

Vehicular Visible Light Communications: A Survey

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Abstract—Visible Light Communications (VLC) is becoming a mature communication technology, particularly for indoor usage. The application in outdoor environments is especially interesting in the scope of Vehicular VLC (V-VLC), however, there are some critical challenges remaining. In general, VLC is a good complement to Radio Frequency (RF)-based communication. For automotive use cases, V-VLC can benefit from the huge available spectrum and the readily available Light Emitting Diode (LED)-based lighting systems of modern cars. Its Line Of Sight (LOS) characteristics, the directionality of the light, and the smaller collision domain substantially reduces interference. In this survey article, we study the state of the art of V-VLC and identify open issues and challenges. We study the V-VLC communication system as a whole and also dig into the characteristics of the VLC channel. For the beginner in the field, this review acts as a guide to the most relevant literature to quickly catch up with current trends and achievements. For the expert, we identify open research questions and also introduce the V-VLC research community as a whole.

Index Terms—Vehicular visible light communication, V-VLC, visible light communication, VLC, vehicular networking, channel modeling, transmitter and receiver design.

I. INTRODUCTION

TRANSPORTATION systems of today are closer than ever bound to experience a major technological transformation. Vehicles on roads have come a long way from the bare metal-on-wheels they used to be, to the sensing and computation capable machines they are today. High-end models of last generation vehicles nowadays are equipped with hundreds of embedded computers and sensors which allow them to perceive their surroundings, and interact with it in semi-autonomous, and eventually, fully-autonomous fashion. Although at a slower pace, the road infrastructure has evolved as well, as adaptive traffic lights and communication capable pay tolls are being deployed on roads.

An anticipated next step in the evolution course of transportation systems is to adopt the concept of communication and enable information exchange between vehicles and with infrastructure. This will unleash the full potential of next generation transportation systems while shifting the paradigm from autonomous driving to cooperative driving. The newly acquired capabilities of vehicles and infrastructure pave the

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way for a set of new applications. As a result, numerous agencies and regulatory bodies worldwide have come forward with standards and strategies to deploy such applications, oftentimes referred to as Intelligent Transportation Systems (ITS) [1], [2]. In essence, the main goal of ITS is to improve road safety, traffic efficiency, and comfort of driving by taking advantage of Vehicle-to-Everything (V2X) communications [3], [4].

The majority of ITS applications proposed until now rely on RF communication. For instance, the ETSI ITS-G5 [5] and the IEEE 1609 WAVE [6] families of standards, which propose full ITS stacks for Europe and U.S., respectively, are built upon WLAN, i.e., the IEEE 802.11p protocol [7]. Also cellular networking solutions have been realized using LTE technologies [8], [9]. In follow-up works, 5G-based approaches have been standardized, most prominently, the current 5G Cellular V2X (C-V2X) solution [10], [11]. This activity is currently further pushed in the scope of the Tactile Internet initiative [12], which also includes ITS applications [13]. WLAN and C-V2X can of course also be used in combination, complementing each other [14], [15].

Another field that has seen major transformation in the last decade is that of lighting technologies. Stimulated by major breakthroughs in Solid State Lighting (SSL) technology and the mass adoption of LEDs for indoor and outdoor illumination, VLC has emerged as a viable communication technology. VLC is an emerging technology that enables data communication by modulating information on the intensity of the light emitted by LEDs.

In recent years, VLC has sparked the interest of the research community and the industry [16]. Namely, the number of publications on VLC has been growing exponentially [17], and multiple comprehensive surveys have been recently published on this topic [17]–[22]. Furthermore, standardization efforts have been taking place in the scope of IEEE Standards Association (IEEE-SA) [23]¹ and Japan Electronics and Information Technology Industries Association (JEITA) [24]–[26]. In the meanwhile, VLC-enabling front-ends, from companies like pureLiFi, Philips, Oledcomm, are already present in the marketplace and are being deployed in homes and industrial buildings.²

Based on the application scenario, VLC can be classified into indoor and outdoor applications. Indoor VLC has attracted more traction and growth, fueled by the success of the Li-Fi [27] concept. Whereas, outdoor VLC has progressed at a slower pace, mainly owing to the more challenging

¹Task groups 7 and 13 within IEEE 802.15 working group; Task group “bb” within IEEE 802.11 working group.

²<http://purelifi.com/case-studies/>

environment and other constraints (e.g., mobility, weather, regulations), but yet with substantial results. Today, ITS are one of the most promising outdoor applications for VLC. Vehicular networking applications can take advantage of the LED-equipped lighting modules and transportation infrastructure to realize V-VLC [22], [28]–[31].

As V-VLC uses the visible light portion of the electromagnetic spectrum, the different characteristics of the light waves can help to complement RF technologies, such as IEEE 802.11p and Long Term Evolution (LTE).

Advantages/Disadvantages of RF: In general, RF technologies in the sub-6 GHz-band as used for vehicular networking have non-directional propagation, relatively long communication range, and can penetrate objects. RF has been very well investigated over the last decades and the technology is quite mature. At the same time, the limited available radio spectrum as well as the congestion level in medium and high node density scenarios are limiting the scalability of RF-based solutions. Finally, potential security attacks, like jamming, eavesdropping, and man-in-the-middle attacks have raised concerns about its usage in safety-critical vehicular networking applications.

Advantages/Disadvantages of V-VLC: The LOS property of V-VLC, its directionality, and the smaller collision domain substantially reduce interference. At the same time, the massive bandwidth available in the visible light spectrum allows huge potential data rates. At the same time, V-VLC requires LOS, which might not always be available in outdoor scenarios, e.g., due to mobility and also environmental impact such as heavy snow. Nevertheless, V-VLC needs a significant amount of further research in order to enable reliable networking complementing RF-based solutions.

The truth is likely to be found in the complementary nature of both RF and V-VLC. RF can make up for VLC's shortcomings, such as short communication range and inability to propagate through opaque objects and V-VLC can offer high data rates with very low interference in LOS scenarios. Such hybrid concepts have already been proposed in the literature [32], [33].

In this survey article, we review the current state of the art of V-VLC. We consider it the first all-inclusive paper looking at the complete V-VLC protocol stack, which considers both Photodiode (PD) and camera-based receivers. We aim to help beginners to quickly get into the concept of V-VLC as well as its applications and properties. For experts, we provide an in-depth discussion of research issues related to transmitter and receiver characteristics, channel modeling, and simulation tools. We also identify the main stake holders, relevant publication venues, and standardization bodies.

The remainder of this article is organized as follows: In Section II, we introduce the field of Vehicular VLC including applications, properties, security aspects, and regulatory requirements for automotive lighting systems. This is followed by a discussion of the core components of a V-VLC system in Section III. Among others, we discuss the system architecture, transmitter front-end characteristics, VLC modulation concepts, as well as typical LED lighting modules used in cars.

In Section IV, we introduce important properties of the V-VLC communication channel such as light distribution, Non-Line Of Sight (NLOS) communication, as well as the impact of mobility, ambient light, and weather conditions. In Section V, we look more closely on modeling issues of the V-VLC channel. In Section VI, we introduce both PD and camera image sensor-based VLC receiver. We discuss the state of the art in simulation-based performance evaluation of V-VLC systems in Section VII. Finally, we conclude this survey on V-VLC with a discussion of research directions, the research community, and current standardization efforts in Section VIII as well as with some concluding remarks in Section IX.

II. VEHICULAR VISIBLE LIGHT COMMUNICATION

V-VLC, which is based on the concept of VLC, is used in vehicular networking applications. In this section, we first briefly outline conceptual and architectural aspects of V-VLC. Next, we discuss the feasibility of this technology for certain vehicular networking applications, and lastly we introduce some of V-VLC's most prominent characteristics.

A. Concept and Architecture

VLC is a medium range optical wireless communication technology which uses the 380–780 nm wavelengths of the electromagnetic spectrum [34]. In vehicles, VLC is enabled by LED-based headlamps and taillamps as transmitters and PDs or camera image sensors as receivers. Figure 1 depicts a typical traffic scenario where V-VLC can be deployed. As illustrated, vehicles can realize Vehicle-to-Vehicle (V2V) communication with the vehicles in their direct vicinity, therefore, establishing head to tail and tail to head links when driving, or head to head links when facing each other, for example, at intersections. Tail to tail links are also possible, however not common in typical driving scenarios. Figure 1 also illustrates Vehicle-to-Infrastructure (V2I) communication, where LED-based infrastructure elements, such as traffic lights, road-side signage, and street lighting, can convey visual information to the driver and digital information to the VLC-enabled vehicles [35], [36]. Originally, V2I applications were the earliest type of V-VLC applications, considered for traffic information systems in late 1990s [37]–[39].

For V-VLC, to support these different communication scenarios (and corresponding applications) careful design decisions need to be made on the system level. This raises a multitude of research questions, in particular regarding Physical Layer (PHY) aspects of the system. For instance, spectrally efficient Modulation and Coding Schemes (MCSs), such as Orthogonal Frequency Division Multiplexing (OFDM), are favorable and have been implemented for V-VLC [40]–[42]. However, hardware limitations of the V-VLC transmitters and receivers (e.g., nonlinearity of the electronics), coupled with the challenging outdoor conditions and restrictive safety regulations, hugely impact the achievable performance. Nonlinear transfer functions, limited dynamic range, and the limited bandwidth of the LEDs used for exterior automotive lighting are some of the major challenges on the transmitting

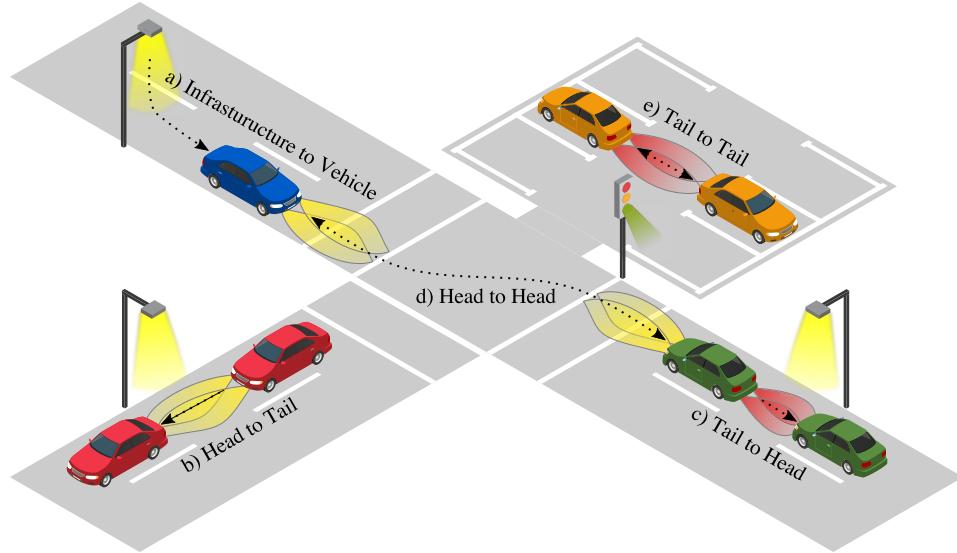


Fig. 1. Vehicular VLC communication patterns and selected potential applications. a) Infrastructure to vehicle communication: can be used for information exchange between VLC-enabled vehicles and intelligent traffic lights, traffic signs, or road lighting. Potential applications include intersection assistance and TIS. Communication patterns between vehicles include: b) Head to tail and c) Tail to head communication: possible in car following situations; can be used for emergency electronic brake light and platooning applications, respectively. d) Head to head communication: possible if vehicles face each other; can be used for intersection coordination and maneuver coordination between vehicles; e) Tail to tail communication: possible if two vehicles are opposed to each other; plausible in parking situation. Note that, bidirectional communication is possible in all vehicle to vehicle cases. However, to maintain clarity, the beams of the taillamp and the headlamp are not illustrated in cases b) Head to tail and c) Tail to head, respectively. Additionally, the size of the head- and taillamp light beams in this figure does not represent the real range and asymmetric shape of these lighting modules. (This figure has been designed using resources from Freepik.com).

side. On the receiving side, it is the “square law” property of the Direct Detection (DD) receivers and the hardware induced noise which affect the communication. These challenges and corresponding solutions are discussed in more detail in Section III-B and VI, respectively.

