

Security and Privacy Challenges in VLC-Based V2X Communications: An Overview and Evaluation

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Abstract: The upcoming Sixth Generation (6G) of wireless systems is considering, among others, technologies such as Wireless Optical Communication (WOC) and Visible Light Communication (VLC) to achieve more advanced and secure transmission systems. Thereby, VLC is offering advantages like high data rates and operating in the unlicensed visible light spectrum while enhancing security and privacy by directional light beams and reducing eavesdropping threats. However, its limitations include dependence on Line-of-Sight (LoS) and susceptibility to obstacles and environmental disturbances. In addition, Vehicle-to-Everything (V2X) communication, a key technology for autonomous driving, has evolved to provide faster and more reliable connectivity among cars and infrastructures. Therefore, this work investigates the integration of VLC into V2X, focusing on security and privacy challenges, as well as weather conditions, ambient light interference, and vehicle movement. Moreover, efforts to address these issues have explored combining VLC with Radio Frequency (RF) technologies and enhancing the Physical Layer Security (PLS) through advanced coding and modulation techniques. In this work, an experimental setup using OpenVLC examines key performance aspects, such as latency and angular optimization, identifying system limitations under varied conditions. Experimental results show that VLC maintains reliable communication with packet loss below 20% within a central angular range. However, at extreme angles, loss increases significantly, reaching nearly 100%, limiting performance under certain conditions. Despite slow receiver movement ($\sim 0.03\text{-}0.05$ m/s), a motion had a negligible impact on overall performance, reinforcing VLC's potential for secure short-range V2X applications. This research aims to lay a foundation for future advancements by addressing the interaction and interplay between VLC and V2X in privacy and security contexts.

Keywords: 6G, VLC, V2X, LoS, Mobility, Security, Privacy

1. Vehicle-to-Everything and Visible Light Communication: Challenges and Opportunities

During the development of Vehicle-to-Everything (V2X) technology, several wireless enablers have been considered to facilitate communication between vehicles (V2V), infrastructure (V2I), and pedestrians (V2P). These technologies include Dedicated Short-Range Communications (DSRC) for direct communications among vehicles in critical security applications, Cellular V2X (C-V2X), Wireless Fidelity (Wi-Fi) for multimedia applications and Internet of Things (IoT) connectivity, and Bluetooth for short-range communications such as multimedia control (Clancy et al., 2024). Early V2X systems faced limitations in terms of speed and latency, as the wireless technologies available at the time, such as early iterations of Wi-Fi and Bluetooth, were not fast or reliable enough to support real-time communication. Despite these challenges, V2X's potential for security and automation is evident. For instance, human factors play a significant role in traffic accidents. According to *Haghshenas et al.* (2023), factors such as inattention, distraction, and impaired driving due to alcohol or drug use are major contributors to road crashes. The study highlights that human-related errors are among the leading causes of accidents, emphasizing the need for advanced safety systems and driver assistance technologies to mitigate these risks.

Furthermore, other Sixth Generation (6G) key enablers, such as Reconfigurable Intelligent Surfaces (RIS), have also been investigated to enhance privacy and security in V2X systems. For instance, RISs have been studied to address Line-of-Sight (LoS) limitations in vehicular communications (Lipps et al., 2024) and to assist V2X dynamic networks (Munoz et al., 2024). Similarly, VLC also relies on direct visibility, which enhances security by reducing eavesdropping risks but limits the communication range.

To overcome this constraint, VLC can be combined with technologies like RIS to extend coverage and improve performance. Figure 1 provides an overview of VLC technology in smart cities, illustrating different types of wireless links and V2V/V2I communications.

