Visible Light Communication for Connected Vehicles: How to Achieve the Omnidirectional Coverage?

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Abstract

Visible light communication (VLC) is based on the idea of modulating the light intensity of LEDs to transmit information and enables the dual use of exterior automotive and road side infrastructure lighting for both illumination and communication purposes. To position VLC as a strong candidate for vehicular connectivity, it is essential to realize multi-directional reception in various deployment scenarios supporting both vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) links. In this paper, we investigate the performance of a vehicular VLC system in different road types (i.e., multi-lane, curved roads), intersections (i.e., T-shaped, Y-shaped intersections) and traffic scenarios (i.e., cruising in the same or different lanes, lane change etc.). We conduct a channel modeling study based on non-sequential ray tracing to quantify the capability of receiving signals in different cases. Our results reveal that deployment of nine photodetectors with carefully determined locations on the vehicle is enough to create the required quasi-omni-directional coverage for both V2V connectivity (in front and back directions) and I2V connectivity.

Index Terms

Vehicular visible light communications, connected vehicle, omni-directional coverage, multi-lane road, curved road, intersections, receiver model.

I. INTRODUCTION

Vehicular communication is one of the key enabling technologies for future intelligent transportation systems (ITSs) [1], [2]. It allows the vehicles to share information with each other and with infrastructures along the road. While vehicle-to-vehicle (V2V) links are particularly important for safety functionalities such as pre-crash sensing and forward collision warning, infrastructure-to-vehicle (I2V) links provide the connected vehicles with a variety of useful information (e.g., traffic density, alternative routes, services along the road etc.) [3]. The earlier works on vehicular communication have mainly focused on radio frequency (RF) technologies [4]–[7]. The widespread utilization of light emitting diode (LED)-based headlights (HLs), taillights (TLs), street lights, and traffic lights in vehicles and road side infrastructures has further prompted the investigation of visible light communication (VLC) as a potential candidate for vehicular connectivity [8]–[12]. VLC is based on the idea of modulating the light intensity of LEDs to transmit information and enables the dual use of exterior automotive and infrastructure lighting for both illumination and communication purposes [13], [14].

There are already a growing number of works on V2V [15]–[31] and I2V [32]–[38] VLC systems. An overview of existing works on V2V and I2V can be found in Table 1 and Table 2, respectively. As can be checked from Table 1 that the common underlying assumption in V2V works is the use of one or two photodetectors (PDs) placed at the back of the vehicle [15]–[26]. This is typically sufficient for establishing connection between two vehicles cruising in the same straight lane with no or small horizontal displacement between each other. To ensure reception in wider roads (i.e., two-lane) and curved roads, more PDs are typically
### TABLE 1. Overview of existing V2V works.

| Ref  | TX       | No. PDs | Road shape                  | Description                                                                 |
|------|----------|---------|-----------------------------|------------------------------------------------------------------------------|
| [15] | HLs      | 1 PD    | Straight road (Single lane) | A V2V system in a straight road and in one direction was considered assuming  |
|      |          |         |                             | a perfect alignment between the vehicles, i.e., $d_h = 0$ m.                  |
| [16, 17] | TL      | 1 PD    | Straight road (Single lane) | A V2V system in straight road was considered where a measured car TL pattern |
|       |          |         |                             | was integrated into a ray tracing platform to investigate the channel path    |
|       |          |         |                             | loss using single PD. The perfect alignment between the vehicles was         |
|       |          |         |                             | assumed, i.e., $d_h = 0$ m.                                                 |
| [18] | TL       | 1 PD    | Straight road (Single lane) | The performance of a V2V system was investigated utilizing an off-the-shelf |
|       |          |         |                             | scooter taillight as the transmitting end and a single PD as the receiver   |
|       |          |         |                             | one. A lateral shift of $d_h \approx \frac{w_1}{2}$ was considered.          |
| [19] | HLs      | 1 PD    | Straight road (Single lane) | A V2V communication system in a straight road and one direction was          |
|       |          |         |                             | considered. A lateral shift of $d_h \approx \frac{w_1}{2}$ was assumed.      |
| [20] | HLs      | 1 PD    | Straight road (Two-lane)    | The time variation of V2V VLC channels was investigated in freeway and        |
|       |          |         |                             | urban areas by low beam headlamp and a single PD.                           |
| [21] | HLs      | 1 PD    | Straight road (Two-lane)    | A V2V communication system in a straight road and in one direction was       |
|       |          |         |                             | considered with a possible lateral shift of $d_h \approx \frac{w_1}{2}$.      |
| [22] | HL       | 1 PD    | Straight road (Two-lane)    | A V2V system in straight and turning path roads was considered. A low beam   |
|       |          |         | Two-lane & Turning path     | HL and a single PD were utilized to investigate the effect of using different |
|       |          |         |                             | lens combinations on the system performance.                                |
| [23] | HLs      | 1 PD    | Straight road (Three-lane)  | A V2V system in a three-lane road and in one direction was considered        |
|       |          |         |                             | utilizing a low beam tungsten lamp and a single PD.                         |
| [24] | HLs      | 1 PD    | Straight road (Three-lane)  | A V2V communication system in a three-lane road and in one direction was     |
|       |          |         |                             | considered. A possible lateral shift of $d_h \approx \frac{w_1}{2}$ was      |
|       |          |         |                             | considered. The performance of three commercial low beam modules and two    |
|       |          |         |                             | high beams are investigated and compared.                                   |
| [25] | HLs      | 12 PDs  | Straight road (Single lane) | A V2V system in a straight road and only in one direction was considered.   |
|       |          |         |                             | Two PDs were combined using BGC scheme to improve the system performance     |
|       |          |         |                             | assuming a perfect alignment, i.e., $d_h = 0$ m.                           |
| [26] | White    | 2 PDs   | Straight road (Single lane) | A V2V system in a straight road and one direction was considered. A           |
|       | LED      |         |                             | phosphor-based white LED was used assuming Lambertian pattern for headlight  |
|       |          |         |                             | where two PDs were combined using MRC scheme.                               |
| [27] | HL & TL  | 2 PDs   | Straight road (Three-lane)  | A V2V system in three lane straight road was considered. The HL and TL of   |
|       |          |         |                             | the vehicle were utilized to achieve the connectivity in the front and back   |
|       |          |         |                             | directions where for each link one PD was utilized to receive the signal.    |
|       |          |         |                             | A lateral shift of $d_h \approx \frac{w_1}{2}$ was considered.               |
| [28] | HL & TL  | 2 PDs   | Straight road (Three-lane)  | A V2V system in a three-lane road was considered. HLs and Tls of the vehicle |
|       |          |         | Three-lane & Turning path   | were used to achieve the communication in two directions. Also, the impact   |
|       |          |         |                             | of the turning path on system performance was emphasized. It was observed a   |
|       |          |         |                             | high outage ratio in the turning path road comparing to the straight one     |
|       |          |         |                             | assuming a single PD.                                                      |
| [29] | White    | 3 PDs   | Straight road (Two-lane)    | A V2V system was considered in a straight and a turning path assuming one    |
|       | LED      |         | Two-lane & Turning path     | direction communication. In which, a white LED (with Lambertian pattern)    |
|       |          |         |                             | was utilized to represent the headlight and three PDs were combined with     |
|       |          |         |                             | different combining schemes.                                               |
| [30] | HLs      | 4 PDs   | Straight road (Single lane) | A V2V communication system in straight road and one direction was considered. |
|       |          |         |                             | An ADR, consists of four PDs, was utilized to improve the system performance. |
| [31] | HLs      | 4 PDs   | Straight road (Two-lane)    | A V2V system in a straight road and in one direction was considered. Two    |
|       |          |         |                             | vehicles follow each other in same lane or different lanes. Four PDs were   |
|       |          |         |                             | distributed around the back and the side of the vehicle to achieve the      |
|       |          |         |                             | omni-directional coverage in such practical cases.                         |
TABLE 2. Overview of existing I2V works.

