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Ph.D. THESIS SUMMARY

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INTEGRATION OF VISIBLE LIGHT COMMUNICATION WITH MULTI-HOP TECHNIQUES-BASED VEHICULAR APPLICATIONS

INTEGRAREA COMUNICAȚIILOR FOLOSIND LUMINA VIZIBILĂ CU APLICATII VEHICULARE BAZATE PE TEHNICI MULTI-HOP

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Abbreviation	Meaning
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VLC	Visible Light Communication
OWC	Optical Wireless Communication
LED	Light Emitting Diode
SNR	Signal-to-Noise Ratio
BER	Bit Error Rate
LOS	Line of Sight
DSRC	Dedicated Short-Range Communication
ITS	Intelligent Transportation Systems
Li-Fi	Light Fidelity
IM/DD	Intensity Modulation and Direct Detection
PD	Photodetector
FOV	Field of View
RF	Radio Frequency
MIMO	Multiple Input Multiple Output
UAV	Unmanned Aerial Vehicle
MHz	Megahertz
GHz	Gigahertz
Tx	Transmitter
Rx	Receiver

Chapter 1

Introduction

Vehicular communication is essential for the advancement of intelligent transportation systems (ITS), enabling data exchange between vehicles and infrastructure to enhance safety and traffic efficiency. Infrastructure-to-vehicle (I2V) communication supports route planning and service updates, while vehicle-to-vehicle (V2V) communication is vital for safety features such as brake warnings and collision avoidance. Although radio frequency (RF) technologies like dedicated short-range communication (DSRC) have supported these applications, they face limitations in reliability and performance, especially in dense traffic and obstructed environments. To address these challenges, Optical Communication has emerged as a strong alternative. Among optical techniques, visible light communication (VLC) stands out for its high bandwidth, immunity to RF interference, and potential for safe, high-speed vehicular networking [1], [2], [3], [4].VLC is an emerging wireless technology that uses white LEDs to transmit both information and illumination. It operates within the visible light spectrum (380–750 nm; 430–790 THz), as shown in Figure 1.1 [1]. VLC offers advantages over RF communication, including safe frequency use for humans, no interference with sensitive electronics, and free unlicensed bandwidth. It is energy-efficient, using compact, low-cost LEDs [1], [5], [6]. VLC is suitable for both indoor and outdoor environments. Following the success of Li-Fi [7], indoor VLC has grown significantly. Vehicular VLC, though promising, progresses slowly due to environmental challenges. In ITS, LEDs support both lighting and communication [8], [9]. VLC enables V2V and V2I links using existing LED infrastructure [1],[10]. Goals include improving safety, reducing accidents, and increasing efficiency. However, challenges include LOS limitations, weather effects, reflections, and varying LED intensity [1].

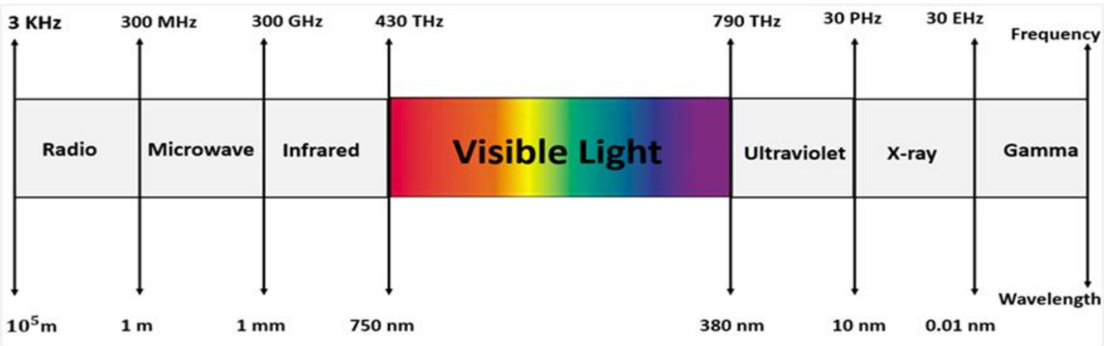


Figure 1.1 Visible light spectrum region

1.1 VLC Architectures

The VLC system includes a transmitter, receiver, and channel. White light from LEDs is modulated and transmitted through the optical wireless channel. At the receiver, a photodetector (PD) detects the modulated light. The most common technique used is Intensity Modulation and Direct Detection (IM/DD),[1],[6],[11],[12].The connection between transmitter and receiver occurs via the optical channel in free space. Light, an electromagnetic wave, decreases with the square of the distance, like other wireless systems. In the VLC design, factors differ between indoor and outdoor environments. Indoor interferences stem from wall or object reflections and nearby users.Outdoor VLC is affected by environmental factors such as sunlight and artificial light, noise, weather-induced attenuation, user movement, traffic, and user density [1], [13], [14], [12].

1.2 Advantages &Challenges of Vehicular VLC

VLC offers several distinct advantages:

- Its frequency spectrum does not pose any risk to human health .
- Ensures reliable performance without interfering with electronic devices .
- It operates in an unlicensed spectrum, offering vast bandwidth without legal restrictions .
- It serves both communication and lighting functions simultaneously.
- It is energy-efficient compared to RF systems, as it utilizes LED lights that are compact, energy-saving, and cost-effective .

However, vehicular VLC systems encounter several challenges:

- Line-of-sight (LOS) dependency, as the LOS link may not always be available along the road.
- The effects of weather conditions, including rain, snow, fog, and ice.
- Interference from both natural and artificial light sources .

For accurate vehicular VLC links, realistic channel models should incorporate the following key parameters:

- **Asymmetrical pattern:**The Lambertian model is widely used for indoor applications [14], [15],assumes symmetric light radiation.However, in vehicular VLC, lighting modules are asymmetric headlamps and taillights serve different roles .
- **Mobility:** The line of sight (LOS) between transmitter and receiver, making accurate spatial alignment critical. Movement can disrupt links between vehicles or with infrastructure .
- **Weather condition:** Adverse weather, like snow, fog, and rain, degrades vehicular VLC communication,Light interacts with atmospheric particles through diffraction, scattering, and absorption, reducing signal strength and quality .

Therefore, the implementation of relay-assisted vehicular VIC systems is critical to expanding communications range. These multi-hop architectures are particularly useful in emerging vehicle platoons, facilitating continuous communication between the lead vehicle and the one following it. The performance of vehicular VIC links is influenced by several key factors, with visibility playing a crucial role in determining the maximum possible distance.

1.3 Research Problem, Objectives, and Limitations

The concept of Vvehicular VLC is a key for intelligent transportation systems (ITS) to improve road safety, traffic flow, and fuel efficiency. To study the performance of VLC systems for vehicles, realistic channel models are the first step.

- Earlier results have focused on modeling indoor channels, which does not apply to vehicular VLC systems with their fundamentally different characteristics. For example, previous studies have assumed an idealized Lambertian model for vehicle light sources, which does not match the illumination characteristics of vehicle headlights and taillights, traffic lights, and streetlights, with their asymmetric intensity distributions. Any modification of the antenna pattern will significantly impact communication performance.
- The performance of vehicular VLC systems can be significantly affected by factors such as road surface reflectivity, road type, weather conditions, vehicle equipment and infrastructure, receiver aperture size, and ambient illumination. Therefore, there is an urgent need for in-depth research in this area, with a particular focus on its specific applications in traffic safety using realistic and practical channel modeling methods.
- Lack of line of sight (LOS) in vehicular VLC systems is a major challenge. Multi-hop communication addresses this problem by transmitting data from the source vehicle through one or more intermediate vehicles called relays until it reaches the destination vehicle.