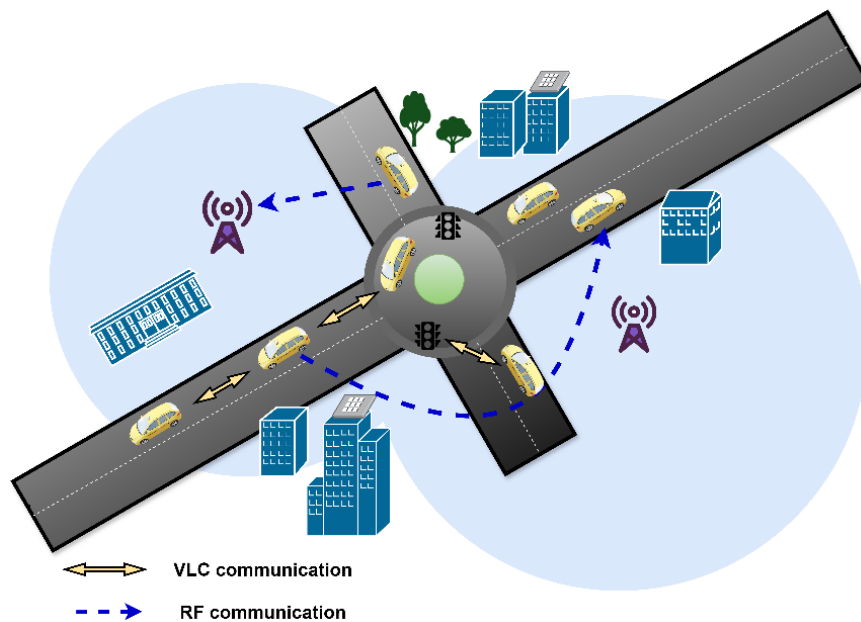


Figure 1: Concept of a smart city utilizing VLC technology to establish wireless links in V2V and V2I scenarios

Nevertheless, the increase in connected cars and the development of new applications, specifically for mobility use cases such as platooning, will impact communication networks. The main effect is on the limited radio frequency bands allocated for V2X communication (Karbalayghareh et al., 2020), (Alzalam, Lipps & Schotten, 2024). In high-traffic density scenarios, such as in city centers or when multiple platoons are passing the same area, the high congestion of allocated frequency bands can lead to high interference, causing delays and packet drops. Not only will performance be affected, but safety will also be compromised, jeopardizing the entire functionality of V2X technology. This could result in dangerous outcomes for use cases that rely on high data rates and low latency, such as autonomous and remote driving (Bammens et al., 2023).

Meanwhile, with the advancements in wireless communication, particularly with the emergence of 6G networks, new technologies, such as VLC have arisen, which leverage Light-Emitting Diodes (LEDs) for high-speed data transmission, offering unique advantages such as high data rate communication, usage of unlicensed spectrum, immunity to electromagnetic interference, enhanced security, and improved reliability. It is considered a promising solution to address the limitations of radio frequency and network congestion issues (Bammens et al., 2023). However, most research on VLC has focused on indoor applications, where controlled environments reduce challenges such as weather conditions and LoS requirements (Rabeh, Gabr and Hosny, 2016). Integrating VLC into V2X systems represents a compelling area of research, as VLC has the potential to enhance security and privacy in vehicular communication. For instance, since VLC uses light for transmission, it inherently reduces the risk of eavesdropping, as signals do not penetrate obstacles and remain confined within the beam's area. Additionally, LoS can be leveraged in high-density areas by utilizing VLC to exchange information with surrounding vehicles or infrastructure. Integrating VLC as a complementary technology to V2X can help alleviate network congestion and interference, enhancing performance (Bammens et al., 2023).

Similarly, conventional V2X technology can overcome VLC limitations caused by weather conditions, obstacles, and the distance between sender and receiver (Singh, et al. 2024). Integrating both technologies could enable future networks to meet the stringent Quality of Service (QoS) requirements for V2X applications (Singh, Srivastva and Bohara, 2022). Exploring how V2X and VLC can complement each other can provide new insights regarding the reliability and safety of future transportation systems. Extensive research is being conducted to assess VLC's feasibility as a complementary or competing technology in V2X applications. Studies focus on VLC's feasibility in outdoor environments affected by weather conditions, obstacles, and daylight. For critical use cases such as platooning, it is crucial to consider participant movement, as establishing a direct LoS can be disrupted by mobility or may only be available at an angle, as seen in multi-lane roads (Refas et al., 2023).