| Ref | TX Type | No. PDs | Road shape         | Description                                                                 |
|-----|---------|---------|--------------------|-----------------------------------------------------------------------------|
| [32] | Array of WLEDs | 1 PD    | Straight road (Single lane) | An I2V system is realized by using array of WLEDs to fit with standard traffic light and a single PD as a receiver. The channel path loss over the distance was calculated where about 42 dB was the recorded attenuation value at 100 m assuming a perfect alignment, i.e., $d_h = 0$ m. |
| [33] | Commercial off-the-shelf LED | 1 PD    | Straight road (Single lane) | An I2V communication system in a straight road was considered. The optical channel path loss between LED traffic light and vehicles was investigating utilizing the commercial-off-the-shelf LED and a single PD where a perfect alignment was assumed, i.e., $d_h = 0$ m. |
| [34] | Streetlight | 1 PD    | Straight road (Single lane) | A comparison between VL, IR, and UV bands in I2V based streetlight system with perfect alignment, i.e., $d_h = 0$ m. In which, the UV band is the worst case in terms of SNR. |
| [35] | Traffic light | 1 PD    | Straight road (Single lane) | A hybrid I2V-V2I VLC system was investigated in a single lane straight road. A regular LED traffic light, was used as a transmitter and a single PD was used as a receiver with perfect alignment, i.e., $d_h = 0$ m. |
| [36] | Traffic light | 1 PD    | Straight road (Single lane) | An I2V VLC system was investigated in a single lane straight road. A regular LED traffic light, was used as a transmitter and a single PD was used as a receiver with perfect alignment, i.e., $d_h = 0$ m. |
| [37] | White LED | 1 PD    | Straight road (Two-lane) | An I2V communication system in a straight road was considered. In which, a white LED was utilized to represent the streetlight lamp and a single PD acted as a receiver where a channel estimation method was proposed. |
| [38] | Streetlight | 1 PD    | Straight road (Two-lane) | An I2V communication system based commercial streetlights in a straight road and with possible lateral shift of $d_h \approx \omega / 2$ was considered. In which, the effect of the nearby cars same as car velocity on the received SNR were investigated |

required. For example, in [29], three PDs are deployed and, among three PDs, the one with maximum received power is chosen. In [30], the performance of the V2V system is investigated utilizing an angle diversity receiver consisting of 4 PDs oriented in different directions. In [31], four PDs are used to prevent outages of a V2V system during lane change in a two-lane straight road.

As seen from Table 2, most of the I2V works [32]–[38] assume a single PD. Some of these [32], [35], [36] assume PD location at the front hood of the vehicle which is typically favorable for reception from traffic light while some [34], [37], [38] consider the top of the vehicle which is more suitable for reception from street lights. Such a single PD use can be justified in a single lane road with clear line-of-sight between the vehicle and the road side infrastructure.

In addition to aforementioned works which focus only on V2V and I2V links, there have been some sporadic efforts how to enable both V2V and I2V reception. In [39], a receiver located at the vehicle’s rooftop is utilized to receive the signals from the infrastructure and from the TLs of the front vehicle. In [40], four PDs are utilized; the PD located at the top of the vehicle is used for the reception from the infrastructure while three PDs, located at the back of the vehicle, are used to receive the signals from the HLs of the following vehicle. These works, however, are limited to simple scenarios where two vehicles follow each other in single-lane or two-lane straight roads.