Consequently, the main objectives of my thesis are as follows:

- Examine the performance of vehicular VLC systems using realistic channel models that take into account the influence of all the factors mentioned above.
- Investigate the performance of vehicular VLC systems based on multi-hop relay techniques to address the problem of the unavailability of the direct LOS link in different applications and to increase the transmission range.
- We first develop a comprehensive closed-form expression for the maximum communication distance of multi-relay V2V-VLC systems as a function of the system's capacity targets, incorporating all major transceiver, system, relay, and environmental parameters. The proposed closed-form expression considers the asymmetrical pattern of the vehicle's headlight and is a function of the following factors:

a. Transmit power P_t.

b. System bandwidth B.

c. Number of relays M.

d. The extinction coefficient of the weather condition c.

e. The aperture size of the detector, D_r.

f. The target system's capacity C.

- We then explore how various parameters influence the achievable communication distance, considering different scenarios and conditions.

- We further compare the results of the proposed expression based on the asymmetrical headlight pattern with the ideal Lambertian pattern.
- Additionally, we compare the performance of the proposed multi-relay V2V-VLC systems with the system without relaying techniques.
- For accurate channel modeling, we utilize the non-sequential ray tracing functionality of the OpticStudio® simulator, as detailed in prior works [16], [17]. The overall system performance is evaluated through simulations that integrate with MATLAB (MathWorks), allowing detailed analysis of the vehicular VLC system under various environmental and geometric conditions.

1.4 Thesis Content

Chapter Two offers a comprehensive review of VLC architecture in vehicular contexts, covering applications like platooning, intersection management, and lane change coordination. It highlights challenges such as road reflections, sunlight, and artificial light interference, and weather impacts, while also addressing key VLC modeling parameters like lighting asymmetry, mobility, and atmospheric effects.

Chapter Three explores V2V VLC performance using non-sequential ray-tracing for accurate channel modeling, considering uneven headlight emissions. It analyzes the effects of lateral displacement, weather, and ambient light on SNR, BER, and capacity, showing these factors significantly impact signal strength, error rates, and data throughput.

Chapter Four presents a detailed evaluation of V2V VLC performance under realistic channel models and environmental conditions, comparing Lambertian, Linear, Exponential, and Comprehensive models across weather scenarios. It assesses BER, SNR, and capacity, with the comprehensive model validated using empirical data for real-world accuracy.

Chapter Five investigates multi-relay V2V VLC performance under realistic conditions, introducing a closed-form model to estimate maximum distance based on capacity. It examines weather effects and transceiver parameters, comparing results with the Lambertian model to reveal its limitations. The study highlights the advantages of multi-relay setups in enhancing range and reliability under poor visibility.

Chapter six concludes the thesis by summarizing the key findings and contributions of the research

Chapter 2

State of the art in VLC and Vehicular VLC

Traffic congestion is a major global concern, especially in developing countries, causing delays, higher fuel use, and pollution. The growing number of vehicles also increases accident rates. According to [18], human error causes about 75% of road accidents. Implementing roadside warning systems can reduce collisions. Intelligent Transportation Systems (ITS) address these challenges by supporting safety applications like pre-collision alerts, emergency braking, lane warnings, and traffic signal violations [19]. ITS enables real-time data exchange between vehicles, including speed, location, acceleration, and engine status, improving safety and traffic management . ITS has been a research focus due to its importance in future smart cities [12], [20],enabling real-time vehicle-infrastructure communication to ease congestion and improve safety and comfort. Companies like Google, Tesla, and Uber are developing autonomous vehicles as part of the ITS advancement. This progress has been supported by emerging technologies enabling advanced transportation solutions. Key examples include vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, collectively called vehicle-to-everything (V2X) systems [1],[2].ITS must use scalable, flexible, and reliable solutions.Recently, research and standardization of V2X technologies, mainly RF-based, have grown significantly. This includes dedicated short-range communications (DSRC), adopted by several automakers [21],and 5G-based cellular V2X (C-V2X) technologies [22].While RF systems are currently suitable for ITS, future traffic density may cause interference, bandwidth limits, higher latency, and reduced transmission rates, harming communication performance.To address these challenges ,visible light communication (VLC) has emerged as a promising alternative or complement to RF technologies [1], [23], [12].VLC leverages existing lighting infrastructure like LED-equipped traffic signals, headlights, and taillights. LEDs offer higher brightness, faster switching, longer life, and lower heat than halogen light [24], making them ideal for intelligent transportation systems. Although indoor VLC research has advanced, outdoor vehicular VLC is still in its early stages and needs further R&D [1], [8], [6]. Vehicular VLC enables lighting and data transmission via LEDs in vehicles. It offers benefits over RF like resistance to interference, jamming, and spoofing, and uses a broad unlicensed spectrum. LOS communication provides secure, efficient links, supporting safety applications like vehicle presence and collision avoidance. However, maintaining LOS is difficult due to obstacles like road surfaces, buildings, vehicles, and reflectors. Environmental factors like fog, rain, snow, and ice also degrade link reliability and system performance [1], [25], [26].

2.1 VLC advantages

- Large unlicensed bandwidth
- Safe for Human Health
- Security and Interference
- Energy-efficient and inexpensive.

2.2 VLC Challenges

- Line-of-sight (LoS) Obstruction:
- Limited Communication Range
- Interference of Ambient Noise

2.3 Challenges and Solutions in Vehicular VLC

2.3.1 Impact of reflection

Weather conditions like snow, rain, and ice further affect surface reflectivity and NLOS link stability [32], [33].Road surfaces may amplify reflected signals, especially at certain angles. The distortion of optical signals through reflection, dispersion, and attenuation impacts the vehicular VLC channel, affecting its performance [1], [10], [32], [33].

2.3.2 Interference from Ambient Light Sources

A major issue for vehicular VLC systems is interference from artificial and natural light, which degrades performance. Sources like streetlights, traffic lights, billboards, and sunlight contribute to this. Direct sunlight can cause backlighting, saturating the receiver and impairing signal detection [1], [25], [34].

2.3.3 Weather Conditions

Rain degrades V2V communication by scattering, diffraction, and absorption of optical signals, leading to significant attenuation and dispersion. Research has shown that fog has the most considerable impact on VLC performance, with simulated and experimental evaluations indicating it outperforms rain and snow in terms of degradation, [1], [25], [35], [36], [37].

2.4 Vehicular VLC Applications

VLC technology enables various smart transportation applications by leveraging LED-based lighting systems. This technology is particularly useful in enhancing road safety and traffic efficiency through applications such as V2V communication, which supports collision warnings, cooperative lane changes, and vehicle coordination. V2I communication also enables vehicles to receive data from traffic signals, LED road signs, and lampposts. VLC also facilitates applications such as emergency vehicle alerts and intersection coordination. Its advantages, such as low latency, resistance to electromagnetic interference, and directional communication accuracy, make it ideal for close-range visibility scenarios in dynamic traffic environments. The following are essential applications of vehicular VLC [1], [5], [38].

- Lane changing
- Intersections Assistance
- Platooning

2.5 Critical parameters in Vehicular VLC

2.5.1 Asymmetrical pattern

Vehicular VLC links are asymmetric due to the higher power emitted by headlights compared to taillights [1], [39], [40].