In the following we discuss the feasibility of V-VLC for different vehicular networking applications and identify the scenarios where it can be beneficial for communication.

B. Applications

Generally, vehicular networking applications can be classified into two major categories: *safety* and *non-safety* applications. Safety applications have very stringent requirements for reliability metrics, such as latency and packet delivery, whereas non-safety applications can require high data rates, but have more relaxed reliability requirements. Depending on the application type, a set of communication requirements needs to be satisfied by the deployed communication technology for the application to perform as desired.

RF-based communication technologies such as IEEE 802.11p and C-V2X have been developed specifically for vehicular networking applications. However, the aforementioned RF technologies might not always be able to support all types of applications, especially those which require frequent transmissions in dense scenarios, where safety-critical metrics can suffer due to channel congestion, e.g., in challenging platooning scenarios [44]. In such cases V-VLC can be used to complement RF to decrease the RF channel load and improving the overall system reliability. Besides offloading

traffic from the RF channel, V-VLC can also provide a redundant communication channel to improve robustness. In this regard, we see V-VLC as a complementary technology in the scope of a heterogeneous vehicular networking system, and not as a replacement for RF-based vehicular networking communications [32], [33], [45]. The presence of multiple communication technologies that can complement each other is an imperative for advanced vehicular networking systems, which will be supporting multiple applications in parallel competing for the same communication resources.

In the following, we assess the feasibility of V-VLC for different vehicular networking applications evaluating it in terms of the communication requirements introduced by Willke *et al.* [43]. This allows us to establish a generic outlook of V-VLC’s capabilities, compare it against other communication technologies, and identify suitable applications. Communication requirements for different vehicular networking applications include: communication latency, communication reliability, scaling, communication scope, and communication group structure [43].

Considering V-VLC’s short communication range and directed transmission, it emerges as a viable communication technology for applications whose scope requires communication with nearby peers (e.g., platooning, emergency electronic brake light), or with a small region (e.g., intersection assistance). V-VLC can also be used for communication beyond this scope (e.g., along a trajectory, or throughout the entire network), however in that case messages need to be forwarded via multi-hop communication, which increases latency, thus rendering V-VLC infeasible if the considered application has

TABLE I
SELECTED APPLICATIONS FOR V-VLC AND CORRESPONDING APPLICATION REQUIREMENTS (FOLLOWING AND ADAPTING SURVEYS BY BOBAN *et al.* [10] AND WILLKE *et al.* [43])

Application	Latency	Reliability	Scaling	Scope	Group Structure
Cooperative Awareness: Forward Collision Warning	Soft real-time (3 ms – 1 s)	Deterministic (> 95 %)	Low-medium (1 – 100 nodes)	Nearby peers	Non-persistent
Cooperative Sensing: See-through	Soft real-time (3 ms – 1 s)	Highly probable (90 – 95 %)	Low-medium (1 – 100 nodes)	Nearby peers	Persistent
Emergency Electronic Brake Light	Hard real-time (< 100 ms)	Highly probable (90 – 95 %)	Low-medium (1 – 100 nodes)	Nearby peers	Non-persistent
Information Query: Traffic Information Systems	Typical network (> 1 s)	Best effort (< 90 %)	High (> 100 nodes)	Trajectory / Entire network	Non-persistent
Intersection Assistance: Intersection Collision Avoidance	Soft real-time (3 ms – 1 s)	Deterministic (> 95 %)	Medium (10 – 100 nodes)	Small region	Persistent
Platooning	Hard real-time (< 100 ms)	Deterministic (> 95 %)	Low-medium (1 – 100 nodes)	Small region	Persistent

real-time requirements. For applications that require communication beyond the local scope, heterogeneous communication technologies with longer communication range like RF can be used.

The scope requirement implicitly affects the scaling requirement (i.e., the number of vehicles that need to communicate) for an application. Therefore, V-VLC can support applications that require communication among a limited number of vehicles, all in LOS. Regarding the group structure requirement, V-VLC can support applications that require both long term (i.e., persistent) and short term (i.e., non-persistent) relationship between vehicles.

As far as delivery latency and delivery reliability requirements are concerned, in theory, V-VLC can support applications that have hard real-time requirements and demand deterministic behavior. However, in practice, this can be possible only for communication with the direct neighbors, and under favorable optical channel conditions. Therefore, for applications with stringent reliability requirements V-VLC should be considered as a secondary communication channel to improve reliability and robustness. Whereas, for applications that can tolerate typical network delays and best-effort delivery, V-VLC can be used as the only communication technology.

Table I lists selected vehicular networking applications that can be realized using V-VLC on its own, or as part of a heterogeneous vehicular networking system. V-VLC can benefit these concrete applications as follows:

Cooperative Awareness: For cooperative awareness applications, like forward collision warning, or emergency vehicle warning, which require communication with the direct neighbors, V-VLC can be used to exchange the messages and therefore reduce channel congestion that would be caused by RF transmissions. This can improve the application performance, except in non-optimal optical channel conditions when it is recommended to use V-VLC in combination with other vehicular networking technologies due to the high reliability requirement of these applications.

Cooperative Sensing/Cooperative Perception: V-VLC can also benefit cooperative sensing and cooperative perception

applications, like see-through video streaming, which includes the sharing of sensory data, e.g., on-board camera, with vehicles in the vicinity, or collective collection of sensor data to perceive a bigger picture of the driving situation. In this context, headlamps and taillamps can be used to transmit high throughput data via V-VLC to the vehicles in the front and back, respectively.

Emergency Electronic Brake Light: This is a safety application that notifies the driver in case that a vehicle ahead brakes suddenly. For this application the tail to head V-VLC link can be used to transmit the emergency brake messages from the vehicle ahead to the following vehicles.

Information Query: V-VLC can be used for the query and dissemination of information in the scope of TIS. These applications do not have strong latency and reliability requirements, but they require high scaling and dissemination throughout the entire network. To facilitate this, in addition to V2V VLC, VLC-based V2I and I2V communication can be utilized. Namely, LED-based traffic lights, traffic signs, or road lighting can disseminate the information in parts of the network where V-VLC links among nearby vehicles is not possible.

Intersection Assistance: Intersection assistance applications, like intersection collision avoidance, are used to improve the safety in intersections by providing means of coordination and warning between vehicles, other than the conventional methods, e.g., traffic lights. When vehicles face each other in an intersection, they can use the head to head V-VLC link for communication with the vehicles in the opposite side of the intersection. In addition to this, LED-based traffic lights, or other elements from the infrastructure, can facilitate the communication.

Platooning: Platooning is one of the main applications that can benefit from V-VLC. In platooning, the platoon members are required to exchange information in timely and frequent manner (at least 10 Hz [46]) in order to maintain short driving distance. In the context of platooning, V-VLC can be used for communication between vehicles directly following each other, while IEEE 802.11p and/or C-V2X can be used for message exchange between the leader and the rest of the platoon [45], [47]. This can significantly reduce the

load on the RF channel, while improving the application performance.

C. Properties

V-VLC is characterized by a set of generic properties owing to the physical characteristics of the light as its transmission medium, and specific properties inherent to the vehicular networking domain. In the following, we identify relevant properties of V-VLC and discuss the advantages and disadvantages of these properties with respect to vehicular networking applications.

1) Propagation Characteristics: Visible light cannot penetrate opaque objects. When an electromagnetic wave of certain frequency encounters an object, the wave can be absorbed, reflected, scattered, or transmitted through the object. The interaction between the wave and the object depends on the wavelength and the amplitude of the wave as well as on the physical and chemical properties of the encountered object. This defines to what extent an object is opaque or transparent to specific wavelengths. For instance, white light consist of a continuous range of wavelengths. Some of these wavelengths are absorbed as they interact with the pigments in the surface of an object. Other wavelengths are scattered or reflected, determining the color of that object as we see it.

In general, signals transmitted via VLC cannot penetrate through objects, which are opaque to the human eye such as wood, metal, and plastic. As these materials are common in most indoor and outdoor setups, the interaction of visible light wavelengths with those materials largely impacts the design decisions for VLC-based applications, including V-VLC. The object can also be transparent (to certain wavelengths), meaning that the light easily passes through it.

2) Directionality of Lighting Function: VLC is highly directional. The directionality of V-VLC is governed mainly by the design of the transmitter lighting modules and the Field Of View (FOV) of the receiving PD. Generally speaking, lighting modules for indoor or outdoor illumination are designed to provide optimal illumination in a certain area of interest. Therefore, they mostly focus the light towards that area. In the case of exterior automotive lighting, the directionality is caused by the use of optical components inside the lighting modules which focus the light beams in the desired direction. The directionality of the light beams impacts many other properties of VLC. For instance, it results in a small collision domain, and allows high spatial reuse of the modulation bandwidth for devices in close proximity.

3) Asymmetric Power Distribution: A unique property of V-VLC is the asymmetry of different lighting modules [48]–[50]. More specifically, as vehicle headlamps and taillamps serve different purposes: illumination vs. signaling, there are substantial differences in their design [51, Chapter 6.1]. Thus, the light emitted by the headlamps is much more stronger than the one emitted by the taillamps. In turn, this results in an asymmetric link between two vehicles communicating with these lighting modules.

