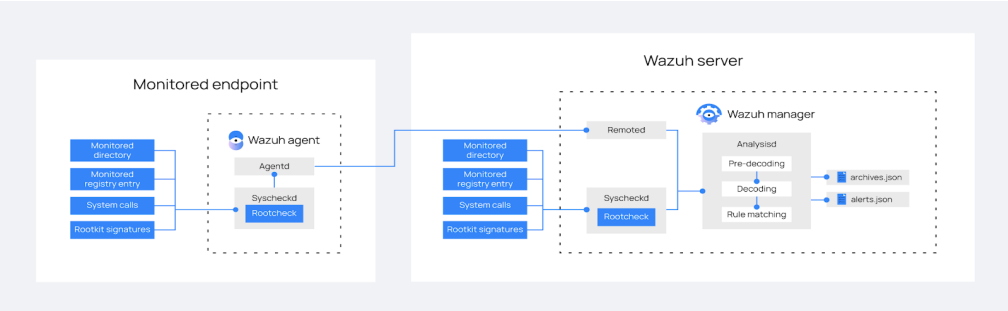


Figure 3: Wazuh threat detection and response workflow

Figure 4 provides a sample of Wazuh Manager configurations. This was followed by adding the active response configuration for response to brute-force attack attempts as shown in Figure 5.

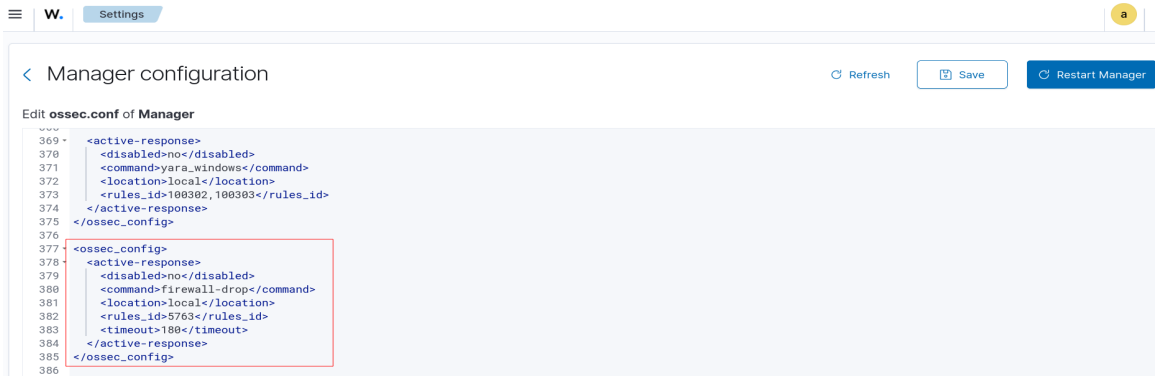


Figure 5: Wazuh Manager configurations for active response to brute-force attack attempts

The attacker and victim endpoints are shown in Figure 6. The adversary launched a ssh brute-force attack on the victim endpoint using a payload through hydra, as shown in Figure 7 Wazuh detected the brute-force attack and logged an alert as shown in Figure 8. After detection of this threat, Wazuh cut the connection between the victim machine and the adversary, as evidenced by the 100% packet loss as shown in Figure 9.

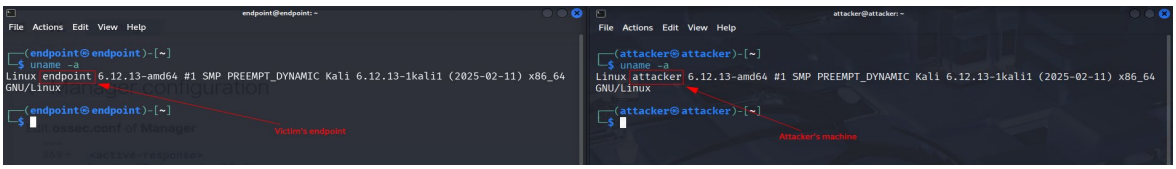


Figure 6: Attacker and Victim machine

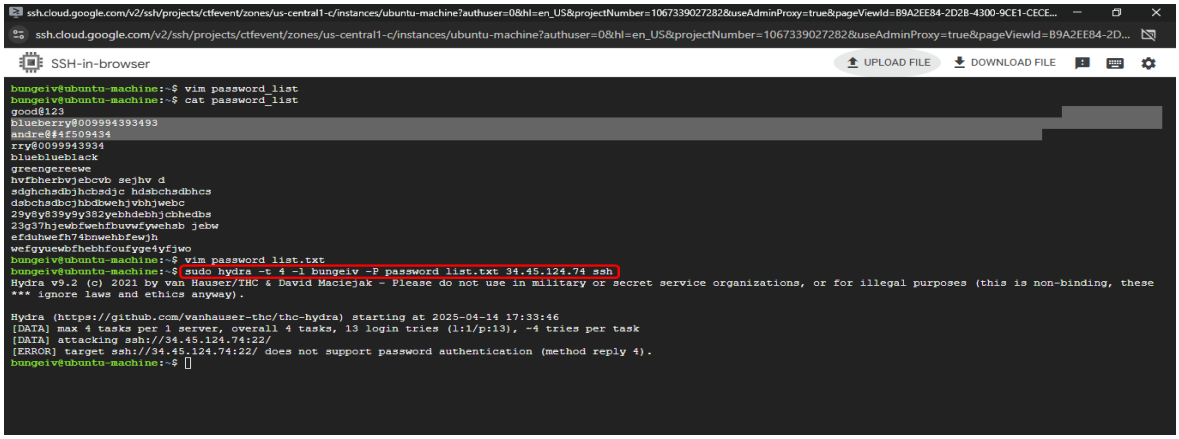


Figure 7: Attacker machine attempts a brute-force attack using hydra

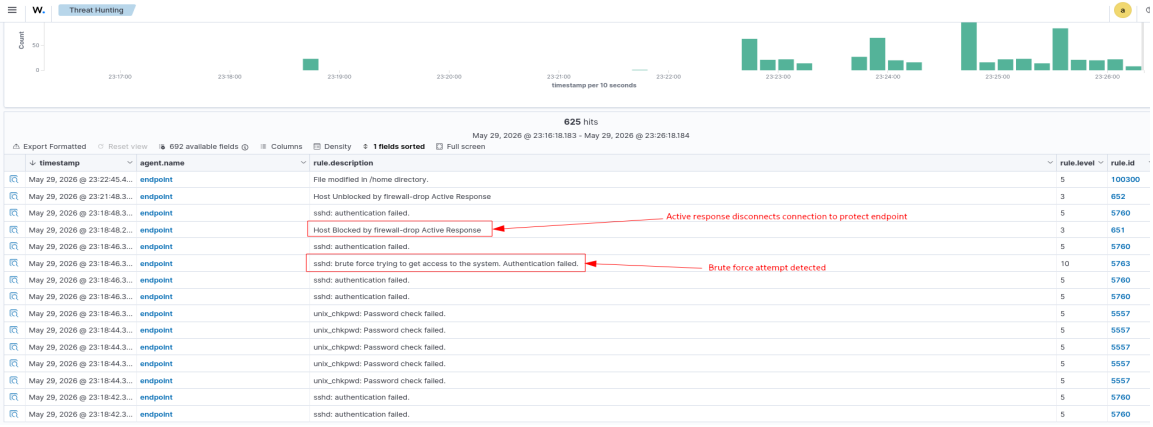


Figure 8: Brute-force attack is detected by Wazuh

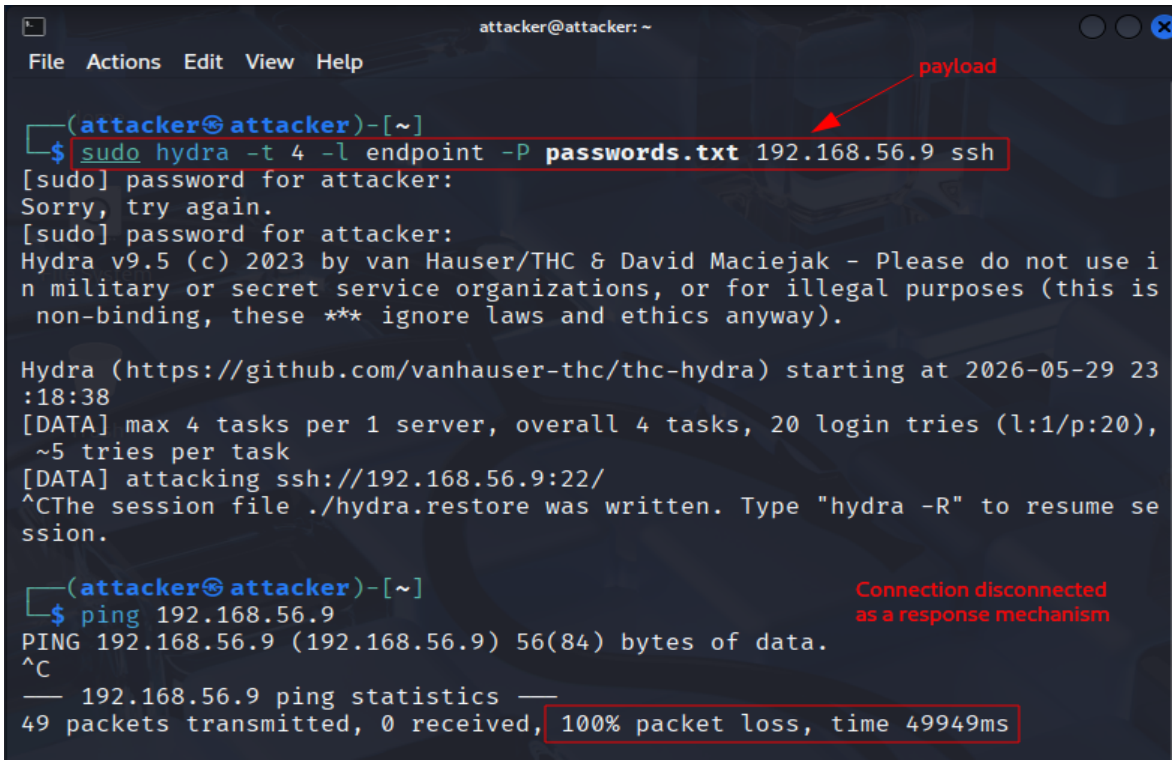


Figure 9: Wazuh responds to attack by disconnecting the connection between attacker machine and victim machine

4.5 Malware Detection

In recent emerging threats, traditional methods that rely solely on signature-based detections fail to capture new threats. Signature-based approaches struggle to detect zero-day attacks, polymorphic malware, and other evasion techniques used by threat actors. As a result, organizations are at risk of undetected data breaches and exfiltration. Having a SIEM in place with malware detection capabilities that not only rely on malware signatures for detection but use heuristics for user and entity behaviour analytics enables organizations to detect and respond to sophisticated and evasive threats effectively.

Our setup integrated threat intelligence sources such as VirusTotal which enabled Wazuh to detect malware in real time and raised alerts when it identified the malicious files by comparing the identified indicators of compromise with the information stored in the CDB lists (constant databases). These lists can store known malware indicators of compromise, including file hashes, IP addresses, and domain names. The screenshots shown in Figure 11 and Figure 12 show the process from the time a malicious file is downloaded to an endpoint to the time it is detected by Wazuh through the VirusTotal Threat intelligence integration.



Figure 11: The malicious file downloaded on the monitored endpoint is detected by Wazuh through VirusTotal threat intelligence integration

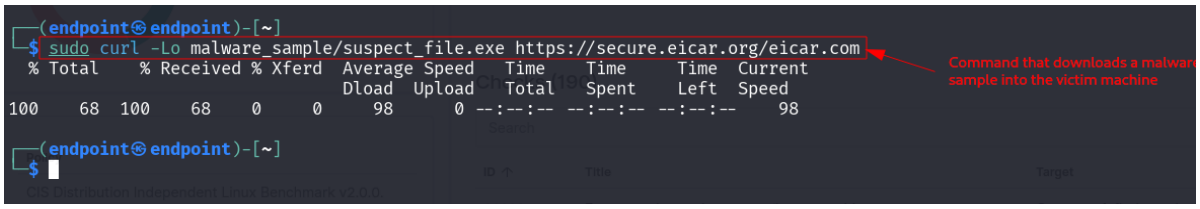


Figure 12: A malicious file is downloaded on the monitored endpoint

Wazuh Manager detected the malware and created an alert of the suspicious executable file as shown in Figure 11. From the alert received on Wazuh we were able to get a link to VirusTotal for this specific malicious file where we checked the threat intelligence sources that reported that it was indeed malicious, as shown on Figure 13.

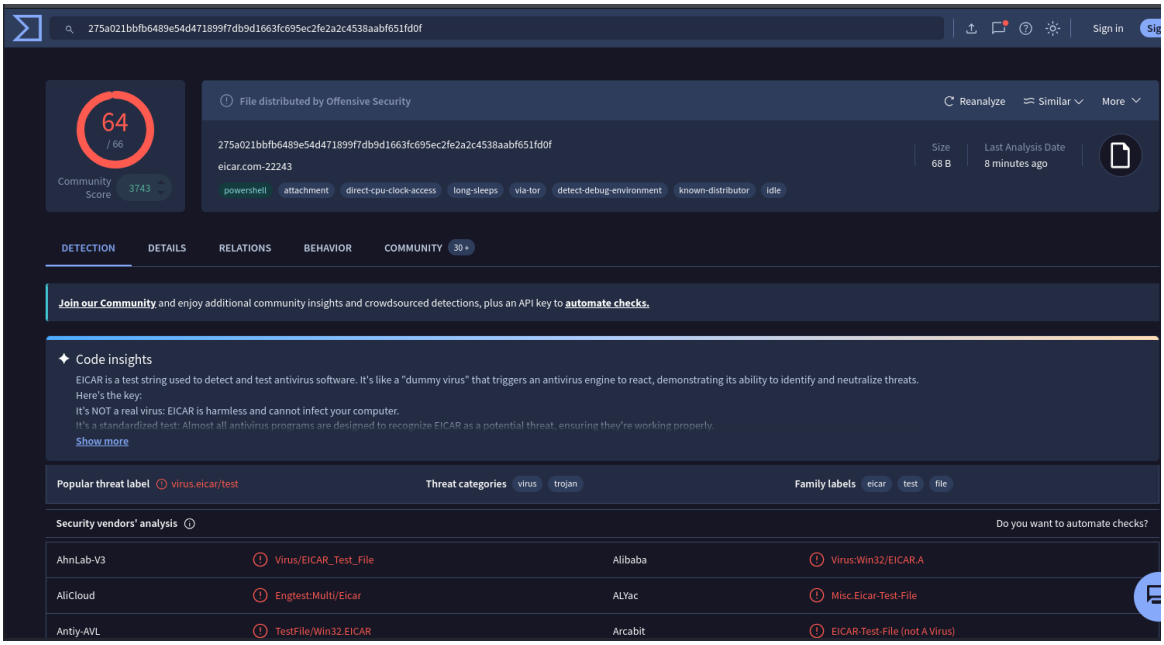


Figure 13: Malware score based on VirusTotal

4.6 Configuration Assessment

Wazuh gave an overview of endpoints based on the operating system running on the endpoint, it then checked this against the Centre for Internet Security benchmark for the specific operating system. This ensured that all endpoints in our experiment were hardened according to the standard.

Wazuh provided a view into the configuration assessment of all endpoints used in our experimental IT infrastructure, as shown in Figure 14. Endpoints are given a percentage score of compliance to the CIS benchmark as well as provide the list of checks that Wazuh ran against the endpoint and the result, making it easier and convenient for system administrators to patch up non-compliant endpoints, ensuring all critical assets are effectively hardened.

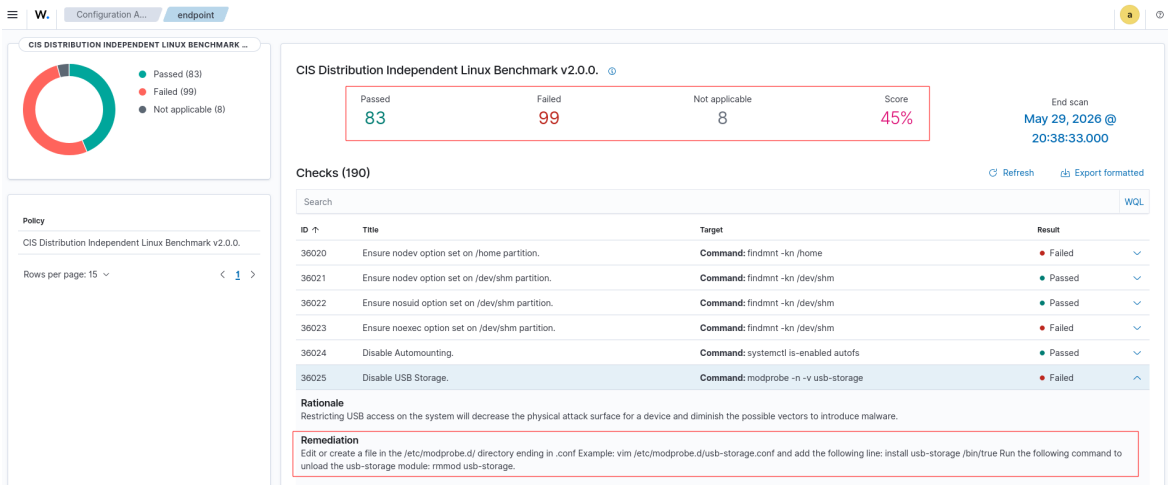


Figure 14: Onboarded endpoints configuration assessment with a score card based on passed and failed checks with recommendations to patch up

4.7 Limitations

Despite providing Extended Detection & Response(XDR) and SIEM capabilities at zero licensing costs, equating the free license with a zero cost or zero risk operation would be detrimental in evaluation of open source solutions. The open-source nature of the platform masks significant architectural, operational and security limitations that shift the burden of platform maturity and scaling efficiency onto the organization. Below are some of the limitations and tradeoffs to consider:

- The platform lacks a built-in load balancing mechanism which would require organization deploying Wazuh at scale to acquire a separate external load balancing solution
- High false positive burden if not properly tuned which necessitates expert level tuning to address false positives which can be time consuming and labor intensive
- Wazuh does not have internal integrity controls over its own alert data. If an attacker gains root access to the Wazuh Manager, logs and alerts can be manipulated. Organizations must implement a compensating control, such as shipping alerts to an immutable storage solution

5. Recommendations

False positives are security alerts incorrectly classified to suggest a threat when there is no threat. This poses a significant challenge in cybersecurity, as alerts often overwhelm security teams, leading to alert fatigue, potentially diverting their attention from detecting and responding to actual threats. Below are some of the recommendations to minimize false positives in your SIEM tool and enhance its effectiveness, as well as boost the productivity of your security team:

- Fine tune SIEM depending on how your IT infrastructure is set up, be it on premise or cloud to minimize false positives.
- Customize SIEM rule sets by enabling only the rules relevant to your environment to reduce noise and focus on genuine threats.
- Set appropriate alert thresholds on SIEM to balance between detecting suspicious activity and avoiding alert fatigue amongst your security teams.
- Use machine learning models for adaptive learning as seen in the evaluation on the use of Large Language Models (LLMs) to classify security alerts with the aim to reduce false positives in a Security Operations Center (J. Roy et al, 2026)

6. Conclusion

In an era defined by decentralized infrastructure and increasingly sophisticated adversarial tactics, a robust SIEM solution is no longer an enterprise luxury, but a strategic necessity for organizations of all sizes. However, the true efficacy of such a system lies not in its deployment alone, but in its customization to unique operational requirements of an organization. When properly tuned, a SIEM provides a vital "360-degree" visibility across hybrid, cloud, and edge environments, effectively bridging the visibility gaps that traditional security perimeters leave behind. By providing real time telemetry and identifying behavioral anomalies, the platform affords security teams the critical lead time necessary to disrupt the attack lifecycle before significant damage occurs.