To position VLC as a strong candidate for vehicular connectivity, it is essential to realize multi-directional reception in various deployment scenarios supporting both V2V and I2V links. It remains an open question what is the sufficient number of required PDs to achieve this. To address this question of practical relevance, we investigate the performance of a vehicular VLC system in different road types (i.e., multi-lane and curved roads), intersections (i.e., T-shaped and Y-shaped intersections) and traffic scenarios (i.e., cruising in the same or different lanes, lane change etc.). We conduct a channel modeling study based on non-sequential ray tracing to quantify the capability of receiving signals in different cases. We first quantify the total received power versus distance for different scenarios under consideration. Our results reveal that deployment of nine PDs with carefully determined locations on the vehicle is sufficient to create the required quasi-omni-directional coverage for both V2V connectivity (in front and back directions) and I2V connectivity. Then, we quantify the contribution of individual PDs to elaborate the main usage cases of each PD. We further investigate the effect of neighbor vehicles and possible blockage on the system performance. To the best of our knowledge, such a comprehensive study on vehicular VLC channel modelling with multiple receive apertures is not available in the literature.

The remainder of this paper is organized as follows. In Section II, we describe our system model and vehicular scenarios under investigation. In Section III, we explain the main steps of our channel modelling approach. In Section IV, we present the simulation results to quantify the total received power versus distance for different scenarios under...
consideration. We further quantify the contribution of individual PDs to elaborate the main usage cases of each. Finally, we conclude in Section V.

II. SYSTEM MODEL AND VEHICULAR SCENARIOS
Since the focus of our paper is to investigate the placement and the number of PDs, we only consider the destination vehicle in V2V and I2V links. As illustrated in Fig. 1, the destination vehicle can receive signals from the front vehicle (where the TLs of the front vehicle serve as the transmitters) or from the preceding vehicle (where the HLs of the preceding vehicle serves as the transmitters). In I2V links, the wireless transmitters are street lights or traffic lights. The scenarios under consideration are summarized in Table 3. We consider V2V links in two-lane roads (Scenarios 1-3), multi-lane roads (Scenarios 4-6), T-shaped intersections (Scenarios 7 and 8), Y-shaped intersections (Scenarios 9 and 10), and curved roads (Scenario 11 and 12). We consider I2V links either with traffic lights (Scenarios 13-15) or street lights (Scenarios 16-18).

In the above scenarios, we have focused on cases where there are no neighbor vehicles or blockage nearby. Finally, in Scenarios 19-21, we investigate the effect of neighbors and possible blockage due to other vehicles in the same lane.

In Scenarios 1-3, we consider a straight road with two lanes each of which has a width of $w_l$. The vehicles are separated with a longitudinal distance of $d$ and a horizontal distance of $d_h$

- **Scenario 1 (Fig. 2.a):** In this ideal scenario widely assumed in the literature, the vehicles follow each other in the same lane and with a perfect alignment, i.e., $d_h = 0$.
- **Scenario 2 (Fig. 2.b):** The vehicles follow each other in the same lane but there is a misalignment between the vehicles. The maximum lateral shift between the two vehicles is $d_h = w_l - w_v$ where $w_v$ denotes the width of the vehicle.

- **Scenario 3 (Fig. 2.c):** The two vehicles move in neighbor lanes and the source vehicle changes its lane approaching to the destination vehicle within the target lane.

In Scenarios 4-6, we consider a multi-lane road where each lane has a width of $w_l$.

- **Scenario 4 (Fig. 2.d):** The source vehicle, located at the center of the 1st lane, communicates with a destination vehicle that travels at the center of the 2nd lane. This creates a lateral shift of $d_h = w_l$ between source and destination vehicles.
- **Scenario 5 (Fig. 2.e):** The source vehicle cruising at the center of the 1st lane, communicates with a destination vehicle cruising at the center of the 3rd lane, effectively resulting in a lateral shift of $d_h = 2w_l$.
- **Scenario 6 (Fig. 2.f):** The source vehicle cruising at the center of the 1st lane, communicates with a destination vehicle cruising at the center of the 4th lane, effectively resulting in a lateral shift of $d_h = 3w_l$.

In Scenarios 7 and 8, we consider T-shaped intersections.

- **Scenario 7 (Fig. 2.g):** In this scenario, the source and the destination vehicles are separated from each other with a longitudinal distance of $d$ and there is a horizontal distance of $d_h \approx w_l/2$ between the source vehicle and the intersection point.
- **Scenario 8 (Fig. 2.g):** This scenario is similar to the previous one, but the destination vehicle is closer to the intersection, i.e., $d_h \approx w_l/4$.

In Scenarios 9 and 10, we consider Y-shaped intersections with an intersection angle of $\theta = \arcsin(2w_l/w_s)$ [41] where $w_s$ denotes the intersection width.
Scenario 9 (Fig. 2.h): In this scenario, the source and destination vehicles are separated with a longitudinal distance of \( d \) in a T-shaped intersection with a large intersection width, i.e., \( w_s \gg 2w_l \).

Scenario 10 (Fig. 2.h): This scenario is similar to the previous one but with relatively smaller intersection width, i.e., \( w_s > 2w_l \).

In Scenarios 11 and 12, we consider a curved road with a radius of \( R \) where the vehicles are separated from each other with a distance of \( d \).

Scenario 11 (Fig. 2.i): In this scenario, we assume a large road radius, i.e., \( R \gg w_l^3 \).

Scenario 12 (Fig. 2.i): In this scenario, we assume a relatively smaller road radius, i.e., \( R \leq w_l^3 \).

In Scenarios 13-15 (Fig. 2.j), we consider I2V link where the traffic light serves as the transmitter which has a height of \( h \). The vehicle is assumed to be at a longitudinal distance of \( d \) with respect to the transmitter.