As platoon participants move, the distance between them fluctuates, affecting data rates and potentially causing delays. The transmission angle is also crucial when leveraging surrounding infrastructure, such as traffic lights and streetlights, to transmit awareness messages to nearby vehicles, whether stationary or in motion. Therefore, this study examines how VLC and V2X complement each other using an experimental setup with OpenVLC, an

open-source tool, and how movements and angle configurations can affect the transmission quality. The rest of this work is organized as follows: Section 2 provides a state-of-the-art overview, presenting studies that explore the integration of VLC with V2X applications. Section 3 discusses use cases related to privacy and security in VLC and V2X. Section 4 describes the experimental setup and highlights key factors that support VLC as a viable technology for V2X. Finally, Section 5 concludes by analyzing the correlation between VLC and V2X regarding privacy and security and outlines potential future research directions in this domain.

2. Related Work

The increase in traffic density and the development of advanced vehicular applications, such as platooning and autonomous driving, have impacted V2X communication standards and may cause congestion in radio frequency bands. Consequently, due to delays and packet loss, the limited radio spectrum has become insufficient to meet the stringent requirements of various V2X applications. These challenges have led to the integration of VLC and other technologies as complementary solutions to existing V2X standards. The feasibility of VLC in different V2X communication applications has been extensively studied by researchers in this context.

For instance, *Karbalayghareh et al.* evaluate the limits of a VLC system in a V2V link under various weather conditions (2020). Their results provide a path loss expression as a function of link distance, lateral shift between two vehicles, weather conditions, transmitter beam divergence angle, and receiver aperture diameter. This expression can be used to determine the maximum achievable V2V communication range under different weather conditions. Meanwhile, *Schettler, Memedi and Dressler* explore the capabilities of RF and VLC-based communication protocols for platooning (2019). The performance of these protocols is analyzed with a focus on communication reliability. Simulations show a significant improvement in reliability when VLC is integrated as a complementary technology to standard RF. They also examine the impact of interference from neighboring vehicles in a multi-lane scenario within a platooning application. The authors propose an adaptive front lighting system with spatial multiplexing to reduce interference and enhance communication robustness.

Similarly, *Bammens et al.* (2023) discuss the need to combine Radio Frequency (RF) and LoS technologies to improve the stability and reliability of V2V communication. They propose a basic hybrid strategy that allows the protocol to select the most suitable technology to enhance communication reliability. Likewise, *Singh, Srivastava and Bohara* introduce a hybrid approach for V2X communication at road intersections, integrating VLC/RF technologies with RIS to extend the communication range for V2V use cases (2022). The results demonstrate significant performance improvements in throughput and low latency compared to conventional RF-based V2V communication. Furthermore, *Singh et al.* (2024) investigate the integration of VLC with RF technologies to develop hybrid V2X systems aimed at enhancing autonomous driving. This combined approach leverages VLC's high data rates and security features alongside RF's reliability and range. The study focuses on achieving Ultra-Reliable Low-Latency Communication (URLLC), which is essential for advanced vehicular applications such as platooning and remote driving.