Crucially, the open-source nature of platforms like Wazuh democratizes high tier security by eliminating the prohibitive licensing fees associated with commercial big data security tools. This accessibility allows small-to-medium businesses which often face the same threats as global corporations but with a fraction of the budget to implement enterprise grade monitoring and compliance frameworks. Furthermore, the integration of automated active response capabilities represents a paradigm shift in incident management. By delegating the mitigation of known commodity threats to automated workflows, organizations can significantly reduce their response time to security incidents. This automation empowers resource constrained security teams to move away from the fatigue of manual triage, allowing them to dedicate their expertise to high-level threat hunting and long-term strategic resilience. Ultimately, by marrying the principles of Zero Trust with the accessible power and customizability of open source monitoring, organizations can transform their security posture from a reactive, fragmented defense into a unified, proactive ecosystem capable of defending the modern digital frontier

Ethical Declaration: Ethical clearance was not required for this research.

AI Declaration: AI was used primarily to rectify grammatical errors and helped to formulate better structured sentences to improve readability.

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The Weaponization of the Marketing Funnel: Adapting Commercial Targeting Strategies for Disinformation Campaigns and Troll Detection

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Abstract: In the era of hybrid warfare, the operational mechanics of troll farms have shifted from random disruption to highly organized campaigns that mirror commercial digital marketing. This paper, grounded in the HYBTRINT project research, investigates how standard marketing strategies—specifically the "marketing funnel"—are weaponized to manipulate the information environment and proposes a technical framework for their detection. The study demonstrates how influence operations guide users from initial sensation to radicalization by exploiting societal "pain points" and creating "dopamine loops" for artificial community validation. To counter these sophisticated strategies, we define a detection framework based on a multimodal scoring system involving linguistic toxicity, reaction latency, and behavioural parameters such as "Activity Consistency". The findings, validated within a controlled experimental "Playground" environment, offer a model for distinguishing between organic engagement and coordinated inauthentic behaviour. The research is supported by an analysis of an experimental asset pool with a cumulative monthly reach exceeding 10 million impressions, providing a statistically significant basis for behavior profiling. This research serves as a basis for developing adaptive monitoring modules for defence and security institutions.

Keywords: Troll account, Troll farm, Troll detection, Disinformation, Marketing, Marketing strategy

1. Introduction

The contemporary information environment has evolved into a sophisticated domain of strategic competition, where cognitive integrity is constantly challenged by coordinated influence operations. In the context of hybrid warfare, the tactics employed by adversarial actors – eferred to as "troll farms" – have undergone a significant paradigm shift. These entities no longer rely solely on primitive, high-volume spamming; instead, they have adopted advanced methodologies pioneered by the digital marketing and advertising industries. Information has become a weapon capable of destabilizing society and undermining trust in democratic institutions faster and more cheaply than conventional military means.

In the current digital landscape, manual monitoring of the information space has become unsustainable due to the sheer volume of data. Human analysts lack the capacity to filter millions of comments in real-time, detect coordinated bot networks, or uncover sophisticated psychological operations without advanced automated aid. The Hybrid Threat Intelligence (HYBTRINT) project responds to this reality by moving beyond manual oversight toward a modular system designed for large-scale data mining and threat identification.

This convergence of propaganda and commercial strategy is most evident in the adaptation of the "marketing funnel". By applying professional audience segmentation, lead generation techniques, and data-driven targeting, influence operations can effectively guide users from initial exposure to fringe narratives toward deep-seated radicalization. This process exploits societal "pain points" such as economic instability, migration, or cultural grievances, transforming them into entry points for psychological manipulation.

While technical capabilities for automated content generation have increased with the advent of Large Language Models (LLMs), the underlying strategic framework remains rooted in human-centric marketing principles. The primary objective of this research is twofold:

1. To provide a theoretical deconstruction of how marketing funnels are re-engineered for disinformation and radicalization purposes.
2. To propose a multidimensional detection framework designed to identify coordinated inauthentic behavior through weighted linguistic and behavioral metrics.

By shifting the focus from individual content pieces to the strategic patterns of a campaign, this paper aims to provide a more robust defense mechanism for security institutions, enabling them to distinguish between organic engagement and professional influence operations.

2. Actors Typology

To effectively detect hybrid threats, it is crucial to distinguish between different types of actors operating within the information space. While the resulting effect – such as the spread of disinformation or societal polarization – may appear identical, their motivations, behavioural patterns, and technical signatures differ fundamentally. The HYBTRINT project defines a triad of actors: the Professional, the Citizen, and the Machine.

Table 1 provides a comparative overview of the identified actors, contrasting the high coordination of "Professional Trolls" and "Bots" with the organic nature of the "Frustrated Citizen." This differentiation is critical for detection, as identifying a professional actor requires sophisticated behavioral analysis (such as monitoring "Managed Attribution") rather than just flagging the linguistic toxicity typical of a frustrated citizen.

A campaign typically begins with a "Professional" seeding a narrative that is artificially inflated by "Bots" to create an illusion of consensus. The ultimate goal is to trigger the "Frustrated Citizen," whose authentic engagement provides a "living shield" of legitimacy that complicates moderation efforts and invites accusations of censorship.

Table 1: Actors Typology Features Comparison

Feature	Professional Troll	Frustrated Citizen	Bots & AI
Primary Motivation	Financial / Ideological (External)	Emotional / Identity-based (Internal)	Algorithmic (Pre-programmed)
Activity Pattern	Regular (Working hours, 8–17)	Irregular (Peak during evenings/weekends)	24/7 or Event-triggered
Content Quality	High (Strategic, Narrative-driven)	Variable (High toxicity, Low grammar)	Repetitive or LLM-generated
Technical Footprint	Managed Attribution (VPN, Proxies)	Single Authenticated Account	Cluster creation, API signatures
Role in Funnel	Seeder / Operator	Amplifier / "Living Shield"	Booster / Metric Inflator
Detection Complexity	High (Requires behavioral analysis)	Low (Linguistic & Toxic analysis)	Medium (Pattern recognition)

2.1 The Professional Troll

This actor operates based on external motivation, typically financial or ideological, and follows a clear hierarchy and strategic assignment. They employ sophisticated "Managed Attribution" infrastructures to manage dozens of fake identities (“sockpuppets”) simultaneously. Their activity mimics standard working hours (e.g., 08:00–17:00) and they cold-bloodedly simulate emotions to provoke a reaction.

2.2 The Frustrated Citizen

Quantitatively the most significant group, these users are not the initiators but rather the "unwitting agents" or amplifiers of disinformation. Their motivation is authentic emotion – fear, anger, or a sense of injustice.

They are characterized by the Dunning-Kruger effect (see Figure 1), where low competence in a field leads to an overestimation of their own knowledge, resulting in aggressive defence of false narratives.

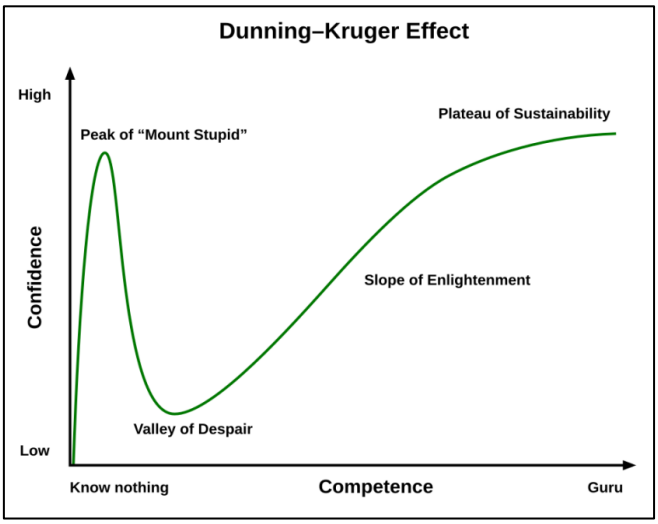


Figure 1:The Dunning-Kruger Effect Graph

2.3 Bots and Automation

These accounts are controlled by software scripts rather than humans. While traditional "Dumb Bots" focus on inflating metrics, modern "Smart Bots" utilize Large Language Models (LLMs) to generate unique content. Their primary detection markers include "superhuman" speed – responding within milliseconds – and 24/7 activity without biological sleep cycles.

3. The Weaponized Marketing Funnel

Modern influence operations have evolved beyond random disinformation; they now represent a sophisticated application of digital marketing and PR procedures. Adversarial actors have "weaponized" methods originally developed for commercial brand building, targeting a citizen's cognitive integrity instead of their consumer behavior. This section explores how the traditional commercial "Customer Journey" is transformed into a systematic process of gradual radicalization.

3.1 Asset Building and Targeting Strategies

In the initial phase, troll farms mirror the activities of marketing agencies by creating "Personas" and profiling vulnerable population segments. To reach these audiences efficiently, attackers utilize low-cost acquisition strategies designed to bypass standard security filters:

- **Bait-and-Switch**: This involves establishing a neutral community (e.g., focused on pets, local history, or nature) to acquire followers at a very low cost-per-result. Once a substantial audience is reached, the page "pivots" its editorial line toward political disinformation.
- **Page Merging and Infrastructure**: Attackers manage multiple smaller thematic pages and subsequently use platform tools to merge them into a single massive entity. This creates an illusion of a large, spontaneous community.
- **Algorithmic Populism**: Content is optimized for conflict. Because social media algorithms prioritize high-emotion engagement (specifically anger), this provides the campaign with massive viral reach without the need for a paid advertising budget.

3.2 Structural Phases of the Radicalization Funnel

The adaptation of the marketing funnel follows a logical progression, guiding a passive reader toward becoming an active, radicalized amplifier. The progression from passive exposure to active amplification is visualized in Figure 2. This process is divided into four key stages:

- **Attract (Awareness)**: The user is exposed to sensationalist headlines or memes designed to trigger an immediate emotional response and "stop the scroll."

- **Inform (Consideration)**: In this phase of "emotional hooking," the user consumes content that offers overly simplistic explanations for complex societal problems, leading to a gradual erosion of trust in mainstream institutions.
- **Convert (Conversion)**: The critical turning point where the user internally adopts the narrative as their own. In this context, conversion is not a purchase, but a shift in attitude or joining a closed, radicalized group.
- **Engage (Loyalty)**: The user becomes an active "Amplifier." They create original content, aggressively defend the narrative against dissent, and become immune to factchecking within a self-reinforcing echo chamber.

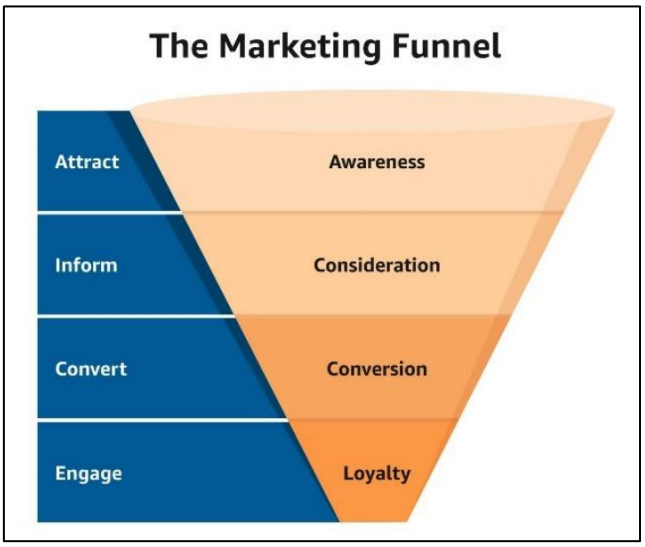


Figure 2: The Marketing Funnel and its Usage for Active Amplification

3.3 Psychological Mechanics: The Dopamine Loop

To ensure the long-term sustainability of the funnel, influence operations leverage the "dopamine loop" of social validation. Professional troll accounts are instructed to provide artificial feedback (likes and supportive comments) to real users who have reached the "Engage" phase. This digital validation provides a sense of belonging and importance. Consequently, the "trained" amplifiers become dependent on this community feedback, eventually forming a self-sustaining ecosystem that requires minimal further intervention from the original attacker.

4. Detection Framework

To counter the sophisticated "weaponized marketing" strategies, the HYBTRINT project defines a multimodal scoring system. Instead of a binary classification, the framework calculates a probability-based risk value, known as the **Hybrid Threat Score (*S*)**. This score is derived from a weighted sum of parameters across three distinct layers: linguistic, behavioral, and platform-specific.

4.1 The Mathematical Model

Each detected parameter (p_i) is assigned a normalized value between 0 and 1. These values are then multiplied by a weight (w_i) reflecting the indicator's severity:

- **Critical (1.0)**: Indicators almost certainly signifying machine behavior or coordinated campaigns (automatic "Red Flag")
- **High (0.7)**: Strong indicators of manipulation requiring cross-verification with other parameters.
- **Medium (0.4)**: Supporting indicators that complete a troll profile when combined with others

The final score is calculated using the following formula:

$$S = \frac{\sum_{i=1}^{n}(w_i \cdot p_i)}{\sum_{i=1}^{n} w_i}$$

Where:

- S: Represents the final **Hybrid Threat Score** within the interval <0, 1>.
- n: The total number of **active detection parameters** evaluated for the specific platform or account.
- w_i: The **weight** assigned to the i-th parameter, reflecting its significance (1.0, 0.7, or 0.4).
- p_i: The **normalized value** of the i-th parameter (<0, 1>), where 0 indicates organic behavior and 1 indicates behavior fully consistent with a threat pattern.

4.2 Detection Layers and Parameters

The detection framework is structured into three distinct analytical layers, each providing a unique perspective on the actor's intent, authenticity, and level of coordination. By combining these layers, the system can identify "Cyborg" accounts—hybrid entities that blend human-like linguistic nuances with machine-like distribution speeds. Given layers, their parameters and weights are summarized in Table 2.

- **Linguistic Layer (NLP Layer):** This layer focuses on the semantic and syntactic properties of the content. Beyond simple keyword matching, it utilizes Natural Language Processing to detect **Toxicity and Sentiment** levels, identifying attempts to exploit societal "pain points" through ad-hominem attacks. The most critical indicator in this layer is **Semantic Duplicity**, which measures the similarity between messages across different accounts. A high similarity score (over 80%) across geographically or socially distant accounts serves as a "Critical" indicator of coordinated "copy-paste" strategies common in professional troll campaigns.
- **Behavioral Layer (Profiling Layer):** This layer shifts the focus from "what" is being said to "how" the actor interacts with the digital environment. It is specifically designed to distinguish between human spontaneity and algorithmic precision. Parameters such as **Reaction Latency**—the time elapsed between a target post's publication and the account's response—are vital. Responses occurring within seconds suggest the use of automated "gaming" of platform algorithms to gain early traction. Furthermore, **Activity Consistency** tracks temporal patterns; a strict adherence to a "working hour" schedule (e.g., 08:00–17:00) reveals a professional operator rather than an organic user.
- **Platform-Specific Layer (Metadata Layer):** This layer utilizes technical footprints unique to individual social networks to uncover hidden infrastructures. For example, on Meta platforms (Facebook/Instagram), a **Follower Spike** that does not correlate with the virality of any specific post is a "Critical" indicator of technical asset building through page merging. Similarly, **Page Renaming** history can reveal a "Bait-and-Switch" operation, where an account originally dedicated to apolitical topics (e.g., "Nature Lovers") is suddenly repurposed for political disinformation.

Table 2: Marketing Techniques and their Technical Vectors

Layer	Parameter	Strategic Link (Marketing/Threat)	Weight
Linguistic	Semantic Duplicity	Test Marketing (Narrative testing/Copy-paste)	Critical
	Toxicity & Sentiment	"Pain Point" exploitation (Rage-baiting)	High
Behavioral	Reaction Latency	Algorithmic Populism (Gaming the algorithm)	Critical
	Activity Consistency	Managed Infrastructure (Scheduling patterns)	High

Layer	Parameter	Strategic Link (Marketing/Threat)	Weight
Platform	Follower Spike	Asset Building (Page merging)	Critical
	Page Renaming	Bait-and-Switch (Content pivot)	High

4.3 Interpretation of Results

The output of the detection mechanism is the Hybrid Threat Score (***S***), a probabilistic value that allows for the efficient prioritization of defensive resources. The weighted approach ensures that a single anomaly (e.g., a user using a single vulgar word) does not trigger a false alarm unless supported by additional behavioral evidence.

- **Safe ($S \in \langle 0.0, 0.3 \rangle$)**: This category includes mostly the organic users. While they may occasionally exhibit high sentiment or frustration, they lack the technical signatures of coordination or automation.
- **Suspicious ($S \in (0.3, 0.7 \rangle$)**: This "Grey Zone" identifies accounts that exhibit significant signs of toxicity or repetitive narrative patterns but lack definitive proof of machine-controlled behavior. These cases are of particular interest for human-AI collaboration; the system flags these profiles for manual validation by security analysts, who can further investigate the nuances of the narrative within the context of the HYBTRINT project.
- **Malicious ($S \in (0.7, 1.0 \rangle$)**: This category is reserved for actors with an overwhelming weighted probability of being professional trolls or automated bots. Profiles in this range exhibit multiple "Critical" indicators, such as near-instant reaction times and high semantic duplicity across known botnet clusters. These results trigger automated reporting and adaptive monitoring modules to mitigate the threat in real-time.

4.4 Illustrative Example of Score Calculation

To demonstrate the practical application of the Hybrid Threat Score (***S***), we present a model calculation for a account labeled **#User-492**, as detected on a microblogging platform. Input data for the illustrative calculation are present in the Table 3.This profile exhibited a mix of high linguistic toxicity and coordination patterns, while maintaining some organic technical characteristics.