2.5.2 Mobility

VLC link alignment is challenging due to vehicle motion and the narrow FOV of photodiode-based receivers. Wider FOV lenses help, but they also raise background noise, thereby reducing signal clarity [1], [38], [41].

2.5.3 Atmospheric conditions

Atmospheric conditions like rain, fog, and snow attenuate vehicular VLC signals by scattering light and blocking photons due to dense water droplets [1], [42], [35], [43], [44].

2.5.4 Receiver aperture size

Larger receiver apertures enhance signal strength, especially in low visibility, but also raise sensitivity to ambient light and misalignment [1], [12], [10].

2.6 Conclusions

Visible light communication (VLC) plays a crucial role in intelligent transportation systems (ITS), facilitating information exchange between vehicles and infrastructure. This technology helps achieve the key objectives of intelligent transportation systems (ITS), such as improving road safety, enhancing passenger comfort, and improving traffic flow. In this chapter, we first review the latest technologies in VLC and vehicular VLC and their diverse applications, including traffic control, intersection assistance, and lane change support. We then highlight the key challenges facing VLC systems, such as the impact of road surface reflections, interference from sunlight and artificial lighting, and the effects of weather fluctuations. In addition, we discuss the key parameters for modeling VLC channels, including factors such as the asymmetric nature of vehicle light sources, vehicle motion, and the characteristics of the atmospheric propagation medium.Based on the research described in this chapter I published the next paper: [1] Al Hasnawi, R., & Marghescu, I.“*A Survey of Vehicular VLC Methodologies*” Sensors 24(2), 598 ,(2024). (WOS:001151044400001)..

Chapter 3

Evaluation of V2V-VLC Performance Based on Environmental Conditions: Theoretical and Simulation

3.1 System and Channel and noise Modeling

3.1.1 System Modeling

In the scenario shown in Figure 3.1, a V2V VLC system is investigated. Two vehicles are traveling on a two-lane road with width Wr. They are separated by a longitudinal distance d, with a possible lateral displacement d_h. The transmitting vehicle (**V1**) is equipped with two headlights (**TX1** and **TX2**) with asymmetric patterns and transmit power P_t .The receiving vehicle (**V2**) is equipped with a photodetector (RX) with a response r and an aperture diameter D_r, which is critical for capturing the light signal. This scenario considers road characteristics, transmitter and receiver configurations, and the location of the two vehicles to evaluate the communication performance between the two vehicles [45], [46], [47].

3.1.2 Channel Modeling

The channel response of the VLC channels can be given by [16], [45], [46], [47].

$$h_i(t) = \sum_{k=1}^{k_i} P_i\,(k)\delta(t-\tau_i(k)) \qquad (3.1)$$

A comprehensive channel model can be given by [17], [16], [45], [46], [16]:

$$H_{Comprehensive\ model} = \left(\frac{D_r\left(\frac{d}{\sqrt{d^2+{d_{h_i}}^2}}\right)^{\frac{1}{\varepsilon}}}{\zeta\sqrt{d^2+{d_{h_i}}^2}}\right)^2 exp\left(-c\sqrt{d^2+{d_{h_i}}^2}\left[\frac{D_R}{\zeta\sqrt{d^2+{d_{h_i}}^2}}\right]^{\frac{\varepsilon}{2}}\right) \qquad (3.2)$$

3.1.3 Noise Modeling

For noise modeling, V2V VLC systems are susceptible to backlight noise (represented by thermal noise and shot noise. Therefore, the total variance of the V2V VLC system can be given by [48], [49], [45], [46].

$$\sigma^2_{total=}\,\sigma^2_{shot} + \sigma^2_{thermal,} \qquad (3.3)$$

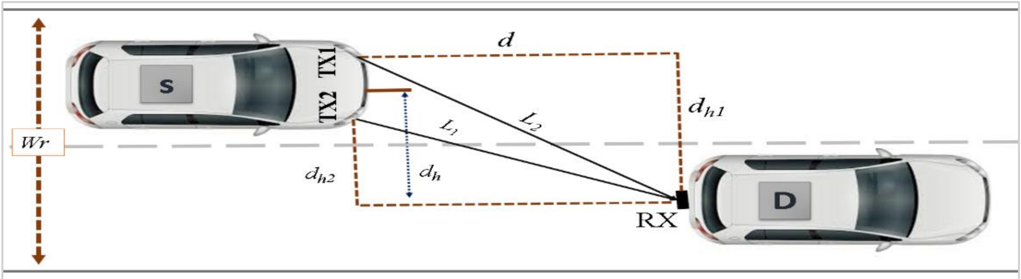


Figure 3.1 Vehicle-to-Vehicle VLC system

3.2 Performance Metrics

3.2.1 SNR performance

The SNR for V2V VLC scenario can be given by [45], [46].

$$SNR_i = \sum_{i=1}^{2} \frac{(R\, P_t\, H_i)^2}{\sigma_{total}^2}, \tag{3.3}$$

3.2.2 BER Performance

The BER for V2V VLC scenario is described by [50], [45], [46]:

$$P_e = \frac{1}{2} erfc\left(\frac{\sqrt{\gamma}}{2\sqrt{2}}\right), \tag{3.4}$$

3.2.3 Capacity Performance

The system capacity of V2V VLC scenario is described by [45], [46]:

$$C \approx \frac{B}{2} ln\left(1 + \frac{exp\,(1)\gamma}{2\pi}\right), \tag{3.5}$$

3.3 Numerical Results and Analytical Discussion

3.3.1 SNR Results

1.Impact of weather conditions

Figure 3.2 (a) investigates SNR versus distance. The fog condition significantly degrades performance due to light absorption and scattering.

2.Impact of lateral shift

Figure 3.2(b) shows SNR versus distance for lateral shifts of 0 m, 1 m, 2 m, and 3.75 m. Small lateral shifts have little impact, but larger lateral shifts significantly degrade performance [43].

3.Impact of ambient light interference

Figure 3.2 (c) shows that the effect of artificial interference is small compared to the noise of sunlight .

3.3.2 BER Results

1.Impact of weather condition

Figure 3.3(a) shows that moderate fog and thick fog have a relatively large effect.

2.Impact of Lateral Shift

Figure 3.3 (b) shows that at the lateral shift the lateral shift d_h =3.75 m, the system performance begins to deteriorate significantly..

3.Impact of ambient light interference

In Figure 3.3 (c), we notice that street light noise has a smaller effect when compared to sunlight noise.

3.3.3 Achievable Capacity Results

1.Impact of Weather Condition

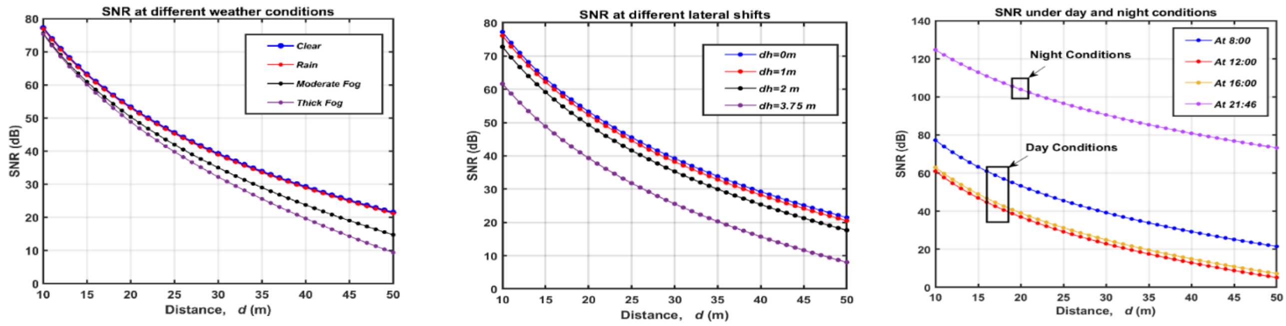
Figure 3.4 (a) shows that moderate fog and thick fog have a relatively large effect.

