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Vehicular Visible Light Communication Channel Models: A systematic review

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Executive Summary

This study reviews current channel models for Vehicular Visible Light Communication (V-VLC) within the context of Intelligent Transportation Systems. While radio-frequency (RF) systems, such as Wi-Fi and cellular networks, face interference, bandwidth challenges, network congestion, and security issues, V-VLC emerges as a promising alternative. Its license-free spectrum, broad bandwidth, energy efficiency, and existing transmitters make it attractive for vehicular communication. Through a combination of V-VLC and traditional RF communication systems, a large ecosystem of connected vehicles could be obtained, improving safety and efficiency for the future fleet of electric (autonomous) vehicles. Despite successful indoor implementations, outdoor applications of V-VLC require further research. The focus of this review is on assessing the advancements of V-VLC as a valuable addition to vehicular networks, with a specific emphasis on photometric aspects of the optical channel models.

1 Introduction

In contemporary times, despite a noticeable decline in road fatalities, traffic accidents persist as a primary cause of mortality worldwide, particularly among young individuals and adults, as highlighted in the *World Health Organization: Global Status Report On Road Safety 2018* [1]. Addressing this issue necessitates augmenting road safety measures through the integration of Advanced Driver Aid Systems (ADAS), intelligent transportation systems (ITS), and autonomous vehicles (AV) within vehicular fleets [2]. The widespread adoption of such technologies requires enhanced vehicle-to-everything (V2X) communication capabilities, of which vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication are the most important ones.

Numerous communication technologies are employed in vehicular environments, primarily relying on radio frequencies (RF) for V2V and V2I communication. However, RF-based communication presents various limitations, including high latency, low data throughput, limited penetration in underground roads, and high interference in crowded urban scenarios [3, 4]. Additionally, spectrum limitations and licensed spectra exacerbate the spectrum crunch for Internet-of-Things (IoT) and machine communications [2, 5, 6]. Visible Light Communication (VLC) emerges as a promising alternative, utilising the license-free visible part of the electromagnetic spectrum for data transmission, offering advantages such as robustness, energy efficiency, wide spectrum availability, low latency, and high data rates [7–9]. Vehicular VLC (V-VLC) specifically holds promise for applications in ITS, facilitating communication between electric vehicles (EVs) and surrounding infrastructure, thereby enhancing traffic monitoring, regulation, flow, and energy consumption. Despite its potential for dual use of data communication and illumination, V-VLC cannot serve as the sole communication method due to limitations such as a limited range and its line-of-sight nature [2, 7]. The latter implies that light has to travel through air from a source or transmitter, up to a detector or receiver. Fig. 1 provides a schematic overview of the V-VLC topology, incorporating considerations of link geometry and atmospheric influences that impact communication quality between transmitter and receiver, as modelled through the optical channel.

Channel models are an essential part to assess the fundamental limits of a communication system and optimise designs [10–13]. In this study a comprehensive summary of the current state of optical channel models for V-VLC based on a systematic literature review is presented. Through a review of the existing research, the most adequate optical channel model for V-VLC using full LED headlamps is searched with a focus on the photometric aspect, i.e. the light source modelling and the propagation of the optical radiation through the optical channel. The article proceeds with a discussion on research methodologies, summarising relevant review papers and recent original research, followed by a discussions on future research directions before concluding.

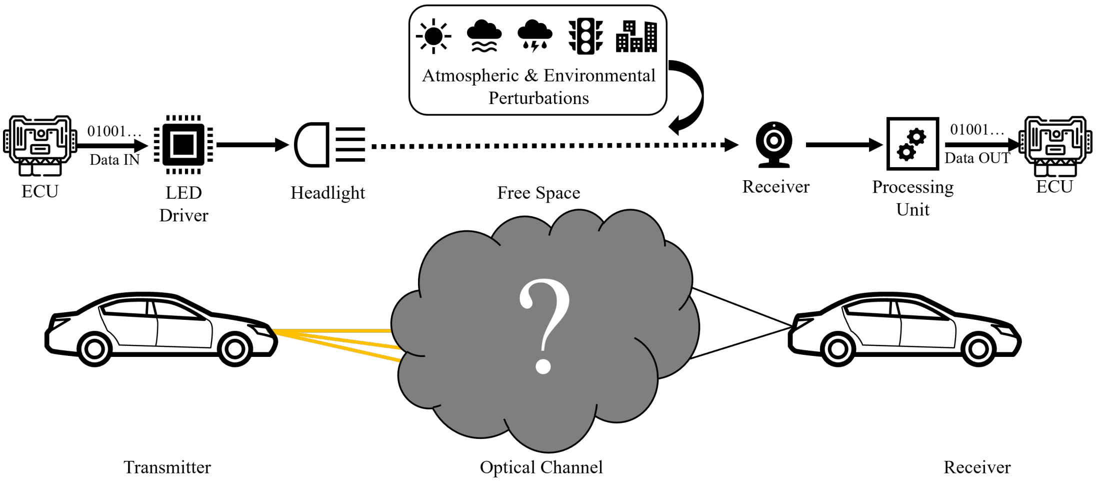


Figure 1: Schematic overview of the V-VLC working principle. The cloud in between transmitting and receiving vehicle represents the optical channel model requiring more attention.