Furthermore, the light distribution of the headlight is not uniform. The idea is to illuminate more areas towards the curb side in order not to glare oncoming traffic. These properties of the V-VLC collision domain should be carefully taken in consideration when designing Medium Access Control (MAC) protocols for V-VLC.

4) LOS vs. NLOS: Propagation characteristics of the light and its directionality usually require a LOS link between the transmitter and the receiver in V-VLC. Maintaining such a stable LOS link under the dynamic mobility conditions of the vehicular traffic is one of the main challenges in V-VLC. In addition to this, in the outdoor environment the light beams are not spatially confined: they travel far distances, therefore, the reflected components cannot maintain sufficient energy for detection and reliable communication.

Although a LOS link is preferred, initial research has shown that NLOS communication via ground reflections can be beneficial for V-VLC [52]. Nevertheless, this depends on weather conditions and ground surface material, as they impact the reflectivity of the ground. Regarding NLOS reflections, V-VLC does not suffer from multipath fading, because of the inherent spatial diversity resulting from the significantly shorter carrier wavelength of visible light waves compared to the detection area of typical receivers [53]. This simplifies the design of V-VLC links.

5) Outdoor Environment: Some of the biggest challenges for V-VLC come from its outdoor operation. Meteorological phenomena like fog, rain, snow, and other particles in the atmosphere degrade the transmitted signal by absorbing and scattering the light waves [54]–[57]. Similarly, dirt or icing accumulated around the lighting modules (or receivers) can hinder the signal. This heavily influences the range and reliability of V-VLC. Icing on the ground, on the other hand, can cause stronger reflections (see Section IV-B).

Natural and artificial light sources impose a challenge for the system. Sunlight causes shot noise at the receiver, while outdoor LED-based light sources (e.g., roadside illumination, advertisement boards) can cause interference [58]–[61]. Further discussion on this topic can be found in Section IV-D and IV-E.

6) Full-Duplex MIMO Communication: A car can transmit and receive at the same time as the directional transmitter does not create self-interference for the local receiver. Thus, full-duplex operation can easily be integrated. As the transmission chain and the reception chain are separated anyhow, consisting of two separate signal processing chains, respectively, there is no additional hardware needed for realizing full-duplex communication.

A pair of head- and taillamps can transmit the same signal in parallel [62]. They can also be used individually to transmit separate multiple output streams concurrently [63]. This can also be realized in smaller scale using different groups of LEDs within a lighting module [64]. Assuming that multiple receivers are used on the receiving side too, Multiple-Input Multiple-Output (MIMO) communication is possible at minimal additional hardware cost. This property can be exploited to improve the robustness and throughput of V-VLC [65].

D. Security Aspects

For any wireless communication technology, security aspects are in general more critical compared to wired networks. Malicious attackers can easily overhear wireless communications and replay those at any point in time. Cryptographic solutions have become the standard solution. Another attack vector is jamming of the wireless channel. This can be done even on a per-packet basis to render all communication impossible [66], [67].

In general, the more directional the wireless channel becomes, the less critical is the security issue. For eavesdropping, replaying, and jamming, the attacker needs to get into LOS. V-VLC benefits here from the directional and confined nature of the light compared to RF-based solutions in the sub-6 GHz band. Security attacks now require precise targeting of the link between the transmitter and receiver. However, this cannot go unnoticed considering the relatively short distance between the transmitter and the receiver. Therefore, carrying out security attacks against VLC is non-trivial. Thus, V-VLC mitigates many security issues that are typical for the vehicular networks based on omni-directional RF communications [32], [33], [45].

Even more important, the use of V-VLC in combination with RF would enable a completely new set of protocols benefiting from each other to further improve security of the overall system. The resilience of VLC to security attacks has been discussed, e.g., in [32], [68]–[70]. Our main focus in this article, however, is on the concept of V-VLC, we therefore decided not to dig deeper into general security issues of VLC and RF-based communication systems.

E. Regulatory Requirements for Automotive Lighting Systems

As visible light can be perceived by the human eye there are multiple standards related to eye-safety, illumination, and automotive industry that entail V-VLC [71]. For instance, the IEC 62471:2006 standard [72] regulates the brightness of all LED-based devices [73]. As such, vehicle lighting modules, traffic lights, and other road signage that deploy LEDs have to comply with the standard.

Regarding vehicle safety, there are two major standards that can impact V-VLC. The US NHTSA standard 571.108 [74], which is used as basis for multiple standards in North America, and United Nations Economic Commission for Europe (UNECE) Regulation No. 112 [75], which has been internationalized through the United Nations (UN) and is adopted mostly in the rest of the world (with few exceptions such as China, India, and Taiwan, which have their own safety standards [76]).

Both NHTSA standard 571.108 and UNECE regulations [75], [110], [115] regulate multiple aspects of vehicle lighting modules, including placement, minimum and maximum luminous intensity, and light distribution (i.e., the shape of the radiation pattern) [51, Ch.6.3]. They also mandate the deployment of a high beam and a low beam in the headlamps. The low beam is required to implement a cutoff, resulting in an asymmetric light distribution. This has been shown to have nontrivial effects on the performance of V-VLC [48]–[50].

Although the two standards comply with each other, they are not identical: UNECE regulation 112 [75] has a sharper cutoff therefore emphasizes glare control, while NHTSA standard 571.108 [74] emphasizes forward visibility.

Other, more generic characteristics of VLC, not pertaining to the vehicular applications have been discussed in detail by Karunatilaka *et al.* [18].

III. VEHICULAR VISIBLE LIGHT COMMUNICATION SYSTEM

In this section, we study the core components of a V-VLC system from sender to receiver. This is quite similar to an RF-based communication system but also includes optical components, which have a strong influence on the communication characteristics.

A. System Architecture

Figure 2 shows a generic representation of the main building blocks of a V-VLC system. The transmitter consists of a signal processing block including the modulator, and the transmitter front-end (i.e., LED-based headlamps and taillamps). The receiver side consists of optical elements, which can be used optionally in front of the receiver, the actual receiver device, and the receiver-specific signal processing block for demodulation and decoding. The space between the transmitter and receiver is referred to as the optical channel.

Modulation and digital-to-analog conversion of the information bits is done in the scope of the signal processing block [19]. The exact structure and functioning of the signal processing block depends on the actual deployed platform. Popular approaches include Software Defined Radio (SDR)-based platforms [77], [78], FPGAs [79], and custom development platforms [80]. However, commercially available VLC-enabling devices, like Li-1st have also been deployed [62]. Since V-VLC is in an early stage of development, most of the platforms from the literature, including the aforementioned, are used for rapid prototyping and small-scale field tests.

The LED driving circuit combines the modulated signal with the bias current required to drive the high-power LEDs [18] (as opposed to low-power LEDs used for indoor VLC). This way, information gets modulated onto the intensity of the light that is emitted by the transmitter front-end [81, Ch. 2.2]. The design of the driver circuit is crucial for VLC as it has to provide correct biasing to ensure that the LEDs are driven at optimal operating point, and there is no signal clipping before modulation. A low operating point of the LED causes clipping of the negative parts of the signal, whereas a high operating point might exceed the linear region of the LED, distorting the signal and possibly damaging the LED. Open Source implementations of the driving circuit have been presented, for example, in [82], [83].

Once the light is emitted by the LEDs, it interacts with the optical elements within the lighting module that control the shape of the emitted beam according to automotive regulations [75]. Optical elements have a strong influence on the resulting signal. For example, lenses can be used to focus

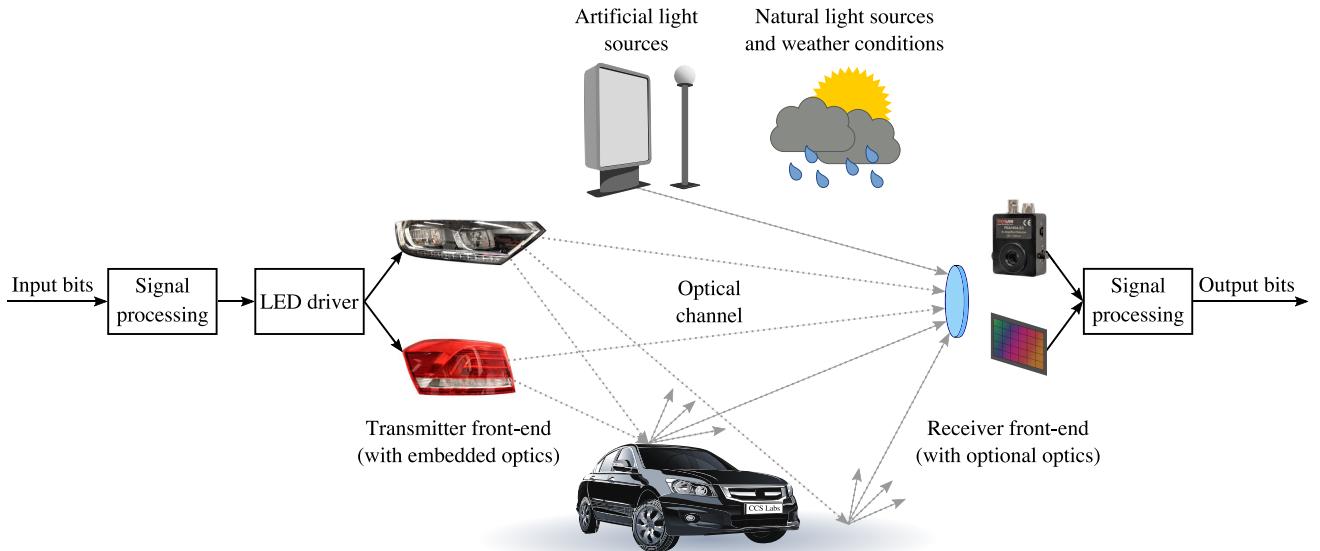


Fig. 2. Building blocks of a generic V-VLC system. The illustration shows, from left to right, the sender including signal processing (encoding, modulation), the LED driver logic, and the optical transmitter front-end; the channel which is influenced by interference from other light sources, weather effects, and reflections; and the receiver, including optical front-end, and the signal processing (demodulation, decoding).

the light on a certain point in the distance, and matrix lights even allow spatial separation of multiple transmissions using the different LEDs pointing in different (but overlapping) directions [64].

As the signal is propagating through the optical channel, it is subject to different propagation phenomena. Also, it is attenuated due to path loss and further degraded due to disturbances of the outdoor channel. A detailed discussion about the characteristics of the V-VLC channel and its modeling is presented in Section IV and V, respectively.

If not attenuated below the sensitivity threshold of the receiver, the signal arrives at the receiver on the direct link or via reflections. On the receiving side, an optical filter can be used in front of the receiver. This helps increasing the Signal-to-Noise Ratio (SNR) of the system by filtering out optical channels that are not of interest and may contain noise. In addition, other optical elements (e.g., lenses) can be used to focus the light towards receiver's aperture, therefore, improving the received signal strength via *optical pre-amplification* (see Section VI-C) [29], [77], [84], [85].

