Performance metrics for vehicular visible light communication systems

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Abstract. Vehicular Visible Light communication (VVLC) presents a new paradigm for providing vehicle connectivity, increasing road safety, and achieving autonomous driving. It can be chosen as an alternative solution to radio frequency-based inter-vehicle communication systems and/or as a complementary solution to ensure redundancy. Nevertheless, there are still significant challenges in incorporating visible light communication systems into vehicular networks. The main purpose of this paper is to provide an outline of the performance metrics of a VVLC system. Furthermore, the study is performed based on a vehicle-to-vehicle dynamic model close to reality, considering the effect of geometrical changes in the LOS path and the variation of the inter-vehicular distance. The analysis of the proposed system is discussed in terms of Signal to noise (SNR), Field of view (FOV), mobility, and average capacity.

Keywords: Visible light communication (VLC), vehicular visible light communication (VVLC), vehicle-to-vehicle (V2V), mobility, performance metrics.

1 Introduction

Vehicular visible light communication is a new promising communication technology that sends data through light waves of the visible spectrum.It relies on the ability to modulate the light intensity of LEDs to communicate information and enables the dual use of headlamps and road traffic for both illumination and communication purposes [1]. Vehicular communication systems are essential in improving intelligent transportation systems (ITS). Specially, in the context of reducing the number of traffic accidents and related fatalities. Enabling real-time data exchange between vehicles and traffic infrastructures has been emerging as one of the key solutions for improving road safety, traffic efficiency, and driver comfort.

Compared to existing forms of wireless communications, VLC offers several advantages, such as huge and unregulated bandwidth, no interference with RF systems, better security in the physical layer, high energy efficiency, and low-cost implementation [2]. In addition, VLC brings a completely new field of possibilities to solve the problem of increasing mobile data traffic exponentially for decades, which has highlighted the limitations of RF-only mobile communications. In contrast, the visible light spectrum, which includes hundreds of terahertz of unlicensed bandwidth, is completely untapped for communication [3]. It can complement RF-based mobile communication systems to design high-capacity mobile data networks. It can also significantly increase the available wireless channel capacity [4],[5].

The VLC technology must enable reliable communications while maintaining the main purpose of the lighting device. Thus, the pattern of light radiation and the optical power output should be in accordance with the regulations, although their adjustment allows significant optimization.

Currently, the most extended version of VLC research is for the indoor environment. Vehicular Visible light communications technology entails more research efforts.

To evaluate the performance of applications enabled by V2V communications, it is vital to determine the time distribution of the communication link between two vehicles. Furthermore, the conditional distribution of the link duration, such as vehicle speed, receiver field of view FOV [6], atmospheric effects, could be modeled to adjust its parameters as [7], so that a loss of connection is less likely to occur in the middle of an active transmission and affect the final performance.

In previous performance evaluation studies [8],[9] some basic performance metrics such as received optical power and signal-to-noise ratio (SNR) have been derived for different road surfaces for a Vehicle to infrastructure(V2I) communication system between a street/ traffic light and a vehicle. The experimental work in [10] has used commercial LEDs and photodiodes

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(PDs) to study the throughput and error rate of VLC-based V2V and V2I links. This work has proved the reliability of vehicular VLC.
Nevertheless, this technology remains in its beginning stage and requires additional research efforts in several areas, including channel modeling and physical layer design.
The study in [11] has evaluated the degradation of data rate, BER, and SNR performance of VLC systems in the presence of sunlight at different locations.
The VLC system performance on a LOS channel is examined in [12], [13].
The distribution of received power and signal-to-noise ratio (SNR) with intersymbol interference (ISI) of directed light is presented [14]. The bit error rate (BER) and outage performance of LOS VLC system is simulated for random orientation of the receiver in [15].
In order to design and implement a communication system, it is necessary to define and study the performance metrics of the overall system.
Up to now, there is no work that defines the metric performance of the outdoor systems based on visible light communication considering the key parameters of a realistic model. Most works do not consider the dynamic aspect of the outdoor model and the variation of angles or distance of the communicating cars.
The objective of this work is to fill this gap by presenting some key performance parameters based on a realistic outdoor VLC simulation model.
The remainder of this paper is organized as follows: first we present the system model for the vehicular visible light communication system, then we present and discuss the key performance metrics. In the third section, we present the simulation results. Finally, the conclusion is presented in the fourth section.