2 Materials and Methods

Consistent with the methodology employed by Yahia et al. [8] and Shaaban et al. [9], this review adopts a systematic approach. The search strategy, databases utilised, and criteria for inclusion and exclusion in the two-stage selection process are transparently presented to ensure reproducibility.
Two primary sources are employed in this paper: review articles and journal papers. Review articles serve to synthesise existing research and track the evolution of ideas, while journal papers highlight the latest advancements in V-VLC channel modelling. Review articles were sought using specific keywords pertinent to the field (see Table 1), within the publication time frame of 2013-2023 to capture research from the past decade. Bibliographic databases used include *Web of Science*, *IEEE*, *Scopus*, and *Springer*, although it should be noted that Springer's database offers less advanced search capabilities, resulting in fewer results. A total of 18 review articles were identified, from which 16 were retrieved and 8 were ultimately included based on predefined inclusion and exclusion criteria outlined in Table 2.

Table 1: Keywords and synonyms used to build a search string employed in the retrieval of review papers.

Boolean	Keyword	Boolean	Synonyms
AND	Vehicular	OR	Vehicle
		OR	Car
		OR	Automotive
		OR	Automobile
		OR	Outdoor
		OR	Transportation
		OR	Transport
		OR	Intelligent Transportation System
		OR	Intelligent Transport System
		OR	ITS
AND	Visible Light Communication	OR	Light Communication
		OR	VLC
		OR	Optical Communication
		OR	Optical Wireless Communication
		OR	OWC
		OR	Optical Camera Communication
		OR	OCC
		OR	Light-Fidelity
		OR	Li-Fi
AND	Review	OR	Survey
		OR	Overview

Drawing on recurring keywords and insights gleaned from the identified review papers, a database of original research papers is compiled to synthesise, critically evaluate, and consolidate the latest advancements. The search

Table 2: Inclusion and exclusion criteria employed for the retrieved review papers.

Inclusion Criteria
Review papers on the subject of V-VLC channel modelling
Publication Date between 2013 and 2023
Publications containing each keyword or their respective synonym in the title, abstract or keywords and metadata
Publications related to the research questions
Exclusion Criteria
Review papers on the general subject of VLC
Review papers not related to the vehicular environment (or associated synonyms)
Papers from which full versions are not available
Papers in a language different from English, French or Dutch
Non review papers
Non peer-reviewed papers

terms utilised to identify papers are detailed in Table 3. Given that the most recent review paper focusing on V-VLC was submitted by the close of 2020, the time frame for sourcing original research papers is confined to the years 2021 through 2024. Moreover, this investigation will confine its scope to peer-reviewed journal publications, excluding conference proceedings. In total, 93 papers have been found. Duplicates were eliminated through the duplicate detection of *Rayyan.ai* resulting in 67 papers for the two rounds of screening. Following the inclusion and exclusion criteria outlined in Table 4, 31 papers are retained based on the abstract and title screening, which was performed by 3 of the authors of this paper. Whenever there were discrepancies, these were discussed afterwards until an agreement was reached. In this procedure it was chosen to give the benefit of the doubt in case there was doubt, meaning it was preferred to include a paper at this stage to make a final decision after the full-text read. After the full read, i.e. second screening stage which was performed solely by the first author of this paper, 16 papers are kept for discussion and analysis. The other papers are rejected because they are out of scope of this concise review, not within the inclusion criteria or belonging to the exclusion criteria.

Table 3: Keywords and synonyms used to build a search string employed in the retrieval of original peer reviewed journal papers.

Boolean	Keyword	Boolean	Synonyms
AND	Vehicular	OR	Vehicle
		OR	Car
		OR	Automotive
		OR	Automobile
		OR	Outdoor
		OR	Transportation
		OR	Transport
		OR	Intelligent Transportation System
		OR	Intelligent Transport System
		OR	ITS
AND	Visible Light Communication	OR	Light Communication
		OR	VLC
		OR	Optical Communication
		OR	Optical Wireless Communication
		OR	OWC
		OR	Optical Camera Communication
		OR	OCC
		OR	Light-Fidelity
		OR	Li-Fi
AND	Channel Model	OR	Channel Characteristics
		OR	Channel
		OR	Optical Model
		OR	Path Loss
		OR	Channel Link
		OR	Channel Simulation
AND	Vehicle to Vehicle	OR	Car to Car
		OR	V2V
		OR	C2C
AND	Luminous Intensity Distribution	OR	Radiation Pattern
		OR	Irradiance Pattern
		OR	Light Propagation
AND	LED	OR	Matrix LED
		OR	Beam
		OR	Headlamp
		OR	Taillight

3 Existing reviews

In this section, the V-VLC systems will be introduced based on established review papers. First, the VLC architecture depicted in Fig. 1 will be elaborated upon, followed by an overview of the channel models developed up to the year 2021, along with a theoretical introduction.

Table 4: Inclusion and exclusion criteria employed for the retrieved original research papers.