Scenario 13: The vehicle moves at the outer side of the road lane, i.e., \( d_h \ll w_l \).
TABLE 3. Vehicular scenarios under consideration.

| Scenario | Road Design | Transmitter | Description |
|----------|-------------|-------------|-------------|
| Scenario 1 | Two-lane Straight road | HLS & TLS | The vehicles follow each other in the same lane and with a perfect alignment, i.e., $d_h = 0$. |
| Scenario 2 | Two-lane Straight road | HLS & TLS | The vehicles follow each other in the same lane but there is a misalignment between the vehicles. The maximum lateral shift is considered, i.e., $d_h = 2w_l$. |
| Scenario 3 | Two-lane Straight road | HLS & TLS | The two vehicles are moving in the neighbor lanes and the source vehicle changes its lane approaching from the destination one on the target lane. |
| Scenario 4 | Multi-lane Straight road | HLS & TLS | The source vehicle, located at the center of the $1^{st}$ lane, communicates with a destination one that travels at the center of the $2^{nd}$ lane, i.e., $d_h = w_l$. |
| Scenario 5 | Multi-lane Straight road | HLS & TLS | The source vehicle, located at the center of the $1^{st}$ lane, communicates with the destination one that travels at the center of the $3^{rd}$ lane, i.e., $d_h = 2w_l$. |
| Scenario 6 | Multi-lane Straight road | HLS & TLS | The source vehicle, located at the center of the $1^{st}$ lane, communicates with the destination one that travels at the center of the $4^{th}$ lane, i.e., $d_h = 3w_l$. |
| Scenario 7 | T-Intersection | HLS & TLS | T-shaped road is considered where a distance of $d_h \approx w_l/2$ between the destination vehicle and the intersection point is considered. |
| Scenario 8 | T-Intersection | HLS & TLS | Similar to scenario 4 but with shorter $d_h$ value, i.e., $d_h \approx w_l/4$. |
| Scenario 9 | Y-Intersection | HLS & TLS | Y-shaped road with intersection angle of $\theta = \sin^{-1}(2w_l/w_a)$ and $w_a \gg 2w_l$ is considered. |
| Scenario 10 | Y-Intersection | HLS & TLS | Similar to scenario 6 but with a larger intersection angle, i.e., $w_a \gg 2w_l$ is assumed. |
| Scenario 11 | Curved-Road | HLS & TLS | Curved road with a large road radius with respect to its width, i.e., $R \gg w_l^2$. |
| Scenario 12 | Curved-Road | HLS & TLS | Similar to scenario 8 but with a shorter road radius, i.e., $R \lesssim w_l^2$. |
| Scenario 13 | Straight road | Traffic light | The vehicle moves at the outer side of the road lane, i.e., $d_h$ is negligible with respect to $w_l$. |
| Scenario 14 | Straight road | Traffic light | The vehicle moves at the center of the road lane, i.e., $d_h \approx w_l/4$. |
| Scenario 15 | Straight road | Traffic light | The vehicle moves at the inner side of the road lane, i.e., $d_h \approx w_l/2$. |
| Scenario 16 | Straight road | Streetlights | The vehicle moves at the outer side of the road lane, i.e., $d_h$ is negligible with respect to $w_l$. |
| Scenario 17 | Straight road | Streetlights | The vehicle moves at the center of the road lane, i.e., $d_h \approx w_l/4$. |
| Scenario 18 | Straight road | Streetlights | The vehicle moves at the inner side of the road lane, i.e., $d_h \approx w_l/2$. |

- **Scenario 14**: The vehicle moves at the center of the road lane, i.e., $d_h$ is comparable with $w_l$.
- **Scenario 15**: The vehicle moves at the inner side of the road lane with the maximum allowable lateral shift, i.e., $d_h = w_l$. Scenarios 16-18 (Fig. 2.k) are identical to Scenarios 13-15 except the fact that the street light now serves as the transmitter. The vehicle moves between two street lights separated with a spacing of $d_s$ where the vehicle can receive the data from the two poles.

In Scenarios 19-21, we consider a straight road with three lanes each of which has a width of $w_l$. The source and destination vehicles are in the middle lane and separated from each other with a longitudinal distance of $d$. There are also neighbor vehicles either in the same or different lanes.

- **Scenario 19 (Fig.2.i)**: This is the benchmark scenario where two connected vehicles follow each other in the middle lane of a three-lane road without any neighbor vehicles.
- **Scenario 20 (Fig.2.m)**: In this scenario, there are some neighbor vehicles in the other lanes. neighbor vehicles are assumed to travel in the middle of their lanes and are separated from each other with $d_n$.
- **Scenario 21 (Fig.2.n)**: In this scenario, there is an additional neighbor vehicle which travels within the same lane and creates partial blocking to transmission between destination and source vehicles.

The number of PDs to be placed over the vehicle is the choice of system designer. It should be decided in such a way that omni-directional coverage should be ensured in various V2V and I2V scenarios while maintaining a reasonable cost. Considering most typical scenarios detailed above, we conjecture that 9 PDs would be enough to provide a quasi-omni-directional coverage. The locations of PDs are depicted in Fig. 3 and described as follows:
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At the back of the vehicle: Two PDs (denoted as PD 1 and PD 2) are installed under the TLs. It is expected that they will be primarily useful to receive signals from HLs.

At the sides of the vehicle: Two PDs (denoted as PD 3 and PD 4) are installed at the side-back of the vehicle and at the same height of PD 1 and PD 2. It is expected that PD 3 and PD 4 will be primarily useful when source and destination vehicles are in different lanes or in a curved road.

At the front of the vehicle: Two PDs (PD 5 and PD 6) are installed under the HLs. They are positioned to receive signals from TLs of the front vehicle.

At the mirrors: Two PDs (PD 7 and PD 8) are installed above the mirrors. They are expected to enable I2V links with traffic light transmitters. They might be also useful for V2V links in multi-lane or curved roads.

At the top of the vehicle: A single PD (PD 9) is installed at the top of the vehicle. This is particularly useful for I2V links with street light transmitters.

III. CHANNEL MODELING METHODOLOGY AND PERFORMANCE METRIC

In this section, we first explain our methodology for channel modeling. Then, we define a performance metric to describe the outage which will be later used to interpret simulation results.