1.1 System model

The VLC system model proposed (presented in Fig. 1), consisting of a transmitter, a light-emitting diode is employed as the lighting source which converts the original electrical signal to the visible-light signal. Then, the optical signal is propagated in the VVLC channel. At the receiver, a photodiode (PD) is used to carry out the optical-electrical conversion.
To model, the point-to-point response of the VLC link, the three main blocks (VLC transmitter, optical wireless channel, and VLC receiver) are used.
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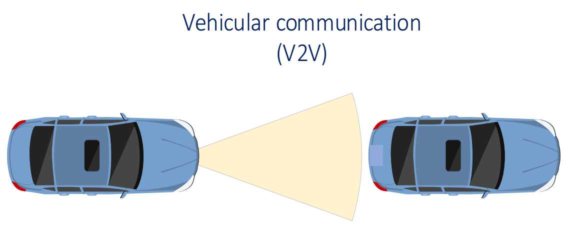

Fig. 1. Illustration of a communication link between two vehicles.

The VLC channel is modeled using the classical path loss additive white Gaussian noise (AWGN) channel model [16].
In this model, the output current Y (t) generated by the photodiode (PD) is related to the transmitted optical power X(t) by:

$$Y(t) = X(t) \otimes h(t) + N(t) \quad (1)$$

where $h(t)$ denotes the channel impulse response.
Based on the Lambertian emission, and it can be modeled (fig.2 shows a simplified model-based LOS path between two vehicles) by [16] :

$$h(t) = \frac{(m+1)A}{2\pi(\mathrm{d}(t))^2} \cos^m(\varphi) T_s(\theta) g(\theta) \cos(\theta) \times \delta\left(t - \frac{\mathrm{d}(t)}{c}\right) \quad (2)$$

Where A is the physical area of the PD, d(t), φ, and θ are the time-varying distance, the angle of irradiance, and the angle of incidence from the transmitter to the receiver, respectively. θ is also known as the field of view of the PD, and $\delta(t - \frac{\mathrm{d}(t)}{c})$ is the propagation delay of the signal.
The inter-vehicular distance between the transmitter and receiver can be expressed by:

$$d = \sqrt{{d_L}^2 + {d_h}^2} \quad (3)$$

Where d_L and d_h are the lateral and the longitudinal distances between the transmitter and the receiver respectively. d_h is directly related to the speed as:

$$d_L(t) = tv(t)\cos(\varphi) \quad (4)$$

$T_s(\theta)$ is an optical filter gain used to block the natural and artificial light signals, g(θ) is the concentrator gain is given as:

$$g(\theta) = \begin{cases} \frac{n^2}{sin^2(\theta)}, 0 \leq \theta \leq FOV \\ 0,\ \theta > FOV \end{cases} \quad (5)$$

in which m is the order of Lambertian model specifying the directivity of the transmitter and obtained by: $m = -\frac{\ln(2)}{\ln(\cos(\varphi_{1/2}))}$, and $\varphi_{1/2}$ is the half-power angle of the radiation and n indicates lens refractive index of PD
The average received optical power P_r is computed by:

$$P_r = H.Pt \quad (6)$$

Where H is the VLC channel gain [17]:

$$H = \frac{(m+1)A}{2\pi({d_L}^2 + {d_h}^2)} \cos^m(\varphi) T_s(\theta) g(\theta) \cos(\theta) \quad (7)$$