Inclusion Criteria
Papers focusing on the subject of V-VLC channel modelling
Papers focusing on the transmitter
Papers focusing on the vehicular environment
Papers published between 2021 and 2024
Papers containing each keyword or their respective synonym in the title, abstract or keywords and metadata
Papers related to the research questions
Papers published in a peer reviewed journal
Exclusion Criteria
Publications not focusing on the channel modelling
Review papers
Papers focusing solely on receivers
Papers focusing on aerial or underwater communication
Papers focusing on indoor communication
Papers focusing on the reflections aspects
Papers from which full versions are not available
Papers in a language different from English, French or Dutch
Conference proceedings
Non peer-reviewed papers
Papers submitted prior to 2021

3.1 VLC Architecture

The main VLC architecture is comprised of three parts (as per Fig. 1): the transmitter (TX), the optical channel and the receiver (RX). These envelop the application (APP), medium access control (MAC) and physical (PHY) layers necessary for a communication system. In this paper the PHY layer will be emphasised.

3.1.1 Transmitter

The transmitter (TX) configuration comprises an Electronic Control Unit (ECU), a light source driver, and a light source emitting waves within the desired electromagnetic (EM) range. The ECU generates a binary code based on the message to be transmitted, adhering to a specific modulation scheme, which significantly influences the achievable data rate, communication range, and security [5, 9]. Typically, the LED driver translates the digital code into physical pulses to modulate the light source, with the prevalent modulation scheme being single carrier non-return to zero (NRZ) On-Off Keying (OOK), wherein the light source is modulated in amplitude (without turning completely off) to represent binary 1s and 0s [2, 14]. Alternatively, more intricate multi-carrier modulation schemes like Orthogonal Frequency Division Multiplexing (OFDM) can be employed, enabling higher data rates and enhancing link robustness against interference by modulating both phase and amplitude [9]. Other modulation schemes include Variable Pulse-Position Modulation (VPPM), Direct Sequence Spread Spectrum (DSSS), Color Shift Keying (CSK), or Wavelength Division Multiplexing (WDM), each offering specific advantages [3, 7]. Notably, regulatory requirements stipulate a minimum modulation frequency to prevent flickering, generally deemed imperceptible above 200 Hz, while ensuring rapid modulation techniques do not compromise lighting functionality, crucial for vehicle visibility and signalling [2, 7]. Nonetheless, a comprehensive analysis of modulation methods extends beyond this review's scope.

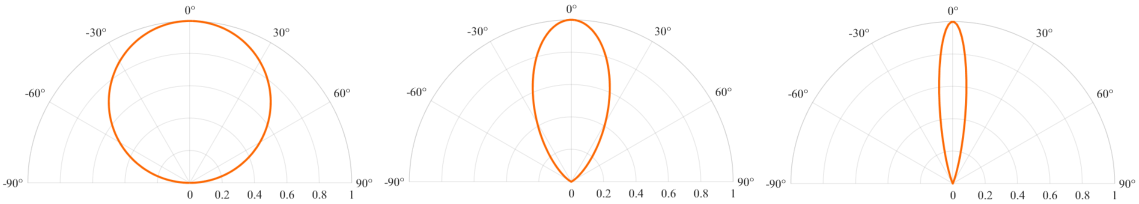
Traditionally, Optical Wireless Communication (OWC) relied on Infra-Red (IR) diodes; however, today Light Emitting Diodes (LEDs) are predominant due to their affordability, durability, efficiency, and rapid switching capabilities [8]. Alternative source include micro-LEDs (μLEDs), Organic LEDs (OLEDs), and Laser Diodes (LDs). LDs offer extended communication ranges and faster data rates than LEDs owing to their quicker switching capabilities and collimated emission nature, albeit with reduced mobility and higher costs [9]. In V-VLC, traditional high-power LEDs remain prevalent, while Adaptive Front-Lighting Systems incorporating matrix-LED headlamps with μLED arrays are emerging. These systems allow individual modulation of LEDs or clusters, enabling dynamic adjustment of illumination patterns to prevent glare and facilitate subgroup selection of LEDs for communication, thereby enhancing V-VLC performance by mitigating multi-user interference through spatial multiplexing with Space Division Multiple Access (SDMA) [7].
Next to the lighting technology used, the radiation pattern from the source plays an important role in the channel modelling. Usually, a generalised Lambertian Luminous Intensity Distribution (LID) is taken to model the emitted light for indoor applications [2, 3, 5, 7, 8, 14]. This rotationally symmetric LID is represented as:

$$I(\alpha, \beta) = I_0 \cos^n (\alpha) \tag{1}$$

The peak intensity I_0 follows the axis of symmetry, also called the optical axis. The angles α and β represent the azimuth and elevation angles respectively. n is the order of the Lambertian emission profile, derived from the Full Width at Half Maximum (FWHM) angle α_{50} of the LID of the source:

$$\cos^n(\alpha_{50}/2) = 0.5 \tag{2}$$

As the value of n increases, the beam becomes narrower. Figure 2 illustrates various LID patterns obtained through this model in polar coordinates. While many studies employ a generalised Lambertian radiation pattern for modelling vehicle headlamps and taillights, Memedi and Dressler [7] highlighted significant differences between the