Table 3: Input Data for the Illustrative Example of Score Calculation

Parameter (Vector)	Measured Value (p_i)	Weight (w_i)	System Comment
Toxicity (NLP)	0.9	0.7 (High)	Extreme aggression vulgarism
Semantic Duplicity	0.8	1.0 (Critical)	Text matches 15 other accounts
Frequency (Flooding)	0.4	1.0 (Critical)	20 tweets/day (within human limits)
Creation Cluster	0.1	1.0 (Critical)	Registration date is unique
Lack of Solution	1.0	0.4 (Medium)	Purely critical, no constructivity

Final Score Calculation:

$$S = \frac{(0.7 \cdot 0.9) + (1.0 \cdot 0.8) + (1.0 \cdot 0.4) + (1.0 \cdot 0.1) + (0.4 \cdot 1.0)}{0.7 + 1.0 + 1.0 + 1.0 + 0.4}$$

$$S = \frac{0.63 + 0.80 + 0.40 + 0.10 + 0.40}{4.1}$$

$$\boldsymbol{S = \frac{2.33}{4.1} \approx 0.568}$$

Result and Classification: With a final score of **S = 0.57,** the actor is placed in the interval (0.3, 0.7) and classified as **SUSPICIOUS**.

Interpretation: The system did not detect a fully automated bot (due to low frequency and a unique registration date). However, given the high semantic duplicity and toxicity, there is a high probability of a coordinated human actor (Troll) or a "Frustrated Citizen" participating in chain-message campaigns. The profile is sent for manual validation by an analyst.

5. Preliminary Validation: The "Playground" Environment

To validate the theoretical models and the proposed detection framework, the research utilized a controlled testing environment known as the **"Playground"**. This infrastructure serves as a living laboratory for analyzing coordinated behavior, asset accumulation, and the algorithmic response to various narrative types.

5.1 Methodology and Scope

The validation was conducted using a managed portfolio of social media assets specifically curated to simulate the full lifecycle of an influence operation. The primary objective was to empirically verify the **"Asset Building"** and **"Bait-and-Switch"** strategies described in Section III.

- Infrastructure Scale: The experiment monitored a network of pages and profiles that achieved a cumulative monthly reach exceeding 10 million impressions.
- Narrative Testing: The "Playground" utilized a diverse content mix, ranging from low-arousal apolitical topics (nostalgia, local interest) to high-arousal polarizing political narratives.
- Data Collection: Technical footprints, including reaction latency, semantic duplication across clusters, and follower acquisition costs (CPA), were continuously logged to provide a baseline for the detection framework's calibration.

5.2 Algorithmic Amplification and Reach Dynamics

One of the key findings from the Playground experiment is the quantifiable disparity in organic reach between different content categories. This data provides the empirical foundation for **Figure 3** (which can be generated using relative reach metrics).

- **Audience Acquisition (The Bait):** Neutral narratives (e.g., nature photography, historical nostalgia) demonstrated the highest efficiency for low-cost follower acquisition. These "assets" allow attackers to build large, legitimate-looking communities with minimal algorithmic friction or user reports.
- **Narrative Pivoting (The Switch):** Once a critical audience mass was reached, the "pivot" to polarizing content revealed that social media algorithms disproportionately favor high-emotion narratives.
- **Viral Reach Efficiency:** Experimental data shows that **Outrage-based content** (fear and anger) achieves significantly higher organic distribution compared to neutral baseline posts. This algorithmic preference acts as a "force multiplier" for coordinated campaigns, allowing them to achieve massive penetration without advertising spend.

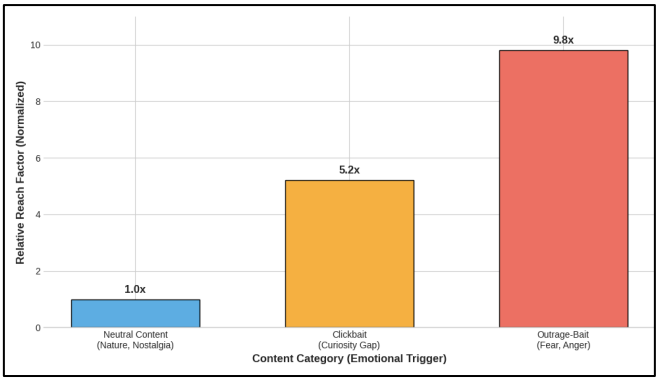


Figure 3: Algorithmic Amplification of Narratives

5.3 Summary of Technical Findings

The preliminary testing within the Playground environment confirmed several critical hypotheses:

- **Low Entry Barrier:** Building a massive, receptive audience is financially and technically accessible, requiring only basic marketing automation tools.
- **Technical Footprinting:** Coordinated clusters exhibited a measurable **"Semantic Duplicity"** and **"Activity Consistency"** that aligned with the Working Hour (8–17) profile of a professional operator.
- **Vulnerability:** Specific demographic segments showed a marked susceptibility to narratives that blend nostalgic sentiment with modern "pain point" exploitation.

6. Conclusion

This paper has demonstrated that modern influence operations have transitioned from sporadic disinformation into a professionalized domain of **weaponized marketing**. By re-engineering the commercial "customer journey" into a systematic radicalization funnel, adversarial actors can efficiently guide users from initial passive exposure to active, self-sustaining amplification.

The empirical data gathered within the **"Playground" environment** confirms the structural vulnerability of current social media landscapes. Our validation shows that while neutral narratives are optimal for low-cost asset building, **outrage-based content achieves nearly 10x (9.8x) the reach efficiency** of baseline information. This confirms that platform algorithms act as unintended force multipliers for coordinated campaigns, providing them with massive, free-of-charge distribution channels.

To counter this, the proposed **Hybrid Threat Score (S)** framework, developed under the HYBTRINT project, shifts the defensive focus from reactive content moderation to proactive behavioral profiling. By integrating linguistic toxicity, reaction latency, and platform-specific metadata into a weighted multimodal system, we provide security institutions with a scalable tool to distinguish between organic engagement and professional manipulation.

The goal of this framework is to provide a baseline for adaptive monitoring modules that can identify and neutralize adversarial infrastructures before they reach the critical phase of societal radicalization.

The research described in this paper was financially supported by the Technology Agency of the Czech Republic (TACR), project No. OZ0102006.

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Reviewing Machine Learning Algorithms for Threat Detection in Cybersecurity

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Abstract: The recent increase in the prevalence and popularity of artificial intelligence in everyday life, such as chat agents like ChatGPT, Claude, and Google Gemini, has led to its incorporation in many fields, cybersecurity notwithstanding. In particular, machine learning, a subset of the artificial intelligence field, has led many researchers to investigate this promising technology as a method to better optimize cybersecurity applications for threat detection. The rise in machine learning comes alongside, and potentially is caused by, an ever-increasing volume of cyberattacks. As attackers have access to more sophisticated tools, using Artificial Intelligence for vectors such as social engineering and automation, cybersecurity specialists are also forced to turn to AI to match the increasing fervor. But are all algorithms created equal? The paper focuses on IEEE-sponsored journals and conferences, identifying keywords like threat detection and machine learning, using studies published within the last year. In doing so, this paper focuses on recent works that relate machine learning to cybersecurity, specifically threat detection models. This survey identifies the types of algorithms used in these applications and how they are implemented. Several baseline algorithms, such as support vector machines, k-nearest-neighbors, and convolutional neural networks, were featured in several works, while others compounded these baseline models into an ensemble algorithm, using various methods. This survey identifies strengths and weaknesses in machine learning threat detection by comparing various researched algorithms and implementations. In doing so, opportunities for future research become apparent, where researchers could attempt to defeat these algorithms or even exploit the algorithm itself to bypass detection. Another avenue for future research involves strengthening the algorithms in areas where they performed poorly by combining models into a new end product or layering them to address specific weaknesses.

Keywords: Cybersecurity, Machine Learning (ML), Artificial Intelligence (AI), Threat detection

1. Introduction

Traditional, rule-based cybersecurity approaches are no longer sufficient to address rapidly evolving cyber threats (S et al. 2025). These threats have swiftly increasing levels of complexity, incorporating Artificial Intelligence (AI) through means such as new zero-day exploits, AI-enhanced Advanced Persistent Threats (APTs), and ransomware. Manikandan, Reddy Onteddu, and Chilimi (2025) expand on this issue, further citing polymorphic malware as a significant cause for concern that can bypass signature-based or rules-based protections. This rise in AI-powered cyber threats has led to a push in demand for similarly capable resources for defense, to which industry research has responded by providing several works investigating the capabilities of, and proposing new AI-based tools for cybersecurity. This work reviews these publications, focusing on threat detection as a subdomain of cybersecurity. By comparing training techniques, utilized models, advantages, and limitations, this work produces a thorough survey of existing literature regarding AI-based threat detection models and provides subjects for future work in the research area.

1.1 Background

AI can be broken down into several subcategories. Most works relating AI to cybersecurity focus on Machine Learning (ML) and Deep Learning (DL). DL is further a subset of ML, where ML describes algorithms that learn from a provided set of data and improve by iterating over that data for increased performance. DL uses the same principles but introduces neural networks, a type of algorithmic model inspired by the human brain, in which various interconnected nodes pass data to one another to improve performance. The surveyed works use a variety of different models that fall into ML and DL, such as Decision Trees (DT), Random Forests (RF), k-Nearest Neighbors (kNN), Gradient Boosting Machines (GBM), and Support Vector Machines (SVM) for ML, while models such as Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Memory Augmented Neural Networks (MANN), Generative Adversarial Networks (GAN), and Long Short Term Memory (LSTM) are DL models. Federated Learning (FL) describes how and where the training is performed, but is not itself a learning algorithm. FL is a learning method where models are partially trained on-site, then the model's improvements are shared with other devices in the learning network to further improve. FL aims to preserve privacy by keeping the data the model trains on internal, preventing unnecessary exposure.

DTs are a classification algorithm that attempts to sort data into the categories provided in the initial training by making binary decisions through various internal steps to sort all data. RFs are an ensemble of DTs, where many DTs are evaluated together to better sort data. kNN is a simple classification algorithm that evaluates which group a datapoint belongs to by looking at the nearest k datapoints, and sorts the new datapoint by choosing the majority of those k datapoints. GBMs are another DT ensemble that aims to evaluate complex relationships within datasets. SVMs are somewhat similar to kNNs as they aim to differentiate between classes using nearby datapoints, but SVMs do so by attempting to find the delimiter that maximizes the space between nodes of different classes.

CNNs are a neural network inspired by neural organization within the visual cortex. CNNs use fully interconnected nodes, and while they typically see use in visual detections, they can be used for anomaly detection in a variety of spaces. RNNs are also fully interlinked, but differentiate themselves from CNNs with an internal memory that the algorithm uses to take information from previous inputs to influence the current evaluation. RNNs are typically used in sequenced information, such as time-oriented data. MANNs also use a memory structure, but MANN memory is external rather than internal. This makes MANNs popular in language processing and reinforcement learning. GANs operate by creating synthetic data from the provided training data. It then uses a discriminator to determine which data is real versus synthetic. These GANs are great at providing additional data for other algorithms to refine themselves on. Lastly, LSTMs are an evolution of the RNN. RNNs struggle to recall long-term dependencies, where LSTMs are specifically designed to counter this loss.

F1-score and inference are the two metrics this work analyzes to gauge performance. F1-score is a zero-to-one scale metric balancing the impact of false positives and false negatives. F1-score is a suitable metric for analyzing cybersecurity models because a false positive indicates the solution would have blocked benign network traffic, reducing usability for clients on the network, and false negatives represent unblocked malicious traffic, both significant impact on a network. Figure 1 below is a graphical representation of this balance. Inference time represents the time it would take a proposed architecture to create an assessment of potentially malicious traffic, an important indicator for real-time solutions.

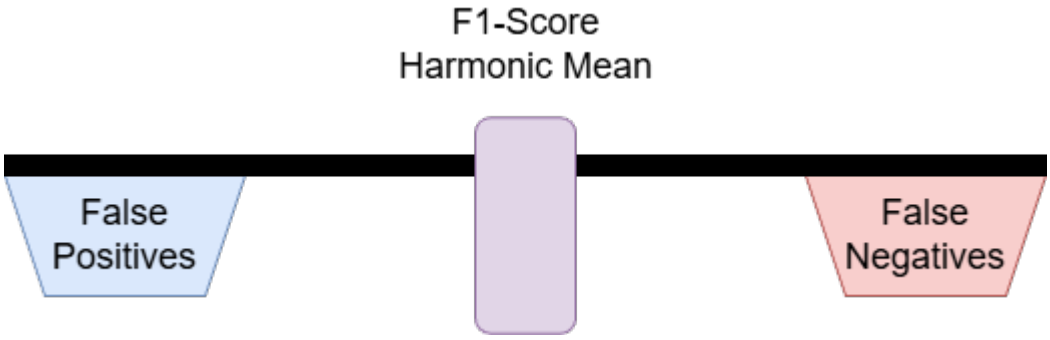


Figure 1: Graphical representation of F1-score. The weights of False Positives and False Negatives are balanced together into the F1-score, representing the harmonic mean of the two. F1-score is often preferred when False Negatives and False Positives are of equal importance

2. Literature Review

This survey reviews several works that introduce a variety of ML and DL models and techniques for cybersecurity. Modern solutions have moved towards more ensemble-based solutions rather than standalone models, and as a result have seen improved performance. Bhuktar et al. (2025) proposes an embedded cybersecurity architecture that uses a CNN-LSTM ensemble model on edge devices for low-cost, distributed computing. These learnings are combined using FL to produce a single comprehensive model. This model is then tested against synthesized data from a GAN, which aims to test system resilience “by generating adversarial scenarios and implementing countermeasures...to handle incipient threats” (Bhuktar et al. 2025). The authors report an F1-score of 98.1% and an inference time of 5.2ms.

Srilakshmi et al. (2025) also investigates Federated CNN-LSTM as an ML-based solution for threat detection. Srilakshmi et al. did not provide an F1-score, but did provide an accuracy score and false positive rate (FPR) of 98.3% and 1.2%, respectively. While the authors additionally provide a detection time metric of 160ms, they do not show their model implementation alongside this latency.

El-Hajj (2025) uses an RF-LSTM ensemble, employing RF for static features and LSTM for temporal features. The authors did not include FL, but recognize it as a target for future work improving privacy protection. El-Hajj

also includes a detailed outline of their real-time integration architecture, serving as a model example for future research to follow and expand upon. The RF-LSTM model produces an F1-score of 98.7% and an inference time of 4.2ms with 12,000 requests per second. El-Hajj goes on to showcase the specific cyber attacks their model performed best on, providing a level of depth not seen elsewhere.

S et al. (2025) proposes a GAN-augmented MANN for their "NeuroShield" model, targeting smart infrastructure and IoT networks. The GAN introduces synthetic data not seen elsewhere, aiming for improved zero-day detection and response. While S et al. provides a figure for false positive rates, it is poorly labeled and thus hard to determine their proposed model's accuracy. They provide an attack success rate, where only 6.1% of attacks intercepted by NeuroShield were successful, but without disclosing the specific attacks used, this figure has little inherent value. NeuroShield also has a response time of 310ms, but the authors do not provide the specifics of their implementation, leaving it hard to compare to other works.

Choudhary et al. (2025) use a four-way ensemble of logistic regression, DT, SVM, and kNN. The ensemble is further improved with a GBM and hyperparameter tuning. While Choudhary et al. does not go in-depth about how they construct their ensemble, they provide an F1-score of ≈91%. Choudhary et al. do not include real-time metrics in their work.

Manikandan, Reddy Onteddu, and Chilimi (2025) researched several standalone models, including SVM, DT, RF, kNN, and CNN. They report a perfect F1-score of 100% for DT and RF, raising concerns of overfitting. kNN has the next-highest F1-score of 99%, but kNN lacks the complexity to appropriately handle complex attacks. While they claim 100,000 malware and benign process sources for their dataset, this information cannot be verified without citations. While Manikandan, Reddy Onteddu, and Chilimi does not analyze a real-time implementation, they do provide relative training times. The authors found that DT and kNN had the fastest training times, claiming this makes them ideal for real-time applications. However, in deployable solutions, all training for non-adaptive models should be done prior to deployment, invalidating this claim.

C S et al. (2025) uses an RF algorithm, chosen out of DT, SVM, and kNN, for RF's ability to handle high dimensionality in the chosen dataset, CICIDS2017. This resulted in an F1-score of 97.5%. Polinati (2025) found CNN among RF, DT, SVM, and RNN to have the highest F1-score at 91.5%, testing on the NSL-KDD and CICIDS2017 datasets. Neither C S et al. nor Polinati provides real-time metrics.

There are also system-specific frameworks for cybersecurity involving ML. Edouard Bouda, Sere, and Ouedraogo (2025) provide one such example by introducing an RF model into an architecture designed to detect malicious DNS requests. Edouard Bouda, Sere, and Ouedraogo achieve this by blending several DNS protection methods together to achieve a F1-score of 99.35% and a processing time of 2.5ms. While this processing time is higher than their other components, the performance improvement justifies the additional overhead.

Other authors have also performed literature reviews in the context of ML-powered cybersecurity. Pandey et al. (2025) reviewed works from 2021 to 2024, finding several challenges in the implementation of ML-based cybersecurity. They end their work by highlighting the importance of transparency and explainability in ML solutions that can keep up with the rapid pace of evolving threats.

3. Comparative Analysis

Section 2 illustrates how Bhuktar et al. (2025) and Srilakshmi et al. (2025) both test CNN-LSTM as a solution for real-time ML-based threat detection. The works have similar figures for accuracy, but Srilakshmi et al. does not show additional statistics like F1-score, precision, or recall as in Bhuktar et al. Furthermore, Srilakshmi et al. has a much higher detection time at 160ms, whereas Bhuktar et al. boasts a 5.2ms inference time. However, direct comparisons between the two works are difficult because Srilakshmi et al. does not provide their implementation architecture, which would provide valuable insights into where the extra delay in inference/detection stems from.

As compared to Bhuktar et al. (2025) and Srilakshmi et al. (2025) using an FL-powered CNN-LSTM, El-Hajj (2025) uses an RF-LSTM model without FL, although it is noted as a topic in their future work. El-Hajj outperformed Bhuktar et al. and Srilakshmi et al. by about 0.5% in F1-score and about 1ms in inference time. Without knowing the architecture of Srilakshmi et al., time comparisons are difficult to evaluate accurately.

S et al. (2025) is difficult to contextually evaluate due to a lack of provided metrics like F1-score. S et al. reported a successful defense rate of 93.9% and a response time of 310ms, but without knowing the specifics of their attack makeup and network architecture, true comparative analysis is difficult.

The last surveyed ensemble model, Choudhary et al. (2025) reported a 91.28% F1-score and a 7.7% error rate. This significantly underperforms compared to El-Hajj (2025), Bhuktar et al. (2025), and Srilakshmi et al. (2025). This could indicate the power of LSTM for network traffic because of its highly temporal nature, as that is the common factor between El-Hajj, Bhuktar et al., and Srilakshmi et al.