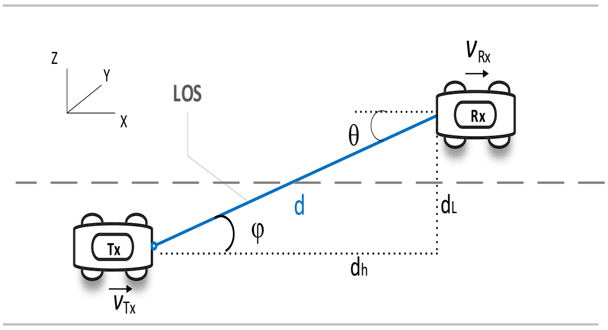

Fig. 2. The V2V system model

2 Performance metrics analysis

In this section, we will propose, evaluate and discuss the main performance measures and their impact in the VVLC system.

2.1 Signal to Noise Ratio Analysis (SNR)

A basic specification used to measure the quality of communication is the signal-to-noise ratio (SNR). We have analyzed the signal-to-noise ratio (SNR), at the detector of the VVLC system.
The quality of the transmission in optical channels is mostly dominated by the shot noise. The shot noises consist mainly of shot noise caused by signals and thermal noise induced by intense ambient light. We assume that the noises are additive white Gaussian noises (AWGN).
The received electrical power S and the SNR are given by:

$$S = \gamma^2 P_{rSignal}^2 \quad (8)$$

where $\boldsymbol{\gamma}$ is the responsivity of the PD. The desired signal power $P_{rSignal}$ is given by:

$$P_{rSignal} = \int_0^T \left(\sum_{i=1}^{LEDs} h_i(t) \otimes X(t)\right) dt \quad (9)$$

The equalizer output contains a Gaussian noise having a total variance N that is the sum of contributions from shot noise, thermal noise [17].

$$N = \sigma_{shot}^2 + \sigma_{thermal}^2 \quad (10)$$

According to [17] the shot and thermal-noise variances are given as:

$$\sigma_{shot}^2 = 2q\gamma\left(P_{rSignal}\right)B + 2qI_{bg}I_2B \quad (11)$$

where q is the electronic charge (1.602×10−19 C), B is equivalent noise bandwidth, Ibg is the received background current.
And we have defined the noise bandwidth factors I2 = 0.562 [18]. The variance of the thermal noise is given by:

$$\sigma_{thermal}^2 = \frac{8\pi K T_K}{G}\eta A I_2 B^2 + \frac{16\pi^2 K T_K \Gamma}{g_m}\eta^2 A^2 I_3 B^3 \quad (12)$$

Where k is Boltzmann's constant, ,G is the voltage gain in open loop, TK is absolute temperature, η is the constant capacitance of photo detector per unit area, Γ is the FET channel noise factor, A is the detection area of the PD, g_m is the FET transconductance, and $I_3 = 0.0868$ [19]. the noise bandwidth factor. In our numerical examples, we choose the following parameter values [17]: T = 298 K, γ = 0.54 A/W, G = 10, gm = 30 mS, Γ = 1.5, η = 112 pF/cm^2 (Table1).
Lastly, the electrical SNR at the receiver, which is a key metric for measuring the quality of the communication link, can be determined by:

$$SNR = \frac{S}{N} = \frac{\left(\Upsilon P_{rSignal}\right)^2}{\sigma_{shot}^2 + \sigma_{thermal}^2} \quad (13)$$

And we assume the background current from direct sum light. The distribution of SNR is shown in Fig. 6 and Fig.7.

2.2 Average Capacity

The average capacity can be used to effectively evaluate the performance of VVLC. For a communication system, it can be defined as the maximum data rate that can be achieved over the channel of the system within a certain bandwidth, considering the noise effect. Unlike conventional radio frequency (RF) communication, VLC adopts the intensity modulation/direct detection (IM/DD) scheme, in which the transmitted information is modulated on the intensity of light. Therefore, the transmitted signal must be real, not negative, and the Gaussian distribution that achieves the conventional channel capacity of RF cannot be used in VLC channels [20].
By taking the noise parameters of equation (9), the system capacity C in bits/s, can be evaluated directly by:

$$C = B\log_2(1 + SNR) \quad (14)$$

The average channel capacity, C_{av} . Mathematically, the average capacity of this system can be calculated as:

$$C_{av} = \int_0^\infty \log_2(1+\mu) f_\mu(\mu) d\mu \quad (15)$$

where μ is the average SNR and $f_\mu(\mu)$ is the PDF of the perturbed system.
$\cos(\varphi)$ and $\cos(\theta)$ represents the effect of receiver vehicle location on channel gain. Based on our model presented in fig.2, Their expressions can be written as:

$$\cos(\varphi) = \cos(\theta) = \frac{d_h}{d} \quad (16)$$

Further in order to obtain a statistical model of channel gain (h), the vehicle receiver position is considered to be random and assuming d_L to be following a uniform distribution with PDF [21]:

$$f_{V_r}(d_r) = \frac{2d_r}{{d_r}^2} \quad (17)$$

The average capacity of the VLC link can be calculated from:

$$C_{av} = \int_{t_{min}}^{t_{max}} \log_2(1+\mu) f_\mu(\mu) d\mu \tag{18}$$

Where: $t_{min} = \frac{K^2}{(R^2+{d_h}^2)^{m+3}}$, and $t_{max} = \frac{K^2}{({d_h}^2)^{m+3}}$.

By replacing (16) in (7), the channel gain is given by [21]:

$$H = \frac{(m+1)AT_s(\theta)g(\theta){d_h}^{m+1}}{2\pi({d_L}^2+{d_h}^2)^{\frac{m+3}{2}}} \tag{19}$$

The PDF of the channel gain can be expressed as [21], [22]:

$$f_H(h) = \frac{2}{(m+3)R^2} K^{\frac{2}{m+3}} h^{-\frac{2}{m+3}-1} \tag{20}$$

Where: $k = \frac{(m+1)AT_s(\theta)g(\theta){d_h}^{m+1}}{2\pi}$, is assumed to simplify our analysis.
Consequently, the PDF of H^2, can be obtained as follows:

$$f_{H^2}(h) = \frac{-K^{\frac{2}{m+3}}}{(m+3)R^2} h^{-\frac{m+5}{m+3}} \tag{21}$$

Substituting Equation (21) in Equation (18), Equation (22) is obtained:

$$C_{av} = \frac{1}{2\log[2]} \int_{t_{min}}^{t_{max}} \log\left(1 + \frac{P_{r\text{Signal}}}{N^2} h\right)\left(\frac{-K^{\frac{2}{m+3}}}{(m+3)R^2} h^{-\frac{m+5}{m+3}}\right) \tag{22}$$

Figure 5 presents the average capacity of the system with respect to the source power.

2.3 Effect of mobility

The FOV is an important factor for defining the visible light range at the receiver.
In visible-light communication, the interferences depend on a data rate and the FOV of receiver since a transmitter should have a wide irradiation angle for the lighting function [23]. Different VLC receivers have various field-of-view angles.
Optical transmissions arrive outside of the field-of-view angle of the receiver are generally not received as the receiver power is negligible.

As the field of view of the VLC receiver has a significant influence on the communication parameters, the performance of the VLC was evaluated for a variable field of view from 20° to 80°.

In this section, we will discuss the relation between received power, FOV, and the variable distance between the two communicating cars.
Figures 2 and 3 show the relation between FOV and received power and distance.

3 Simulation results and discussion

In this section, we conducted simulations of the vehicle-to-vehicle key performance metrics.
The performance of the different V2V-VLC system configurations is discussed in this subsection in terms of key performance metrics.

The main simulation parameters are illustrated in Table1.

Table 1. System model parameters.