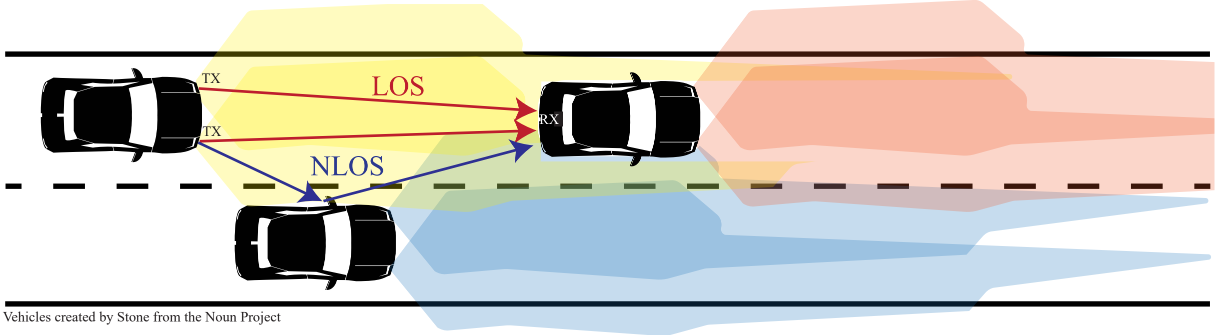


(a) n = 0, Lambertian

(b) n = 5

(c) n = 50, narrow beam

Figure 2: Polar representation of the LID in arbitrary units (A.U.) following a generalised Lambertian pattern with n values of (a) 0, (b) 5 and (c) 50. This corresponds to FWHM values of 60°, 27° and $\simeq 9.4°$ respectively.



Vehicles created by Stone from the Noun Project

Figure 3: Schematic representation of a V2V V-VLC link geometry considering both LOS and NLOS links. The transmitter (with the yellow headlamp light distribution) has a direct LOS link with the receiving car (with the orange headlamp light distribution) indicated by the red arrow. A NLOS link through a reflection on the vehicle on the adjacent lane is indicated by the blue arrow. The direct LOS link is obtained through both headlamps, while only the right headlamp contributes to the NLOS link.

actual headlamp radiation and the Lambertian pattern. Specifically, low beam headlamps display an asymmetrical and non-uniform radiation pattern with a cutoff line mandated by UN/ECE R112 [15] regulations to mitigate glare for oncoming traffic. Conversely, high beams exhibit more symmetrical patterns but their use is restricted due to glare concerns. Further details regarding the impact of radiation patterns on the V-VLC channel model are provided in section 3.2.

3.1.2 Optical Channel

The light emitted by the source propagates to a receiver via the optical channel. In V-VLC, this channel operates in free space, exposing it to atmospheric and environmental variations as well as changing geometric configurations due to the dynamic vehicular environment. The latter describes how the transmitting and receiving components are spatially arranged within the vehicular environment. Key factors influencing this configuration include the emission angle, angle of arrival, and communication distance. This setup can result in either a line-of-sight (LOS) or non-line-of-sight (NLOS) communication scenario. LOS communication involves a direct, visible connection between the source and receiver, which is the focus of most channel models. Conversely, NLOS communication occurs via reflections. Figure 3 illustrates the geometry of a V2V V-VLC link, highlighting both LOS and NLOS paths, and also illustrating that even when there is an unobstructed path between transmitter and receiver, both LOS and NLOS paths exist between them.

Atmospheric disturbances involve the attenuation of the transmitted signal due to scattering, absorption, and transmission characteristics under specific atmospheric conditions. Rain, mist, and snow notably affect outdoor VLC connections [3, 7, 8, 14, 16]. Environmental disruptions encompass interference caused by multiple reflections of emitted light by nearby structures in rural settings, road surfaces, and neighbouring vehicles [8]. These reflections are often deemed constructive, enhancing the communication link by elevating the Signal-to-Noise Ratio (SNR) [3, 7]. Limited research on NLOS modelling exists due to the complexity of modelling the environment alongside realistic reflection coefficients. Some attempts have employed Computer-Aided Design (CAD) or treated each reflection as an individual source, yet experimental validation remains challenging. Finally, the impact of other modulated light sources (parasitic light sources) has been observed to introduce noise and must be filtered out [2]. These sources include LED traffic signals, billboards, and road signs, among others.

3.1.3 Receivers

Upon traversing the optical channel, the diminished light arrives at a receiver, typically photodiodes (PDs) or cameras [17]. When cameras are employed as receivers, the system is termed Optical Camera Communication (OCC) [3], offering the advantage of pre-existing transmitters and receivers in vehicles [7]. More advanced detectors, including Single Photon Avalanche Diodes (SPADs), are gaining traction due to their heightened sensitivity, enabling extended communication ranges in low-light environments [2, 5, 8]. However, all detectors operate on a similar principle, converting incoming luminous radiation into an electrical current [7], which is subsequently processed and interpreted by the processing unit and ECU, respectively. This review primarily focuses on the impact of the transmitter's radiation pattern on the optical channel; thus, a comprehensive examination of detectors is beyond its scope. Interested readers are directed to Cailean and Dimian [16] for an extensive overview of V-VLC receivers and to Hassan et al. [3] for a review specifically dedicated to OCC.