2.Impact of Lateral Shift

Figure 3.5 (b) shows at the lateral shift d_h = 3.75 m, the system performance begins to deteriorate significantly.

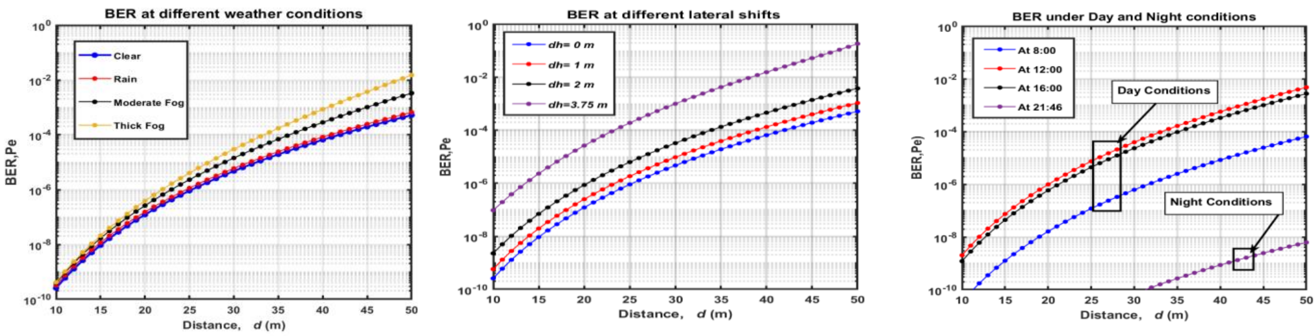
3.Impact of Ambient lights

In Figure 3.4(c), we notice that street light noise during the night has a smaller effect when compared to sunlight noise during the day.



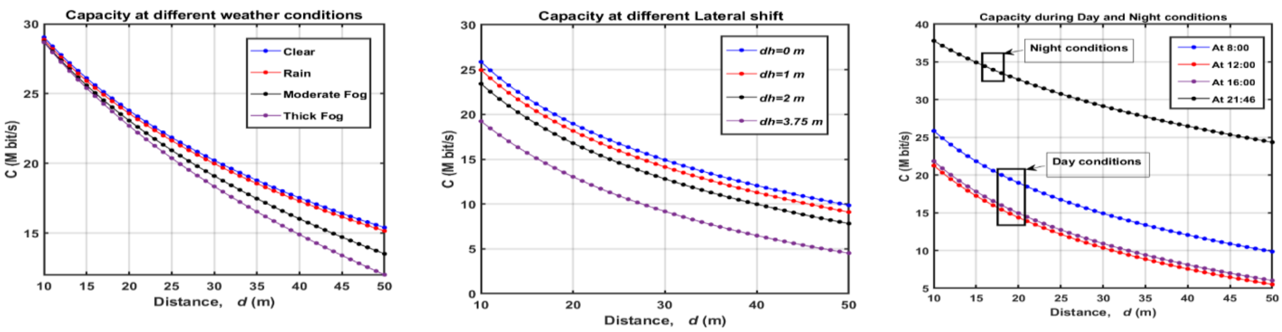
(a) (b) (c)

Figure 3.2 SNR versus distance for:(a) weather conditions, (b) lateral shifts, (c) Ambient lights



(a) (b) (c)

Figure 3.3 BER versus distance for (a) weather conditions, (b) lateral shifts, (c) Ambient lights



(a) (b) (c)

Figure 3.4 Capacity versus distance:(a) weather conditions, (b) lateral shifts,(c) Ambient lights

3.4 Conclusion

This chapter provides a comprehensive evaluation of the performance of a V2VVLC system. The analysis uses a non-sequential ray tracing method that takes into account the non-uniform distribution of headlight emissions. Key performance metrics, such as signal-to-noise ratio (SNR), bit error rate (BER), and system capacity, are thoroughly examined. The study examines the effects of lateral displacement, varying weather conditions, and ambient light interference.The results emphasize the critical role of weather conditions, particularly fog density, in degrading V2V VLC system performance. Thick fog causes significant attenuation due to scattering and absorption, significantly reducing the number of photons reaching the receiver. The study also confirms that lateral shifts directly impacts performance. While small deviations cause minor degradation, larger shifts significantly reduce the SNR ratio and reduce communication range. The analysis shows that direct sunlight poses a greater than artificial streetlights. Sunlight induces high-intensity spectral noise that can saturate photodetectors, significantly degrading signal integrity. In contrast, street lighting exhibits lower intensity and, therefore, has a relatively small impact on system performance. The findings presented in this chapter have been published in:

1. [46] Al Hasnawi, R., Marghescu, I., & Rusu-Casandra, A.“*Reliability and Capacity Evaluation for Vehicle-to-Vehicle VLC*”.In 15th International Conference on Communications (COMM 2024, October)(pp. 1-6). IEEE xplore, (DOI :10.1109/COMM62355.2024.10741390).

2. [45] Al Hasnawi, R., Marghescu, I., & Amjed A Al-Mudhafar.“*Comprehensive Evaluation of Environmental Impact on the Performance of V2V Visible Light Communication*”. In 5th Middle East and North Africa Communications Conference (MENACOMM 2025)(pp.1-6). IEEE xplore, (DOI:10.1109/MENACOMM62946.2025.10911014).

Chapter 4

Benchmarking Channel Models for Realistic V2V-VLC Systems

4.1 System Model

For the system model, we consider the V2V-VLC scenario shown in Chapter Three (Figure 3.1).

4.2 Channel Model

4.2.1 Comprehensive Model

For the comprehensive model, as we explained earlier in chapter 3 (see Eq. (3.2)).

4.2.2 Exponential Model

The channel gain is written as [47], [16], [53]:

$$H_{Exponential\ model} = P_t \underbrace{Ad^{-2B}\ exp\ (-cd)}_{p} \tag{4.1}$$

4.2.3 Linear Model

The corresponding channel gain is defined as follows [54], [47]:

$$H_{Linear\ model} = P_t(\alpha d + \beta), \tag{4.2}$$

4.2.4 Lambertian Model

The channel gain is expressed as follows: [55], [14], [47]:

$$Hi_{\substack{Lambertian= \\ Model}} 10log_{10}\left(\frac{1}{2}\sum_{i=1}^{2}\left(\left(\frac{\frac{\pi {D_R}^2}{4}(m+1)}{2\pi\sqrt{d^2+{d_{h_i}}^2}}cos^m(\theta_i)\,cos(\emptyset_i)\right)\right)exp\left(-c\sqrt{d^2+{d_{h_i}}^2}\right)\right) \tag{4.4}$$

4.2.5 Empirical model

The channel model from [40],derived through curve fitting to empirical data, is expressed as

$$H_{Empirical} = \alpha + \beta 10 \cdot log\ \ 10(\frac{1}{d+\gamma}) \tag{4.5}$$

4.3 Results and discussions

4.3.1 BER Results

Figure 4.1 shows BER vs. distance. The comprehensive model aligns well across weather types. The Lambertian model deviates under bad weather, and the linear model ignores weather effects.The exponential model fits closely with the comprehensive model.