A. CHANNEL MODELING METHODOLOGY

Our channel modeling methodology is based on the non-sequential ray tracing features of OpticStudio®. This approach was firstly deployed to model the indoor VLC channels [42]–[44] and experimentally validated in [45], [46]. More recently, it was utilized to model vehicular VLC channels [19], [38], [47]. This approach allows the evaluation of the impulse responses of VLC scenarios with complex geometries and realistic light sources. Radiation pattern of a light source can be defined in the simulation platform by importing its photometric data which contains the luminous intensity in all different planes. It further allows to consider large number of reflections and wavelength-dependent reflectance of the surface material for an accurate modeling. Different types of reflections (specular, diffuse or mixed) can be taken into account by defining the scatter fraction value in the software.

The main steps of this channel modeling methodology are illustrated in Fig. 4. The 3D CAD models for vehicles, roads, and infrastructure poles are designed and imported to the OpticStudio®. The specifications of these CAD models such as coating material, reflectance, and type of reflections are defined. The specifications of the light sources (orientation, radiation pattern, emitted power, etc.) and of the PD (orientation, field-of-view angle, sensitive area, etc.) are provided as other inputs. After the simulation scenario is constructed, non-sequential ray tracing is run to generate an output file containing information about the path length and the received power for each ray emitted from the light source and captured by the detector. Finally, this information is imported into MATLAB® in order to construct the channel impulse response (CIR) for each particular scenario.

B. PERFORMANCE METRIC

Consider the $i^{th}$ transmitter and the $j^{th}$ receiver. Let $P_{t,i}^l$ and $\tau_{t,i}^l$ denote the optical power and the propagation delay of the $l^{th}$ ray transmitted from the $i^{th}$ LED and received by the $j^{th}$ PD, respectively, $l = 1, \ldots, L_{ij}$. The normalized CIR for unit transmit power is given by [19], [23]

$$h_{i,j}(t) = \sum_{l=1}^{L_{ij}} P_{t,i}^l \delta(t - \tau_{t,i}^l)$$

where $\delta(t)$ denotes the Dirac delta function. For a given transmit power of $P_t (t)$, the received optical power at the $j^{th}$ PD from the $i^{th}$ transmitter can be then calculated as

$$P_{r_{i,j}} = 10 \log_{10} \left( P_t \int_0^\infty h_{i,j}(t) \, dt \right)$$
The signal-to-noise ratio (SNR) is obtained as

$$\gamma = \left( \frac{\eta \sum_{j=1}^{N_r} P_{r_j}}{N_0 B} \right)^2$$

(3)

where $\eta$ is the optical-to-electrical conversion ratio, $N_r$ is the number of PDs, $N_0$ is the noise power spectral density, and $B$ is the bandwidth. Let $BER_{th}$ denote the targeted BER value. In order to avoid outage, the received SNR of the link should be higher than a threshold SNR value of $\gamma_{th}$ calculated from $BER_{th}$. Under the assumption of on-off keying (OOK), the minimum required value of received optical power to avoid outage is obtained by [48]

$$P_{r_{req}} = \sqrt{\frac{N_0 B}{\eta^2 \left( Q^{-1} (BER_{th}) \right)^2}}$$

(4)

IV. SIMULATION RESULTS

In this section, we present simulation results for vehicular scenarios under consideration based on non-sequential ray tracing. In our simulation study, Philips Luxeon Rebel white light LEDs [49] and Osram-TOPOLED red light LEDs [50] are used for HLs and TLs, respectively. For street lights and traffic lights, Vestel Ephesus M4S [51] and Osram-OSLON® [50] are utilized, respectively. The radiation patterns for HL, TL, traffic light, and street light are presented in Fig. 5. All simulation parameters are provided in Table 4. We consider two different use cases:

- **High-speed communication with $B = 10$ MHz:** This is required to support higher data rates for infotainment applications such as video streaming [53], [54]. This requires a received power of $P_{r_{req}} \geq -64.7$ dB.

  In the following, we first present the total received power versus distance discussing what type of communications can be supported (Section IV.a). Then, in Section IV.b, we discuss the individual contributions of each PD to the total received power and highlight the main use case of each PD.

A. TOTAL RECEIVED POWER VERSUS DISTANCE

In Fig. 6, we present the received power versus distance for Scenarios 1-3 based on either HL transmitters (Fig. 6.a) or TL transmitters (Fig. 6.b). As expected, the received power takes its maximum value when two cars are in perfect alignment (i.e., Scenario 1). In Scenario 2, we assume that there is a misalignment of $d_h = 2$ m between the two vehicles. This misalignment is particularly effective at shorter longitudinal distances. For example, the received power for perfect alignment is $-30.8$ dB at $d = 10$ m under the assumption of HL transmitters (see Fig. 6.a). This reduces to $-32.75$ dB in the presence of misalignment. In Scenario 3, it is observed that the rate of change in the received power during the lane changing range (from 15 m to 30 m) is much higher than that in trailing period (from 30 m to 50 m). This is due to that during the lane switching, there is a change in both inter-vehicle distance ($d$) and lateral shift one ($d_h$). From Fig. 6, it can be concluded that the received power is sufficient (i.e., $P_r > -45$ dB) for both low- and high-speed communications in these three scenarios when HL transmitters are used to communicate with the preceding vehicle. On the other hand, with the use of TL transmitters, the received...
power (i.e., $P_r > -73$ dB) is sufficient only for low-speed communication.