3.2 VLC Channel models

The VLC system can be modelled as a Linear Time Invariant (LTI) system [3, 8]:

$$P_r(t) = R\,P_t(t) * h(t) + N(t) \tag{3}$$

with $P_r(t)$ the received optical power, R the detector responsivity, $P_t(t)$ the transmitted optical power, h(t) the channel impulse response (CIR), N(t) the detector noise and $*$ referring to represent a convolution. The detector noise comprises different factors, often limited to shot noise and thermal noise from the detector, modelled as an Additive White Gaussian Noise (AWGN) [14]. The CIR consists of both the LOS and NLOS components. Hence it is modelled as the the sum of both:

$$h(t) = \sum_{0}^{k} h^{(k)}(t) \tag{4}$$

with *k* the maximum amount of bounces. $h^{(0)}$ represents the LOS response and $h^{(k)}$ the response after *k* bounces. The geometrical attenuation of the optical channel are evaluated using optical path losses (PLs), i.e. the decay in received signal strength during its propagation through free space. The PLs allow to determine the required emission power of the light source and the sensitivity of the receiver. The geometrical losses are characterised by the link geometry, i.e. alignment between vehicles, distance between transmitter and receiver and the amount of reflections considered. To represent this, Gfeller [18] proposed an IR based Direct Current (DC) channel gain $H(0)$. This was later applied by Khan and Barry [19, 20] for indoor VLC and is still the most used LOS model. The DC gain is based on the irradiation of the optical receiver considering the inverse square law and represents the average optical power impinging on the detector [5, 7, 8]:

$$H(0) = \frac{I_e(\alpha)\,A_{\text{eff}}}{d^2} \tag{5}$$

Where $I_e(\alpha)$ is the Radiant Intensity Distribution (RID) of the source, α the emission angle, A_{eff} the effective surface of the detector and d the distance between the source and the detector. The RID is equivalent to the LID, yet without accounting for the spectral sensitivity of the human eye. Only the amplitude of the optical power is changed, but not the spatial distribution it. Hence, in the remainder of this document, the RID will be employed as the observer in the case of a VLC system is an electronic detector not affected by the sensitivity of the human eye. The DC channel gain utilised to evaluate the path losses attributed to the predominantly flat frequency response of the IR channel, is also applicable to VLC [7, 8]. Ideally, in outdoor settings, the frequency response should encompass wavelength-dependent atmospheric attenuation, including reflections, refraction, and absorption. Nevertheless, mostly the channel DC gain is used in the literature, leading to the following PL expression:

$$PL = -10\log_{10} H(0) \tag{6}$$

Based on the PL, a multitude of channel characteristics can be derived allowing to improve the system design.
As can be seen from Eq. 5, the DC channel gain is proportional to the radiation pattern. Depending on the modelling approach considered, the RID takes on slightly different forms. Based on the existing literature reviews, four modelling approaches have been identified: LOS analytical models, Geometric Based models, Ray Tracing (RT) models and measured models. Furthermore, a distinction between deterministic and stochastic models can be made [8]. The former considers specific scenario's in terms of receiver-transmitter geometry and surrounding environment, leading to a site-specific model. They are evaluated by means of RT computations, empirically or trough recursive models [21,22]. The latter aims to identify the channel's statistical behaviour by modelling the link geometry and the influence of the environment as a set of statistical probability density functions (PDFs) [23]. The different scattering function of each reflective surface or interfering environment are based either on measurements or analytical models. Deterministic models offer more accuracy at the cost of a lower computational efficiency and flexibility when compared to stochastic models. LOS analytical models aim to solve mathematical expressions reflecting the channel characteristics and system performance. For example, provided an analytical expression for the RID of the employed light source, the PL for a wide range of geometric settings can be computed through Eq. 5 and Eq. 6. Unfortunately, not all sources have a readily available RID. Therefore, alternative modelling methods have been employed to overcome this problem and allowing to introduce more variables such as channel mobility and environmental influences.

An alternative to the LOS analytical approach are the Geometric Based models (GBM), which view the environment around the VLC link as consisting of multiple reflecting surfaces. This consideration allows for the inclusion of NLOS components in the DC channel gain. These NLOS components do not diminish the signal but instead enhance the received signal strength (RSS) [7]. In the deterministic variant, each reflecting surface is assigned a reflection function, which depends on the material properties and can be described analytically or empirically. Geometric Based Stochastic Models (GBSM) describe the reflection function statistically and introduce variability by incorporating multiple reflections and non-stationary models based on a predefined PDF [8, 21]. Note however that no information is given regarding the type of reflection function used.