A platooning scenario using VLC is illustrated in Figure 2. Additionally, *Saikrishnan et al.* (2024) examine the integration of VLC into a hybrid V2X system, particularly for vehicular platooning applications. VLC offers high data transmission rates and immunity to electromagnetic interference, making it a promising candidate for improving communication reliability and safety in vehicle platoons. By combining VLC with RF communication, the study aims to mitigate the challenges posed by varying weather conditions and enhance overall system performance. On the other hand, *Joshi et al.* (2019) analyze the performance of VLC-based V2X communication under various environmental conditions, such as fog and smoke. They explore V2X transmission under non-LoS conditions and evaluate the impact of distance and angular variations. The results indicate that VLC technology is feasible only for short-range V2X communication under adverse weather conditions. Meanwhile, *Yahia et al.* (2021) investigate the impact of angle diversity in multi-directional V2V communication using VLC technology. The scenario consists of multiple cars on a multi-lane road, where vehicle headlights are used to transmit messages to a receiving car. The effect of photodetector angles on the received Signal-to-Noise Ratio (SNR) is investigated. In addition, the impact of transmitting high data rates on system performance is examined. Despite significant efforts, further research is needed to integrate VLC into V2X applications, as it represents a promising solution for enhancing security and reliability.

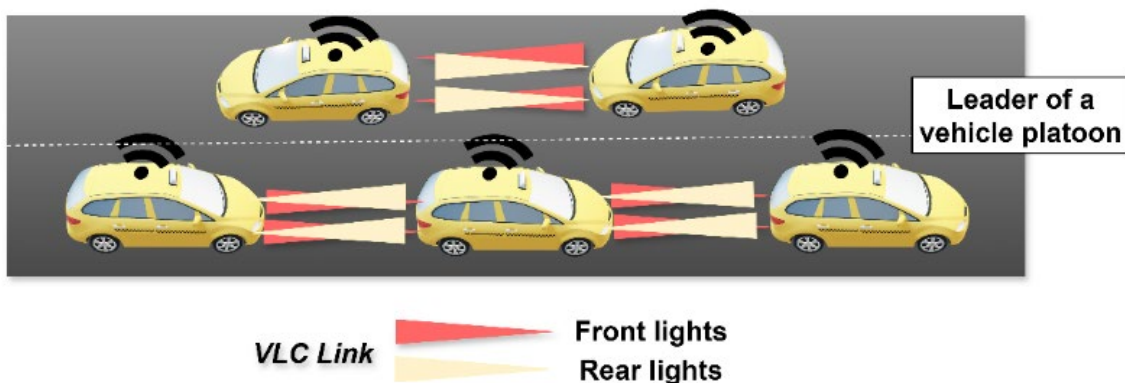


Figure 2: Platooning scenario illustrating VLC links established through vehicle headlights and taillights

While weather and LoS conditions are crucial for VLC in mobility use cases, other factors also play a role. To address VLC’s reliability limitations in mobility applications, it is essential to further investigate key factors such as direction, speed, and transmission angle. For this reason, this study examines how movement, speed, and angle affect VLC transmission quality using an experimental setup with OpenVLC.

Table 1: Summary of VLC-based V2X communication research focusing on security and privacy considerations

Author/ Year	Objective/ Problem	Approach/ Technology	Key Findings	Security and Privacy Considerations	Limitations/ Observations
<i>Joshi et al., 2019</i>	Evaluate VLC performance under adverse conditions such as fog and smoke	Pure VLC	Feasible for short-range communication; significant issues in non-LoS conditions	Strong environmental attenuation (e.g., dense smoke) could limit signal exposure, confining data transmission to short ranges	Effective only at short ranges in adverse weather conditions
<i>Schettler et al., 2019</i>	Enhance reliability in VLC-based platooning applications	Hybrid VLC + RF	VLC complements RF, significantly improving reliability in congested environments	Integrating VLC with RF reduces interference and enhances reliability, potentially improving communication safety in dense environments	Challenges remain in mitigating interference in high-density environments
<i>Karbalayghareh et al., 2020</i>	Evaluate VLC in V2V under different weather conditions	Pure VLC	Developed a path loss model and estimated the maximum communication range under different weather conditions	Path loss and limited distance in adverse weather could confine signals to specific areas, reducing external interception risks	Limited to specific conditions (climate, short distances)
<i>Yahia et al., 2021</i>	Investigate angular diversity in multi-lane roads	VLC (headlights as transmitters)	Analyzed the impact of photodetector angles on system performance	The use of narrow FoV and half angles confines the communication to specific spatial ranges	Does not address external interference or complex mobility
<i>Singh et al., 2022</i>	Extend communication range at road intersections	Hybrid VLC + RF with RIS	Improved throughput and low latency compared to conventional RF technologies	RIS implementation enhances privacy and mitigates eavesdropping risks	Dependency on RIS infrastructure for full implementation