4.3.2 Capacity Results

Figure 4.3 shows system capacity vs. distance for four weather conditions . The comprehensive model performs reliably, while Lambertian deviates in bad weather. The linear model ignores weather effects, and the exponential model aligns well. Capacity drops in fog due to photon loss.

4.3.3 Evaluation of Empirical and Comprehensive Models

This section compares the comprehensive and empirical models. In clear weather in Figure 4.2, they align closely; however, under thick fog, the comprehensive model deviates due to scattering, while the empirical model remains unchanged.

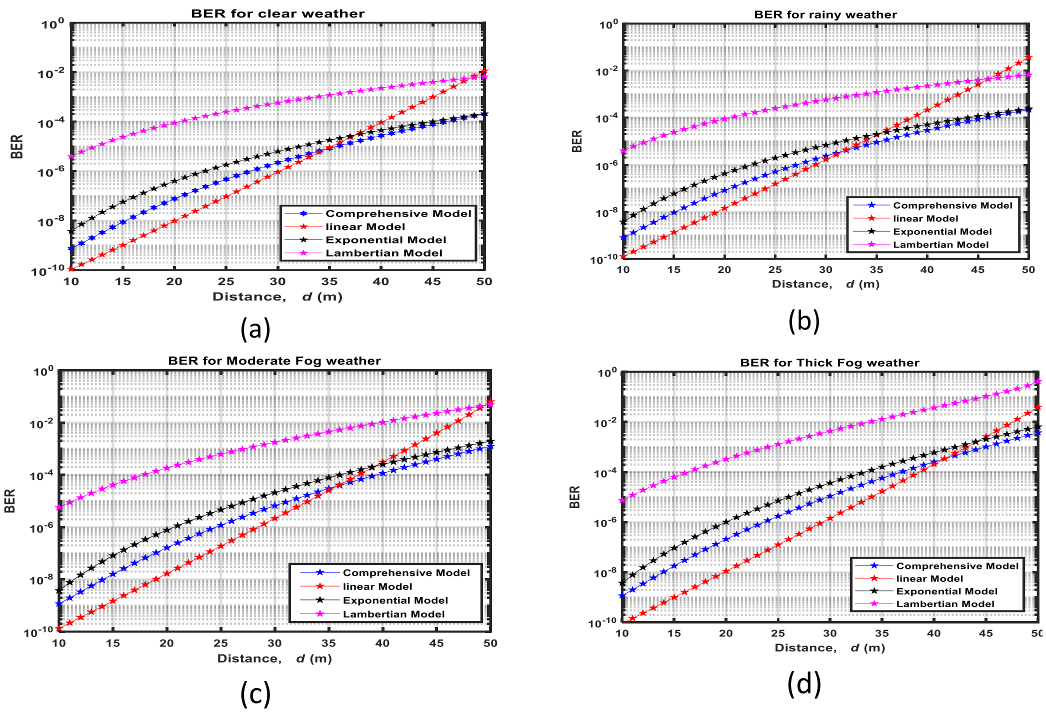


Figure 4.1 BER Results Under Different Weather Conditions

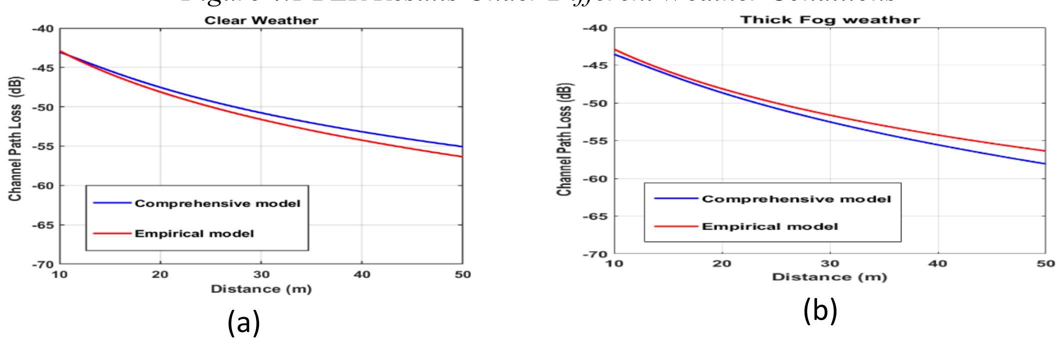


Figure 4.2 Comparison: Comprehensive vs. Empirical Model in (a) Clear and (b) Thick Fog

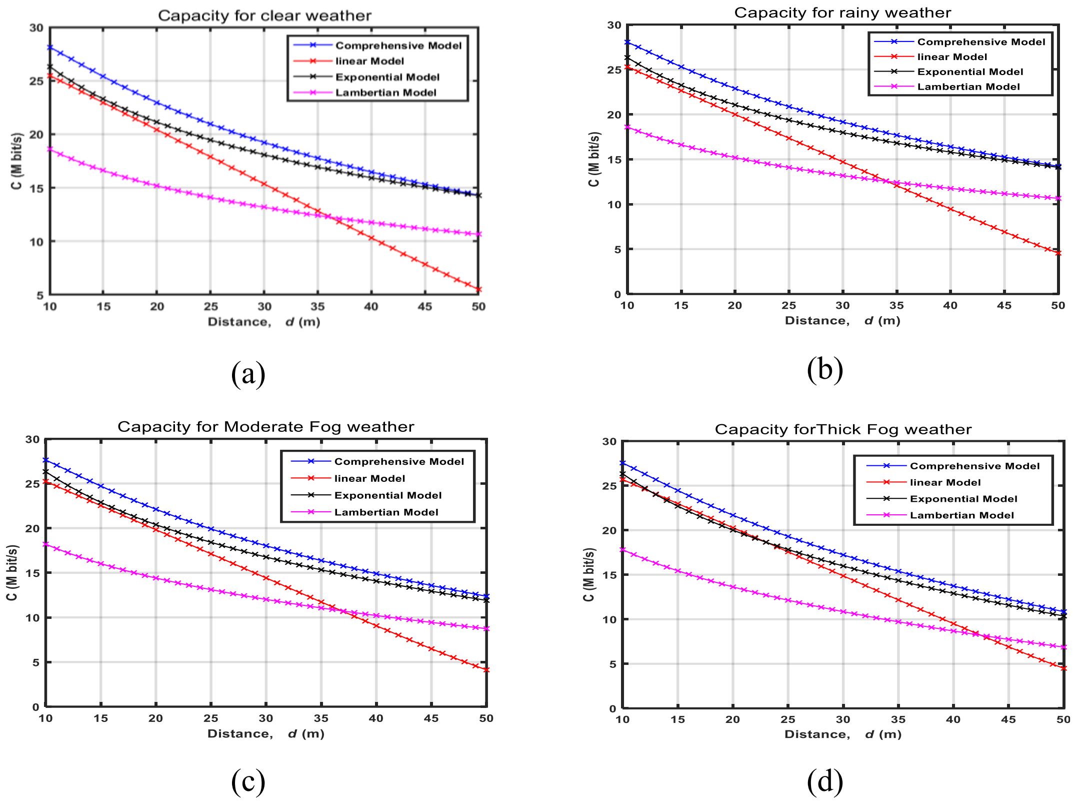


Figure 4.3 System capacity under different weather conditions.