At the receiver, a PD or a camera image sensor is used to convert the optical signal to an electrical current. A transimpedance circuit can be used to convert the generated photocurrent to a voltage [34]. For camera image sensors, this is done by the readout circuit [86, Ch. 8.3.2].

The final step is the signal processing block at the receiver. Due to substantial architectural differences between PD and image sensor-based receivers, the signal processing steps differ as well. For instance, camera image sensor-based VLC requires an image processing step, which does not apply to PD-based VLC (see Section VI-B). In general, during the signal processing the analog current signal is converted back to digital signal and the information bits are decoded. We discuss the differences between the PDs and camera image sensors and their properties in more detail in Section VI.

B. Transmitter Front-End Characteristics

The LED is an optoelectronic device that transduces electrical energy to optical energy by emitting incoherent light when driven under forward current. Electrical and optical properties (e.g., current-voltage (I-V) characteristic, capacitance, color) of the LEDs can directly impact communication performance.

There are two conventional techniques to produce white light using LEDs. One technique requires the proper combination of two or more LEDs of different color in a single chip [87]. The most common implementation of this technique is the combination of red, green, and blue LEDs to obtain a tri-chromatic White LED (WLED). From the communication perspective, the presence of multiple LEDs in a single chip is advantageous as it allows the use of modulation techniques that can modulate each of the individual LEDs, hence provide higher data rates [23], [88]. On the other hand, having multiple LEDs increases the complexity and the cost of such devices.

The other technique for producing WLEDs uses phosphor coating with one or more monochromatic or ultraviolet LEDs [87]. The most popular implementation of phosphor-coated WLED is the coating of a blue LED with yellow phosphor layer. In this configuration, some of the blue photons emitted by the LED are converted to yellow photons as they interact with the phosphor layer, whereas other photons escape unaltered. The mix of blue and yellow photons results in white light. The thickness of the phosphor coating determines the color temperature of the resulting white light: the thicker the yellow phosphor, the warmer the color temperature. Vehicle headlamps typically have a cold color temperature between 4000–6000 K [75].

During the blue-to-yellow conversion the converted photons are subject to Stokes shift [87], i.e., the loss of photon energy due to shift from shorter wavelength to longer wavelength. This affects the luminous efficiency of phosphor-coated WLEDs. Nevertheless, because of the simpler design, lower

manufacturing costs, and better color rendering, phosphor-coated WLEDs are preferred over multi-chip WLEDs.

The modulation bandwidth of phosphor-coated WLEDs is affected by the slow response time of the phosphor coating, which introduces delays and deteriorates the communication performance. To mitigate this issue, one could use a transmissive blue optical filter on the receiving side to filter out the yellow light and to focus on the blue component, which can be modulated faster. This approach can increase the modulation bandwidth to tens of MHz and to support higher data rates [89]. However, it does so at the expense of decreased SNR, as a large portion of the received optical power from the yellow bands is filtered out [90]. This, in turn, can degrade the performance of multi-carrier modulation schemes [91].

One of the main problems on the transmitting end of VLC systems is the distortion caused by front-end nonlinearities. LEDs have a nonlinear I-V characteristic [92], which results in a nonlinear relation between the forward current and the radiated optical power [93]. This presents a major challenge in VLC, in particular when multi-carrier modulation schemes are used [94, Chapter 8.3.3]. In such cases, the intensity of the different subcarriers can be added constructively resulting in values beyond the linear range of the transmitter, thus, the signal gets distorted. A typical example of this is OFDM and its high Peak-to-Average Power Ratio (PAPR) [95].

A multitude of different techniques have been used to address challenges like nonlinearities and bandwidth limitations in VLC. We focus on V-VLC, therefore, a discussion regarding fundamental system-level VLC performance challenges and corresponding solutions is beyond the scope of this work. Very good discussions on this matter can be found in [18], [96].

C. Intensity Modulation/Direct Detection

LEDs are incoherent light sources that emit optical waves with random phase relationship. As such, in the absence of a consistent carrier phase [97], it is impractical to use (angle-based) modulation techniques like phase or frequency modulation. Therefore, different from conventional RF communications, where the signal can be modulated in phase, frequency, and amplitude, VLC systems rely on modulating the intensity of the optical wave [98, Ch. 2.1]. In optical wireless communications, this is known as Intensity Modulation (IM). Once the signal is intensity modulated, it is transduced via the LEDs from the electrical domain to the optical domain, and it passes through the optical channel. Since the intensity cannot be negative, IM imposes that the modulating signal has to be non-negative unipolar and real valued, as opposed to the bipolar complex valued RF signal [40], [81]. After the signal is adjusted appropriately, many MCSs originally designed for RF communications can be used for VLC too. Popular choices in the literature include, On-Off Keying (OOK), OFDM, and Direct Sequence Spread Spectrum (DSSS) [77], [79], [99]. Color-based MCSs, like Color Shift Keying (CSK) or Wavelength Division Multiplexing (WDM), can also be used for V-VLC, given that the lighting module deploys multi-color LEDs [100]. A crucial point to consider

when designing and deploying MCSs for V-VLC is that, they should be spectrally efficient to accommodate application's requirements (e.g., throughput, delay, robustness) within the limited bandwidth of LEDs used in exterior automotive lighting (see Section III-E). A detailed discussion regarding MCSs for VLC can be found in [17]–[19].

As the light emitted by the optical emitters is perceivable by the human eye, the modulated signal has to adhere to various rather restrictive regulations [72], [74], [75]. These regulations impact important properties of the emitted signal, such as the average optical power [72] or the minimum modulation frequency.³ Furthermore, any modulation carried out on the transmitted signal should not impact optical front-end's primary functionality, which is illumination and/or signaling.

On the receiving side, Direct Detection (DD) is used to demodulate an IM modulated optical signal. DD is an incoherent detection technique, where the data-carrying signal is extracted from the optical intensity incident on the PD.

Due to the square law nature of the PD, the electrical SNR for an IM/DD VLC link is calculated as the square of the average received optical power [96, Ch. 2.4], whereas for RF links it is proportional to the average received electrical power. As a result, a VLC system requires more optical power to deliver the same performance as in RF. This imposes a challenging constraint given the restrictive standards limiting the average optical power for LED-based devices.

D. LED-Based Exterior Automotive Lighting

Traditionally, exterior lighting systems in vehicles facilitate active safety by providing proper *forward illumination* and *signaling*. The former helps for *seeing*, while the latter for *being seen* [103]. The signaling functionality also conveys information to the traffic regarding the presence, dimensions, as well as the current maneuver of the vehicle (e.g., turning, breaking, stopping, reversing). Advanced applications like glare-free high beam, Adaptive Front-Lighting System (AFS) [104], and, most recently, matrix LED-based AFS [64], have been further developed to improve the signaling and illumination functions.

The initial use of LEDs for exterior automotive lighting dates back to 1980s, when red LEDs were first used in vehicles' rear lighting system, more specifically in the central high-mount stop lamp. By mid-2000s LEDs debuted in the headlamps of high-end models of different car manufacturers, while today they are becoming commonplace in all cars [105]–[107]. A selection of first application of LED lamps in cars is shown in Table II.

There are numerous advantages to using LEDs for exterior automotive lighting. For instance, improved robustness against vibrations extends the lifespan of the lighting modules, even beyond the lifetime of a typical vehicle. Improved energy efficiency of the LEDs results in lower fuel consumption, and the smaller form factor allows more space and design freedom. Most importantly, the quick raise time of LEDs has

³Minimum modulation frequency is defined according to the Critical Fusion Frequency (CFF) [101]. It should be higher than 200 Hz to avoid flickering [102].

TABLE II
SELECTED MILESTONES IN LED TECHNOLOGY FOR EXTERIOR AUTOMOTIVE LIGHTING IN PRODUCTION CARS

Milestone	Year	Model
First use of LEDs for exterior lighting (central high-mount stop lamp) [105]	1980s	-
First full-LED taillights	2004	Cadillac DTS
First use of LEDs in headlamps (daytime running lamp) [105], [106]	2004	Audi A8 W12
First use of LEDs for multiple functions in headlamps	2007	Lexus LS 600h
First full-LED headlamps (North America segment)	2007	Cadillac Escalade
First full-LED headlamps [106]	2008	Audi R8

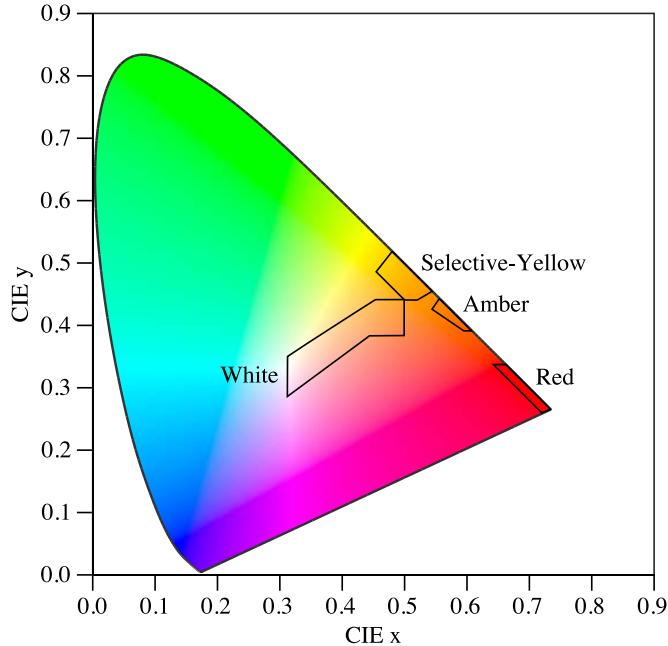


Fig. 3. CIE 1931 color space diagram with annotations for chromaticity areas of colors emitted by automotive lighting modules. Trichromatic coordinates for the color boundaries are specified in [75] and [110]. Intersection points for the chromaticity areas are taken from [111].

safety implications: It provokes quicker reaction from other drivers [108] and, therefore, can extend the stopping distance in safety-critical situations [109].

Figure 3 shows the CIE chromaticity diagram for vehicles' lighting modules. Historically, specific colors required in traffic lights and in automotive lighting, such as red, amber, and green, were obtained by using lenses and bulbs coated with the desired color. Nowadays, the lenses can be transparent whereas the desired color is obtained by using colored LEDs.

Although active safety remains the main application for exterior automotive lighting, the presence of LEDs in these devices makes them readily available for V-VLC.