Of the standalone models researched by Manikandan, Reddy Onteddu, and Chilimi (2025), C S et al. (2025), and Polinati (2025), only Manikandan, Reddy Onteddu, and Chilimi reported an F1-score higher than those of ensemble counterparts at 100% for DT and RF models. However, a perfect score raises concerns of overfitting the models to the source dataset and reducing their general usability. The next highest F1-score was C S et al. with a RF at 97.5%, still less than that of ensemble models. While Manikandan, Reddy Onteddu, and Chilimi reports a training time statistic for their researched models, this is irrelevant for real-time response, as all training should be done before deployment.

All ensemble models outperformed work done via standalone models a la Manikandan, Reddy Onteddu, and Chilimi, C S et al., and Polinati versus works done by El-Hajj, S et al., Bhuktar et al., and Choudhary et al. There is, however, an exception in Edouard Bouda, Sere, and Ouedraogo (2025) with their DNS-specific implementation of a single-model ML algorithm. For this work, however, it is important to note that the ML component is augmenting non-ML solutions and is not the whole solution in and of itself. Even still, this application may be made even stronger by implementing an ensemble model in place of a single RF. Table 1 below collates these results for easy viewing.

Table 1: Comparison between research done by surveyed literature

Author & Year	Title	Model	Metrics	Summary
Bhuktar et al., 2025	Real-Time Cyber Threats... using Embedded AI	CNN-LSTM w/ FL	98.1% F1-score, FPR 1.6%. Inf. time 5.2 ms	Embedded system for RT threat detection.
Srilakshmi et al., 2025	Real-Time IoT Cybersecurity... to Train Generative Robots	CNN-LSTM w/ FL	98.3% accuracy, FPR 1.2%. 160 ms response	Uses GenAI robots to automate security and threat responses in real-time.
El-Hajj, 2025	AI-Powered Threat Detection and Response...	RF-LSTM	98.7% F1-score. Avg latency 4.2 ms, 12,000 rqs/sec.	Hybrid framework for RT-IDS. RF-LSTM deployed with Apache Kafka and TensorRT.
S et al., 2025	Neural Cybersecurity... Deep Learning for Real-Time Threat Detection	MANN, DRL	310 ms response, firewalls 1250 ms, other AI 740 ms. 93.9\% defense, 61.3\% baseline.	Self-supervised deep learning, Cyber Swarm Intelligence, Quantum-Secure AI Encryption
Choudhary et al., 2025	AI-Driven Threat Simulation in Wireless Networks...	4-way ensemble	91.28% F1-score. and 7.7% error	Verbose ensemble w/ XGBoost, hyperparameter optimization
Manikandan et al., 2025	Next-Gen Malware Detection using AI...	DT, RF, KNN, CNN	Near-100%% acc. for DT, RF, & KNN. DT & KNN fastest, CNN 97.79% acc., costly	Feature engineering for critical information, testing on a large dataset of 100,000 samples
C S et al., 2025	AI Driven Threat Detection... using Machine Learning Techniques	RF, DT, SVM, KNN	RF 97.5% F1-score	Highly robust, effective ident. of Botnet, DDoS, and Heartbleed. Trained and tested using CIC-IDS2017.
Polinati, 2025	AI and Deep Learning-Powered Threat Intelligence	RF, DT, SVM, CNN, RNN	CNN, 93.7\% accuracy, 91.5\% F1-score. $<$2s response w/ automated response system.	Evaluates RF, DT, SVM, CNN, and RNN on datasets like NSL-KDD and CICIDS 2017.
Edouard Bouda et al., 2025	Improved Domain Name System Threat Detection	DGA + RF, RPZ + DGA + AI	DGA + RF 99.94\% accuracy, 98.81\% precision. RPZ + DGA + AI 100\% recall. 2.5ms overhead	Combines RPZ, DGA, and RF classifier for malicious DNS requests.
Pandey et al., 2025	AI-Powered Defenses: A Machine Learning Approaches...	---	---	Highlights data privacy, “black box”, vulnerable models. Hybrid models, FL for future works.Review of ML in cybersecurity. Surveys model's ability to detect various threats.

4. Challenges and Limitations

Several challenges come with pushing ML into cybersecurity. Notably, reliance on a limited number of benchmarks and integration into real-time response units. S et al. (2025) even directly mentions these weaknesses, additionally citing real-time detection and explainability as barriers to successful applications. Few current, usable benchmarks for training and developing ML tools for cybersecurity exist; Four of the cited works use CICIDS-2017, a network traffic benchmark with benign and malicious data. A further three use KDD-Cup 1999, another network traffic benchmark, while Edouard Bouda, Sere, and Ouedraogo use a DNS-specific dataset of malicious domain names. The remaining two works do not cite their datasets at all, casting doubt on their sources. The limited number of benchmarks restricts research in the area, potentially leading to stagnation. Introducing new, relevant datasets and benchmarks, or showing how the existing sources are still relevant, could help alleviate this issue.

Additionally, many ML applications are often perceived as a "black box" as described in Pandey et al. (2025), with a heavily obscured decision-making process that makes it difficult for an end-user to trust the reported outcome fully. For critical security applications, this lack of transparency makes trusting the model's decision-making, even if the model is highly accurate, difficult. This challenge cannot be easily solved within existing models. Instead, breakthroughs in explainable AI are required to handle this issue.

5. Trend and Future Directions

As shown in C S et al. (2025), El-Hajj (2025), Srilakshmi et al. (2025), Bhuktar et al. (2025), and Choudhary et al.

(2025), FL shows extreme promise for reducing the cost of training through a distributed architecture and for privacy-preserving training. This double-benefit makes FL a must-implement in all future ML models for cybersecurity, as the distributed architecture allows for continuous training without mass downtime for computationally expensive traditional training.

Given the performance gap between standalone models and ensemble models, except for novel research producing a new model, there remains little to be gained by implementing single models for ML-based cybersecurity solutions. Future works in this field should focus on how to best hybridize various models to cover individual weaknesses, and then how to implement these models into a realistic architecture to limit latency and network overhead caused by introducing the model.

Lastly, researchers should pursue explainable AI to address the explainability and trust issues described in Pandey et al. (2025). Without addressing the "black box" issue, cybersecurity specialists may never trust ML models, regardless of their performance. This trust barrier will inherently reduce the effectiveness of any solution and place additional strain on those cybersecurity specialists.

6. Conclusion

This paper surveyed recent literature on implementing ML algorithms in cybersecurity, particularly studying threat detection. Through this survey, it compared recent publications within the last year. Each researched work was measured against the others, comparing models, training techniques, and performance metrics. Ensemble models generally outperform standalone ML models, highlighting how combining different models together helps to overcome their individual weaknesses. In particular, the DL model LSTM showed high promise for analyzing network traffic because of its affinity for temporal data. FL also emerged as a critical training method, offering many benefits in preserving data privacy and enabling continuous training through a distributed architecture.

This work also identified various challenges in this field, such as a limited number of dated benchmarks and the opaque nature of the decision-making process in many ML applications. This "black box" decision-making makes it difficult to trust these applications and may hinder deployment. For future research, works should prioritize model hybridization to create new ensembles, testing different combinations to determine their effectiveness. Research should also focus on real-time architectures to limit latency and overhead while also supporting a rapid response time. Lastly, improving the transparency and explainability of these models is paramount for ensuring a smooth integration into deployable environments.

Disclaimer: The views expressed are those of the author and do not reflect the official policy or position of the US Air Force, Department of Defense, or the US Government.

Ethics Declaration: This work required no ethical clearance.

AI Declaration: This work did not use any AI tools in its creation.

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Strengthening Analytical Competence in (Cyber) Intelligence

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Abstract: Sweden's intelligence education system lacks the technical-domain competence required to meet the analytical demands of contemporary cyber intelligence. This finding emerges from a diagnostic analysis of eleven international intelligence education programmes using the Intelligence Competence Framework (ICF), which combines a multi-level analytical structure (strategic, operational, tactical) with the domain classification (technical, formal, informal) of the Systemic-Holistic Approach. When applied to the programmes referenced by Sweden's government inquiry on intelligence reform (SOU 2025:78), the framework reveals that formal and informal domains receive strong coverage across all programmes while the technical domain is systematically underarticulated — particularly at the tactical level, where only one of eleven programmes achieves strong coverage. Three interdependent capability requirements emerge from an analysis of SOU 2025:78, five international programme models (the German BND, the Danish MICS, the French DIReM, the ICE CIADM module, and the Norwegian Etteretningsskolen), consultations with Swedish intelligence practitioners, and contemporary analyses of AI-supported intelligence (NSCAI, Snow Globe, Emergent Intelligence). Organisationally, the proposed intelligence academy requires a professional authority function that sets competence standards across the intelligence community rather than delivering education alone. Educationally, programmes that integrate technical content with professional practice through apprenticeship models, twin-track specialisations, and practitioner-led instruction produce broader competence coverage than purely academic programmes. Technologically, baseline digital literacy encompassing data provenance, tool limitations, and AI-assisted analytical workflows must be treated as a structural requirement in curriculum design rather than as an optional specialisation. The practitioner consultations identified three specific capability gaps in the current Swedish system: OSINT training that moves beyond keyword searching, exposure to AI-assisted analytical workflows before operational deployment, and secure technical environments for realistic practice. A Swedish intelligence academy built on existing European models will inherit the same technical-domain deficit unless technical competence is embedded as a design principle from the outset.

Keywords: (Cyber) intelligence, Competence development, Intelligence education, Offensive cyberspace operations, Open-source intelligence, Systemic-holistic approach

1. Introduction

Sweden's security environment is marked by persistent cyber intrusions, foreign intelligence activity, and organised influence operations. The deteriorating threat environment — including the limitations revealed by the intelligence assessment of Russia's political intent prior to the 2022 invasion of Ukraine — created the policy impetus for a comprehensive review of Sweden's intelligence system. The resulting government inquiry, *En reformerad underrättelseverksamhet* (SOU 2025:78), proposes the establishment of a new civilian foreign intelligence agency, restructured oversight mechanisms, and a joint education platform with the long-term objective of an intelligence academy developed in Nordic cooperation.

The inquiry identifies competence development as a strategic priority. It proposes that the Swedish Defence University (FHS) develop a research-based training platform for the intelligence and security services. However, while the inquiry articulates what the intelligence system should achieve at a strategic level, it does not specify what competence intelligence professionals need in order to work effectively within the technical systems through which intelligence is collected, processed, and disseminated. The gap between strategic ambition and tactical competence specification is the problem this article addresses.

A diagnostic analysis using the Intelligence Competence Framework (ICF) — which combines the Multi-Level, Multi-Dimensional (MLMD) framework with Yngström's (1996) Systemic-Holistic Approach (SHA) — reveals an asymmetry in the technical domain of European intelligence education programmes (Huskaj and Axelsson, 2026). This distributional pattern mirrors, in reverse, the finding of Björck and Yngström (2000) that information security research concentrated 83 per cent of its output in the technical domain while neglecting the formal and informal domains.

The question this article addresses is: *what organisational, educational, and technological capabilities are required to build national competence in (cyber) intelligence for Sweden?* The article draws on SOU 2025:78, international intelligence education models, consultations with practitioners in the Swedish intelligence community conducted during the development of the intelligence academy concept, and contemporary

analyses of AI-supported intelligence. The article is structured as follows. Section 2 provides the theoretical framework, and Section 3 describes the method and sources. Section 4 presents the results, organised around three capability domains. Section 5 discusses the implications for Sweden's emerging reform agenda. Section 6 concludes.

2. Theoretical Framework

Intelligence education operates across multiple disciplines and institutional contexts. Mapping this landscape requires an analytical framework that can identify where competence is concentrated and where it is absent. Two prior efforts provide the foundation. Coulthart and Crosston (2015) mapped 17 American intelligence programmes and identified significant curricular variation in the absence of accreditation standards. Ramsay and Macpherson (2024) examined 28 U.S. graduate programmes and found that only 25 per cent offered classes across all seven educational categories defined by the International Association for Intelligence Education. Both studies demonstrate that intelligence education develops unevenly — but neither provides a multi-dimensional framework that distinguishes between technical, formal, and informal competence domains.

The Intelligence Competence Framework (ICF) addresses this gap. The ICF combines two analytical traditions. The first is the Multi-Level, Multi-Dimensional (MLMD) framework, developed in the author's doctoral research and formalised in the forthcoming monograph *Organizing for Cyber Power* (Huskaj, forthcoming). The MLMD framework structures analysis across three levels — strategic, operational, and tactical — and integrates deterrence theory, intelligence theory, and the theory of offensive cyberspace operations. The second tradition is the Systemic-Holistic Approach (SHA), developed by Yngström (1996) for information security education. The SHA classifies competence into three domains: technical, formal, and informal. Björck and Yngström (2000) applied this classification to 125 papers from the IFIP SEC 2000 conference and found that 83 per cent concentrated in the technical domain while only 14 per cent addressed the formal domain and 3 per cent the informal domain.

The ICF combines the MLMD's three levels with the SHA's three domains to produce a 3×3 diagnostic matrix (Table 1).

Table 1: The Intelligence Competence Framework (adapted from Huskaj and Axelsson, 2026).

Level / Domain	Technical Domain	Formal Domain	Informal Domain
Strategic	National analytic infrastructures; system reliability and timeliness; performance constraints shaping strategic feasibility.	Mandates, oversight, classification, disclosure rules; authority conditions shaping signalling and deterrence posture.	Leadership risk posture; escalation norms; credibility expectations influencing strategic judgement.
Operational	Data integration, analytic tooling, secure workflows; feedback loops linking tasking, collection, analysis, and dissemination.	Tasking structures, governance routines, resource prioritisation; institutional coupling between intelligence output and planning.	Coordination routines, incentives, trust, organisational friction; communication norms shaping analytic consistency.
Tactical	System mapping, data provenance, tool limitations, error modes; time-sensitive interpretation of technical artefacts.	Handling constraints, dissemination boundaries, authorisation rules; operational compliance under time pressure.	Tradecraft norms; bias mitigation; judgement under uncertainty and temporal constraint.

Each cell represents a specific competence intersection — for example, the tactical-technical cell represents the competence required when intelligence professionals interact with technical systems under operational conditions. When applied to eleven international intelligence education programmes referenced by SOU 2025:78, the ICF reveals a structural asymmetry that is the inverse of the Björck and Yngström finding. The formal domain receives strong coverage in 76 per cent of possible cells across the matrix. The informal domain receives strong coverage in 73 per cent. The technical domain receives strong coverage in only 18 per cent. Technical-domain coverage weakens at each successive level, from 2 of 11 programmes at the strategic level to 1 of 11 at the tactical level (Huskaj and Axelsson, 2026). This diagnostic finding establishes the empirical starting point for the prescriptive analysis that follows.

Recent European intelligence education scholarship describes the same landscape from different analytical perspectives. Dylan et al. (2017) document how the Norwegian Intelligence School merged professional training with academic standards through four academic modules on the historical, functional, structural, and decision-maker dimensions of intelligence. Berger et al. (2025) present the ICE Cyber Intelligence and Data-Driven Decision Support module as the German effort to integrate IT capability into European intelligence education, arguing that data science and digitisation must become integral to curriculum design. Gruszczak (2025) analyses ICE through institutional isomorphism and concludes that its contribution operates through cultural diffusion at the strategic-informal level. These perspectives align with the ICF finding: European intelligence education is well-developed in the formal and informal domains, and technical-domain competence is the area where scholarly and institutional attention is most actively being requested.

3. Method

The article employs a structured-focused comparison (George and Bennett, 2005) of international intelligence education models to extract transferable design principles for a Swedish intelligence academy. The comparison is structured by a consistent analytical framework — the Intelligence Competence Framework (ICF) — and focused on a specific research question: what capabilities are required to build national competence in (cyber) intelligence.

The analysis draws on four source categories. The first source is Sweden's government inquiry on intelligence reform (SOU 2025:78), which provides the policy context, the institutional proposals, and the competence requirements articulated by the inquiry. The second source is the programme descriptions of five international intelligence education programmes that score most broadly in the technical domain of the ICF: the German Bundesnachrichtendienst (BND) training pathways, the Danish Master of Intelligence and Cyber Studies (MICS), the French Diplôme inter-universitaire Renseignement et Menaces (DIReM) at Sciences Po Saint-Germain-en-Laye, the Intelligence College in Europe (ICE) Cyber Intelligence module (CIADM), and the Norwegian Intelligence School (Etteretningsskolen). These programmes were selected because they address the technical domain more extensively than the academic programmes in the dataset.

The third source is consultations with practitioners in the Swedish intelligence community, conducted during the development of a concept note for the proposed intelligence academy in 2025–2026. These consultations involved professionals from the Swedish Armed Forces, the Swedish Defence University, Stockholm University, and affiliated research institutions. The consultations were informal and unstructured, conducted under conditions of professional confidentiality. They do not constitute formal interviews and no individual statements are attributed. However, the patterns that emerged from these consultations inform the identification of capability requirements in Section 4. No ethical clearance was required because the consultations did not constitute formal interviews and no individual statements were attributed.

The fourth source comprises contemporary analyses of AI-supported intelligence, including the final report of the U.S. National Security Commission on Artificial Intelligence (NSCAI, 2021), the CIA's Snow Globe experiment in human-AI teaming (Brennan et al., 2025), and the "Emergent Intelligence" assessment of intelligence work in the AI era (Studies in Intelligence, 2025). These sources identify the technological transformation that shapes the competence requirements the article examines.

In accordance with the principles of transparent and reproducible science, the author used Anthropic's Claude Opus 4.6 as a research assistant during the preparation of this article. The tool was used to support structured literature screening, to verify coding consistency, and to assist with formatting during drafting. All analytical judgements were made by the author. The author assumes full responsibility for the accuracy of all claims and any errors that remain.

4. Results

The results are organised around three interdependent capability domains: organisational, educational, and technological. Each domain addresses a dimension of the research question and draws on the international models and practitioner consultations described in Section 2.

4.1 Organisational Capabilities

The Norwegian Intelligence School (Etteretningsskolen) provides the clearest model for the organisational function that a Swedish intelligence academy would need to perform. The school exercises *fagmyndighet* — professional authority — for intelligence on behalf of the Chief of the Norwegian Intelligence Service (Dylan et

al., 2017). This institutional function means that the school does not merely teach intelligence; it defines what intelligence competence means for the entire Norwegian Defence. It sets unified competence requirements, issues and revises intelligence doctrine, and advises on capability projects related to intelligence.

This distinction between teaching and standard-setting is the central organisational insight from the international comparison. SOU 2025:78 proposes that FHS develop a joint education platform. However, the inquiry does not assign the platform a professional authority function equivalent to the Norwegian model. Without such a function, the platform risks becoming a course catalogue rather than a competence architecture. The consultations with Swedish practitioners confirmed this concern: multiple interlocutors identified the absence of a single institution with the authority to define competence requirements across the intelligence community as a structural gap in the current system.