In Fig. 7, we present the received power versus distance for Scenarios 4-6 based on either HL transmitters (Fig. 7.a) or TL transmitters (Fig. 7.b). It is observed that despite the relatively large horizontal displacements, two vehicles in different lanes can successfully communicate with each other. For example, the received power for Scenario 4 (i.e., source and destination vehicles are in neighbor lanes) is $-40.9$ dB at $d = 25$ m with HL transmitters. This reduces to $-47.2$ dB and $-51.7$ dB, respectively for Scenario 5 (i.e., source and destination vehicles are separated from each other with a lane), and Scenario 6 (i.e., source and destination vehicles are separated from each other with two lanes). It can be readily checked that both low- and high-speed communications can be supported when the HLs act as the transmitters. On the other hand, with TL transmitters, the received power is $P_r > -79.87$ dB and therefore satisfies the minimum level to support low-speed communication.

In Fig. 8, we present the received powers versus distance for Scenarios 7-10 where T- and Y-shaped intersections are considered. For T- shaped intersections (Scenarios 7 and 8), it is observed that the value of $d_h$ (the distance between the destination vehicle and the intersection point) has a significant impact on the received power. For example, assuming $d = 25$ m and HL transmitters, the received power for $d_h = 1$ m is $-42.7$ dB. This reduces to $-49.2$ dB for $d_h = 2$ m. For Y-shaped intersections (Scenarios 9 and 10), an exponential decay in the received power with $d$ is observed. It is also observed that the intersection angle $\theta$ has a little effect on the received power. For example, the received power for $\theta = 45^\circ$.

| Table 4. Simulation parameters. |
|---------------------------------|
| **Receiver specifications**     | **Road specifications**     |
| Area                            | Type                        |
| Field-of-view (FoV)            | Material                    |
| Responsivity ($\eta$)          | Lane width ($w_l$)          |
| Noise density ($N_0$)          | Road design                 |
| Bandwidth ($B$)                | Straight, Intersections, Curved |
| $1 \text{ cm}^2$              | $R2$                        |
| $90^\circ$                     | Asphalt                     |
| $0.84 \text{ (A/W)}$          | 3.75 m                      |
| $1 \times 10^{-21} \text{ (A}^2\text{Hz)}$ | Straight, Intersections, Curved |
| $10 \text{ kHz}, 10 \text{ MHz}$ | **Vehicle specifications**  |
| **Street light pole specifications** | **Traffic light pole specifications** |
| Material                       | Material                    |
| Spacing ($d_s$)                | Galvanized steel metal      |
| Height ($h$)                   | $20$ m                      |
| Material                       | Black gloss paint           |
| **Traffic light pole specifications** | **Vehicle specifications**  |
| Height ($h$)                   | **Street light pole specifications** |
| $2$ m                          | Material                    |

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is $-64.4$ dB assuming TL transmitters and $d = 30$ m. This slightly reduces to $-64.75$ dB for $\theta = 60^\circ$. From Fig. 8, it can be concluded that the received power is sufficient (i.e., $Pr > -51.5$ dB) for both low- and high-speed communications in these four scenarios with HL transmitters. Based on the use of TL transmitters, the received power is sufficient (i.e., $Pr > -81.5$ dB) only for low-speed communication.

In Fig. 9, we present the received power versus distance for Scenarios 11-12 where a curved road is considered. It is observed that the received power significantly reduces when the road radius ($R$) decreases. For example, consider $d = 40$ m and HL transmitters. As observed from Fig. 9.a, the received powers for $R = 100$ m and $R = 50$ m are respectively $-55.5$ dB and $-69.6$ dB. It can be also observed that the received power much depends on the curve radius same as the propagation distance. At shorter radius together with larger distance, the received power is much reduced, and the system outage might occur particularly take place when high data rate is targeted. It can be readily checked that the received power in Scenario 11 is sufficient (i.e., $Pr > -61.9$ dB) for both low- and high-speed communications with HL transmitters while the received power in Scenario 12 remains lower than the minimum level of $-64.7$ dB. Based on the use of TL transmitters, the received power in these scenarios is sufficient (i.e., $Pr > -79$ dB) only for low-speed communication.

In Fig. 10, we present the received power versus distance for I2V scenarios based on either traffic light transmitters (Scenarios 13-15, Fig. 10.a) or street light transmitters (Scenarios 16-18, Fig. 10.b). It is observed from Fig. 10.a that the received power is affected by the particular position of the vehicle with respect to traffic light transmitter. As observed from Fig. 10.a, the received power at $d = 10$ m for $d_h = 0$ m (i.e., the vehicle is located at the outer side of the road lane) is $-43.6$ dB. This reduces to $-44.55$ dB and $-45.53$ dB for $d_h = 1$ m and $d_h = 2$ m, respectively.
In Fig. 10.b, the street lights serve as transmitters where the vehicle moves between two street light poles separated with $d_S = 20$ m. Under the first pole, only PD 9 (located on the top of the vehicle) can collect a significant amount of the power. This is due to the fact that PDs 5-8 cannot see this transmitter, and PDs 1-4 (which are looking to the second pole) are still far. When the vehicle moves away from the first pole, the received power decreases. If the distance becomes sufficiently large ($d > 4$ m), the PDs 5-8 are now able to collect power. In particular PD 7 and 8 (located on the top of the mirrors) along with PD9 collect most of the power. When the vehicle approaches the second pole, the contributions of PDs 5-8 relatively decrease while there is some increase in received powers of PDs 1-4. In particular, PD 4 (located at same side of closer street lights) reaches its maximum value at $d = 16$ m. After that, it reduces to reach its minimum value when the vehicle arrives under the second pole ($d = 20$ m). At this point, a significant power is only collected again by PD 9. It can be readily checked that for all I2V scenarios under consideration, the received power is much higher than the required power to support both low- and high-speed communications.