3. VLC in V2X: About Security and Privacy

Vehicular communication plays a crucial role in Intelligent Transportation Systems (ITS), enhancing safety and efficiency in transportation. However, it also presents challenges such as security threats, environmental factors, communication disruptions, and power consumption. To address these issues, numerous researchers have

proposed experimental solutions. *Ouamma, Madini and Zouine* investigate the transformative potential of 6G technologies in V2X to enhance ITS (2022). Their work highlights innovations such as integrating hybrid RF-VLC systems to enable ultra-high data rates and improve security. Additionally, they explore Non-Orthogonal Multiple Access (NOMA) for efficient spectrum utilization in massive connectivity, the use of high-frequency spectra like mmWave and THz to increase bandwidth, and the application of Machine Learning to enhance physical layer efficiency in V2X networks. Despite these advancements, several challenges remain, including light interference, vehicle mobility, backward compatibility, and propagation loss.

3.1 Challenges of VLC in V2X Communication

Extensive research has focused on VLC technology for indoor applications, where it has demonstrated high efficiency due to its wide available bandwidth and high data rates (Yahia et al., 2021). However, outdoor V2X applications introduce several challenges that require further investigation. Even though VLC offers high security—as its signals do not penetrate walls—VLC-based V2X communication is highly dependent on LoS. In mobility use cases, absolute LoS is not always guaranteed and may only be partially available. Additionally, moving vehicles can obstruct LoS, disrupting communication. Daylight and artificial light interference further degrade data rates and connectivity reliability (Singh, Srivastava & Bohara, 2022). Another critical factor is the modulation scheme used in VLC transmissions, which significantly impacts performance, especially for outdoor applications. Selecting a robust and efficient modulation technique is crucial for safety-related applications, ensuring compliance with strict QoS requirements (Amjad et al., 2021). For instance, *Schettler, Memedi and Dressler* (2019a) demonstrate that VLC transmission suffers packet loss when acknowledgments are not used in a platooning scenario.