The Intelligence College in Europe (ICE) demonstrates a different organisational model. ICE operates as a platform for professional and academic exchange rather than a degree-granting institution (Gruszczak, 2025). Its contribution is cultural diffusion at the strategic-informal level: building a common strategic intelligence culture across European member states. ICE's 28-country membership, 89 affiliated intelligence agencies, and 33-institution academic network provide a horizontal cooperation structure. However, ICE does not deliver structured technical training and does not exercise professional authority over competence standards. For Sweden, ICE's model is relevant as a networking and cultural exchange mechanism but insufficient as the primary vehicle for technical competence development.

The BND's organisational model reflects a third approach: service-internal training that integrates education with operational practice. The BND offers three distinct training pathways — a general intelligence apprenticeship, a SIGINT apprenticeship, and a physical security apprenticeship — each combining theoretical instruction with practical placements across departments. This model ensures that competence development is directly governed by the operational requirements of the service. The BND's breadth across the ICF matrix reflects its institutional character as a system that trains for the full range of intelligence functions. The trade-off is that service-internal models are not designed to serve a broader national intelligence community.

The organisational capability requirement for Sweden is therefore a hybrid: a professional authority function that sets competence standards for the entire intelligence community (the Norwegian model), combined with structured cooperation with operational services that grounds education in professional practice (the BND principle), and connected to international networks for strategic culture development (the ICE function). SOU 2025:78's proposal for a Council for Intelligence Research and Education could serve as the governance mechanism for this hybrid model, provided it is given the authority to define competence requirements and not only to coordinate existing offerings.

The consultations with Swedish practitioners reinforced the need for a multi-institutional collaboration model. No single institution possesses the full range of capabilities required. The Swedish Defence University holds the defence education mandate and proximity to the intelligence community but lacks depth in AI and data science. Stockholm University's Department of Computer and Systems Sciences leads in data science, AI, and decision support but operates outside the security-cleared environment. The Swedish Defence Research Agency (FOI) conducts applied research in intelligence-relevant domains but does not deliver degree programmes. Lund University has cultivated Sweden's most sustained tradition in intelligence analysis but its institutional capacity in this area is concentrated in a small number of senior scholars.

Thus, the discussions revealed that an inclusive model — one that draws on each institution's specific strengths under a coordinating governance structure — is the only architecture that can meet the breadth of competence requirements. As one respondent observed, the priority must be to ensure that no existing knowledge or competence is lost in the transition to a new institutional structure. This observation carries particular urgency given that several of Sweden's most experienced intelligence scholars are approaching or have passed retirement. The intelligence academy is therefore not only a forward-looking construction project but also a preservation mechanism for competence that currently exists in individuals rather than in institutions.

4.2 Educational Capabilities

The diagnostic analysis using the ICF confirms that the technical domain is the weakest across the eleven programmes, with the formal and informal domains receiving strong coverage in the majority of cells (Huskaj and Axelsson, 2026). The three programmes that score most broadly across the technical column — BND,

MICS, and DIReM — share a common design principle: each integrates technical content with professional practice rather than treating technology as a separate academic subject.

The Danish MICS programme provides the most relevant Nordic model for educational design. MICS is a joint programme between the Danish Defence University and the University of Southern Denmark, explicitly addressing the cyber domain in a security-political context. The programme includes twin specialisation tracks — intelligence and cyber — and builds competence through practice-oriented expertise combined with an analytical track. MICS is designed for personnel with experience from the intelligence or cyber domain. This twin-track model ensures that technical competence is developed alongside strategic and analytical competence rather than in isolation.

The French DIReM at Sciences Po Saint-Germain-en-Laye offers a different educational model: practitioner-led instruction within a broader analytical framework. The *veille et analyse des données* module develops practitioner competence in geolocation, imagery verification, and structured open-source techniques alongside political and sociological perspectives. Practitioner lecturers from the DGSI, DGSE, and armed forces contribute to instruction in the security-cleared environment of the Académie du renseignement. DIReM's strength is the integration of technical methods with legal and sociological analysis.

The ICE CIADM module, developed by Berger et al. (2025) for the German Master of Intelligence and Security Studies (MISS) and adapted for ICE delivery, provides a five-day curriculum model addressing cyber intelligence and data-driven decision support. The module covers cyber intelligence concepts, threat assessment, AI-based analytical tools, operational analysis, and horizon scanning. It combines critical reflection with a problem-solving focus, targeting intelligence practitioners at an earlier career stage. The module demonstrates that structured technical content can be delivered in a compact format within an international, multi-agency setting.

The educational capability requirement is a structured progression from strategic understanding through operational application to tactical proficiency. SOU 2025:78 proposes a joint education platform but does not articulate what this progression should contain. The international models suggest that the progression should include: strategic-level courses on how technology reshapes the intelligence enterprise (following the MICS model); operational-level modules on AI-supported analytical workflows, OSINT tool proficiency, and data-fusion methods (following the DIReM and CIADM models); and tactical-level training through practical placements in technical departments where analysts interact with collection systems under operational conditions (following the BND model).

The practitioner consultations also identified a governance dimension to educational design. Multiple respondents noted that Sweden currently lacks a mechanism for coordinating intelligence education across institutions. Courses are developed and delivered by individual departments — at FHS, at DSV, at Lund, at FOI — without a shared framework for ensuring that the aggregate output meets the intelligence community's competence requirements. The proposed Council for Intelligence Research and Education (SOU 2025:78) could address this gap if it is empowered to commission education based on identified competence needs rather than to merely catalogue existing offerings. The consultations suggested that a steering function — analogous to a curriculum board with representation from the intelligence services, academia, and the research institutes — would be necessary to translate the competence requirements identified through the ICF into specific course designs, practicum placements, and assessment criteria.

4.3 Technological Capabilities

The NSCAI (2021) report identifies AI competence as a national security requirement and argues that the United States must prepare the intelligence workforce for a future in which AI augments human analytical capacity. The Snow Globe experiment demonstrated that participants with greater prior digital experience used AI assistants more systematically and critically, suggesting that baseline digital literacy shapes the quality of human-AI interaction in intelligence settings (Brennan et al., 2025). The "Emergent Intelligence" assessment identifies the competence intersection where intelligence professionals interact with AI tools as the baseline requirement for the next generation of intelligence work (Studies in Intelligence, 2025).

The MI6 chief's first public address emphasised that in a "faster, more dangerous and technology-mediated world," the rediscovery of human agency alongside technological capability will determine how the future unfolds (Metreweli, 2025). This framing positions technical competence not as a replacement for human judgement but as a precondition for its effective exercise. Intelligence professionals who do not understand how AI tools generate their outputs cannot exercise meaningful judgement over those outputs.

The consultations with Swedish practitioners identified three specific technological capability gaps. First, the absence of structured OSINT training that moves beyond keyword searching to encompass geolocation, reverse image search, social media pattern analysis, and data provenance verification. Second, the lack of exposure to AI-assisted analytical workflows — including the limitations and failure modes of machine learning systems — before analysts encounter these tools in operational settings. Third, the absence of secure technical environments where analysts can practise with realistic data without compromising operational security.

SOU 2025:78 identifies cloud-based data processing, AI, and cross-domain integration as priority capability areas. However, the inquiry describes what technology should achieve for the intelligence system at a strategic level. It does not specify what competence intelligence professionals need in order to work effectively within such systems. The technological capability requirement is therefore not about acquiring specific tools but about developing the analytical competence to evaluate, use, and critically assess the outputs of technical systems. This competence includes understanding data provenance, recognising tool limitations, identifying system error modes, and making time-sensitive judgements about technical artefacts.

The Geneva Centre for Security Policy's (GCSP) Global Cyber and Security Policy Programme demonstrates that a holistic, systems-based, and comprehensive approach to cyber and security policy challenges is already in operation internationally (GCSP, 2024). The programme integrates training and executive education, dialogue and outreach, and security policy-relevant research into a systemic architecture. This model provides evidence that the prescriptive framework proposed here — integrating organisational, educational, and technological capabilities — is operationally viable.

5. Discussion

The answer to the research question — what organisational, educational, and technological capabilities are required to build national competence in (cyber) intelligence for Sweden? — is that the three capability domains are interdependent and must be developed in parallel. Organisational authority without educational content produces empty mandates. Educational programmes without organisational authority produce competent individuals who return to institutions that do not recognise their competence. Technical training without organisational integration produces specialists who cannot connect their skills to the intelligence mission.

5.1 The Technical-domain Deficit as a Design Problem

The diagnostic analysis (Huskaj and Axelsson, 2026) reveals that the technical domain receives strong coverage in 18 per cent of possible cells across eleven European programmes, compared to 76 per cent for the formal domain and 73 per cent for the informal domain. The ratio — approximately 1:4 — quantifies the structural asymmetry. This is not a failure of individual programmes. It is a systemic pattern that reflects how intelligence education has historically been structured: around policy, law, governance, and professional culture rather than around technical systems and their analytical exploitation.

For Sweden, this pattern has a specific policy implication. SOU 2025:78 references the eleven programmes analysed in the diagnostic study as benchmarks for the proposed intelligence academy. If the academy is designed by replicating the educational patterns of these benchmarks, it will inherit the same distributional asymmetry. The technical domain will remain the weakest area of competence — precisely the domain that the NSCAI, Snow Globe, and Emergent Intelligence assessments identify as the most urgent requirement.

The Swedish public debate on SOU 2025:78 has focused on organisational structure rather than competence. Critics have warned that the proposed reform risks defence capability, is badly timed, and centralises too much (Wiktorin, 2025). The Must chief has responded that the intelligence services have sufficient work for all agencies and that broadening the intelligence service is necessary (Nilsson, 2026). Both sides of the debate accept that analytical competence must be strengthened. The disagreement is about how to organise the institutional architecture, not about the competence requirement itself. This article contributes to the uncontested ground: specifying what competence is needed and how it should be structured.

5.2 Design Principles for the Intelligence Academy

Five design principles emerge from the analysis. First, the academy should exercise a professional authority function that defines competence requirements for the entire intelligence community, following the Norwegian fagmyndighet model. This function should include the authority to issue intelligence education doctrine and to certify that competence requirements are met.

Second, the academy should integrate technical content with professional practice through structured practical placements in operational services. The BND model demonstrates that this integration produces graduates with both academic qualifications and operational competence. For Sweden, this implies formal cooperation agreements between the academy and the intelligence services that provide placements in technical departments.

Third, the academy should offer twin-track specialisations that link cyber intelligence with strategic analysis, following the MICS model. This design ensures that technical specialists understand the strategic context of their work and that strategic analysts understand the capabilities and limitations of the technical systems that produce the intelligence they assess.

Fourth, OSINT tool training should be embedded within a broader analytical framework that includes legal, ethical, and sociological perspectives, following the DIReM model. The consultations with Swedish practitioners identified OSINT as the area where the gap between existing competence and operational requirement is widest. The DIReM model demonstrates that OSINT proficiency can be developed alongside policy and legal analysis rather than as a standalone technical course.

Fifth, the academy should establish a secure technical environment — a laboratory or testbed — where analysts can practise with realistic data and AI-assisted tools without compromising operational security. This requirement emerged consistently in the practitioner consultations and is consistent with the broader NSCAI emphasis on preparing the intelligence workforce for AI-augmented analytical work.

5.3 Nordic Cooperation and NATO Integration

SOU 2025:78 articulates a long-term vision of an intelligence academy developed in Nordic cooperation. The Norwegian Etteretningsskolen already collaborates with King's College London for master-level education. The Danish MICS is a joint programme between a military and a civilian university. ICE provides a European platform. Sweden's NATO membership, effective since 2024, generates new requirements for the interoperability of intelligence cooperation. An intelligence academy that meets NATO's competence standards while maintaining the Nordic tradition of combining profession and academe (Dylan et al., 2017) would position Sweden as a contributor to collective intelligence capability rather than a consumer.

The Berger et al. (2025) analysis of the ICE experience demonstrates that European intelligence education benefits from combining the critical reflection of academic programmes with the problem-solving focus of practitioner training. The German MISS and the ICE CIADM module exemplify this combination. For Sweden, the implication is that the proposed academy should be designed to both receive and contribute modules to the ICE network, ensuring that Swedish intelligence education is integrated into the European landscape from the outset.

5.4 The Governance gap Between Mandate and Capacity

The practitioner consultations identified a structural tension that SOU 2025:78 does not fully resolve. FHS has been assigned the mandate to develop the joint education platform. However, the technical capacity required to deliver AI-enabled analytical training, data science instruction, and secure laboratory environments does not reside at FHS. It resides at DSV/SU, at FOI, at RISE, and within the intelligence services themselves. The mandate and the capacity are located in different institutions. Without a governance mechanism that bridges this gap, the mandate risks remaining unfulfilled — or fulfilled in a manner that replicates the formal-domain concentration of existing programmes because FHS's institutional strengths lie in precisely that domain.

The Norwegian model resolves this tension through the fagmyndighet function: the Etteretningsskolen both defines competence requirements and delivers education, with external academic partners contributing to specific programmes. The Danish model resolves it through joint institutional design: MICS is formally a programme of two universities, one military and one civilian. For Sweden, neither model can be directly transplanted. The Swedish intelligence community is larger and more institutionally fragmented than Norway's, and the proposed academy must serve multiple agencies rather than a single service.

A fuller picture of the governance gap requires acknowledging the Swedish institutional structures that already operate in the adjacent space. Campus Totalförsvar is a strategic collaboration led by FHS, Örebro University, and Luleå University of Technology, launched in 2024 with thirty million SEK in government funding to strengthen Sweden's total defence through coordinated education and research across more than thirty participating higher education institutions (Campus Totalförsvar, 2024). Cybercampus Sweden, inaugurated at KTH in 2024 with over one hundred million SEK in government funding, is a national initiative led by KTH, RISE,

the Swedish Armed Forces, Karlstad University, Saab, Ericsson, and MCF (formerly MSB) to deliver research, innovation, and education for cybersecurity and defence beyond what individual organisations can achieve alone (Cybercampus Sweden, 2024). Both initiatives address parts of the competence terrain that a Swedish intelligence academy would also need to cover.

Campus Totalförsvar organises research and educational activities across the civil-military spectrum of total defence. Cybercampus Sweden builds national capacity in cyber security and cyber defence, including through the CDIS collaboration between KTH, the Swedish Armed Forces, FOI, FRA, FHS, and MCF. The proposed intelligence academy cannot be designed in isolation from these structures. Two governance implications follow. First, the academy's technical-domain competence requirements should be specified in coordination with Cybercampus Sweden rather than developed in parallel — the technical capacity for cyber intelligence training already exists in the Cybercampus network, and duplication would be institutionally wasteful. Second, Campus Totalförsvar provides an existing coordination architecture that the intelligence academy could integrate with rather than replicate. The technical-domain deficit identified in European intelligence education programmes is not a gap in Swedish technical capacity as such — it is a gap in the institutional connection between Swedish technical capacity and the intelligence application domain.

The governance requirement is therefore a coordinating authority that can commission research and education from multiple institutions, ensure that the aggregate output covers all cells of the ICF matrix, articulate the intelligence academy's relationship with Campus Totalförsvar and Cybercampus Sweden, and monitor whether the technical-domain deficit is being addressed over time.

6. Conclusion

The answer to the research question — what organisational, educational, and technological capabilities are required to build national competence in (cyber) intelligence for Sweden? — is that the three capability domains are interdependent and must be developed in parallel. A professional authority function is required to set competence standards across the intelligence community. An educational progression from strategic understanding through operational application to tactical proficiency is required to populate the technical domain that existing programmes underarticulate. Baseline digital literacy — encompassing data provenance, tool limitations, and AI-assisted analytical workflows — must be treated as a structural requirement in curriculum design.

The five design principles identified in this article — professional authority, practice-integrated education, twin-track specialisation, embedded OSINT training, and secure technical environments — provide a framework for translating the diagnostic finding into institutional design. Without structured attention to the technical domain, a Swedish intelligence academy built on existing European models will inherit the same distributional asymmetry that characterises the field. The Intelligence Competence Framework provides the diagnostic instrument for monitoring whether future curriculum design addresses this challenge.

Acknowledgements

The author gratefully acknowledges the foundational work of Prof Emerita Louise Yngström and Dr Fredrik Blix (formerly Björck) on the Systemic-Holistic Approach and the SEC 2000 classification, which this article adapts for intelligence education.

AI Declaration: The first author used Anthropic's Claude Opus 4.6 as a research assistant during the preparation of this article. The tool was used to support structured literature screening, to verify coding consistency across programme descriptions, and to assist with formatting and style calibration during drafting. All analytical judgements — including the design of the framework, the interpretation of findings, and the formulation of design principles — were made by the author. The author assumes full responsibility for the accuracy of all claims and any errors that remain in the published text.

Ethics Declaration: The research did not require ethical clearance under the Swedish Ethical Review Act (2003:460). No personal data were processed and no statements in the paper are attributed to identifiable individuals.

Disclaimer: The views expressed in this paper are solely those of the authors and do not necessarily reflect the official policies or positions of the Geneva Centre for Security Policy, or Stockholm University. The analysis and conclusions are presented for academic and policy discussion purposes only.

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Cyber Warfare, Cyberbullying and Psychological Warfare: Ethical and Anticipated Ethical Issues

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Abstract: This analysis takes as its starting point the view that ideas that originate in the civilian arena can migrate to the area of warfare and cyber warfare. The central idea is that distinctions that apply for cyberbullying can be applied to issues in cyber warfare. The analysis addresses the escalation of individual-level psychological warfare exhibited in cyberbullying to the level of psychological warfare in cyber warfare by analyzing the intersection of social engineering and algorithmic vulnerabilities. It is in this way that cyberbullying is related to cyber warfare. This discussion employs a method that draws upon distinctions taken from computer science, conceptual ethical analysis and case studies. Utilizing case studies from the domain of cyberbullying, this analysis examines four distinct incidents involving Tyler Clementi, Amanda Todd, Jay Taylor and Elijah Heacock. Cyberbullying represents a form of psychological operation that can also operate in cyberwarfare because it weaponizes digital communications to manipulate emotions, erode morale, and destabilize individuals and groups. The goal of the analysis is to identify the evolution of threat modalities related to psychological warfare involving cyber bullying from unauthorized webcams to AI powered velocity sextortion and gamified harassment groups, to the domain of cyber warfare. The cyberbullying cases are analyzed through the lens of Anticipatory Ethics, which is ethical analysis focused on developing technologies, specifically highlighting the failure of social media platforms to uphold the "Sociotechnical Imperative" and the "Post-Deployment Mandate." To mitigate against human factor risks associated with psychological warfare and cyberbullying and cyber warfare, various defensive AI frameworks can be implemented: Behavioral Graph AI to break grooming funnels, Stylometric Analysis to prevent ban evasion and Acoustic Coercion Analysis to detect the real-time sources of psychological distress. This research, employing analysis and definitions of standard concepts from cyberbullying and Cyberwarfare, concludes that proactive, AI driven detection grounded in ethical analysis and the ACM Code of Ethics is essential for securing the safety of the human element in digital infrastructure. Future analysis will explore more directly how cyber bullying is being employed in cyber warfare.