E. Head and Taillamps as V-VLC Transmitters

Repurposing of existing vehicle headlamps and taillamps for communication is technically possible, however, their use as V-VLC transmitters must not hinder the primary function of illumination. There are many architectural and system-level



Fig. 4. Different lighting functions of an LED-based Audi A8 headlamp. The high beam functions are realized in combination with the low beam. The low beam and the bend lighting are realized independently. Other functions like DRL, direction indicator, are not shown. Image adapted with kind permission from HELLA GmbH & Co. KGaA.

features of automotive lighting modules that can positively or negatively impact the communication aspect. For instance, even simple manufacturing technicalities, like series or parallel connection of the LEDs have an impact [112].

One of the main V-VLC performance bottlenecks comes from the high-brightness LEDs that are used in exterior automotive lighting. These are high power LEDs with high capacitance (therefore slow rise time), which limits the modulation bandwidth (and therefore the effective communication time) only to a few MHz [48], [84], [112], [113]. Still, it has been demonstrated in the literature that certain LEDs have an *almost linear* frequency response beyond the 3 dB bandwidth, which can be exploited if the modulating waveform is optimized to generate a flat response for the bandwidth beyond the 3 dB bandwidth [112].

Another system-level feature of vehicle lighting modules that largely impacts the communication aspect is the function carried out by the optical elements within the lighting module: A complex optical system (consisting of, e.g., projection module, reflectors, cover lens) controls the shape of the emitted light beam, intrinsically performing spatial *beam shaping*, to ensure that the emitted light pattern complies with the road safety regulations (to minimize glare of oncoming traffic, and backward reflections to the driver) [75]. Considering that in a V-VLC system the lighting module is the *antenna*, any modification of the *antenna pattern* naturally impacts the communication performance [49], [114].

Additionally, as headlamps and taillamps are important styling elements of a vehicle's overall appearance, their design varies depending on vehicle type and model. Such design differences result in slightly different radiation patterns, which, in turn, can have nontrivial impact on the V-VLC performance [50].

While high-brightness LEDs, optics, and design variances can have unwanted side effects on V-VLC, there are other features of exterior automotive lighting systems that can benefit it. As shown in Figure 4, the head (as well as tail) lighting modules consist of multiple lighting submodules. A typical headlamp has a daytime running lamp, a low beam (also known as dipped-beam lamp), and a high beam (also known as

main-beam lamp). A typical taillamp has, among others, a rear position lamp, a brake lamp, and a reverse lamp [115]. Each of these lighting functions has different illumination characteristics, which can be exploited for best-effort communication in a given scenario. For instance, due to the stronger and more directed radiation compared to a low beam, the high beam can be used for communication to farther distances.

Of course, to not disturb other traffic, the high beam cannot be used at all times. This presents a trade-off in terms of practicality and communication for V-VLC: It is implied that a lighting module needs to be turned on if it is to be used as a V-VLC transmitter. In reality, however, this cannot be guaranteed in all situations, except for countries where daytime operation of selected lighting modules is mandatory. In such cases, it is safe to assume that a subset of lighting modules (i.e., daytime running lamp, low beam) will be on and, therefore, available for communication. If safety regulations do not permit the operation of a lighting submodule at all times (e.g., the high beam), modulation techniques with a very low duty cycle, such as the DarkLight concept [83] where the frequency of the pulses is so low that the light is not visible to the human eye, can be used. Such a low duty cycle, however, comes at the expense of lower data rate.

One important advantage of exterior automotive lighting is that the lighting modules come in pairs. This enables the implementation of MIMO techniques, like *transmit diversity* or *spatial multiplexing*, for V-VLC at no cost for additional antenna deployment. Initial simulative [116] and empirical [62], [63] studies on this matter have demonstrated the feasibility of MIMO for V-VLC. However, as shown by Turan *et al.* [62] and Narmanlioglu *et al.* [63], it is important to carefully choose the system parameters and transmitter combinations for such techniques to be beneficial for V-VLC, else they can be counterproductive.

V-VLC can also benefit from state of the art adaptive front-lighting technologies used for forward illumination. These systems adjust the illumination characteristics of the headlamps for best visibility and comfort in different driving situations, based on sensory feedback (e.g., camera). Some features of AFS include automatic switch between low beam and high beam mode depending on oncoming traffic, weather conditions, and road curvature.

Most recent AFSs use matrix-LED technology, where a subgroup of LEDs from the LED matrix can be selectively turned on and off, for example, to avoid shining light on the windshield of oncoming traffic. Since individual LEDs have sharply separated radiation beams, it is possible to select subgroups of LEDs to communicate with multiple communication partners [64]. As a result, spatial multiplexing can be implemented at a more granular level, i.e., groups of LEDs within a module, instead of whole modules. In some first work, Tebruegge *et al.* [64] have shown that Space Division Multiple Access (SDMA) implemented using matrix LED-based Adaptive Front-Lighting System can effectively reduce multiuser interference and help medium access for V-VLC. Similarly, Segata *et al.* [117] and Schettler *et al.* [118] demonstrated its benefits for platooning. It is worth noting that advanced lighting technologies, like matrix LED-based AFS,

are only implemented for headlamps, however, they would also be helpful for taillamps (e.g., for tail to head communications as in the case of V-VLC-based platooning [118]).

While architectural and system-level features of lighting modules can impact V-VLC, it is also possible that V-VLC impacts them. As stated initially, using exterior automotive lighting for communication must not affect their illumination function. However, the frequent switching of the LEDs can degrade the illumination quality and shorten their service life over time. The reason for this is junction temperature variation due to increased current density [119]–[121]. In the current literature there is no comprehensive research on the impact of V-VLC on the deployed LEDs and/or on the overall exterior lighting performance.

IV. FACTORS THAT INFLUENCE V-VLC COMMUNICATION

Generic V-VLC properties, which derive from the physical characteristics of the light waves, have been briefly discussed in Section II-C. We now have a detailed look into more specific V-VLC channel properties and influencing factors.

A. Impact of Lighting Module Light Distribution

V-VLC is predominantly a LOS technology, which requires a LOS link between the transmitter and the receiver for effective communication. We already mentioned the very specific “antenna pattern,” i.e., light distribution pattern of vehicle lighting modules and how the deployed optical elements dictate the shape of the radiation pattern. In this section, we have a more detailed look at the light distribution by typical headlights as their radiation pattern is irregular and more challenging compared to taillamps, which have a rather symmetric radiation pattern [48].

The resulting light distribution is depicted in Figure 5. This non-uniform light distribution of the headlights stems from the vehicle safety regulations. The effect can be seen in Figures 5a and 5b, for the horizontal plane and the vertical plane, respectively. Due to the peculiar antenna pattern of the headlight modules, establishing a link between the transmitter and the receiver and, therefore, the channel conditions in V-VLC, largely depend on the radiation pattern of the lighting module and the position of the receiver within that radiation pattern. In the literature, it has been shown that even dirt deposits in front of the lighting modules can influence the shape of the radiation pattern [30].

The asymmetric and non-uniform property of headlights’ radiation pattern poses a challenge in terms of modeling of V-VLC communication. We deepen this discussion in Section V when introducing the mathematical modeling background.

B. Impact of NLOS Communication

Besides LOS communication, in V-VLC there also exist NLOS links via reflections from the ground, vehicles, buildings, and other objects in the environment. However, reliable communication via those links cannot be guaranteed as the received signal strength largely depends on the reflection characteristics of the building material of the

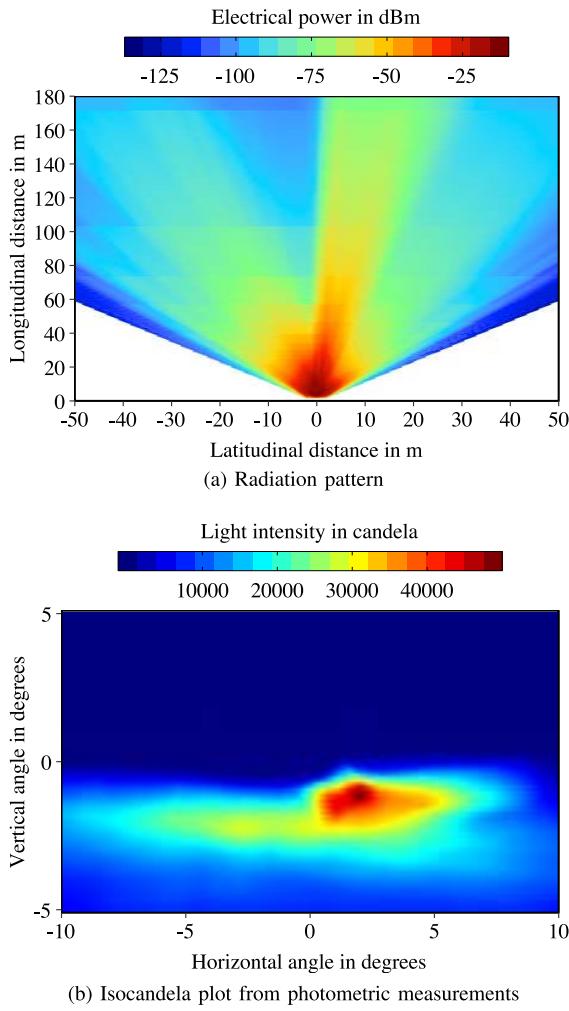


Fig. 5. Radiation pattern (for both headlights) showing the receivable electrical power for the horizontal plane, and the isocandela plot (of the right headlight) showing the light intensity distribution on the vertical plane. The plots are based on measurements presented in [50].

object [29], [30], [52], [112], [122]. In V-VLC, the ground surface area between a transmitter and receiver provides the strongest NLOS components. These reflections are typically characterized as a mix of specular and diffuse [30]. Besides the pavement material, also the weather conditions influence the strength of the reflections. For example, rain, ice, and snow affect the surface conditions of the road, which, in turn influence the reflectivity, hence, the strength of the NLOS links [30], [123].

The NLOS components can have comparable signal strength to the LOS component [112] in scenarios with highly reflective road conditions (see [52], where a wet road is emulated by a shiny linoleum indoor pavement), and certain transmitter-receiver distance, where the reflections from the ground are stronger due to convenient reflection angle.

In general, NLOS communication can be beneficial in V-VLC, as the NLOS links of the signal contribute as constructive interference: Assuming typical V-VLC LED bandwidth and modulation and coding schemes, the maximum delay from the reflection paths is orders of magnitude smaller than the symbol duration, hence, the symbols are not negatively

affected [52]. Besides the NLOS links from the ground, nearby vehicles can also cause constructive interference in V-VLC [112]. More extended discussion about small-scale effects in the V-VLC channel, regarding the frequency response, time dispersion characteristics, and multipath effects in different scenarios can be found in [112], [122], [124].

Due to the complexity of capturing all of the impacting factors, and the infeasibility of conducting corresponding experiments, there is only sporadic work in the literature focusing on modeling NLOS V-VLC. Some approaches, have modeled the NLOS V-VLC links similar to the *two-ray ground-reflection model*, where the reflective area on the ground is modeled as a secondary light source [30]. Other approaches have used Computer-Aided Design (CAD) and simulation tools [122], [124].