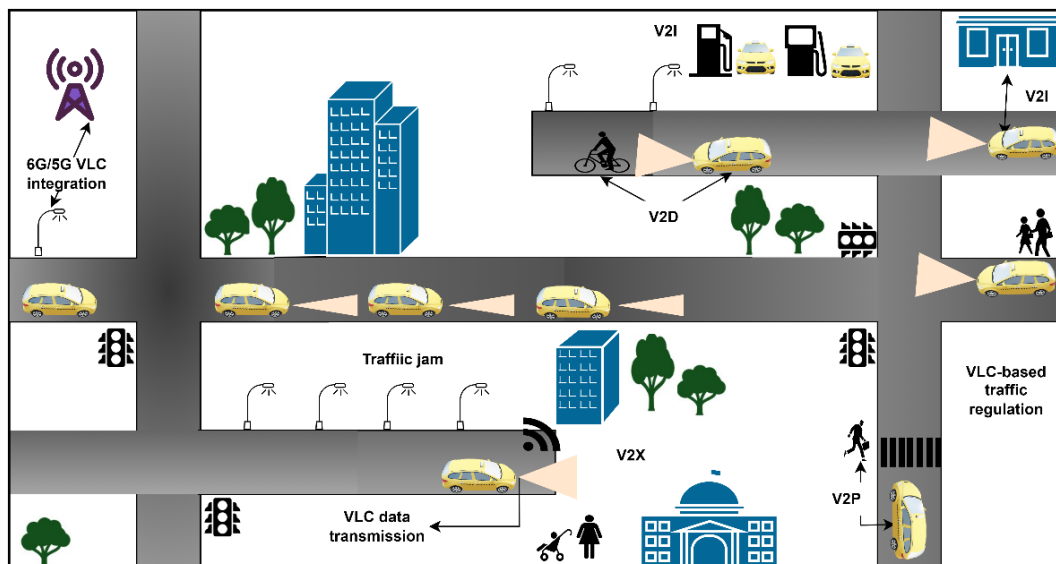


Figure 3: Various use cases of complementary VLC and RF in V2X communication, including V2V, V2I and V2D scenarios

3.2 Hardware and Security Challenges

On the one hand, VLC is considered a low-cost technology since vehicles are already equipped with potential transmitters (headlights and taillights). However, existing vehicle lighting systems have narrow beams and do not support advanced modulation schemes. Specialized LEDs are required to control transmission characteristics such as power levels and beam patterns (Bammens et al., 2023), (Schettler, Memedi, and Dressler, 2019b). This hardware limitation also introduces security vulnerabilities. The broadcast nature of VLC messages exposes them to potential attacks, particularly when simple modulation schemes are used (Arfaoui et al., 2020). Figure 3 illustrates various VLC use cases in V2X communication.

3.3 Environmental and Interoperability Considerations

On the other hand, weather conditions such as rain, snow, and dense fog can degrade system performance, affecting the reliability and transmission range of VLC. As a result, VLC alone may not meet the stringent QoS requirements for future V2X applications (Bammens et al., 2023), (Singh, Srivastava & Bohara, 2022). Despite its advantages and limitations, the interoperability between VLC and other V2X technologies remains an open

research topic. Coordinating these technologies is essential to maximize performance under different conditions, as they are complementary rather than standalone solutions. Due to its characteristics, VLC is particularly suitable for short-range V2X applications, where all participants maintain LoS and experience minimal deviations. Use cases include platooning, where vehicles exchange control and safety information, and emergency message transmission between vehicles and infrastructure.

Additionally, VLC can serve as a mitigation strategy against jamming attacks or RF spectrum congestion in high-traffic urban areas. Another potential application is using streetlights or other vehicles as relays to transmit messages at intersections and blind curves (Arfaoui et al., 2020), (Noor-A-Rahim et al., 2022).

4. VLC Experimental Setup

An experimental setup simulating real vehicle scenarios was developed to evaluate the feasibility and performance of V2X communication using VLC. This study investigates the effects of slow receiver movements and resulting angle variations. As a VLC setup, OpenVLC version 1.3 was used—an open-source system developed by Galisteo, Juara and Giustiniano (2019). The system comprises two BeagleBone Boards (BBB) and operates with a high-power LED (2.8 W, 400 lm) equipped with an additional lens for improved optical focusing on the transmitting side, while a photodiode on the receiving side detects the signal at a transmission frequency of 1 MHz. A more detailed description of this setup's adaptations is provided by Tjabben et al. (2023).

Bergkemper et al. (2024) compared VLC, Bluetooth, Wi-Fi, and Ethernet, demonstrating that VLC is well suited for specific applications or, in some cases, as a complementary technology (2024). This study focuses on motion dynamics and angle variations, extending previous work that analyzed the effects of distance and interference on transmission reliability (Tjabben et al., 2023). That study examined the OpenVLC system's performance under different transmitter-receiver distances and brightness conditions, including daylight, office lighting, and dark environments. For consistency, in the previous work, the receiver and transmitter were always aligned for power measurements at static angles, with no obstacles interfering with the communication, ensuring direct LoS. To build upon these findings, this study investigates the effects of motion on the OpenVLC system. The receiver was mounted on a model train, while the transmitter was positioned at the same height as the receiver, maintaining alignment at distances of 50 cm and 100 cm. Figure 4 illustrates the setup.