Keywords: Cyber warfare, Psychological operations, Cyberbullying, Anticipatory ethics, Artificial intelligence, Sextortion

1. Introduction

In the modern digital landscape, the distinction between individual level cyber harassment and state sponsored information warfare has grown increasingly less clear. While traditional definitions of bullying emphasize physical intimidation, violence and verbal abuse within a confined physical space, cyberbullying represents a fundamental shift in the manner and space within which aggression takes place. It is defined as "willful and repeated harm inflicted through the use of computers, cell phones, and other electronic devices." (Kresic, 2020) However, when analyzed through the lens of cybersecurity studies cyberbullying is revealed to be a form of psychological operation (PSYOP). Like military PSYOPS cyberbullying weaponizes digital communication to manipulate emotions, degrade morale, and destabilize the psychological state of targeted individuals.

The importance of addressing the issue of cyberbullying is complimented by the escalation of cyberbullying's reach and the ubiquity of digital aggression. Statistics indicate that 1 in 6 school aged children now experience cyberbullying (WHO, 2024). Unlike schoolyard bullying which ends when the victim returns home, cyberbullying is unique in three distinct ways: anonymity, perpetrators can hide behind screens; permanence, digital footprints are hard to erase; and reach, which grants aggressors 24/7 access to their victims.

This analysis investigates the evolution of these threatening characteristics of cyber bullying through four seminal case studies: Tyler Clementi, Amanda Todd, Jay Taylor, and Elijah Heacock. These cases provide a technological trajectory that exhibits how methods from cyber bullying can be applied to cyber warfare from simple hardware misuse to complex, AI-powered attacks. The following cyber bullying cases give examples of techniques that can be adapted to cyber warfare.

- Tyler Clementi (2010) represents the era of unauthorized surveillance and privacy violation.
- Amanda Todd (2012) demonstrates the weaponization of persistence and cross-platform harassment.
- Jay Taylor (2022) marks the shift towards "gamified harassment," where organized groups like "764" treat human suffering as a scored competition.

- Elijah Heacock (2025) shows the emergence of "velocity sextortion," where perpetrators use AI tools to enable professional criminal organizations to execute sextortion scripts in under 45 minutes.

This paper analyzes these incidents through the lens of Anticipatory Ethics and the application of the ACM Code of Ethics, arguing that social media platforms have failed to uphold the "Sociotechnical Imperative" – the obligation for developers to consider the social systems in which their artifacts are embedded (Miller et al., 2011). Furthermore, it proposes that the only feasible defense against this form of psychological warfare is the implementation of defensive AI frameworks. Key defensive frameworks include Stylometric Analysis and Acoustic Coercion Analysis, which aim at detecting and intercepting threats before psychological damage to intended targets becomes permanent.

2. Technical Issues

Understanding cyberbullying as a type of psychological warfare requires an understanding of the technology that facilitates it. The core technical issue lies in the misuse of consumer-grade technology. Everyday devices and platforms, designed for connecting people, are repeatedly weaponized for unauthorized surveillance while allowing for the amplification of harassment.

In the case of Tyler Clementi, the technology was a standard webcam. Webcams are intended for video communication, yet this technology was repurposed to allow for the unauthorized surveillance of a private, intimate act. This represents a failure of physical privacy controls in the digital age. In the case of Amanda Todd, social media served as the "amplification engine" for digital harassment. Social media platforms make abuse public permanent, and inescapable, violating the victim's human right to dignity. These same distinctions can apply to cyber warfare.

However, as we move towards the more recent cases of Taylor and Heacock, technology has evolved and become much more sophisticated. The threat landscape for cyber bullying is now defined by the introduction of the hierarchy of Artificial Intelligence:

1. Artificial Intelligence (AI): The broad science of building machines that mimic human intelligence.
2. Machine Learning (ML): Systems that learn from data without explicit programming.
3. Generative AI (GAI): The specific subset of AI is used to create new content.

Generative AI has introduced a new avenue of "velocity" to psychological warfare.

In the Heacock case, predators utilized AI tools to generate sexually explicit fake images of the victim. This lowers the barrier of entry for sextortionists, they no longer require real images, they can simply generate fake ones. Fake images can also be created for use in the context of cyber warfare The rapid advance of technology requires a shift in ethical analysis from reactive judgement to Anticipatory Ethics, which focuses on the study of the development of technological artifacts and how they will develop and work in the future.

3. Ethical Issues

To understand these ethical issues, we introduce distinctions developed by Furrow. As Furrow states, ethics is related to evaluating actions, and actions are performed by those capable of being moral agents. As Furrow says, "When we evaluate an action, we can focus on various dimensions of the action. We can evaluate the person who is acting, the intention or motive of the person acting, the nature of the act itself, or the consequences." (Furrow, 2005) A moral agent can justify their intentions, actions and outcomes produced by actions by referring to ethical principles. The themes discussed below revolve around how the widespread use of techniques of cyberbullying can easily be extended into the domain of psychological warfare and cyberwarfare. This ethical analysis applies standard ethical frameworks to the three primary stakeholder groups: the victims, the perpetrators, and the platforms.

The ethical defense of the victims is grounded in Kantian Deontology and Rights Ethics. In the case of Tyler Clementi, under Kantian Deontology categorical imperative 1, morality is derived from universal duties. Clementi had the right to be treated with dignity and privacy. This holds for victims of cyber bullying. This duty was also violated along with ACM Principle 1.6: *Respect Privacy.* The case of Amanda Todd can be viewed through Rights Ethics, which focuses on fundamental human rights. Todd possessed the rights to security of person and freedom from degrading treatment (Alabama Policy Institute, 2020). The ruthless digital harassment directed at her violated these rights, violating ACM Principle 1.1: *Contribute to society and human well-being*. The dual cases of Elija Heacock and Jay Taylor invoke the 'Vulnerability Principle' which dictates that special ethical care is owed to vulnerable populations, such as minors. Due to his age Heacock was unable to discern that he was interacting

with professional criminals and a professional script. Furthermore, the Sanctity of Life principle argues that life itself has inherent value. The "764" group, an international online network involved in child exploitation, coercion, and extremist activities, violated this principle by treating Jay Taylor's life as a "toy" to be broken for amusement. This is a violation of ACM Principle 1.2: *Avoid Harm*.

The intentions and ethical failures of the perpetrators of cyber bullying reveal the psychological warfare mindset. In the Tyler Clementi case, Dhuran Ravi's actions can be analyzed as a flawed application of Act Utilitarianism. He performed a distorted analysis related to the greater good, where the amusement of his Twitter followers was weighed more heavily than the harm to Clementi. Like the professional/organized cases of the "764" Network and Sextortion Rings: these actors operate under Ethical Egoism and Nihilistic Hedonism. They reject all moral principles in favor of experiencing immediate pleasure from causing pain to victims. Leaders of the "764" group, such as "Felix" or "Rabid," engaged in Predatory Pragmatism, a criminalized form of efficiency where the victim is dehumanized by treating victims according to a "conversion rate." In this situation, "conversion rate" has become a sanitized corporate metric that has been manipulated for measuring the percentage of targeted participants under the legal age that have been successfully coerced into producing explicit content or committing acts of harm against themselves; thus dehumanizing a person's life into only two values: successful or unsuccessful. This represents a complete rejection of ACM Principle 1.3: *Be honest and trustworthy.*

In these cases, social media platforms (Twitter/X, Meta, Discord) bear significant ethical responsibility for actions performed on their platforms. When analyzing Twitter (now X) which failed to have checks in place to prevent the broadcasting of non-consensual intimate footage in the Clementi case, they violated Virtue Ethics. This is also a failure of ACM Principle 3.7: *Recognize and take care of systems that become integrated into society.* Facebook (now Meta) failed to apply the ethical principle entitled Duty of Care. In the Todd case they failed to connect 22 different aliases to a single user (Coban) quickly enough to stop the cyber stalking that occurred in the case. There was a lack of recognition of product Liability among all the platforms, algorithms such as "People You May Know" often facilitate the initial connection between a predator and a minor. This failure to evaluate the risk of the algorithm violates ACM Principle 2.5: *Give comprehensive evaluations of computer systems and their risks.*

4. AI in Cyber Warfare Context

Before conducting an analysis of specific cases, it is important to contextualize the role of AI in cyber bullying to AI applied to cyber warfare. This paper analyzes AI in the context of Human-Targeting Operations. The convergence of AI and cyberbullying have created what security experts refer to as Automated Social Engineering Environment (Seymour & Tully, 2016). Traditional bullying required human efforts such as typing messages, finding photos, engaging in verbal abuse. AI automates these activities using three tactics: Deep Learning Surveillance, AI algorithms now curate the "targets" for bullies by identifying vulnerable users through sentiment analysis of their posts (Ferrara et al., 2016). Generative Adversarial Networks (GANs), as seen in the Heacock case, GANs can generate realistic images that never actually existed, which creates "evidence" for blackmail where none previously existed. LLM-Driven Psyops, here Large Language Models can now conduct conversations with thousands of victims simultaneously. These models can follow a specialized "sextortion script" optimized for maximized psychological expression. These tactics move cyberbullying from being a social issue to the level of being an example of a technological weapons system.

5. Case 1: Tyler Clementi (2010)

Tyler Clementi, a freshman at Rutgers University became the target of a localized surveillance operation by his roommate Dharun Ravi. On September 19, 2010, Ravi used a remote desktop application to activate the webcam from his friend's room. Ravi used the webcam in his shared dorm with Clementi, to spy on him engaging in an intimate act with another man. Ravi broadcasted this stream and subsequently announced the violation on Twitter, inviting others to watch a planned second attempt.

Surveillance and Exposure as defined in the lexicon of cyber warfare applies to this case, because the incident represents an Insider threat utilizing Unauthorized Surveillance. The webcam, a trusted node in the room's digital environment, was repurposed to act as a sensor. The psychological impact on Clementi was the destruction of his "Sanctuary," an important concept in psychological resilience. By proving that Clementi's most private moments were subject to public observation, Ravi successfully executed an Information Dominance operation. The humiliation related to the surveillance of a private act was related to the act itself and to the

broadcasting of the act. Through the lens of cyber warfare this could be perceived to be the dissemination of 'intelligence' to a hostile audience.

The technical failure is the lack of Hardware-Level Privacy Controls. The webcam software did not provide a distinct and undeniable indicator (hard-wired LED or shutter) that could indicate that the webcam was active and recording. From the perspective of ethics, this was a failure of the Sociotechnical Imperative -- as defined by Miller et al. (2011). This imperative requires creators of technology to anticipate the social context of the use of the technology. The designers of the webcam and the remote software did not anticipate that they would be used for voyeurism in a shared living space. Tyler Clementi died by suicide on September 22, 2010, a direct result of Ravi's information operation.

6. Case 2: Amanda Todd (2012)

Amanda Todd's case demonstrates the weaponization of Persistence. At age 15, Todd was coerced into exposing herself on a webcam by a predator, Aydin Coban. Unlike the Clementi case, which was a specific event, this was a sustained campaign of attrition. Coban utilized 22 different aliases to harass Todd across Facebook, YouTube, and other platforms. When Todd blocked one account, Coban immediately engaged with another attack vector on another platform. When she changed schools, Coban utilized Open-Source Intelligence (OSINT) tactics to locate her new peer group and distributed the explicit images to them.

Coban used the tactics of Attrition and Swarming. These tactics mirror Swarming in military doctrine, an attack from multiple directions designed to overwhelm the target's defenses. By using multiple accounts, Coban created the illusion of a mob despite the attacks being the product of a single actor. The goal was Psychological Attrition: wearing down the victim's will to resist over time. The "safe zones" (new schools and profiles) were systematically breached, creating a state of "learned helplessness" within the victim.

The technical and ethical failures here lay in Identity Management and the Post-Deployment Mandate. Platforms like Facebook had deployed "blocking" tools, but they were ineffective against a determined attacker using "Sybil attacks" (creating many fake identities). The platforms failed to monitor the artifact's effects post-deployment. These shortcomings materialized in the failure to recognize that a ban on an email address alone is insufficient in a cyberbullying/cyberwarfare context. Amanda Todd committed suicide in 2012, succumbing to attrition.

7. Case 3: Jay Taylor (2022)

The Jay Taylor case introduces the concept of Gamified Warfare into the domain of cyberbullying. Taylor, aged 13, was targeted by a recruiter for a gaming server who befriended him. He was then coerced into performing degrading acts on livestream. The perpetrators were members of the "764" network, an online group that "gamified' abuse. Members of this network earned points and status ("clout") based on how far they could push their targeted victims.

In a Cyber Warfare context, the predators used Dehumanization and C2 Structures. The "764" network operates like a decentralized paramilitary group. They utilize Encrypted Command and Control (C2) channels (specifically private channels in Discord servers) to coordinate attacks. The use of gamification in this context serves two purposes: it incentivizes attackers and desensitizes them to the suffering of their victims. This technique in psychology is known as Operant Conditioning. This is indistinguishable from the dehumanization training used to prepare soldiers for kinetic warfare. In the Jay Taylor case, the victim of the attack was no longer viewed as being human; predators have an objective of capturing and destroying a victim for a high score.

This case highlights the danger of Encrypted Enclaves. The "764" network operated in "invite only servers" where platform moderation bots couldn't scan for content. This violated ACM Principle 2.9: *Design and implement systems that are robustly and usably secure.* The platforms failed to detect the Behavioral Signature of the grooming funnel, which involved the movement of a minor from a public gaming lobby (Roblox) to a high risk encrypted private server. Jay Taylor's death was broadcast live, a final act of Propaganda of the deed by the aggressors.

8. Case 4: Elija Heacock (2025)

The death of Elijah Heacock represents the arrival of AI-Automated Kinetic Effects. In 2025, 16-year-old Elijah was contacted by a predator on social media. Unlike previous eras where compromising photos had to be stolen or coerced, the predator used Generative AI tools to fabricate fake explicit images of Elijah using just a photo of

his face. The predator then threatened to release the deep-faked images unless paid. The entire interaction lasted less than 45 minutes from the first "Hello" to Elijah's suicide (WHAS11 Staff, 2023).

In the context of Cyber Warfare this parallels what is referred to as Hyperwar (Velocity) in future warfare studies. Hyperwar refers to conflicts conducted at machine speed, faster than the reaction time of human cognition. The Heacock case is a civilian instance of Hyperwar. The sextortion ring used automated scripts and AI generation to execute the "OODA Loop" (Observe, Orient, Decide, Act) faster than Elijah could process the threat. The Velocity of the attack was the primary weapon employed in the attack. The victim was cajoled into a state of panic (a "cognitive siege") so rapidly that he could not seek help.

This highlights the failure of Foreseeability of Effect (Rule 1) from Miller et al. (2011), according to which the developers are morally responsible. The developers of the Generative AI tools failed to anticipate that their software could be used to manufacture non-consensual pornography involving minors (Tiku, 2022). Technically, the social platforms failed to detect the "Velocity signature"—the rapid escalation of a conversation from a new contact to high pressure demands within minutes.

9. Anticipatory Ethics

Anticipatory Ethics is a future oriented ethical framework that studies potential ethical issues that arise from new and emerging technologies before they are fully integrated into society. As defined by Phillip Brey, Anticipatory Technology Ethics (ATE) requires that we move beyond reactive judgements about the effects of technologies after an event has occurred to a proactive forecasting of the dangers that these technologies pose. This section analyzes the failure of social media platforms to apply basic Anticipatory Ethical analysis to their technologies. These failures lead to the Collingridge Dilemma: (Collingridge, 1980) the problem where impacts cannot be easily predicted until the technology is extensively developed, at which point control becomes exceedingly difficult.

The Prediction Problem and Uncertainty: The central challenge in Anticipatory Ethics is the "Problem of Uncertainty." In the development of the webcam (Clementi case) or Generative AI (Heacock case), developers typically argue they cannot foresee malicious use of their technology. However, Brey argues that ethical forecasting must include "Dark Scenarios." Dark Scenarios specifically model how a bad actor would abuse the system. In the case of generative AI, the "Dark Scenario" of non-consensual deepfakes was not a bug, it was a foreseeable capability involving the misuse of the technology distributed with the built-in ability to manipulate reality. By failing to anticipate this, developers allowed the technology to reach the "entrenched" phase of the Collingridge Dilemma. The entrenched phase is where technology is widely available and impossible to fully recall.

We apply the rules of "Moral Responsibility for Computing Artifacts" (Miller et al.) to bridge the gap between technical design and ethical obligations. According to Rule 4: The Sociotechnical Imperative: This rule states that "People who design, develop, or deploy a computing artifact can do so responsibly only when they make a reasonable effort to take into account the sociotechnical systems in which the artifact is embedded." (Miller et al., 2011). In the case of Clementi, webcam designers failed to apply the Sociotechnical Imperative. The developers designed the camera for a sterile "communication" context, ignoring the "dorm room" sociotechnical context where privacy is not always a given. A responsible design would have included a hardware-level shutter that physically blocks the lens, making remote activation impossible. Rule 2: The Post-Deployment Mandate: This rule asserts that "A person's responsibility includes being answerable for the behaviors of the artifact and for the artifact's effects after deployment." (Miller et al., 2011). In the Amanda Todd case, platforms such as Facebook failed this mandate. They deployed primitive "blocking" features that were functional but insufficient, therefore useless against a "swarming" attacker with multiple accounts. The mandate requires the platform to monitor the effect of the tool (did the harassment stop?), not just the function of the tool (did the block button work?). Rule 1: The Foreseeability of Effect: "The people who design, develop, or deploy a computing artifact are morally responsible for that artifact, and for the foreseeable effects of that artifact." (Miller et al., 2011). In the Heacock case, the creators of text to image generators bear some degree of moral responsibility. It is reasonably foreseeable that a tool can generate "any image" and could potentially be used to generate specific "harmful images." The lack of "Watermarking" or "Provenance" technologies at launch represents a failure of the developers to foresee harm and take steps to mitigate it. Rule 5: Honesty in Promotion declares that "People who design, develop, or deploy a computing artifact must not deceive the users about the artifact." (Miller et al., 2011). Gaming platforms market themselves as "community hubs" or "safe spaces for play." However, the architecture of these platforms, specifically the integration of unmoderated, encrypted channels (such as private

Discord servers) creates a zone of impunity for groups like 764. By promoting the platform as safe for minors while knowing that their encryption architecture prevents the detection of grooming rings, the developers violated Rule 5. They sold a “community” but delivered a “dark room” where any meaningful oversight was impossible.

10. Proposed Solutions: The Cognitive Security Architecture

To counter the speed, persistence and anonymity of modern psychological warfare, we recommend a Defensive AI Architecture that mirrors the OODA Loop (Observe, Orient, Decide, Act) of an AI-driven attacker which is too fast for human moderators to intercept. Therefore, we propose a shift to Automated Cognitive Security; a multilayered AI defense architecture designed to intercept and block threats at the network and application layers, preventing psychological damage to potential victims. This architecture integrates specific recommendations based on the case study analysis at 3 levels: Stylometric Analysis, Behavioral Graph Analysis, and Acoustic Coercion Analysis.