4.4 Conclusion

This chapter presents a comprehensive analysis of V2V-VLC systems using four channel models under various environmental conditions. The comprehensive model showed the highest accuracy, though fog reduced its performance. The Lambertian model performed poorly in adverse weather, while the linear model ignored environmental effects. The exponential model closely matched the comprehensive one, showing good adaptability. In clear conditions, the comprehensive model aligned well with empirical data, which remained unaffected by weather changes.

The findings discussed in this chapter have been published in the following paper:

[47] Al Hasnawi, R., Militaru, N., & Rusu-Casandra, A."*Influence of Channel Modeling and Atmospheric Conditions on the Reliability and Capacity of V2V VLC Systems*". In 15th International Conference on Communications (COMM 2024, October), (pp. 1-6). IEEE xplore (DOI: 10.1109/COMM62355.2024.10741462).

Chapter 5

Evaluating Multi-Hop Performance in Vehicular VLC Systems

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5.1 System Model

We consider a multi-hop V2V-VLC system (Figure 5.1) where vehicles move in a single lane along a road of width W.The source (**S**) and destination (**D**) are separated by distance *dx*, with *M* intermediate relay vehicles (**V1, V2, ..., VR**) spaced by d_{Relay}. Each vehicle uses two headlights (HLs) as VLC transmitters, and a rear photodetector with response *r* and aperture diameter *Dr* [53].The VLC channel impulse response (CIR) can be described as [17], [53]:

$$h(t) = \sum_{m=1}^{M} P_m \, \delta\,(t - \tau_m), \tag{5.1}$$

The channel gain between transmission and the receiving is given by [17], [53]:

$$H = \left(\frac{Dr}{\zeta dx}\right)^2 exp\left(-cdx\,\left(\frac{Dr}{\zeta dx}\right)^{\varepsilon/2}\right), \tag{5.2}$$

5.2 Performance Criteria

We evaluate V2V-VLC performance under two scenarios: direct and multi-hop relay links.

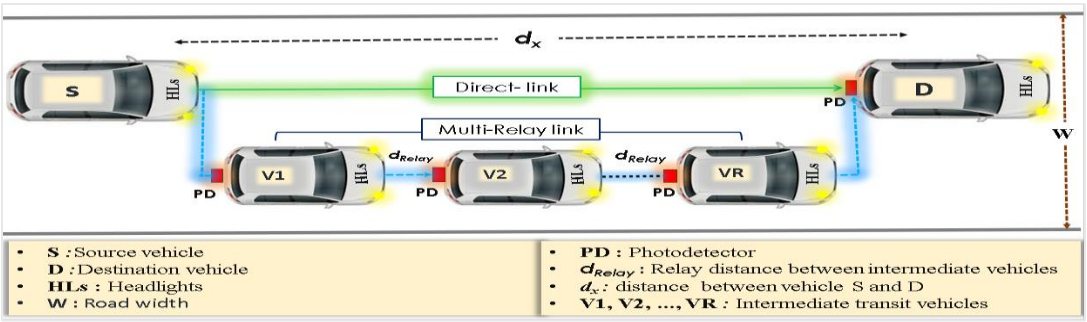


Figure 5.1 Multi- hop relay link for Vehicle-to-Vehicle VLC system

5.2.1 Direct- link

We consider a direct connection (i.e.,*M*=0), we derive the mathematical expression for the transmission range dx can be determined from (5.1) using the Lambert W function [17], [53].

$$d_x = \left(\frac{\mathrm{W}\left(\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)\, H^{\left(\frac{\varepsilon-2}{4}\right)}\right)}{\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)^{\frac{\varepsilon}{2}}}\right)^{\frac{2}{2-\varepsilon}}, \tag{5.3}$$

Moreover, the system capacity and BER are given by [53]:

$$C \approx \frac{B}{2} ln\left(1 + \frac{\exp(1)\gamma}{2\pi}\right), \tag{5.4}$$

$$P_e = \frac{1}{2}\, erfc\left(\frac{\sqrt{\gamma}}{2\sqrt{2}}\right), \tag{5.5}$$

Where γ denotes the signal-to-noise ratio (SNR), can be written as [17]:

$$SNR = \frac{(\eta\, r\, H)^2 P_t}{\sigma_n^2}, \tag{5.6}$$

where the noise variance is $\sigma_n^2 = N_0 B$, by substituting (5.6) into (5.4) ,solving for H, we can then obtain:

$$H = \sqrt{\frac{2\pi\sigma_n^2}{exp(1)Pt\,\eta^2 r^2}}\left(exp\left(\frac{2C}{B}\right) - 1\right)^{\frac{1}{2}}, \tag{5.7}$$

From (5.3) and (5.7),we derive the maximum communication distance that satisfies a capacity target as:

$$d_{Cx} = \left(\frac{W\left(\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)\left(\sqrt{\frac{2\pi\sigma_n^2}{exp(1)Pt\,\eta^2 r^2}}\left(exp\left(\frac{2C}{B}\right)-1\right)^{\frac{1}{2}}\right)^{\left(\frac{\varepsilon-2}{4}\right)}\right)}{\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)^{\frac{\varepsilon}{2}}}\right)^{\frac{2}{2-\varepsilon}}, \tag{5.8}$$

Similarly, the maximum communication distance that satisfies a BER target as [57]:

$$d_{ex} = \left(\frac{W\left(\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)\left(2\sqrt{2}\left(\sqrt{\frac{\sigma_n^2}{P_t\,\eta^2 r^2}}\right)(erfc^{-1}(2P_e)\right)^{\left(\frac{\varepsilon-2}{4}\right)}\right)}{\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)^{\frac{\varepsilon}{2}}}\right)^{\frac{2}{2-\varepsilon}}, \tag{5.9}$$

5.2.2 Multi-Relay link

We consider a multi-relay link relying on deploying intermediate M relays (Figure 5.1) with equal separation distance (d_{relay}), hence the capacity for all relays C_{relay} is given by :

$$C_{relay} \approx \frac{C_T}{M+1}, \tag{5.10}$$

From (5.8) and (5.10), the maximum distance for the multi-relay link based on target capacity is given by:

$$d_x < (M+1)\left(\left(\frac{W\left(\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)\left(\sqrt{\frac{2\pi\sigma_n^2(M+1)}{exp(1)Pt\,\eta^2 r^2}}\left(exp\left(\frac{2C}{B(M+1)}\right)-1\right)^{\frac{1}{2}}\right)^{\left(\frac{\varepsilon-2}{4}\right)}\right)}{\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)^{\frac{\varepsilon}{2}}}\right)^{\frac{2}{2-\varepsilon}}\right), \tag{5.11}$$

Similarly,the maximum distance for the multi-relay link as a function of the BER target is derived as [57].

$$d_x < (M+1)\left(\left(\frac{W\left(\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)\left(2\sqrt{2}\left(\sqrt{\frac{\sigma_n^2(M+1)}{P_t\,\eta^2 r^2}}\right)(erfc^{-1}\left(\frac{2P_e}{(M+1)}\right)\right)^{\left(\frac{\varepsilon-2}{4}\right)}\right)}{\frac{c}{4}(2-\varepsilon)\left(\frac{Dr}{\zeta}\right)^{\frac{\varepsilon}{2}}}\right)^{\frac{2}{2-\varepsilon}}\right), \tag{5.12}$$

5.3 Impact of the atmospheric conditions

5.3.1 Direct-link Scenario

Figure 5.2 shows the maximum distance a direct link ($M = 0$) ,we note the rain has a minor impact, while moderate and thick fog reduces the range significantly. Higher power improves range, but fog still degrades performance.