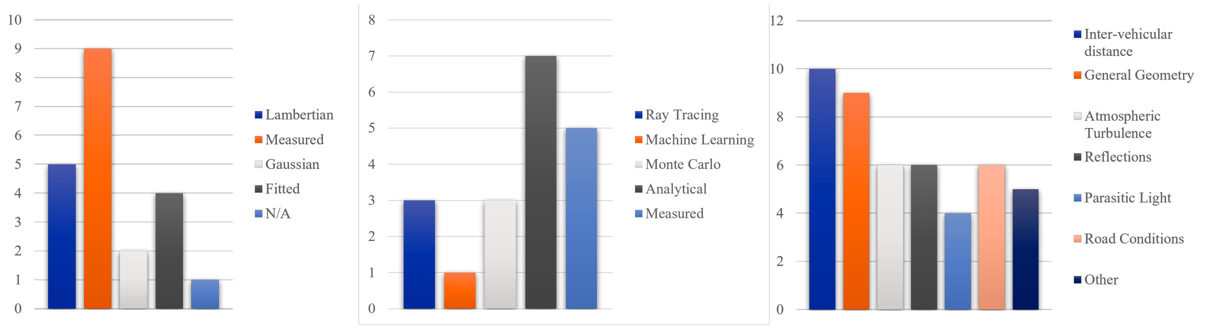
Ray tracing-based channel models utilise optical simulation software, to simulate the optical environment comprehensively. This includes the Solid State Light (SSL) sources and their optical elements, as well as the surrounding road, buildings, and environment. Each light ray emitted by the source is meticulously traced, considering the influence of all components along its trajectory. This approach encompasses all aspects of the V-VLC channel. However, these models are constrained to a single scenario and are notably intricate and time-consuming to develop [7, 8]. Additionally, the precise optical designs of vehicular optical components are often unavailable. Consequently, many researchers have relied on available LIDs, utilising only a fraction of the ray tracing capabilities. Nonetheless, these models represent the most accurate simulations available to date.

Finally, empirical models emerge resulting in the most realistic representation of a specific system in a specific configuration [8]. These models do not require any modelling and simply measure the channel output resulting from a specific V-VLC configuration. While this approach allows to consider a multitude of influences (road conditions, road reflections, vehicle reflections, parasitic lighting, weather conditions, ...), only the studied system performance is reflected. Hence, scaling the designed system to other environments and tweaking parameters to obtain desired performances proves cumbersome [7]. Furthermore, owing to the uncontrollable environment, this approach results in a lot of variability, and tends to be expensive as well as time-consuming.

Irrespective of the method used, both analytical and measured RIDs are used. Most analytical models employ a rotational symmetric generalised Lambertian emission profile as given in Eq. 1 [2, 3, 5, 7, 8, 14]. Contrary to indoor lighting, sometimes following a Lambertian distribution, V-VLC makes use of the vehicle lights. Headlights, Daytime Running Lights (DRL) and taillights are the predominant sources for V-VLC. Except for the diffuse taillights, vehicle lights cannot be modelled using a Lambertian emission profile [7]. Low beam (or dipped beam) headlights have to adhere to strict regulations resulting in an asymmetrical pattern following UN/ECE R112 [15] regulations (see Fig. 3 for a schematic top view of the headlight distribution). Therefore, most studies provide an underestimation of the V-VLC channel performance in terms of available range, while the mobility is overestimated. Measured beam patterns better reflect the actual performances compared to the simplified generalised Lambertian RID. Up to now, halogen reference tables of market weighted LIDs for the most sold vehicles in the U.S. or EU (see tabulated LIDs from [24, 25]) have been used the most as indicated by Yahia et al. [8]. However, V-VLC uses LED technology, hence, the LED headlamp patterns should be used, available from e.g. Flannagan et al. [26]. Experimental models utilising taillights and/or fog lights provide novel measurements. Nonetheless, taillights generally display a diffused nature, albeit with a slight angular deviation. Hence, for this source the generalised Lambertian distribution would not deviate much from reality. The use of fog lights do not offer a precise scenario as they are not intended for permanent use and are mounted at a very low height, resulting in a restricted communication range. Notably, DRLs have not received much attention while this source could prove useful for an all-day and -night communication without influencing the illumination characteristics as this source is predominantly used "to be seen". Therefore it does not have to adhere to any specific requirements.

4 Research Papers

In this section, the most recent research papers as highlighted in section 2 are discussed. Three aspects are analysed: the modelling approach, the light source modelling and the considered influencing factors.



(a) Radiation Pattern (b) Modelling Approach (c) Influencing Factors

Figure 4: Summary of (a) the used modelling approaches; (b) the used light source models; (c) the considered influencing factors. The vertical axis represents the amount of times the factors/models have been employed/considered.

4.1 Modelling approach

Different channel modelling approaches are presented in the research papers included in this review. As for the case for the review articles, the most common techniques include ray tracing simulations [11, 27, 28], analytical expressions [6, 23, 29–33] and measurement campaigns [10, 13, 31, 34, 35]. Alternatively, machine learning [21] and Monte Carlo simulations [29, 30, 36] have been used. Ray tracing simulations present the most detailed channel estimations, if measured light sources are used. Currently, all models employed consider the sources as radiating points, rather than using exact measurements considering the variation of the light output over the source's surface, which can result in large discrepancies as shown by Dotreppe et al. [37]. Nevertheless, ray tracing not only considers the light source characteristics, but can also encompass the influence of the environment through accurate CAD models considering the reflections on adjacent vehicles, buildings and the road surface. Notably, all ray tracing analyses have been done through OpticStudio.

Analytical expressions present robust idealised situations, useful for preliminary studies. However, whether deterministic or stochastic, these models are limited to a certain specific environments and quickly become cumbersome due to the long expressions required to encompass a multitude of influencing factors.

Measurement campaigns best reflect reality and are enable to asses the performance of a V-VLC system in real world conditions considering many factors difficult to model through alternative techniques. However, this approach is expensive, time consuming and prone to a lot of errors if not performed correctly.