Layer 1: Stylometric Identity Resolution. The target threat of Layer 1 is Anonymity and persistence inspired by the Amanda Todd case. The technical concept is: Current platform defenses rely on “Ban by Attribution” which blocks a specific IP address, device ID, or email address. The Amanda Todd case demonstrates that a motivated attacker can easily avoid defensive strategies by using VPN’s, burner phones, and fake accounts. To counter these tactics, we propose Stylometric Identity Resolution. This relies on the linguistic theory of “Idiolect.” Idiolect states that everyone possesses a unique, subconscious cognitive fingerprint in how they construct language. The implementation of this engine would operate using a Support Vector Machine (SVM) or a Long Short-Term Memory (LTSM) neural network trained on three feature sets (Narayanan et al., 2012): Lexical Features, the statistical distribution of vocabulary richness, unique word usage, and grammatical mistakes. Syntactic Features relate to the frequency of function words (e.g., "the," "and," "but"), punctuation patterns, and sentence length variability. Idiosyncratic Features involve specific uncommon grammar or slang unique to a user. The operational workflow would function as follows: When a user is banned for severe harassment (a “High Confidence Threat Actor”), their writeprint is hashed and stored in a “Recidivism Database.” When a new account interacts with the victim the proposed engine will analyze the first N messages. If the new accounts writeprint correlates with the banned writeprint with a confidence interval of over 95% the account will subsequently be flagged as a “Sockpuppet.” Following this identification the system executes a Shadowban, which hides the users’ profile and activity from the new accounts, effectively neutralizing the attacker. This fulfills the Post-Deployment Mandate by ensuring the “block” functionality is resilient against emerging threats (Narayanan et al., 2012).

Layer 2: Behavioral Graph Anomaly Detection. Predatory groups like the members of the “764” network rely on a specific social structure. They use a “Grooming Funnel” to move victims from high-visibility public spaces (e.g., Roblox lobbies) to low-visibility encrypted spaces (e.g., private Discord servers). Traditional content scanning fails to detect the predator’s presence because the invitation is typically inconspicuous. But what lays underneath is the metadata which reveals the threat. An implementation of this concept would look like: using Graph Theory to detect Topological Anomalies (Akoglu et al., 2015). The social network is modeled as a graph G = (V, E), where nodes (V) are users and edges (E) are interactions. This engine would calculate the Centrality Metrics to spot “Grooming Hubs.” A grooming ring will normally display a “Star Topology” where the central hub (predator) forms rapid connections with multiple unrelated leaf nodes (minors). For The “Swarm Signature” to be identified, the system looks for a specific sequence of graph updates: Cluster Formation, a group of High-Risk nodes enter a Low-Risk environment. Rapid Edge Creation, these nodes initiate friend requests with the target nodes (victims). Funneling, the target node receives a URL to an external, encrypted domain within T minutes of connection. If this “Swarm Signature” is detected, the AI triggers an off switch. The invite link is killed, and the minor’s account is placed in “isolation mode” which prevents new friend requests and messages from new accounts. This breaks the Command and Control (C2) structure of the gamified harassment group (Levine, 2025).

Layer 3: Acoustic Coercion Analysis. The threat to a target at this layer is real-time psychological distress which was demonstrated in the Jay Taylor case. In the Jay Taylor case, the abuse happened in a voice chat. Text filters cannot detect audio coercion, and recording all calls for transcriptions violates privacy laws per the GDPR/CCPA. To solve this, we recommend Acoustic Coercion Analysis using Edge AI. This approach analyses how something is said and not what is said, which preserves privacy by never transcribing words. The Acoustic Coercion Analysis model is a lightweight Convolutional Neural Network deployed on the user’s device (Edge Computing). It extracts Paralinguistic Features from the audio stream (Guyer et al., 2021): Jitter (Frequency Perturbation), micro-fluctuations in pitch. High jitter is biologically correlated with the fight or flight response which causes a lack of laryngeal control caused by fear. Shimmer (Amplitude Perturbation), which is caused by small fluctuations in

loudness. And Fundamental Frequency(F0): Sudden spikes in pitch indicating panic or screaming. The model establishes a "Baseline Calm" profile for the user. If the audio stream deviates from the baseline into the "Distress Cluster" (high jitter + high energy) for a prolonged duration (over 30 seconds), the system infers Psychological Duress. Once triggered, the defense system takes over. The system can automatically mute incoming audio from the aggressor, lower volume, or display a "Safety Check" pop-up ("Are you okay? Click here to exit call and report"). This acts as a sensor for detecting physiological signs of the psychological attack (Guyer et al., 2021).

Layer 4: LLM-Based script Interdiction. The target threat is velocity and automation that were tactics used against Elijah Heacock. The "Velocity Sextortion" attack on Elijah Heacock succeeded because it was faster than the speed of human cognitive processing. The attackers used a professional script. To counter this, we treat sextortion scripts as Malware Signatures. To solve this problem, we can utilize a Large Language Model (LLM) trained on a dataset of known sextortion transcripts. Unlike simple keyword matching, the LLM uses Vector Embeddings to understand intent (Huang et al., 2023). It scans Direct Message requests from unknown users for the "Sextortion Flow":

- 1. Phase 1: Grooming (Hyper-complimentary language).
- 2. Phase 2: Escalation (Request for image or platform migration).
- 3. Phase 3: The Turn (Threat of exposure)

If an incoming direct message sequence matches this semantic flow with high probability, the message is pre-flagged. The recipient (victim) receives a modified version of the message covered by a "Safety Blur" with a warning message: *"This message matches patterns used by financial extortion scams. Do not send images."* This intervention will happen in milliseconds, breaking the OODA Loop of the attacker before the victim can be psychologically compromised.

11. Limitations and Ethical Considerations of Cognitive Security Architecture

While Defensive AI offers a great shield against psychological warfare for both cyberbullying and cyber warfare, it introduces unique ethical and technical challenges. First, it can create a False Positive Dilemma. In a "Cyber Warfare" context, a False Negative (failing to stop an attack) can result in loss of life. Inversely a False Positive can result in censorship. With cyber bullying, Sylometric Analysis might flag a sibling using the same computer as a banned user. To mitigate against this, we propose an escalation policy where AI can quarantine an attacker, but permanent bans require human review. Additionally, privacy concerns are raised when discussing Acoustic Coercion Analysis, which requires constant monitoring of the microphone. Even if processing is done "on the edge" (system side) and data is never sent to the cloud, this still raises surveillance concerns. The implementation of Acoustic Coercion Analysis requires Transparent Consent. Gamers must opt-in to "Safety Monitoring" not dissimilar from how driver's opt-in to telematics insurance (Nissenbaum, 2009). The third and final issue addressed here is an Adversarial Arms Race. Just as anti-virus software spurred the creation of polymorphic viruses, Defensive AI will most likely spur the development of Adversarial AI. Technologically proficient aggressors or online black-market merchants may develop tools to obfuscate their writeprints or use voice changers to defeat acoustic analysis. This necessitates a continuous cycle of anticipatory ethics applied to design, where developers must constantly Red Team their own systems to find vulnerabilities to patch before attackers exploit these vulnerabilities.

12. Conclusion

The evolution of the form of threats in this study from unauthorized surveillance of Tyler Clementi (2010) to the swarming attrition of Amanda Todd (2012), to the gamified harassment of Jay Taylor (2022), and to the machine-speed sextortion of Elijah Heacock (2025) all demonstrate that cyberbullying is now more than a social nuisance. It has evolved into localized, asymmetrical Psychological Warfare. This analysis has shown that the tactical procedures of modern cyberbullies mirror military Information Operations and vice versa. They utilize surveillance to locate targets, use attrition to degrade morale, and "Hyperwar" velocities to overwhelm human cognitive defenses. The integration of Generative AI and Encrypted Command and Control (C2) channels effectively multiply the force of the perpetrators, making tradition human-centric moderation problematic. Through the lens of Anticipatory Ethics, we conclude that the failure to protect these victims was not an inevitable tragedy but a breakdown of the Sociotechnical Imperative. Developers of computer hardware, social platforms and AI models failed to anticipate the darker scenarios that could develop because of their creations. Therefore, this paper argues that the security industry must adopt a new mandate: Cognitive Security. User reports are insufficient for attacks that occur in milliseconds. We must deploy the Cognitive Security Architecture

proposed. Stylometric Identity Resolution to strip anonymity, Behavioral Graph Analysis to destroy grooming funnels, and Acoustic Coercion Analysis to detect real-time distress. These tools transfer the burden of defense from the vulnerable individual to the proposed system. Ultimately, the defense of the "Human Element" is no longer a matter of policy, it is a matter of engineering. Firewalls protect the network layer, antiviruses protect the application layer, Cognitive Defense AI must now protect the psychological layer. It is the moral obligation of the computing profession, grounded in the ACM Code of Ethics, to build this shield before the next evolution of psychological warfare claims another child's life.

13. Future Work

While the study focused on individual-level psychological warfare, the defensive frameworks proposed have broader applications. Future research should focus on applying this same technical analysis, specifically Behavioral Graph Anomaly Detection and Stylometric Identity Resolution, to state-level Cyber Warfare cases. By analyzing "writeprints" and "swarm topologies" of Advanced Persistent Threats (APTs), researchers may identify overlapping operational modes of attack between individual aggressors and state-sponsored aggression at the level of cyber warfare.

Ethics Declaration: No human participants or personally identifiable information were involved. All data sources were publicly available.

AI Tools Declaration: ChatGPT 5.1 for drafting and refinement. Human authors verified all content. Gemini 3.0 pro used for aiding in sourcing.

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Libraries as Frontline Defenders Against Disinformation Warfare: Fact or Fiction?

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Abstract: The spread of disinformation in the digital age is an unprecedented threat to democratic governance, public health, and social cohesion. Libraries are increasingly becoming the main bulwark against false and misleading information. This paper examines the evolving role of public, academic and school libraries in the fight against disinformation, drawing on research from library and information science, media literacy studies, information warfare and epistemology. Adopting a critical narrative literature review design, the paper synthesises peer-reviewed and grey literature published between 2018 and 2026 around an explicit thematic framework rather than a systematic search protocol. It analyses library strategies and the challenges they face, including resource constraints, political sensitivities, educational shortcomings, and tensions between intellectual freedom and tackling disinformation. Drawing on epistemic justice and the cybersecurity principle of defence-in-depth, the paper argues that libraries are not called upon to determine the truth, but to facilitate the collective critical appraisal of information in the community, while functioning as one necessary but insufficient layer within a wider counter-disinformation ecosystem. The review shows that libraries contribute significantly to media and information literacy, civic participation, and community resilience but are still hampered by structural, technological and political constraints. The paper also finds that isolated interventions in libraries are not sufficient to counter large-scale disinformation ecosystems. The study contributes to the growing discourse on countering disinformation by proposing that libraries should be integrated into wider interdisciplinary and societal frameworks, including education, technology governance, public policy and initiatives on digital citizenship.

Keywords: Libraries, Disinformation, Misinformation, Information literacy, Fake news, Information warfare, Epistemic justice, Digital citizenship, Information equity

1. Introduction: The Epistemic Crisis and Libraries' Historical Role

The digital age has fundamentally altered the information landscape and has created an epistemic crisis characterised by the exponential spread of misinformation, disinformation and disinformation on social media platforms (Spitzberg, 2025). The consequences are serious: erosion of public trust in institutions, democratic processes compromised, delays in responding to public health, and the fracturing of social cohesion. Misinformation, defined as false information shared without malicious intent, is distinguished from disinformation, defined as deliberately false information disseminated with the intention of deception or manipulation (Dowse & Bachmann, 2022). Disinformation is weaponised information used strategically by state and non-state actors to undermine public trust, polarise societies and destabilise democratic processes (Bachmann, Putter & Duczynski, 2023; Matei, 2025). Libraries have emerged as a critical institution in this context. Their position in the information ecosystem is not arbitrary, as publicly funded, widely accessible institutions with a mandate for information literacy, community information and resource assessment, libraries differ structurally from schools (smaller audiences), media organisations (commercial interests) and tech platforms (structures of engagement rather than accuracy). Historically regarded as neutral repositories of knowledge, libraries are increasingly fighting misinformation through commitments to intellectual freedom and access to information (Adewojo, Esan & Aleem, 2024; Mandal & Lama, 2025). But are libraries really equipped to counter sophisticated disinformation campaigns, or is the rhetoric exaggerating the modest role they play in educating people? This paper examines whether this reorientation is justified in theory, feasible in practice and ethically sustainable.

2. Background: The Disinformation Threat Landscape

Disinformation warfare is the deliberate use of information ecosystems for political, military or economic purposes (Dowse & Bachmann, 2022). According to Matei (2025), disinformation is a fundamental shift in power competition, with novelty and narrative increasingly taking precedence over objectivity and truth. Research has shown that it has a significant impact in the geopolitical and economic context. Bachmann et al. (2023), for example shows how disinformation has been a powerful multiplier in the Russia-Ukraine war, while Tredinnick (2023) highlights its role in reputational attacks and market manipulation. Spitzberg (2025) extends the debate by introducing the concept of maliformation, which includes misinformation, disinformation and other forms of deliberate epistemic sabotage. Disinformation is spread by algorithmic amplification, cognitive biases, and emotionally charged content that can override critical judgment (Gill et al., 2019). The emergence of large-scale

linguistic models has further increased the scope and effectiveness of misinformation campaigns, while at the same time reducing their costs (Raman et al., 2024; Imam, 2025). Tsang's typology (2024) distinguishes between misinformation, disinformation and fraud and highlights the need for different responses by libraries. These differences are shown in Table 1.

Table 1: Adapted by the author from Bachmann et al. (2023), Matei (2025), Gergelewicz (2025), Gill et al. (2019), and Spitzberg (2025): Sources, mechanisms, and societal impacts of disinformation warfare

Source / Actor	Mechanism	Societal Impact	Domain
State actors (e.g. Russia, hybrid warfare)	Algorithmic amplification on social media	Undermines democratic governance & elections	Geopolitical
Non-state / political actors	Exploitation of cognitive biases	Erodes public trust in institutions	Political
Automated bots & deepfake technologies	Emotionally charged narratives bypassing evaluation	Polarises society; destabilises democracies	Technological
Commercial actors	Coordinated inauthentic behaviour	Market manipulation; public health crises	Economic / Public Health

These differences have direct operational implications for library practice, as shown in Table 1. Misinformation (false content shared without intent to mislead) is dealt with by correcting information and training in the assessment of the source. Disinformation (intentionally false content intended to mislead) calls for programmes of early childhood education and literacy. Malinformative (measured and weaponised) information requires contextual and ethical thinking skills (Tsang, 2024; Spitzberg, 2025; Becker, 2025). Understanding this spectrum is crucial to judging what libraries can realistically achieve.

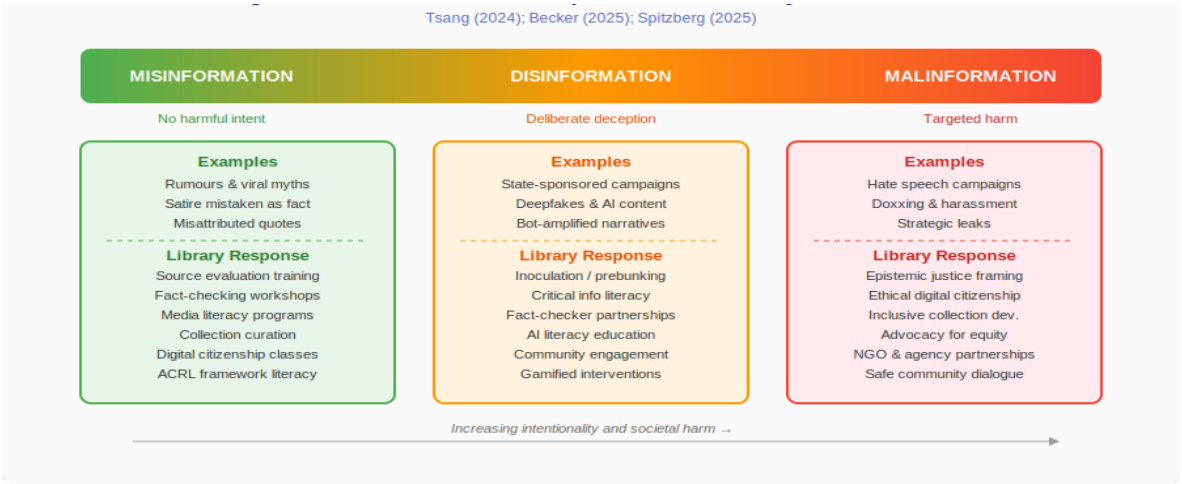


Figure 1: The Disinformation Spectrum and Library Interventions

3. Problem Statement

Disinformation is a constant feature of the modern information environment, driven by state actors, automated systems, and algorithms that favour immediacy over accuracy. Libraries are increasingly expected to help combat misinformation, but their capacity is often limited by limited funding, insufficient training, lack of outreach to vulnerable groups and lack of evidence of the long-term effectiveness of their interventions. Many librarians cite information overload (84%) and lack of training (56) as the main problems (Jahangir, 2025). These challenges are compounded by artificial intelligence (AI), which allows large-scale synthetic content creation (Raman et al., 2024; Imam, 2025), supports coordinated disinformation campaigns (Bachmann et al., 2023; Matei, 2025), and contributes to the algorithmic dissemination of misinformation (Seargeant & Tagg, 2018). If left unchecked, these developments could increase the susceptibility to disinformation, undermine democratic processes, and widen social divisions. Although libraries remain highly trusted institutions (Jahangir, 2025), their role in the fight against disinformation remains under-funded and under-appreciated.

3.1 Rationale

Historically, libraries have been trusted, publicly funded repositories of knowledge and consistently ranked among the most trustworthy institutions in democratic societies (Adewojo, Esan and Aleem, 2024; Jahangir, 2025). Eighty-five percent of library users believe that libraries should fight against misinformation, although this figure is likely to reflect a self-selection of library users (Jahangir, 2025) and may not represent a broader audience. Despite this, there is still limited rigorous empirical evaluation of library-based interventions: Broda and Strömbach (2024) identified important gaps in understanding long-term efficacy, and Tripodi et al. (2023) noted that librarians rely on outdated search literacy techniques, while state-sponsored disinformation campaigns use specialised staff, budgets and sophisticated tools (Bachmann et al., 2023) - asymmetries requiring multi-disciplinary responses (Munandar et al., 2026; Saunders, 2025).

3.2 Research Objectives

The study focuses on four objectives: (RO1) to assess the theoretical foundations underpinning libraries' role as defenders of public, academic, and educational information, drawing on the epistemic justice and information equity frameworks; (RO2) to document and evaluate the strategies used by libraries to counter disinformation; (RO3) to assess the empirical evidence base for library-based interventions; and (RO4) to propose an integrated interdisciplinary framework for countering disinformation within a multi-stakeholder ecosystem.