C. Impact of the Vehicular Environment

1) *Mobility*: Assuming no disturbances in the channel, the geometry between the sender and the receiver (i.e., relative distance and orientation) and the corresponding hardware characteristics (e.g., receiver's Field Of View and active collection area, transmitter's radiation pattern) have the largest impact on the large-scale channel conditions [125]. The geometric parameters are mainly influenced by vehicles' mobility, which, in turn, impacts the temporal characteristics of the channel.

The optical channel, characterized by the Channel Impulse Response (CIR), does not change significantly if the transmitter-receiver pair move in the order of a wavelength [125]. In the vehicular environment, however, typical displacements are orders of magnitude larger than the VLC wavelengths, making the V-VLC channel a highly dynamic one. In the V-VLC literature, temporal characteristics of the channel have been described using coherence time and link duration [114], [126], [127].

Typical driving maneuvers, such as left/right turning, stop-and-go situations, overtaking, and red light stopping, contribute to the channel variation in time. It has been demonstrated that there is a large variance in the received optical power when vehicles perform turning maneuvers [126]. Although this variation depends highly on the driving maneuver, it is relatively slow compared to the communication speed. Thus, it can be effectively addressed with adaptive gain control at the receiver.

2) *Road Conditions*: Besides the driving maneuvers, which mainly introduce horizontal movement, the road conditions also have an impact on temporal characteristics of the channel. Road irregularities can introduce vibration and vertical movement that impacts the transmitter-receiver alignment and, in turn, causes intermittent variation in the optical power. The likelihood for this type of variations is smaller in freeways, due to the more regular road structure, as compared to urban roads [126]. In general, also due to the more stable driving behavior on highways, the V-VLC channel varies slower in time (i.e., has longer coherence time) and the link duration is longer than in the urban scenarios [114], [126].

D. Impact of Ambient Light

Natural and artificial light sources and interference are the main factors in the outdoor channel that can impact V-VLC. This includes ambient light from sunlight and skylight (i.e., natural light sources), and light from artificial light sources, like incandescent and fluorescent lamps, which are deployed outdoors, e.g., for road illumination, advertisement boards [53], [128]. If the background radiation is strong, i.e., the average optical power from natural and artificial light sources is stronger than the desired signal, the communication is impaired. Under certain conditions (e.g., direct sunlight), the background radiation can be too high and the receiver is completely saturated.

Since natural light sources, like sunlight and skylight, are not modulated, the electrical signal generated at the PD output is essentially DC current, which can be mostly mitigated by a low-pass filter and by using higher frequencies for communication [18], [95]. In addition to this, the background radiation induces photogenerated noise, characterized as *shot noise*, caused by the statistical fluctuation of the number of photons randomly arriving at the PD [19], [96, Sec. 2.6]. The main cause of shot noise is the solar irradiance, while artificial light sources contribute to the variance in the shot noise, which can further deteriorate the communication [53]. The shot noise is a limiting factor in V-VLC systems in daytime, particularly during sunset and sunrise when the sun is at angles that can saturate the PD [29], [58], [128]. Sunny weather also reduces the effective bandwidth of the LEDs [112].

Apart from the techniques mentioned above, optics-based approaches can be utilized to address ambient light induced noise. One potential solution is to use highly directional receivers that can separate the desired signal from the noise source. However, this can impact the system's tolerance to mobility due to a reduced FOV at the receiver [29]. Also, optical filtering of particular wavelengths (e.g., blue filtering) has been explored [129]. Yet, with this technique, besides the noise, substantial amounts of signal power can be left out on the blocked wavelengths [90], [91].

In terms of receiver hardware, image sensor receivers are advantageous in dealing with ambient noise as they enable the separation of the signal source from the noise source by isolating the pixels which contain noise. Further, very thorough discussion about the outdoor channel for optical communications can be found in [95, Ch. 5], [96, Ch. 3.3].

E. Impact of Weather Conditions

Other factors in the outdoor channel that heavily affect the V-VLC channel are the challenging weather conditions like fog, rain, and snow. Normally, molecules and particles in the atmosphere interact with the light (via absorption, scattering, diffraction) thus, diverging the beams and attenuating the transmitted signal. Under bad weather conditions these effects are much more severe, as fog, rain, and snow consist of larger particles which have large-scale impact on V-VLC. This, in turn, affects the range and reliability of the V-VLC system.

Initial studies characterizing the impact of weather conditions on V-VLC performance have considered different

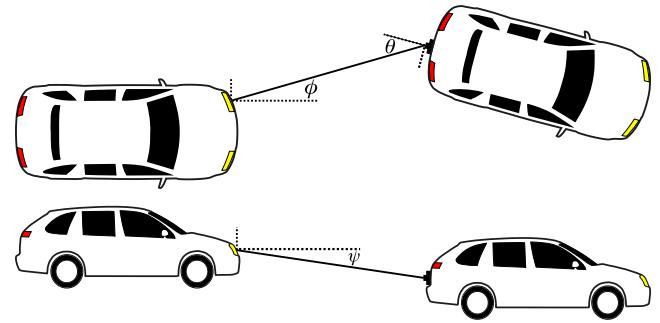


Fig. 6. Angle of irradiance ϕ is the horizontal angle between the axis perpendicular to the LED surface and the transmitter-receiver line (drawn as solid black line) [114]. Angle of incidence θ is the horizontal angle between the axis perpendicular to the PD surface and the transmitter-receiver line [114]. Angle of elevation ψ is the vertical angle between the axis perpendicular to the LED surface and the transmitter-receiver line [134].

weather phenomena, including fog [54]–[58], rain [55], [57], [130], [131], snow [59], turbulence [57], [61], [130], and solar irradiance [58], [128]. Empirical and simulation-based studies have demonstrated that fog has the biggest impact on V-VLC compared to rain and snow [55], [57], [131], while a few analytical studies show that dry snow can be more detrimental to the system performance than fog [58], [59]. According to empirical measurements, for the most challenging scenario, that is dense fog, reliable communication up to 20 m with image sensor receiver, and up to 15 m with PD for the highest permissible modulation scheme is possible [55]–[57], [131].

V. CHANNEL MODELING

A. Modeling Channel DC Gain

Since visible light and infrared have comparable wavelength, they share similar properties. As a result, multiple models and techniques for characterizing the VLC channel have been directly adopted from the results published on infrared communication [21], [53]. One of the most widely used models for calculating path loss in VLC channels is based on the *channel DC gain* $H(0)$, introduced by Kahn and Barry [53] for IM/DD-based indoor infrared communications. $H(0)$ relates received optical power P and transmitted optical power P_t as

$$P = H(0)P_t. \quad (1)$$

$H(0)$ does not consider any frequency dependent effects, since infrared channels have a relatively flat frequency response near DC [132], [133], which also holds true for VLC channels [86, Ch. 2.4.1], [112].

B. Transmitter and Receiver Modeling Using Channel DC Gain

Channel DC Gain considers the hardware characteristics of the transmitter and the receiver, and the geometry between them: the transmitter-receiver distance d , and the angles of irradiance ϕ and incidence θ (see Figure 6).

Channel DC gain $H(0)$ for a LOS link is given as

$$H(0) = \frac{A}{d^\gamma} R_o(\phi) T_s(\theta) g(\theta) \cos(\theta), \quad (2)$$

where A is photodiode's active area, γ is the path loss exponent (with a typical value of 2), and $R_o(\phi)$ is transmitter's radiant intensity. Assuming that optical elements (i.e., filter and concentrator) are used in the system, $T_s(\theta)$ models the signal transmission of the optical filter and $g(\theta)$ models the gain from the optical concentrator.

Channel DC gain $H(0)$ assumes that the transmitter has a Lambertian emission profile (i.e., is a Lambertian emitter), with radiant intensity $R_o(\phi) = [(n+1)/2\pi] \cos^n(\theta)$. Assuming no further optical elements, $H(0)$ for a generalized Lambertian transmitter can be expressed as

$$H(0) = \frac{(n+1)A}{2\pi d^\gamma} \cos^n(\phi) \cos(\theta), \quad (3)$$

where $n = -\frac{\ln 2}{\ln \cos(\phi_{1/2})}$ is the order of the Lambertian model, which is related to the half-power angle $\phi_{1/2}$ of the transmitter. Equation (3) has been widely used in the V-VLC literature, both for V2V [28], [65], [134] and V2I [39], [79], [135] applications. A modified version of it, which also accounts for the elevation angle ψ , to model the height difference between the transmitter and the receiver, has been used in [136].

Even though the Lambertian emission profile might be a good approximation for transmitters with a regular and symmetric emission profile, this does not hold true for exterior automotive lighting, which use beam shaping components [137]. Automotive headlamps use complex optical systems to implement an asymmetric radiation pattern with non-uniform light distribution (see Figure 5) as required by automotive regulations (see Section II-C). This characteristic cannot be captured by the Lambertian emission based models, which is one of the main challenges for accurate V-VLC channel modeling.

C. More Realistic V-VLC Transmitter and Receiver Modeling

Since the Lambertian emission profile is not the ideal approach for modeling V-VLC transmitters' radiation pattern, more realistic approaches have been considered in the literature. Some approaches use empirically measured radiation patterns from vehicles' actual lighting modules, which are analytically fitted and used for vehicular networking simulation frameworks [49], [138]. These models can rather accurately model the difference in light distribution within a lighting module's radiation pattern, but they are limited to the particular measurement setup (e.g., lighting module, photodiode, geometry) and cannot always be generalized. This can be a shortcoming, having in mind the design variances among vehicle manufacturers and models [114], which has significant impact on V-VLC performance [50]. A more realistic modeling of the transmitter is possible when using CAD models [122], [124] or high resolution measurements of the light distribution of lighting modules provided by the vendors [50].

One factor that can impact transmitter's radiation pattern but is seldom considered in the literature is the presence of particles, i.e., dirt or other formations, in front of the lenses. This factor should be considered in conjunction with the modeled weather conditions, as the type of deposits in front of the lenses will largely depend on the weather and the resulting road conditions [30], [139].

Modeling of the V-VLC receiver is easier compared to the transmitters, because the hardware characteristics of the receiver do not have any peculiar characteristics (e.g., as the non-uniform radiation pattern of the headlights). The simplest way to model a PD receiver is to account for simple hardware specifications, such as detector's active area, and the optional optical elements in front of the receiver (as in Equation (2)). However, for a more realistic modeling of the system further parameters, including but not limited to, the FOV, responsivity curve, and amplifier gain should be considered. In [50], the authors use the responsivity curve of the PD to calculate the photocurrent I_{PD} for a particular LED and PD combination:

$$I_{PD} = \int_0^{\infty} \frac{d\Phi_{V,\Omega}(\lambda) \cdot \mathcal{R}(\lambda)}{K_m \cdot V(\lambda) d\lambda}, \quad (4)$$

where $\Phi_{V,\Omega}(\lambda)$ is the luminous flux on the receiver surface, \mathcal{R} is the responsivity curve, which describes the wavelength-dependent current output of the PD, K_m is the maximum value of the photometric radiation equivalent, and $V(\lambda)$ is the luminosity function representing the sensitivity of the human eye. A highly descriptive analytical model considering multiple parameters of a V-VLC system is presented in [30].