In Fig. 11, we present the received power versus distance for Scenarios 19-21 where the effect of neighbor vehicles and partial blockage are considered. In Scenario 20, it is observed that the received power slightly increases in comparison to the benchmark scenario (i.e., Scenario 19) as a result of receiving additional amount of power reflected from the neighbor vehicles. This is observed only at sufficiently large distances ($d \geq 40$ m). The reason for that is at larger distances, the reflecting surface at the two sides of neighbor vehicles increases and hence the number of reflected rays reaching the PD increases. At shorter distances, the amount of received power from such reflections is negligible. In Scenario 21, a significant reduction in the received power is observed in
comparison with Scenarios 19 and 20. This is due to the effect of partial blockage by the neighbor vehicle which travels in the same lane. For example, consider $d = 50$ m. The received power for scenario 19 is $-42.6$ dB. This increases to $-42$ dB and reduces to $-47.4$ dB for scenario 20 and 21, respectively. From Fig. 11, it can be further concluded that the received power is sufficient (i.e., $P_r > -47.5$ dB) for both low- and high-speed communications.

B. CONTRIBUTIONS OF EACH PD AND DISCUSSIONS ON USE CASES

In the previous section, we presented the total power versus distance for different scenarios under consideration. In this section, we quantify which PDs contribute at what extent to total received power.

In Fig. 12.a, we present pie charts for Scenarios 1, 2 and 3 based on HL transmitters.

- In Scenario 1 where two cars are perfectly aligned, the deployment of only two photodetectors in the back (i.e., PD 1 and PD 2) would be sufficient. These two PDs collect 98% or more of the total power based on the distance. For large distances, PD 3 and PD 4 collect a small amount as a result of road reflections if the distance between two vehicles is sufficiently large, e.g., about 2% at a distance of $d = 50$ m.

- In Scenario 2 when there is some displacement (towards the left-hand side) between two vehicles, it is observed that PD 1 and PD 3 (located on left-hand side of the destination vehicle) are primary receptors. The contribution of PD 2 increases with the increase in distance since the effect of lateral displacement becomes negligible for large distances. It should be noted that if the displacement is towards the right-hand side, PD 2 and PD 4 would be primary receptors.

- In Scenario 3, the lane change occurs from the left-hand side to the right-hand side. It is observed that within initialization range (from 10 m to 15 m), PD 1 and PD 2 can collect almost all power (i.e., 100%) due to the proper alignment between the two vehicles. However, during the lane change range (from 15 m to 30 m) and trailing range (from 30 m to 50 m), PD 3 collects the highest amount of received power (i.e., 40%) while the contributions of PD 1 and PD 2 are reduced.

In Fig. 12.b, we present pie charts for Scenarios 1, 2 and 3 based on TL transmitters.

- In Scenario 1 where two cars are perfectly aligned, PD 5 and PD 6 capture most of the received power if the distance is sufficiently small. When distance gets larger, the contributions of PD 7 and PD 8 are more pronounced since the height difference between the TL transmitters and PD 7 / PD 8 gets smaller.
In Scenario 2 when there is some displacement (towards the left-hand side) between two vehicles, PD 5 and PD 6 remain as the primary receptors. However, in comparison to Scenario 1, the contribution of PD 6 is now reduced since it is located on the other side of the displacement.

In Scenario 3, PD 5 and PD 6 collect most of the power within the initialization range (from 10 m to 15 m) while a small amount of received power is collected with PD 7 and PD 8. During the lane change range (from 15 m to 30 m) and trailing range (from 30 m to 50 m), PD 5, PD 6 and PD 7 collect almost all power and the contribution of PD 8 becomes negligible.

In Fig. 13.a, we present pie charts for Scenarios 4, 5, and 6 based on HL transmitters.

In these three scenarios, PD1 and PD 3 (located on the same side of the source vehicle) are the primary receptors. PD2 also contributes to the received power to some
extent. With the increase in distance, the contribution of PD 2 increases. Because at sufficiently large distances, PD 2 is able to see both HLs of the source vehicle.

In Fig.13.b, we present pie charts for Scenarios 4, 5, and 6 based on TL transmitters.

- In these three scenarios, PD5 and PD 7 (located on the same side of the source vehicle) are the primary receptors. PD 6 comes as the third largest contributor to the received power. Its contribution particularly becomes large for large distances. Finally, only a very small received power is collected by PD 8 as a result of road reflections if the distance between two vehicles is sufficiently large.

In Fig. 14.a, we present pie charts for Scenarios 7, 8, 9, and 10 based on HL transmitters.

- In Scenarios 7 and 8 where T-shaped intersection is considered, PD 3 collects most of the received power (e.g., 73% or more) due to its location on the side of
intersection point. The rest of received power is collected by PD 1 and PD 2 and their contribution further decreases when either the longitudinal distance ($d$) or the horizontal one ($d_h$) increases.

- In Scenarios 9 and 10 where Y-shaped intersection is considered, PD 1 and PD 3 are the main receptors. For Scenario 9 where lower skew angle is considered (i.e., $\theta = 45^\circ$), the contribution of PD 3 is approximately twice of PD 1 if the distance between the vehicles is sufficiently large. In Scenario 10 where a larger skew angle is considered (i.e., $\theta = 60^\circ$), PD 1 is able to collect approximately same power amount of PD 3. In addition, PD 2 collects some power which increases when the distance gets larger.

In Fig. 14.b, we present pie charts for Scenarios 7, 8, 9, and 10 based on TL transmitters.

- In Scenarios 7 and 8 where T-shaped intersection is considered, PD 5 and PD 6 collect the highest amount of received power for shorter longitudinal distances. When the distance between two vehicles increases,
FIGURE 15. Contribution of each PD for V2V in curved road scenarios based on (a) HLs (b) TLs.

the contribution of PD 7 much increases while the received power using PD 6 is significantly reduced because of its location on the other side of intersection point. A very small portion of received power is collected by PD 8 as a result of road reflections for sufficiently large distances.

In scenarios 9 and 10 where Y-shaped intersection is considered, PD 5 collects the highest amount of received power for short distances. At larger distances, the contribution of PD 5 decreases while the contribution of PD 7 increases. Particularly at shorter distances, a significant amount of received power is collected by PD 6.