Parameters	Symbol	Value
FOV of the PD	θ	70
PD area	A_r	1 (cm^2)
Order of Lambertian diffuser	m	1
Luminous efficacy of radiation	LER	250.3 (lm/W)
Responsivity of PD	γ	0.54 (A/W)
Electronic charge	q	1.6×10^{-19} (C)
Received background noise current	I_{bg}	5100 (μA)
Noise bandwidth factor	I_2	0.562
Boltzmann's constant	K	1.38×10^{-23} (J/K)
Absolute temperature	T_k	298 (K)
Open-loop voltage gain	G	10
FET channel noise factor	Γ	1.5
FET transconductance	g_m	30 (mS)
System bandwidth	B	2 (MHz)
Fixed capacitance of PD per unit area	η	112 (pF/cm^2)

Figure 3 depicts Pr and distance for different values of FOVs.

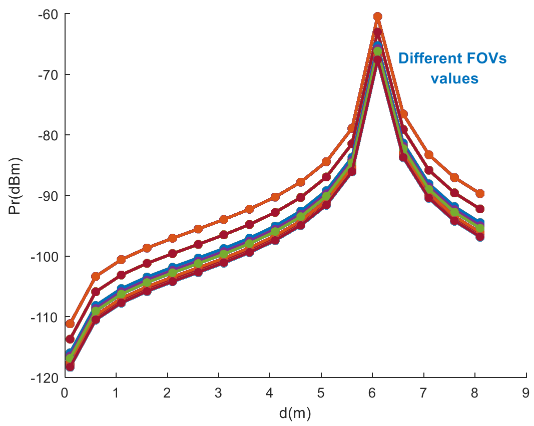

Fig.3. Power received vs. distance for different FOVs values

Figure 4 shows the effect FOV on the distribution of received optical power. Clearly that with increasing FOV, received optical power decrease.

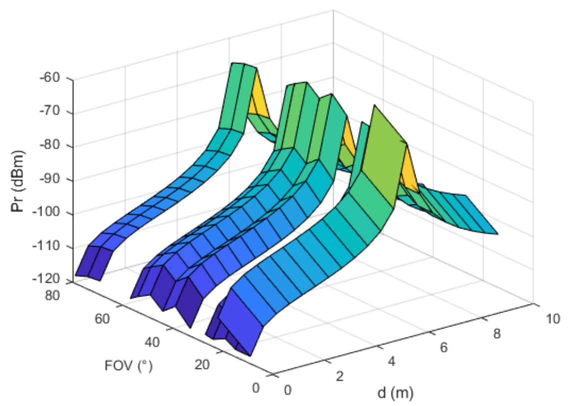

Fig. 4. The distribution of Power received vs. distance for different FOVs values

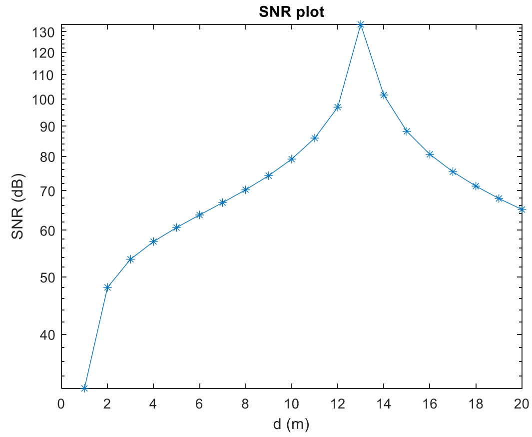

Fig. 6. The relation between the SNR and the distance

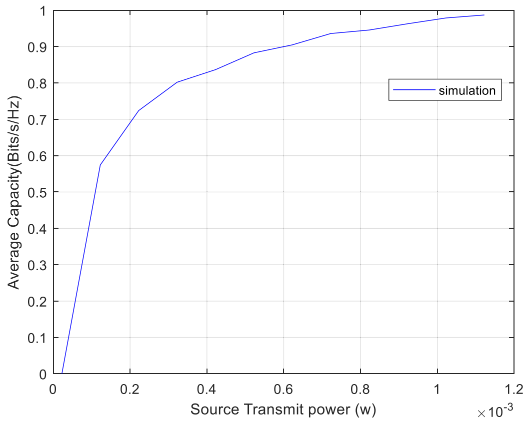

Fig. 5. Average capacity for VVLC based system with respect to source transmit power