D. Modeling Noise

There are two types of noise usually considered in the V-VLC literature: Shot noise induced by the background radiation from ambient light sources (see Section IV-D) and thermal noise from the thermal fluctuation of the electrons in receiver (pre-amplification) circuits [96, Ch. 2.4.6]. This is the dominant type of noise in the absence of ambient light. Both, shot and thermal noise are signal-independent and can be modeled as Gaussian noise. The total noise variance for a typical V-VLC system is given as

$$\sigma_{\text{total}}^2 = \sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2. \quad (5)$$

According to Luo *et al.* [30], the variance of the shot noise can be expressed as

$$\sigma_{\text{shot}}^2 = 2eB_s(RP_r + I_b I_2), \quad (6)$$

where $e = 1.602 \times 10^{-19}$ C is the elementary positive charge, B_s is the system bandwidth, R is the average responsivity of the PD, P_r is the average received optical power, I_b is noise current from received background radiation, and $I_2 = 0.562$ is the noise bandwidth factor for the background noise [140].

Considering a resistor of resistance R at absolute temperature T , the variance of the thermal noise for a system bandwidth B_s is expressed as [141]

$$\sigma_{\text{thermal}}^2 = \frac{4k_B T}{R} B_s, \quad (7)$$

where $k_B = 1.380649 \times 10^{-23}$ J/K is the Boltzmann constant. In the literature R is modeled as load resistance at 50Ω [48], [50].

More elaborate equations of shot and thermal noise, accounting for receiver's hardware specifics (e.g., PIN/FET transimpedance receiver, feedback resistor noise, FET channel noise), can be found in [61], [140]. Note that, the noise

characteristics of the system will vary depending on the particular receiver, as well as receiver type (PD, camera image sensor) [96, Ch. 2.6], [86, Ch. 8.3.3]. However, as the predominant types of noise, shot noise and thermal noise are generally sufficient to model the channel.

E. Modeling of Atmospheric Attenuation

There is only sporadic work in the V-VLC literature that models the impact of weather phenomena (e.g., fog, rain, or snow) for V-VLC. This is due to the difficulty of conducting empirical experiments to characterize V-VLC under different weather conditions.

The existing V-VLC literature on this topic adopts well-established models (e.g., Mie theory [142], Kim model [143]) from the field of (laser-based) optical wireless communications. These models allow the calculation of an atmospheric attenuation coefficient for foggy weather. As this coefficient is related to atmospheric visibility parameter it has been generalized for rain and snow [56], [59]. The main challenge when using this models is to find the correct physical parameters (e.g., liquid water content, particle size distribution, average particle size, visibility reduction), which describe the particular weather phenomena. Further elaboration of the aforementioned models is out of the scope of our work, but thorough discussion can be found in [96, Ch. 3.3], [144].

When modeling the weather conditions one should consider the indirect effects that they can have on communication. While bad weather conditions certainly impair the LOS link, in certain cases they can impact the reflectivity of the ground (e.g., wet road due to rain or snow) and, thus, improve the NLOS links. This aspect has been considered in [55], where a CAD tool is used to model reflective characteristics of the environment (e.g., road surface, cars), as well as the physical properties required to represent fog and rain (according to Mie scattering theory). Besides road reflectivity, weather conditions impact the type of deposits that are accumulated in front of a lighting module, which in turn influence the light output of that lighting module.

VI. VEHICULAR VLC RECEIVERS

A V-VLC system can deploy a PD or a camera image sensor to receive the optical signal transmitted by the LED-based head- and taillamps. The intensity-modulated optical signal is converted to an electrical current signal and passed for decoding and demodulation to the rest of the receiver chain.

Both, PD and camera-based receivers have been widely considered for V-VLC [22], [28], [29], [145], [146]. As these two types of receivers differ fundamentally in terms of hardware architecture and design, the way how they “see” the optical signal and process it differs as well. Basically, this architectural difference determines the overall design of the V-VLC system and its performance: Modulation and coding schemes, mitigation of noise and interference, medium access control, etc. are all designed differently depending on whether a PD or an image sensor receiver is used. In the following, we discuss PD receivers, camera-based V-VLC, and potential optical enhancements for V-VLC.

A. Photodiode-Based Receivers

The PD is an optical-to-electrical transducer that generates an electron for each impinging photon [96, Ch. 2.4]. The generated photocurrent is proportional to the optical power on the PD’s surface (i.e., irradiance) [98, Ch. 2.1]. The electrical power, being proportional to the square of the current, is proportional to the square of the optical power. This makes the PD a *square law* device. As mentioned previously, this property is a limiting factor in V-VLC, as the electrical SNR for an IM/DD link is calculated as the square of the average received optical power. In contrast, in RF communication systems, it is proportional to the average received electrical power.

There are two types of PDs that are typically used for V-VLC systems: PIN (p-n diode) and Avalanche Photodiode (APD). APDs have higher sensitivity and provide better gain compared to PIN PDs. There exist high-sensitivity APDs, like the Single-Photon Avalanche Diode (SPAD), which, in simulation, have been demonstrated to perform better than conventional APDs, even in adverse weather conditions [147]. Despite this, PIN PDs are more favorable for V-VLC due to the better linearity performance, high temperature tolerance, and lower cost [18].

When choosing the PD receiver for a V-VLC system, one should aim for optimal performance while considering hardware properties, such as size of the active area, adequate bandwidth, high sensitivity, low noise, and broad linearity range. These parameters can greatly impact the performance of the V-VLC application. For instance, a PD with a large FOV will have higher tolerance to horizontal and vertical movement in real driving scenarios, however, it allows the reception of undesired signals, which can reduce the SNR [29], [126].

Most setups described in the V-VLC literature prefer commercially available off-the-shelf products to demonstrate the feasibility of implementing the system both in terms of cost and effort [77]. However, custom-built solutions are used whenever the system uses more advanced techniques [148]. The design of low cost PD-based V-VLC systems is important as, unlike image sensor-based V-VLC, which can potentially be realized using the front and rear view cameras readily available in modern vehicles, PD-based V-VLC requires the installation of new devices on the vehicle, which, in turn, increases the overall vehicle cost.

Further discussion regarding PIN PDs and APDs, including the technical differences and comparison between them, can be found in [96, Ch. 2.4] [98, Ch. 2.2.2].

B. Camera Image Sensor-Based V-VLC

V-VLC based on camera image sensor receiver falls in the domain of Optical Camera Communication (OCC) [149], [150]. A substantial amount of work in the V-VLC literature has focused on the use of camera image sensors as receivers [151]. Cameras are already deployed in modern vehicles for safety applications, like pedestrian detection, lane detection, and parking assist. Therefore, such cameras are ready to use for V-VLC [145], [152]. There are many advantages of using cameras for V-VLC: The rather high spatial resolution of cameras allows separation of noise and signal

sources and detection of multiple transmitters and, therefore, enabling efficient MIMO V-VLC [150].

A typical OCC receiver consists of an imaging lens, an image sensor, and a readout circuit. The image sensor consists of multiple micron sized PD pixels, which generate voltage proportional to the number of impinging photons. The light from the imaging lens projected onto the image sensor is converted to binary data by the readout circuit [86, Ch. 8.1.2]. Based on the readout circuit configuration, image sensors can be classified into rolling shutter and global shutter image sensors [153]. The global shutter technology, typically used with Charge Coupled Device (CCD) image sensors, exposes all of the pixel at once, whereas the rolling shutter technology, typically used with CMOS image sensors, reads pixels one row/column at a time. This allows comparatively higher data rate. Due to this property, rolling shutter image sensors are preferred for VLC.

An important limitation of typical CMOS image sensors is their low frame rate (typically 30–100 fps), which limits the throughput to tens of bits per second—a fairly low data rate for vehicular networking applications [154]. As an alternative, high frame rate cameras can be used, however, they are quite expensive [155]. In addition to commercial solutions, custom designed cameras, like Optical Communication Image Sensor (OCI) and Dynamic Vision Sensor (DVS) camera, optimized for automotive applications, have been introduced [146], [156]–[158]. For instance, the DVS camera offers advantages in terms of improved throughput and noise elimination [157]. The pixels of the DVS camera only register a signal whenever there is a significant change in light intensity, otherwise they are treated as still and can easily be discarded, thus, solving noise issues. Additionally, not having to read all of the pixels (i.e., a frame), as in commodity cameras, saves valuable bandwidth [158]. Although custom design cameras for V-VLC can deliver better performance, they do it at the expense of higher complexity and cost.

The fundamental difference in camera-based VLC is the need to use image processing techniques on the receiver side for the detection/tracking of the transmitters, and for extracting the transmitted signal. The goal here is to ensure accurate and real-time image processing in order to avoid delay penalties on the application performance, while effectively mitigating imaging-related issues like blur and perspective distortion [159]. The distance also plays an important role. With increasing distance between the transmitter and the receiver, the number of pixels occupied by the transmitter becomes smaller and their brightness fades. This hinders the detection of the transmitter and extraction of the transmitted signal. Thorough discussion regarding camera-based VLC, also applicable to vehicular scenarios, can be found in [86, Ch. 8], [149], [150].

C. Optical Improvements

In V-VLC, it is typical that optical devices (e.g., lenses, Liquid Crystal (LC) panels, Digital Micromirror Device (DMD)) are used in front of the receiver to enhance the communication performance (see Figure 2). This provides

an additional degree of freedom (comparable to sophisticated antenna technology for RF-based communication) that can be exploited to improve multiple aspects of the system (e.g., better SNR and improved medium access). Optical pre-amplification of the signal even by means of very simple optics can result in significant performance gains [29], [54], [77], [128].

Typically, simple optical lenses with concentrating functionality and optical filters are deployed in VLC systems. The optical filter is used to exclude out-of-band light from natural and artificial light sources, thus, improving the SNR [96, Ch. 5.7.1]. The optical lenses help to amplify the transmitted light and focus it into the aperture of the receiver. The lenses can also be used to reduce the FOV of the receiver in order to minimize the noise from light sources other than the transmitter. For instance, Tu *et al.* [160] have presented a V-VLC system which uses adjustable attenuator (i.e., density filter) with dynamic saturation control to mitigate strong background radiation (see Section IV-D).