3.3 Methodology

This paper adopts a critical narrative literature review design, structured around an explicit analytical framework rather than a free-form synthesis. Sources were drawn from library and information science, media and information literacy, disinformation studies, and epistemology, selected for their relevance to the research objectives (RO1–RO4) rather than through a systematic search protocol. The review primarily examines literature published between 2018 and 2026, while incorporating key foundational works where relevant. Sources are synthesised into the thematic structure presented in Sections 4–10, culminating in the frameworks shown in Figures 2 and 3. As the study is based on critical appraisal of published literature rather than new empirical data, its findings constitute a conceptual and theoretical contribution. This approach aligns with established practice in critical narrative reviews, where rigour is achieved through a transparent analytical framework rather than a systematic search process (Grant & Booth, 2009; Baker, 2016).

4. Theoretical Foundations: Libraries' Role in the Information Ecosystem

The theoretical role of libraries as defenders against disinformation is based on a basic democratic principle: access to reliable information is a precondition for an informed citizenry. As publicly funded institutions committed to universal access, libraries are uniquely placed to provide curated and validated sources of information (Becker, 2025). The ACRL framework for information literacy articulates critical competences, including the recognition of the constructed nature of information, the critical assessment of sources and understanding of the social and economic context of information production, which directly equip individuals to counter misinformation. Libraries remain trusted institutions in democratic societies (Jahangir, 2025).

4.1 The Intellectual Freedom Paradox

For decades, the American Library Association and its affiliates have espoused intellectual freedom as a core value: the principle that individuals have the right to access a variety of perspectives without interference from the institution. The paradox is obvious: how can libraries protect intellectual freedom while fighting misinformation, which requires judgment about what is true and what is false? Libraries should not restrict access to information but equip users with skills to evaluate truth, credibility, and context. In practice, however, the distinction between user empowerment and access restriction is more blurred than in theory: curation and programming decisions include implicit judgments of the quality of the information. Acharya (2025) argues that transparency of the evaluation standards is an effective ethical guarantee, rather than denying that gatekeeping takes place. Salisbury (2019) expands on this criticism and notes that information literacy education tends to focus on tools and skills rather than educating learners about the nature of information itself.

4.2 Epistemic Justice and Information Equity

The concept of epistemic justice recognises individuals and communities as legitimate knowers whose perspectives deserve epistemic respect. In this context, libraries are facilitators of critical dialogue rather than arbiters of absolute truth. Epistemic justice focuses on equitable participation in knowledge production, while epistemic authority refers to the credibility granted to institutions or individuals as reliable sources of

knowledge. Epistemic trust, in turn, relates to the public confidence placed in those institutions and information systems. Libraries therefore play an important role in supporting critical engagement with information while making visible the structural inequalities that shape information access and credibility (Gonzalez, 2026). This framework also highlights broader inequalities in digital participation, particularly among low-income and marginalised communities with limited access to digital infrastructure and evaluation skills (Munandar et al., 2026).

4.3 A Structural Lens: Libraries as One Layer in a Defence-in-Depth System

Alongside epistemic justice, this review uses the defence-in-depth concept from cybersecurity, which recognises that no single measure can stop every threat and that multiple layers of protection are needed (Zurko, 2022). The two perspectives serve different purposes. Epistemic justice explains what libraries should do by helping people engage critically and fairly with information rather than deciding what is true. Defence-in-depth explains where libraries fit within the wider response to misinformation. It views libraries as one important layer in a broader system that also includes fact-checkers, platform governance, and policy actors (Mazurczyk, Lee & Vlachos, 2024). This approach helps address the gap between well-resourced disinformation campaigns and the more limited resources available to libraries. The framework is developed further in the four-layer model presented in Section 8.1 and revisited in the conclusion.

5. Strategies and Initiatives: What Libraries Are Doing

Libraries are addressing misinformation through information literacy training, source-evaluation workshops, digital citizenship programmes, community partnerships, fact-checking collaborations, staff development, and policy advocacy (Ogboru & Arharhile, 2026; Detlor et al., 2024). Figure 2 groups these activities into three layers: educational interventions, community engagement, and systemic support. The framework shows that no single approach is sufficient. Educational programmes have limited impact without community engagement, while community initiatives require institutional support to be sustainable.

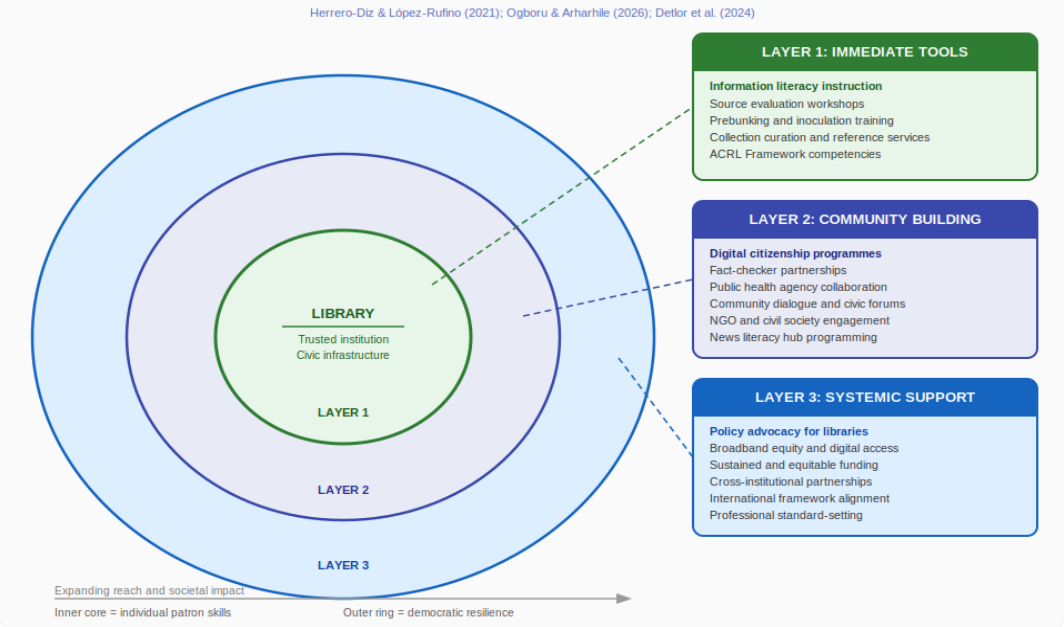


Figure 2: Library's Multi-layered Defence Framework Against Disinformation

5.1 Community Engagement and Digital Citizenship Initiatives

Libraries engage with communities through digital citizenship initiatives that address the detection of misinformation, digital security and the use of ethical technologies (Iskandar et al., 2025). Jahangir (2025) reports on digital citizenship activities in 72 to 88 per cent of the institutions covered. Libraries also work with fact-checking networks, health agencies and civil society organisations - Ogboru and Arharhile (2026) argue that libraries are ideally placed to act as hubs for news literacy, with their community links, trusted sources and trained staff.

5.2 Partnerships and Collection Curation

Formal partnerships between libraries and fact-checking organisations have multiplied. Kerrigan and colleagues. (2022) documents a collaboration between Irish universities and public libraries which produced a media literacy course with Meta and civil society organisations, a model which is increasingly being replicated in public health agencies. Curating reliable sources remains fundamental: academic libraries are expanding repositories open to the public, while public libraries are building collections centred on primary sources and peer-reviewed material (Becker, 2025).

6. Empirical Evidence: Do Library Interventions Work?

Recent research provides encouraging evidence that media and information literacy interventions can improve users' ability to identify misinformation. Studies of media literacy programmes in secondary schools report significant improvements in learners' ability to assess source credibility (Awololon & Sharma, 2024). Similarly, a meta-analysis of 33 inoculation studies (N = 37,025) found that gamified and video-based interventions improved users' ability to distinguish between reliable and unreliable information (Simchon et al., 2025). Feedback exercises on gamified platforms also improved misinformation detection (Leder et al., 2024). The evidence suggests that such interventions are particularly effective in producing short-term improvements in critical evaluation skills and attitudes toward misinformation. Longitudinal studies (N = 11,759) further show that inoculation interventions remain effective for approximately one month, while booster interventions can significantly extend these effects (Maertens et al., 2025). This indicates that preventative information literacy education may be more effective when reinforced over time rather than delivered as a once-off intervention.

6.1 Methodological Limitations and Gaps

Most studies focus on short-term effects in controlled settings rather than long-term behaviour in real-life situations (Broda & Strömbach, 2024). The impact of interventions is often small, and some media literacy programmes may even make people overconfident in their ability to detect misinformation (Bulger & Davison, 2018). Results also vary across contexts, with better outcomes among university students and in high-uncertainty environments, which limits how widely findings can be applied (Huang et al., 2024). Librarians are also not immune to misinformation or bias (Jaeger & Taylor, 2021). In addition, most research comes from Western, English-speaking countries, leaving gaps in understanding other contexts.

7. Challenges and Limitations

7.1 Resource Constraints and Funding Precarity

LaPierre and Kitzie (2019) found that the most frequently cited reason for not participating in media literacy initiatives was a lack of staff time; Jahangir (2025) similarly found that 56 percent reported a lack of training. Rural libraries face compounding challenges: limited digital infrastructure, insufficient staff and insufficient training hamper their anti-disinformation functions (Ogboru and Arharhile, 2026).

7.2 Political Weaponisation and Scale Mismatch

The term *fake news* is often used to discredit opposing views, including legitimate journalism (Acharya, 2025). This makes it difficult for libraries, as their efforts to counter disinformation may be seen as censorship or may increase political tension. At the same time, state-sponsored disinformation operates on a much larger scale, using funding, expert teams, bots, and technologies like deepfakes (Bachmann et al., 2023). Library interventions such as training workshops are much smaller and cannot match this speed or reach, so calling them a "first line of defence" risks creating unrealistic expectations. Research on inoculation and prebunking shows that teaching people early about common misinformation tricks helps them recognise and resist false information before they encounter it (Lewandowsky & van der Linden, 2021; Maertens et al., 2025), with effects that can spread through communities over time. This is, in effect, an asymmetric threat-actor problem familiar from cyber security: a well-resourced, adaptive adversary operating at machine speed against a comparatively under-resourced, largely manual defender.

7.3 Professional Training Deficits and Reach Limitations

Tripodi et al. (2023) found that librarians rely on outdated techniques of search literacy and are reluctant to confront patrons with politically sensitive information. Research on European fact-checkers has found that AI literacy is still in its early stages (Gonzales et al., 2024) - a finding that is also valid for librarians dealing with AI-generated misinformation. Library programmes mainly reach voluntary participants. The groups most

vulnerable to disinformation - those with lower educational attainment, limited digital access or high political mistrust - are least likely to participate. Hancock (2025) found that half of the professors surveyed had never used library resources related to false news, which illustrates the epistemic paradox.

7.4 Intellectual Freedom, Censorship, and Library Ethics

One of the greatest challenges libraries face is to manage the line between the work of countering disinformation and censorship. Curating authoritative sources or excluding unreliable material risks reinforcing dominant narratives and silencing marginalised voices. Acharya (2025) argues that the term fake news should be removed from professional discourse, as it has been so weaponised by political actors that its continued use undermines the work of information integrity. From the point of view of epistemic justice, the role of libraries is not to adjudicate the truth, but to facilitate a critical dialogue in which citizens collectively assess evidence and recognize how systemic power shapes access to information (Gonzalez, 2026). This requires transparent evaluation criteria, procedural fairness, and "protection of marginalised voices from systematic silencing."

8. Discussion of Findings

The findings show that, rather than acting as direct "frontline defenders," libraries play an important but limited role, mainly strengthening critical thinking, information literacy, and public trust. Their role is therefore better understood as supporting long-term democratic resilience rather than directly stopping misinformation campaigns. Research also shows that preventive information literacy education is generally more effective than reactive fact-checking after misinformation has already spread (Lewandowsky & van der Linden, 2021; Maertens et al., 2025). From the perspective of epistemic justice, libraries are not responsible for deciding absolute truth, but for helping communities critically evaluate information and different knowledge claims (Gonzalez, 2026). At the same time, several structural limitations reduce the effectiveness of library interventions: limited funding, unequal digital access, and restricted outreach make it difficult to reach those most vulnerable to misinformation. Libraries also face a major imbalance when competing against large-scale disinformation systems that use AI-generated content, automated technologies, and algorithmic amplification. There remains still limited long-term evidence measuring the impact of library interventions. Research also shows that librarians themselves are not immune to misinformation and cognitive bias (Jaeger & Taylor, 2021). Therefore, presenting libraries as primary defenders against disinformation without recognising these limitations may create unrealistic expectations and overlook the broader systemic nature of the problem

8.1 Toward an Integrated Framework: Libraries Within Multi-Stakeholder Ecosystems

Borrowing the defence-in-depth principle from cyber security, where overlapping layers of control compensate for the inevitable failure of any single safeguard, this framework treats counter-disinformation as a layered defence problem rather than a single point of failure. Figure 3 presents a conceptual-operational four-layer framework for countering disinformation within a multi-stakeholder ecosystem. Layer 1 positions libraries as the foundational actors providing information literacy, curated resources, and community trust. Layer 2 includes fact-checking organisations, civil society groups, and public health partners that verify and distribute corrected information. Layer 3 consists of platform governance and regulatory mechanisms, including moderation systems and algorithmic controls. Layer 4 involves national and international coordination structures responsible for broader policy responses and cross-border cooperation (Saunders, 2025; Gergelewicz, 2025; Raman et al., 2024). Together, the layers demonstrate that libraries are indispensable but insufficient on their own, with an early warning system linking the layers through cross-institutional information sharing to reinforce coordinated rather than isolated response.

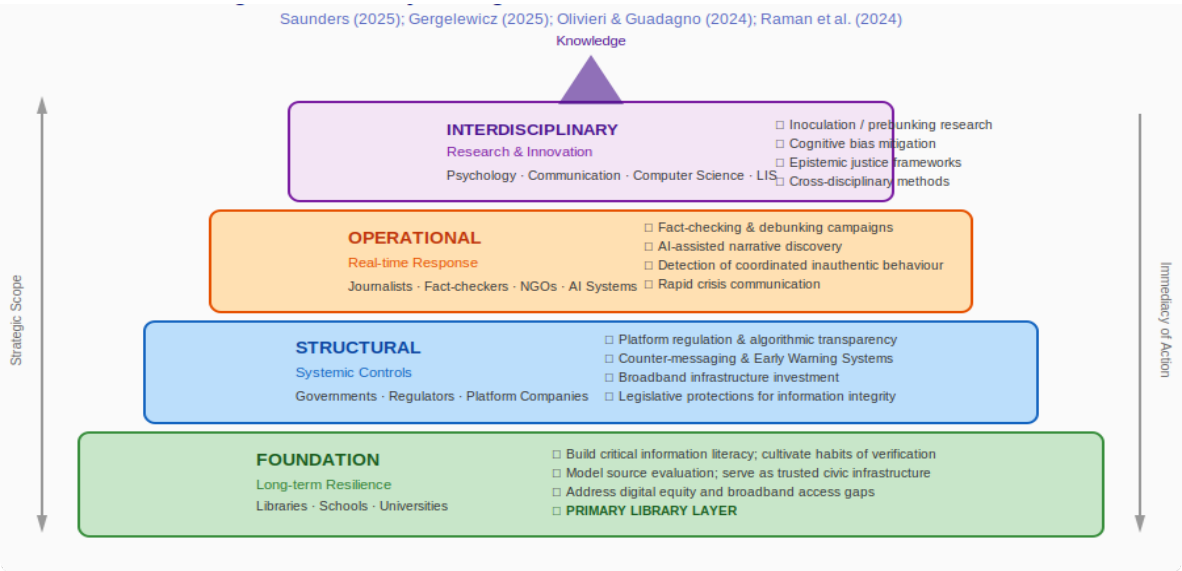


Figure 3: Four-layer Integrated Counter-disinformation Framework

9. Recommendations

9.1 For Library Leadership and Professional Associations

- Adopt transparent source-evaluation standards grounded in epistemic fairness principles (Gonzalez, 2026; Acharya, 2025), easing tensions between intellectual freedom and misinformation.
- Formalise partnerships with fact-checking organisations and public health authorities to integrate verified information into library reference and outreach services (Kerrigan et al., 2022; Becker, 2025).
- Integrate information literacy, cognitive psychology, communication studies, and computational deception detection into LIS curricula to strengthen librarians' preparedness for AI-generated and algorithmically amplified disinformation (Saunders, 2025; Kaspar, 2024).

9.2 Areas for Further Research

Future research should investigate whether library-led interventions produce lasting changes in users' ability to detect and respond to misinformation (Bulger & Davison, 2018; Broda & Strömbach, 2024), examine how cultural and infrastructural factors influence the effectiveness of anti-disinformation efforts in non-Western and developing contexts (Adewojo, 2026), and explore how libraries can be more effectively integrated into broader anti-disinformation systems, including fact-checking networks, prebunking initiatives, and AI-based detection mechanisms (Saunders, 2025; Gergelewiczbi, 2025).

10. Conclusion: Libraries as Necessary but Insufficient Defenders

Libraries are not merely information gatekeepers or providers of truth. They are essential in strengthening society's resistance to false information, but their contribution is not enough. From the standpoint of epistemic justice, libraries assist communities in critically analysing information rather than serving as arbiters of truth, emphasizing long-term critical thinking over reacting to specific instances of disinformation. Libraries are framed in this paper's four-layer model as the base layer of a defense-in-depth system. The defence-in-depth lens introduced in Section 4.3 supplies the structural counterpart to this normative commitment: libraries are framed in this paper's four-layer model as the base layer of a defense-in-depth system. While fact-checkers, platform governance, and policy actors offer more focused detection, control, and coordination, they promote population-wide resilience. Similar to cybersecurity, no single layer can prevent every threat; instead, by bolstering baseline resistance, the foundational layer lowers overall vulnerability. Specialized tasks like content removal and attribution fall under the purview of cybersecurity and intelligence systems, not libraries. Like basic security awareness training that lessens exposure to phishing and manipulation, their role is preventive and human-centered. This foundational layer shifts avoidable burdens onto higher-level responses, weakening the system as a whole if it is underfunded. Therefore, investing in professional capacity and acknowledging by funders and policymakers that information literacy is a fundamental component of national resilience are necessary to strengthen libraries. Taken together, epistemic justice explains what libraries

should do, while defence-in-depth explains where they fit within a broader response to misinformation. These perspectives show that libraries are a vital, yet underfunded, part of a wider defence against disinformation.

Ethics Declaration: This study did not require ethical clearance as it used publicly available data and involved no human participants or sensitive information.

AI Declaration: AI tools were used only for language refinement. The analysis, interpretation, and conclusions remain solely the responsibility of the author.

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