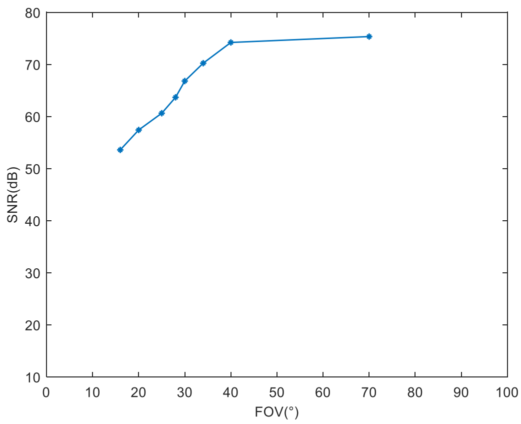

Fig. 7. The relation between the SNR and FOV

In Figure 5 the average capacity of the system is plotted with respect to the source power. As can be seen, with the increase of the source transmit power, the average capacity increases. This indicates that performance system becomes more evident due to the higher transmission power source.

On the other side, Figure 6 shows the SNR against the relative distance between two vehicles.

As the SNR decreases with the increase of perception rate. The SNR has very close behavioral curves at small distances. The maximum SNR that a vehicle can receive in the case of variable speed is 133.75 dB at 13 m ranging.

Ultimately, Fig 7 shows the dependence of SNR on FOV. So, when FOV is smaller than 20 deg., the blind area exists. However, up to 40 deg the SNR has increased until 70 deg. From this figure, with respect to SNR performance, it was found that for very narrow and larger FOVs, lower SNR values were found.

The effect of changes in the dynamic behavior of the system parameters is also included for all parameters studied. The discussion began with Figure 2, where the total received power performance at the receiver was analyzed by varying the FOV.

The performance of automotive VLC receivers can be significantly improved by making the FOV dynamic and adaptable by following the position of the sensor and the receiving vehicle. Because a narrow FOV also restricts the system's mobility, as useful light may also be prevented from reaching the VLC receiver.

However, the narrowing of the FOV also reduces the amount of optical noise (i.e., from artificial light or sunlight) that reaches the PD detector, and it can be considered among the simplest solutions to avoid the saturation of the photosensitive element is therefore improve the signal-to-noise ratio. Another advantage is that it can increase the dominance of the line of sight (LOS).

This means that an appropriate FOV adjustment is very critical to achieve good illumination and higher data rate in a V2V-VLC link. Therefore, the problem of maintaining a direct line of sight between vehicles is very challenging and needs further study.

Through figure 5, it is noticeable that the capacity improves as the input power increases. On the other hand, through fig.6 a performance degradation is clearly visible when the distance varying between the Tx and the Rx increases.

4 Conclusion

In this paper, we have investigated the key performance metrics of V2V-VLC link. The proposed system performance is measured by its power receiver (Pr), Signal to Noise Ratio (SNR), field-of-view (FOV), mobility and average capacity.

We discussed those requirements and investigated their impact in the system performance. The results simulations showed that the performance of the proposed system is affected by variations in: the field of view, mobility (variable distance inter-vehicles) and input power.

The study presented in this paper was performed based on one specific scenario. We will further investigate and develop the performance metrics considering other scenarios with the impact of disturbing elements such as atmospheric effects and re-specify and confirm the approach in future work.

Furthermore, we intend also to find the optimal values of different metrics in various situations specific to outdoor VLC in order to maximize the system performance.