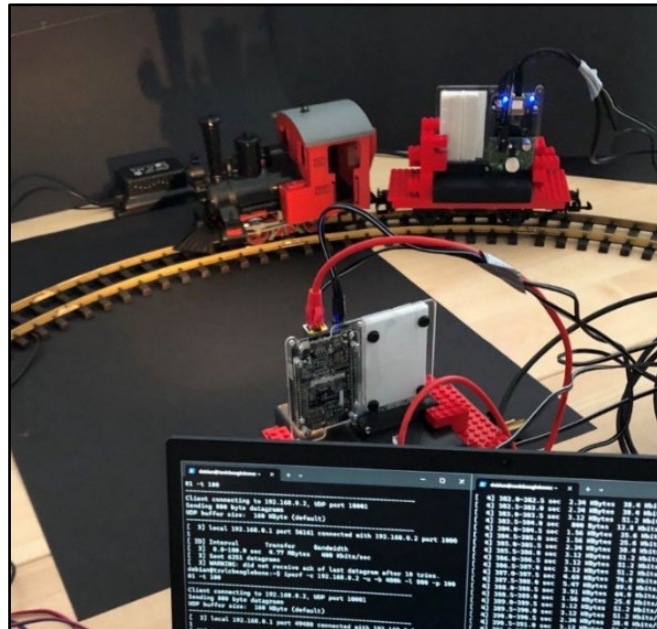


Figure 4: Model train setup used to evaluate the impact of movement and angle variations on VLC communication

The model train moves uniformly along a circular path, simulating steady motion and allowing for controlled angle variations between the transmitter and receiver. Performance is evaluated by transmitting data packets at various angles using the iPerf protocol (Dugan et al., 2023), and the percentage of lost data packets is measured. For each angle, a minimum of three measurements were recorded, each lasting 100 seconds and comprising 6,251 data packets. While VLC offers significant advantages for security and privacy, particularly in short-range V2X communication, its limitations highlight the need to integrate VLC with complementary

technologies. Further research is required to address these challenges. This study explores experimental results and practical implementations to evaluate these aspects in greater depth.

Initially, the maximum angle was determined, measuring approximately 60 degrees between the endpoints for a 50 cm distance and 40 degrees for 100 cm. The next step in the evaluation process involved strategically positioning the receiver along the trajectory of the moving train. Results confirmed that data reception is restricted to predefined areas. During this phase, the initial and final values were mapped to the predefined starting and upper bound angles (Bergkemper et al., 2024).

To minimize potential biases, the train moved in both forward and reverse directions. To ensure consistent result scaling, data measurement points were linearly interpolated over the angles, ensuring an even distribution across the evaluation area under the assumption of uniform motion. This procedure was repeated for distances of 50 cm and 100 cm, with the receiver directly aligned to the transmitter at a 0-degree angle.