While the machine learning approach requires a large amount of measurement data to train the model, the obtained results are accurate and allow the assessment of many different scenarios considering various influencing factors depicted in section 4.3.

Finally, Monte Carlo simulations have proven to be a powerful and simple method to asses the influence of the inter-vehicular distance [6, 30], lateral shift between vehicles, atmospheric conditions, vertical oscillations [30] or PLs [36] modelled through PDFs. The summary of the amount of times each modelling approach has been used in given as a bar chart in Fig. 4 (a).

It can be understood that each presented modelling approach has its own merits. The analytical approach is useful for preliminary studies owing to its theoretical exact solutions, yet it lacks versatility and quickly becomes cumbersome. Measurement campaigns best reflect the reality, but are time consuming and expensive. Ray tracing simulations offer a lot of versatility and an accurate light representation if used to its full extend, something which has not been done yet. Machine learning approaches are a promising emerging modelling approach, however, requiring a large set of measurement data for training purposes. Monte Carlo simulations employ PDFs to statistically represent time dependent situations. This proves useful to represent the dynamic vehicular environment in terms of mobility, weather conditions, NLOS characteristics, etc. Hence, rather than considering each method separately, perhaps the answer to efficient and accurate channel modelling, lies in the combination of several methods to encompass all their various advantages.

4.2 Light Source Modelling

The light source modelling employed in recent research papers are summarised in the bar chart shown in Fig. 4 (b). As can be seen, the used models are very similar to the ones used during the past decade. The most popular model is still the piece-wise or generalised Lambertian emission pattern [29, 31–33, 36]. Alternatively, the Gaussian model is also used for similar LIDs [33, 36]. However, these models only represent narrow beams or diffuse distributions, not accurately reflecting the low beam headlamps [28, 29, 36]. For high beam headlamps and taillights this approach might be applicable, yet this depends on the manufacturer, as a high variety of LIDs is observed across different car brands [11]. A better representation of the reality is obtained through measured patterns [6, 11, 13, 23, 27, 28, 30, 31, 34, 35]. This approach is gaining popularity, yet without providing many details about the measurement procedure (with the exception of Aly et al. [13] who are using a VISO LabSpion photogoniometer to capture the LID of a low-beam headlamp [38]). Most measured LIDs are extracted from previous literature, mainly from Karbalayghareh et al. [39] and Memedi et al. [40]. Furthermore, often only two places are considered, while in reality the light distribution is different for every direction due to the stringent regulations on low beam headlamps. Fitted models refer to the fact that the radiation pattern of the light source is derived from a data fit, either on the measured radiation pattern itself [33, 34], or on the measured PLs [6, 10]. One paper from Turan et al. [21] does not provide any type of radiation pattern for the light source as the authors make use of a machine learning approach, where the model is trained with large data bases of measured channel frequency response (CFR) and received signal strength (RSS). The attentive reader will notice that the total number of light models exceeds the number of included papers, i.e. 16. This is due to the fact that several studies considered different modelling approaches.

4.3 Considered Influencing Factors

Through the channel modelling, the influence of various factors can be analysed. Mainly, the inter-vehicular distance [6, 10, 11, 21, 23, 29, 30, 32–34, 36], geometrical factors (later shift, receiving and emission angle) [13, 21, 27, 30, 31, 33–36], atmospheric turbulence due to adverse weather conditions [6, 21, 23, 31, 32, 35], road conditions [6, 13, 21, 23, 29, 32, 36] and reflections on neighbouring vehicles are considered [6, 10, 11, 27, 29]. The modelling of these factors are performed through statistical modelling using PDFs, real world measurements, or mathematical expressions.

Road conditions are a critical modelling parameter as they reflect the real world inter-vehicle distance. During rush hours, reflecting dense traffic conditions, the inter-vehicle distance will be less than during off-peak hours. Furthermore, the amount of reflecting surfaces will be increased as the amount of vehicles on the road increases. This results in a higher contribution of the NLOS path through reflections on neighbouring vehicles, but can also induce important inter symbol interference. Liu et al. [32] derived the relationship between vehicle speed and density based on the Green-Shields model. It is observed that as the speed increases, so does the average distance based on a density analysis on a single lane. Accordingly, the higher the vehicle speed, the lower the SNR. This shows that different factors depend on each other. The geometrical factors also depend on road conditions as they are referring to the dynamic nature of the vehicular environment. This includes the lateral shift between vehicles on a single lane, the geometrical distribution of vehicles across multiple lanes, bends and turns, etc. inducing variations of the emission and arrival angle as well as the distance between RX and TX.

The NLOS paths can be obtained through surface reflections, either on the surrounding buildings, or on the neighbouring vehicles. These vehicles can be either in line with the transmitting vehicle, or in an adjacent lane [10]. In both cases, the inter-vehicular distance and the lateral shift play an important role in the characterisation of the NLOS effects, hence the road conditions and geometrical factors need to be included. Note that the azimuth angle is often omitted due to the limited vertical oscillations and slow time variation. Furthermore, the detector is generally considered to be mounted at the same height as the emitter (taillight or headlamp) [34]. Nevertheless, the influence of the mounting height is analysed by Aly et al. [13], where it was noticed that misalignment due to vertical oscillations altered the PLs distribution as a function of the distance. Mounting the detector lower than the headlights resulted in higher received power, an effect which reduced with the distance as the light beam spread to a wider region. This is a direct influence of the asymmetrical light distribution of the vehicle headlights, oriented in a downwards orientation. Road reflections are rarely considered, yet, like the vehicular reflections, they are shown to always enhance the received optical power through NLOS contributions to the channel gain [11, 36].