5.3.2 Multi-Relay Scenarios

Figure 5.3 shows the maximum distance a multi-relay (M = 3) under different weather conditions and power levels. We note rain has a minor effect, while fog significantly reduces range due to photon scattering and absorption.

5.3.3 Evaluation of Direct and Multi-Relay Link Models

Figure 5.4 shows the maximum distance for direct and multi-relay links under clear and thick fog, comparing the proposed and Lambertian models. Results show that the Lambertian model underestimates range by ignoring key factors like atmospheric effects, angular misalignment, and beam divergence [53].

5.4 Different Receiver Apertures Impact

Figure 5.5 examines the maximum distance versus capacity for different aperture sizes (1 cm,2 cm,3cm,4cm). The results reveal that increasing the diameter significantly enhances the maximum range, owing to the larger receiving area, which allows the receiver to capture more rays.

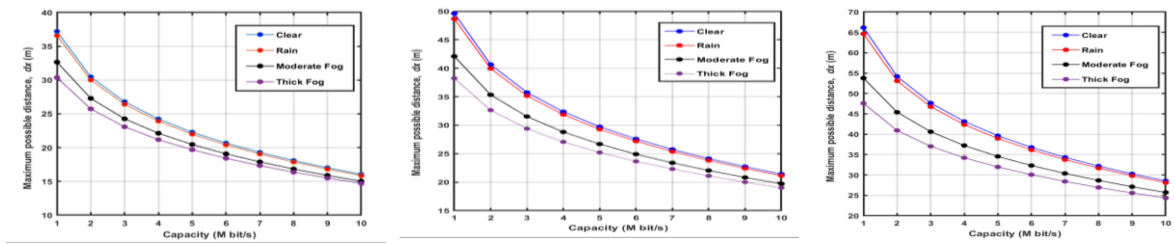
5.5 Impact of Relay Number,Capacity, BER

5.5.1 Impact of relay numbers on Max distance

Figure 5.6 shows that the effect of increasing the number of relays greatly enhances the transmission distance.These findings confirm that incorporating more relays enhances system reliability and expands coverage .

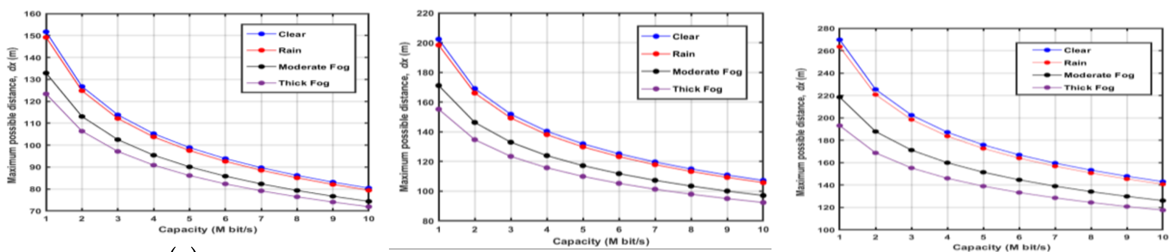
5.5.2 Influence of Capacity and BER on Max distance.

Figure 5.7 analyzes the impact of capacity levels on maximum distance.It is observed the transmission distance improves as the number of intermediate relays rises. It is observed the maximum distance improves as the number of relays rises. Additionally, it is observed that a stricter BER requirement results in a reduced transmission range.This trend highlights the trade-off between achieving lower BER values and the corresponding decrease in the achievable transmission distance.



(a) (b) (c)

Figure 5.2 Maximum distance of direct-link vs. capacity under different conditions



(a) (b) (c)

Figure 5.3 Maximum distance of multi-relay vs. capacity under different conditions

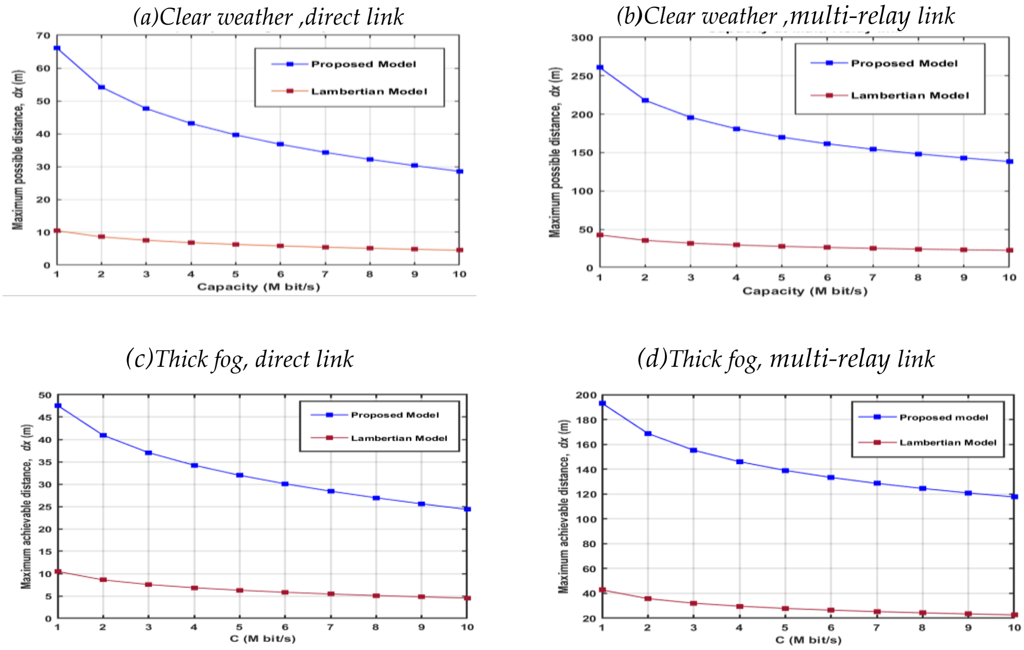
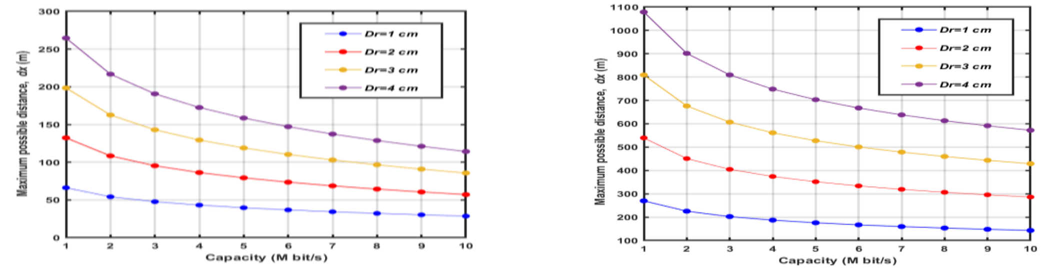
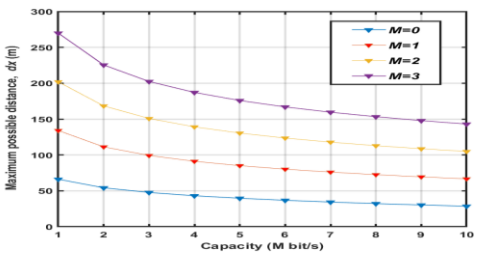


Figure 5.4 Maximum dx for proposed and Lambertian models:for direct and multi-relay links.