In Scenarios 11 and 12, curved roads with radii of \( R = 100 \) m and \( R = 50 \) m are considered, respectively. At shorter distances PD 3 collects the highest amount of received power (i.e., 69\% at \( d = 10 \) m and Scenario 11) while contributions of PD 1 and PD 2 are somewhat limited. When the distance increases, the received power using PD 1 and PD 2 increases. For sufficiently large distance, the contribution of PD 2 becomes the maximum (41\%) followed by PD 1 (34\%) and PD 3 (24\%). This is due to that with increasing the distance the direction of the source vehicle moves away from PD 3 and towards PD 2. In other words, the angle of arrival at PD 2 is smaller compared to PD 3.

In Fig. 15.b, we present pie charts for Scenarios 11 and 12 based on TL transmitters.

- In Scenarios 11 and 12, it is observed that PD 5 and PD 6 always collect the highest received powers (i.e., 70\% or more based on the distance). The contribution of PD7 decreases with increase in distance.
In Fig. 16, we present pie charts for Scenarios 13-15 based on traffic light transmitters and for Scenarios 16-18 based on street light transmitters.

- In Scenarios 13-15 (see Fig. 16.a), the traffic light is the transmitter. It is observed that PD 5 and PD 7, located at the right-hand side, collect the highest amount of received power, i.e., 59% and more. In Scenario 13 ($d_h = 0$ m), a small difference is observed between received powers of PD 5 and PD 7.

- In Scenarios 14 and 15 where $d_h$ increases respectively to 1 m and 2 m, the difference gets larger particularly at shorter distances. It is further observed that contributions of PD 6 and PD 8 (located at the left-hand side) improve with the increase in distance.

- In Scenarios 16-18 (see Fig. 16.b), the street lights are transmitters. At small distances, PD 9 located at the top of the vehicle is the primary receptor. As distance increases, all 9 PDs contribute at different levels to
the received power although PD 9 always receives the highest received power.

In Fig. 17, we present pie charts for Scenarios 19, 20, and 21.

- In Scenario 19 and 20 where two vehicles follow each other in the middle lane with and without neighbor vehicles (i.e., no blockage), PD 1 and PD 2 are the main receptors. These two PDs collect 96% or more of the total power based on the distance. A small amount of received power is collected using PD 3 and PD 4 because of road reflections if the distance between two vehicles is sufficiently large.

- In Scenario 21 where partial blockage occurs, PD 1 becomes the primary receptor which collects 94% or more of the total power based on the distance. On the other side, the received power using PD 2 becomes negligible (i.e., only 2% due to reflections and at sufficiently larger distances). This is due to its location on the side of blockage vehicle. It should be noted that if the blockage vehicle is re-located at the left-hand side, PD 2 would be primary receptor.

**C. EFFECT OF NEIGHBOR VEHICLES ON SINR**

It should be emphasized that received power by its own might not be sufficient to evaluate the performance in Scenarios 19, 20, and 21 where there are neighbor vehicles. In particular, we need to impose some assumption on the transmitters of the neighbor vehicles and accordingly calculate signal-to-interference-plus-noise ratio (SINR). In the first case, the neighbor vehicles are assumed to have inactive HLs transmitters. In this case, the HLs are used only for illumination purposes with no signal transmission. The received light from neighbors with inactive transmitters is treated as shot noise in SINR calculation. The second case where the transmitters are assumed to be active, the received lights from neighbor vehicles are considered as interfering signals in SINR calculation.

In Fig. 18.a, we present the SINR results for the case of inactive transmitters and assume high speed communication, i.e., $B = 10$ MHz. Similar to our earlier observations in Fig.11, the presence of neighbor vehicles in other lanes improves received SINR due to additional reflections. On the other side, when there is a blockage (i.e., Scenario 21) the received SINR is significantly degraded.

In Fig. 18.b, we consider the case of active transmitters and assume $B = 10$ MHz. It is observed in Scenario 20 that the received SINR value significantly reduces (i.e., $\geq 57$ dB) with respect to Scenario 19. In Scenario 21, it is observed that the blockage vehicle further reduces the SINR values (i.e., $\leq 6$ dB) with respect to Scenario 20. This is due to the fact that the blockage affects both the desired and the interfering signals. Despite the degrading effects of neighbor vehicles, the received power values are sufficient for both low-speed and high-speed communication use cases. In particular, the threshold SINR value required to achieve our target of $\text{BER}_{th} = 10^{-3}$ is given as $\gamma_{th} = 9$ dB.\(^1\) It is observed from Fig. 18 that SINR value of 15.7 dB is achieved at a

\(^1\)For OOK under consideration, the threshold SINR ($\gamma_{th}$) required to achieve a target BER of ($\text{BER}_{th}$) is given as $\gamma_{th} = \left( Q^{-1}(\text{BER}_{th}) \right)^2$ [47]. For $\text{BER}_{th} = 3.8 \times 10^{-3}$ (i.e., the 7% forward error correction BER limit [48]), a threshold SNR of $\gamma_{th} = 8.6$ dB is required.
which PDs are the primary and optional receptors for each scenario under investigation.

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FIGURE 18. Effect of neighboring vehicles and blockage on the received SINR (a) Case A, i.e., inactive transmitters and (b) Case B, i.e., active transmitters.

V. CONCLUSION

In this paper, we investigated the coverage of a vehicular VLC system in an effort to determine the number and location of PDs. Based on non-sequential ray tracing, we conducted a channel modeling study to determine the received powers for various V2V and I2V scenarios. Our results revealed that deployment of nine PDs with carefully determined locations on the vehicle would be sufficient to support both V2V connectivity (in front and back directions) and I2V connectivity in different road types, intersections, and traffic scenarios. The contribution of each PD was also quantified to indicate distance of 50 m even in the case of heavy traffic described by Scenario 21.
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