Nearly all models consider the shot and thermal noise from the detectors. Both noise sources relate to the undesired random fluctuations in the output signal of a photodetector caused by thermal generation of charge carriers (thermal noise) and from the statistical variation in the number of photons detected due to their discrete nature (shot noise). Parasitic sources (sun light, traffic lights, neighbouring vehicles, LED information panels, ...) induce an additional noise through the unwanted contribution to the measured optical signal. The amount of time the various influencing factors have been used in the research papers considered, are represented graphically in Fig. 4 (c). Note that the category labelled as ”other” refers to factors which have only be considered once, e.g. vehicle speed, transmit power, LED current, bandwidth, number of relay nodes and the location of intelligent reflecting surfaces.

It can be concluded that all the influencing parameters are interlaced, making it difficult to analyse the effect of every factor individually. Therefore, the statistical modelling approach through PDFs prove useful and scalable in order to consider a wide range of influencing factors realistically.

5 Discussion and Future Improvements

Most research using analytical models make use of simplifications in terms of transmitter characteristics, considering a radiating point source with a Lambertian (or generalised piece-wise Lambertian) LID as depicted by [2, 3, 5, 7, 8, 14]. However, it is acknowledged that vehicular headlights are not Lambertian and show strong asymmetrical patters [28, 29, 36]. Analytical channel models make use of the LIDs and remain very useful due to their wide application area, reduced cost and easy adaptations. Therefore more sophisticated LID representations are required to obtain realistic analytical channel models for V-VLC [7, 9]. For example, a universal, mathematical, low beam headlamp LID adhering to the ECE R112 [15] regulations would prove useful to alleviate the discrepancies between the different LIDs observed across various car manufacturers obtained from measurements and improve the representation of the optical channel compared to a generalised Lambertian LID [36]. This way, reproducible results can be obtained.

The influence of the NLOS link is considered more often in current literature. However, the methodology employed to include this path is not well detailed. The spectral Bidirectional Scattering Distribution Function (BSDF) would be the most accurate method to assess the real world influence of reflecting radiation on an neighbouring surface area to the emitter. The spectrally resolved version of the BSFD allows to consider the spectrally dependent transmission and reflection characteristics of a material. Due to the wide nature of reflecting surfaces within the vehicular environment, this is a consideration worth making. Nevertheless, studies employing (or mentioning) this reflection function are lacking.

Furthermore, while many vehicles nowadays use LED sources, more and more vehicles start to be equipped with matrix LED headlights, pixel headlights or even laser headlights. Hence, it would be interesting to see more of these different types of sources used for V-VLC and evaluate their capabilities.

Finally, each method has its advantages and disadvantages. A smart combination of the different modelling approaches would provide an improved channel model. For example, Monte Carlo simulations can consider the vehicle mobility and density (hence inter-vehicular distance) on a multi-lane road through a PDF, based on an extensive measurement campaign of the road conditions at various times of the day. Ray Tracing simulations can incorporate many different factors such as realistic optical transmission through the atmosphere, and reflections on nearby vehicles and infrastructure. Therefore, combining RT simulations to obtain realistic beam patterns and optical power propagation with a Monte Carlo simulation for the inter-vehicular distance considering the vehicle mobility and density, and including measured reflection functions for the vehicle coating and adjacent buildings would result in a more complete model. Validations of the observations could then be provided through a comparison with a prototype device reflecting the modelled parameters and considering different sources of error. Nevertheless, such modelling approach is lacking in the current literature.

6 Conclusion

Through a systematic review approach, this paper evaluates the current trends in Vehicular Visible Light Communication (V-VLC). Initially, a comprehensive overview of research spanning the past decade is provided by analysing review papers published between 2013 and 2023. This analysis offers insights into the theoretical framework underlying VLC architecture and channel models. Subsequently, attention shifts to recent research papers published from 2021 to 2024, bridging the gap between the latest review paper and the present day. These papers are scrutinised in terms of their general modelling approaches (analytical, experimental, ray tracing, or statistical), as well as their methodologies for light source modelling and consideration of influencing factors.

Focusing on the photometric aspects of modelling, particularly the representation of light sources and their spatial extensions, it becomes evident that generalised Lambertian Light Intensity Distributions (LIDs) and measured channels predominate. However, generalised Lambertian models fail to accurately capture the regulated beam patterns of low beam headlamps, high beam headlamps, and taillights, exhibiting asymmetries that are not accounted for. While measured channels offer a more realistic portrayal of reality, they are constrained to specific scenarios and lack the scalability of other modelling approaches.

Furthermore, regardless of the modelling approach employed, all research papers utilise radiating point sources, which do not accurately reflect the light source distribution at closer distances, a critical consideration for V-VLC. Therefore, there is a clear need to enhance these models initially to provide more precise representations of light distribution as an essential preliminary design step.

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