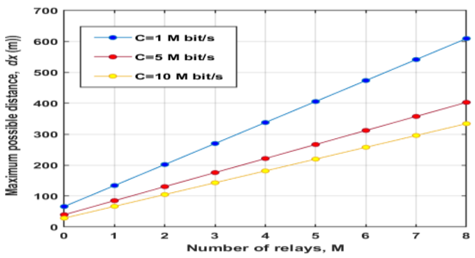


(**a**) (**b**)

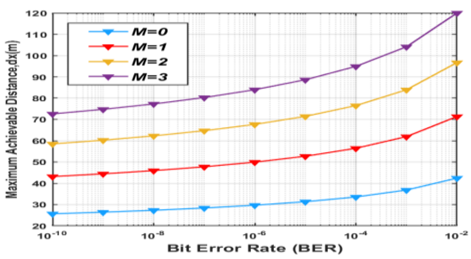
Figure 5.5 Max. distance vs. capacity at varying apertures (a) direct link (b) multi-relay link.



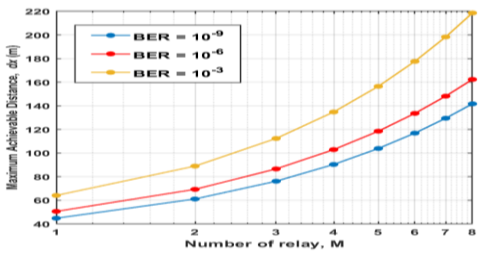
(a)



(a)



(b)



(b)

Figure 5.6.Maximum distance vs. (a) Capacity and (b) BER at various relay numbers (M).

Figure 5.7.Maximum distance vs. relay number for (a) Capacities,(b) BER

5.6 Conclusions

This chapter evaluates multi-hop V2V-VLC performance under realistic channel conditions, considering asymmetric headlight patterns. A closed-form model estimates maximum communication distance based on system capacity, accounting for various weather conditions and system parameters. Results show dense fog reduces direct range by ~19.5% (to 33 m at 25 dBm), while three relays extend it to 140 m in fog and 170 m in clear weather. Compared to the Lambertian model, the proposed model offers higher accuracy. A 4 cm aperture supports up to 700 m, and seven relays achieve 358 m at 5 Mbps. Multi-hop relays significantly enhance coverage and reliability in challenging environments. These findings highlight the effectiveness of multi-hop strategies in enhancing V2V-VLC performance and reliability across diverse real-world conditions.

The findings discussed in this chapter have been published in the following paper:

[53] Al Hasnawi, R., Marghescu, C. I., & Rusu-Casandra, A. "*Enhancing Vehicular VLC Systems with Multi-RelayTechniques: A Performance Evaluation. Electronics*", 14(6),1170. (2025) .(WOS: 001453878700001).

Chapter 6

Conclusions

Visible Light Communication (VLC) technology has emerged as a promising alternative to traditional radio communications, particularly in vehicular networks. By enabling seamless data exchange between vehicles and infrastructure, VLC plays a critical role in intelligent transportation systems (ITS), supporting key objectives such as enhancing road safety, improving passenger experience, and optimizing traffic management. This thesis focuses on the integration of VLC with multi-hop techniques-based vehicular applications, a novel approach aimed at improving the performance, coverage, and reliability of vehicular systems, especially in challenging environments and non-line-of-sight scenarios. This work contributes to the development of robust and efficient Vehicle-to-Vehicle (V2V) communication systems.The thesis consists of six chapters :

Chapter 1 introduces Visible Light Communication (VLC), highlighting its characteristics, vehicular applications, and the main objectives of the thesis focused on improving vehicular communication performance using VLC and multi-hop techniques.

Chapter 2 presents an in-depth literature review of vehicular VLC systems and their applications (e.g., platooning, intersection management, lane changing). It also discusses major challenges such as reflections, interference from sunlight/artificial light, and atmospheric conditions, along with essential parameters for accurate channel modeling, like asymmetric headlight patterns and vehicle mobility.

Chapter 3 details a realistic V2V-VLC channel model using non-sequential ray tracing to reflect non-uniform headlight emissions. It analyzes the impact of lateral displacement, ambient light, and weather on key metrics such as signal-to-noise ratio (SNR), bit error rate (BER), and system capacity.

Chapter 4 offers a comparative analysis of four channel models (Lambertian, Linear, Exponential, and Comprehensive) under various weather conditions. The comprehensive model, validated through realistic data, shows superior accuracy in predicting system performance in terms of BER, SNR, and capacity.

Chapter 5 investigates a multi-relay V2V-VLC system under realistic conditions, considering asymmetric headlight emissions and atmospheric effects. A closed-form model is developed to estimate maximum communication range based on system parameters and capacity constraints. Results confirm the effectiveness of multi-hop relaying in improving range, coverage, and reliability, particularly in low-visibility scenarios.

Chapter 6 concludes the thesis, summarizing key findings and suggesting future research directions.

6.1 List of original publications

• Papers published during the PhD stage

1- Al Hasnawi, R., & Marghescu, I. "*A survey of vehicular VLC methodologies*". Sensors, 24(2), 598,(2024). (WOS:001151044400001), [1].

2- Al Hasnawi, R., Marghescu, I., & Rusu-Casandra, A."*Reliability and Capacity Evaluation for Vehicle-to-Vehicle VLC* ".In 15th International Conference on Communications (COMM 2024, October)(pp. 1-6). IEEE xplore,(DOI :10.1109/COMM62355.2024.10741390), [46].

3- Al Hasnawi, R., Marghescu, I., & Amjed A Al-Mudhafar.“*Comprehensive Evaluation of Environmental Impact on the Performance of V2V Visible Light Communication*”.In 5th Middle East and North Africa Communications Conference (MENACOMM 2025)(pp.1-6).IEEE xplore, (DOI :10.1109 /MENACOMM 62946.2025.10911014) [45].

4- Al Hasnawi, R., Militaru, N., & Rusu-Casandra, A.“ *Influence of Channel Modeling and Atmospheric Conditions on the Reliability and Capacity of V2V VLC Systems*”. In 15th International Conference on Communications (COMM 2024, October), (pp. 1-6). IEEE xplore, (DOI: 10.1109/COMM 62355. 2024. 10741462), [47].

5- Al Hasnawi, R., Marghescu, C. I., & Rusu-Casandra, A.“*Enhancing Vehicular VLC Systems with Multi-Relay Techniques: A Performance Evaluation*”. Electronics, 14(6), 1170,(2025).(WOS:001453878700001), [53].

6.2 Future Works

In the future, further exploration of in-vehicle visible communication technologies and applications could significantly enhance safety within intelligent transportation systems ITS . Key research directions include:

1. Artificial intelligence and machine learning:The application of AI and machine learning algorithms toin-vehicle visible communication offers promising potential for improving system performance and enhancing safety, making in-vehicle visible systems more adaptive and robust.

2. Hybrid Communications Integration: Exploring the integration of "dedicated short-range communications (DSRC)" and "cellular V2X (C-V2X)" communications with VLC to improve vehicular communication efficiency.The hybrid approach could enhance both communication reliability and data capacity, especially in environments with varying communication requirements.

3. Experimental Validation in Real-Life Scenarios: Conducting field experiments in urban and rural environments is essential to evaluate the practical performance of the V2V-VLC systems.Practical tests will provide valuable data for system optimization and guidance for future improvements.

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