Simple optics aside, more sophisticated systems have already been proposed in the literature to improve V-VLC. Kratochvil [152] uses a DMD array in addition to the optical lenses. The DMD array serves as a filter: the micromirrors only reflect signals from the intended transmitters, while filtering out the rest of the light. In a conceptually similar, but rather more advanced system, Tebruegge *et al.* [85] use an optical system with two lenses and an LC panel. By individually controlling the pixels of the LC panel, they allow (or block) light coming from different light sources, depending whether it is a desired transmitter or not. This system can also protect the PD from saturation by programmatically blocking the extra saturating light shining on particular subset of the pixels. The aforementioned systems can effectively filter ambient light and interference exploiting the spatial resolution of the DMD and the LC panel.

In [61], the authors deploy orthogonal linear polarizers for each respective transmitter-receiver pair. By exploiting the polarization property of the light they ensure that light from different transmitters does not cause interference on the other receiver.

VII. V-VLC SIMULATION TOOLS

There are three major techniques for performance evaluation in the V-VLC literature (and in vehicular networking in general): analytical evaluation, field operational tests, and simulation [4].

Analytical evaluations are good at approximating the theoretical bounds of a V-VLC system, but they cannot be comprehensive enough to capture all aspects of it, thus, can oversimplify a rather complex system. On the other end, field operational tests provide the highest degree of realism, however, they can be impacted by the non-suppressible side effects that can occur during measurement campaigns. Also, they do not scale well: only a small set of potential scenarios can be investigated at a time. Considering the advantages and disadvantages of the aforementioned performance evaluation techniques, simulation arises as a practicable middle

ground. Simulation can provide a high degree of realism, and allows investigation of a broad range of different scenarios. Due to these advantages, simulation has been heavily used for studying the performance of V-VLC.

There are different tools used for simulative performance evaluation in the literature. Some studies use vehicular networking simulation tools extended with V-VLC capabilities [33], [49], [65]. Sometimes, such simulation tools are exclusively devised for a given study using, for example, MATLAB/Simulink [162], [163] or JiST/SWAN [164]. Other works use specialized tools like CAD software and ray-tracing to investigate V-VLC channel properties [55], [122], [124]. This allows to model V-VLC scenarios in greater detail, including the objects in the scenario, their build material and reflection properties, weather conditions, as well as transmitter and receiver characteristics (e.g., radiation pattern, FOV). However, these simulations can be computationally expensive, while obtaining the particular software can be costly as well.

The use of accurate and realistic models that lead to scientifically sound conclusions and reproducibility of the simulation studies for independent validation are imperatives to simulation-based performance evaluation. In many cases, these criteria are not always fulfilled. For instance, the use of a Lambertian transmitter for the vehicle headlamps continues to be a common misconception [65], [164], although models that can reasonably approximate [138] or realistically model [49] the headlamp characteristics exist in the literature. Regarding reproducibility, in some studies the simulation models are not available to the public. Examples include the VENTOS extension by Ucar *et al.* [33], the SHINE extension by Masini *et al.* [65], the simulator used by Ishihara *et al.* [32], which have been developed to investigate V-VLC but, despite the important findings reported in the related research papers, were not made Open Source for re-use in our research community.

More recently, Veins VLC⁴ has been published, which, to the best of our knowledge, is the only Open Source approach to V-VLC. The tool makes use of channel models based on realistic head- and taillamp radiation patterns obtained via empirical measurements [48] or provided by vendors [50] and, therefore, accurately models the light distribution of different vehicles. Being based on the Veins simulation framework [165], it can readily be used for investigating heterogeneous communication approaches combining V-VLC and RF-based communication.

VIII. FURTHER DISCUSSION

In this section, we discuss a range of relevant topics for V-VLC, including future research directions, the V-VLC research community, and standardization efforts.

A. Future Research

Since V-VLC is a rather novel technology, the V-VLC research community has mainly focused on the understanding and characterization of the V-VLC channel and, more recently,

the development of first prototypes for V-VLC. There are still many open questions regarding physical layer aspects of this technology, in particular regarding the performance of V-VLC in the outdoor channel and the development of more realistic channel models. Nonetheless, experimental studies in real-driving scenarios have shown promising results with respect to the feasibility of this technology for vehicular networking applications [84], [99].

While the fundamental physical layer aspects of V-VLC are being addressed in the literature, as a natural next step, research will now also focus on higher layer protocols. Medium access is one topic that has not been investigated in depth so far. Initial results have shown that in certain scenarios (e.g., close to intersections) interference from headlamps of vehicles that face each other can cause substantial packet loss [166] – a problem which can be addressed by a MAC protocol [65]. The design of a MAC, however, needs to take in consideration V-VLC specific properties, such as headlamp/taillamp asymmetry and the directional collision domain, that can greatly impact the protocol design. The advantage of V-VLC is that a potential MAC protocol can be designed not only to solve the medium access problem as in traditional RF directional communications, but also by taking advantage of the specific receiver hardware used in V-VLC, e.g., an onboard camera can be used to detect different transmitters and coordinate medium access accordingly.

Another interesting research topic that requires further investigation is the integration (and coexistence) of V-VLC with other vehicular communication technologies such as IEEE 802.11p and C-V2X. In such a heterogeneous system, different technologies can compensate for the drawbacks of each other and improve the overall application performance. Initial results have shown that a V-VLC and RF heterogeneous system can highly benefit platooning application, both in highway and urban scenarios [45], [47], [118], as well as improve platoon security [32], [33].

Considering the dynamic nature of the vehicular environment, V-VLC can benefit from adaptive techniques both in physical layer and receiver design. For instance, a variable gain control can be deployed at the receiver to address the problem of channel fluctuation when the transmitter-receiver distance varies slowly. In addition to this, it is possible to design a system which dynamically adapts the MCS based on the available SNR [167]. On the hardware level, the V-VLC receiver can be modified to enable dynamic adaptation of its FOV, or use an adjustable optical attenuator [160], to minimize incoming noise, while an electronic system, which allows real-time tracking of the transmitters for improved signal reception, can be incorporated with the receiver [168].

Another potential future research direction is the exploration of novel automotive lighting technologies for V-VLC. For instance, the SmartCorner headlamp system with V-VLC capabilities, which also integrates a LIDAR, infrared camera, and a PD has been presented in [169]. We have already shown the benefits of matrix LED-based AFS for V-VLC [64]. This, for example, can be extended to MIMO systems, where subsets of the LEDs from the LED matrix can be used to transmit different streams of data in parallel. This can be complemented

⁴<https://ccs-labs.org/software/veins-vlc/>

by receive diversity techniques to overcome interference scenarios [170]. AFS can further be exploited for best effort communication, where the most fitting lighting function is chosen for communication (see Section III-E).

The use of exterior automotive lighting for novel applications in addition to V-VLC is an interesting topic to look into. Potential alternatives in the literature include positioning [28], speed estimation [171], distance measurement [162].

B. V-VLC Research Community

The V-VLC research community is at the intersection between the vehicular networking community and the VLC/OCC community from the field of optical wireless communications. Due to this diversity, research in this field has been produced by researchers of different backgrounds and published in a wide range of conferences and journals from the fields of optics, photonics, and wireless (vehicular) networking. Many articles have been published on journals and conference proceedings from the Society of Photo-Optical Instrumentation Engineers (SPIE), the IEEE Communications Society, and the IEEE Photonics Society. Recently, the IEEE Vehicular Networking Conference (VNC) has played a particular role as a preferred publication venue for many impactful works in the field. Unfortunately, the V-VLC community is still rather scattered. However, some prominent stakeholders are already collaborating together, for example, in the scope of the Horizon 2020 Visible light based Interoperability and Networking (VisIoN) project, which focuses on research on VLC for different scenarios, including smart transportation. As the V-VLC landscape is constantly evolving, we have created a website⁵ to keep track of recent developments in the field.

C. Standardization Efforts

Although multiple VLC-related standards have been published so far (and others are in preparation in the meanwhile), these standards are mostly not tailored specifically for vehicular applications. The first VLC-related standards have been published by JEITA [24]–[26], whereas IEEE has published the IEEE 802.15.7 standard [23], which defines a PHY and MAC for VLC. These standards are generally intended for indoor VLC. The IEEE 802.15.7 standard proposes three different PHYs – one of them for outdoor communications, therefore, potentially applicable to V-VLC. However, there are not many prototypes in the V-VLC literature that follow the IEEE 802.15.7 standard (a few systems have been presented in [172]–[174]), mainly because the standard was not designed with vehicular applications in mind, and its specification rather increases the complexity (and cost) of the system. An exhaustive discussion regarding the feasibility of the IEEE 802.15.7 standard for V-VLC is provided by Cailean and Dimian [175]. Currently, there is a task group in the scope of IEEE 802.15 working on the revision of the standard [23] by focusing on OCC and LED-based identification, but there are no particular efforts to adapt it for V-VLC.

In addition to IEEE 802.15.7 standard, there are two ongoing standardization efforts in the scope of IEEE: Task group 13,

within the IEEE 802.15 working group; and task group “bb”, within the IEEE 802.11 working group. IEEE 802.15.13 is a revision of IEEE 802.15.7 focusing on high-rate PD-based VLC. It defines a PHY and a MAC capable of delivering data rates up to 10 Gbit/s at distances up to 200 m for LOS communication. Standard compliant V-VLC systems have been presented in [174], [176]. Given the target data rate and its capabilities, the IEEE 802.15.13 standard might be a better fit for V-VLC applications, although it is not explicitly designed for this purpose.

The IEEE 802.11bb task group works on another VLC-related standard. The goal of this task group is to develop an amendment for base IEEE 802.11 standards which would allow communication via the light medium. By introducing changes to the PHY and the MAC, the idea is to take advantage of already established protocols for IEEE 802.11 and ensure interoperability with IEEE 802.11 compliant devices. This strategy might have many benefits for indoor VLC and consumer electronics, however its implications for V-VLC need to be investigated. In that regard, a potential interoperability between V-VLC and IEEE 802.11p can be particularly interesting. Very recently, Amjad *et al.* [77] presented an IEEE 802.11 compliant V-VLC system, which can likely be adapted to IEEE 802.11bb.

IX. CONCLUSION

In conclusion, it can be said that the V-VLC research domain is catching more and more momentum, both in the academic research community as well as in the automotive industry. Building upon concept, methods, and technologies known from indoor VLC as well as from IEEE 802.11 WLAN, substantial progress has been made recently. This ranges from early conceptual studies to simulation experiments and now to first prototypes. Nevertheless, there are still many open questions that need to be investigated in order to mature the technology. In this survey, we revisited the state of the art in V-VLC communication systems and highlighted open challenges to be studied by our research community. We see this survey as a reference as well as a guide for both experts and beginners in the field.

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⁵<https://www.v-vlc.org/>

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