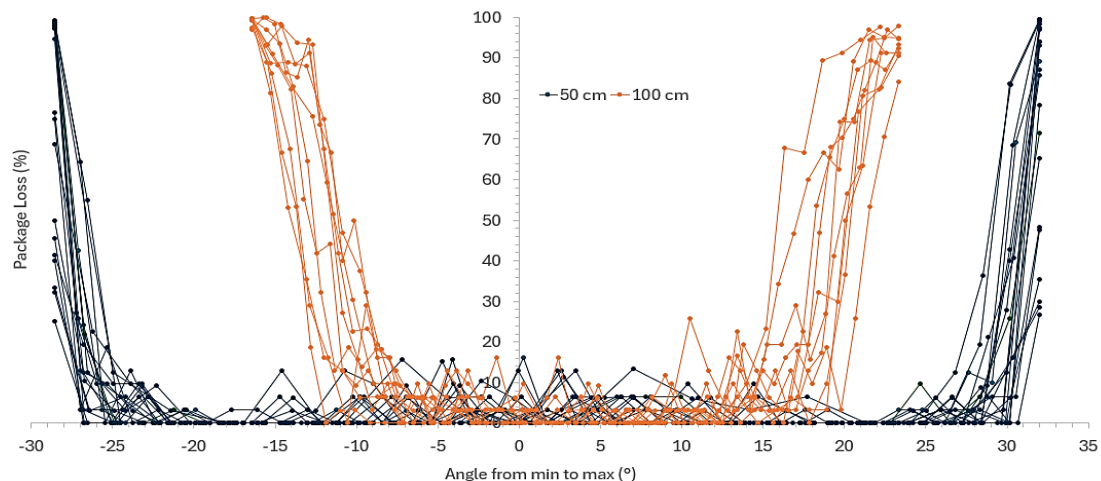


Figure 5: Packet loss in moving trains, with a 50 cm Tx-Rx distance shown in blue and 100 cm in orange

After determining the upper angular limits (typically corresponding to positions with packet loss close to 100%), the data sets were processed using linear interpolation along the x-axis, mapping the y-values to the corresponding x-values (see Figure 5). Packet loss significantly increases at both left and right boundaries. In the edge areas, a noticeable rise in packet loss is observed, whereas within the central region, loss remains consistently below 20%. Minimal signal loss occurs in the inner area, but as the receiver moves towards the periphery, signal degradation becomes increasingly significant. This transition corresponds to the edge of the field of view. However, the movement has a negligible impact on overall performance. These findings suggest that VLC maintains reliable communication within specific angular ranges, reinforcing its potential for secure short-range V2X applications when angles and distances are carefully controlled.

The experiments were conducted at an average speed of approximately 0.03 m/s for a 100 cm distance and 0.05 m/s for 50 cm. Although these speeds are relatively low, higher velocities were not feasible within the given experimental setup, as they would not allow for the collection of sufficient data records.

5. Conclusion and Future Work

While the 6G technology is still being developed (standardization starts in 2025), several enabling technologies, including Visible Light Communication, are considered key enablers. For instance, VLC can provide high data transmission rates, immunity to electromagnetic interference, and narrow beam properties, making it a promising solution for security and privacy applications by mitigating eavesdropping and jamming risks. Similarly, V2X communication has become an essential technology, facilitating low-latency, high-speed connectivity - critical for the future of autonomous driving and intelligent transportation systems.

This work examined the integration of VLC into V2X systems, focusing on security and privacy considerations. The feasibility of this integration was explored through experimental validation, demonstrating that VLC enables reliable communication within specific angular ranges (up to 60°) and at low relative speeds (up to 0.03 m/s). These findings suggest that VLC is suitable for short-range applications, including platooning, emergency message exchanges, and mitigating spectrum congestion in high-traffic areas. However, its applicability is primarily beneficial in controlled environments where LoS is maintained. Despite its advantages, the

experiments revealed several limitations: i) VLC's strong dependence on LoS and ii) its susceptibility to environmental factors, such as ambient light and adverse weather conditions, constrain its applicability in dynamic vehicular scenarios. The experimental setup was also restricted to short distances and low speeds, highlighting the need for further research to assess VLC's scalability in real-world V2X applications.

Future research will aim to expand these experiments by testing VLC under more dynamic and challenging conditions, including longer distances, higher vehicle speeds, and diverse weather scenarios. The integration of VLC with complementary technologies, such as RF communication, could mitigate some of VLC's limitations, leveraging both technologies' strengths to enhance reliability and coverage. Advancements in vehicle lighting hardware, particularly the development of programmable LEDs with enhanced beam control, will be crucial for optimizing VLC performance in practical vehicular scenarios. Exploring hybrid VLC-RF approaches and adaptive modulation techniques may further improve VLC's robustness in challenging V2X environments. This study provided initial insights into the integration of VLC in V2X communication systems. While the results remain exploratory, they underscore VLC's potential as an efficient and complementary technology for future intelligent transportation systems. By addressing current limitations and exploring hybrid approaches, VLC can contribute to enhancing communication reliability and security in real-world V2X applications.

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