References

1. A. Memedi and F. Dressler, "Vehicular Visible Light Communications: A Survey," IEEE Commun. Surv. Tutor., vol. 23, no. 1, Art. no. 1, 2021.
2. S. U. Rehman, S. Ullah, P. H. J. Chong, S. Yongchareon, and D. Komosny, "Visible Light Communication: A System Perspective—Overview and Challenges," Sensors, vol. 19, no. 5, Art. no. 5, Jan. 2019.
3. P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges," IEEE Commun. Surv. Tutor., vol. 17, no. 4, Art. no. 4, Fourthquarter 2015.
4. A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," IEEE Commun. Mag., vol. 51, no. 12, Art. no. 12, Dec. 2013.
5. G. Pang, T. Kwan, C.-H. Chan, and H. Liu, "LED traffic light as a communications device," in Proceedings 199 IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems (Cat. No.99TH8383), Oct. 1999, pp. 788–793.
6. H. B. Eldeeb and M. Uysal, "Vehicle-to-Vehicle Visible Light Communication: How to select receiver locations for optimal performance?," in 2019 11th International Conference on Electrical and Electronics Engineering (ELECO), Nov. 2019, pp. 402–405.
7. M. Karbalayghareh, F. Miramirkhani, H. B. Eldeeb, R. C. Kizilirmak, S. M. Sait, and M. Uysal, "Channel Modelling and Performance Limits of Vehicular Visible Light Communication Systems," IEEE Trans. Veh. Technol., vol. 69, no. 7, pp. 6891–6901, Jul. 2020.
8. M. Akanegawa, Y. Tanaka, and M. Nakagawa, "Basic study on traffic information system using LED traffic lights," IEEE Trans. Intell. Transp. Syst., vol. 2, no. 4, Art. no. 4, Dec. 2001.
9. S. Kitano, S. Haruyama, and M. Nakagawa, "LED road illumination communications system," in 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No.03CH37484), Oct. 2003, vol. 5, pp. 3346-3350 Vol.5.
10. C. B. Liu, B. Sadeghi, and E. W. Knightly, "Enabling vehicular visible light communication (V2LC) networks," in Proceedings of the Eighth ACM international workshop on Vehicular inter-networking, New York, NY, USA, Sep. 2011, pp. 41–50.
11. M. S. Islim and H. Haas, "An investigation of the solar irradiance effect on visible light communications," in 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Oct. 2017, pp. 1–6.
12. P. Luo, Z. Ghassemlooy, H. Le Minh, E. Bentley, A. Burton, and X. Tang, "Fundamental analysis of a car to car visible light communication system," in 2014 9th International Symposium on Communication Systems, Networks & Digital Sign (CSNDSP), Manchester, UK, Jul. 2014, pp. 1011–1016.
13. P. Luo, Z. Ghassemlooy, H. L. Minh, E. Bentley, A. Burton, and X. Tang, "Performance analysis of a car-to-car visible light communication system," Appl. Opt., vol. 54, no. 7, Art. no. 7, Mar. 2015.
14. M. Uysal, Z. Ghassemlooy, A. Bekkali, A. Kadri, and H. Menouar, "Visible Light Communication for Vehicular Networking: Performance Study of a V2V System Using a Measured Headlamp Beam Pattern Model," IEEE Veh. Technol. Mag., vol. 10, no. 4, pp. 45–53, Dec. 2015.
15. M. Irfan et al., "Optical-Interference Mitigation in Visible Light Communication for Intelligent Transport Systems Applications," Energies, vol. 13, no. 19, Art. no. 19, Jan. 2020.
16. J. M. Kahn and J. R. Barry, "Wireless infrared communications," Proc. IEEE, vol. 85, no. 2, pp. 265–298, Feb. 1997.
17. T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Transactions on Consumer Electronics, vol. 50, no. 1, pp. 100–107, Feb. 2004.
18. T. Komine, J. H. Lee, S. Haruyama, and M. Nakagawa, "Adaptive equalization system for visible light wireless communication utilizing multiple white LED lighting equipment," IEEE Trans. Wirel. Commun., vol. 8, no. 6, pp. 2892–2900, Jun. 2009.
19. I. E. Lee, M. L. Sim, and F. W. L. Kung, "Performance enhancement of outdoor visible-light communication system using selective combining receiver," IET Optoelectron., vol. 3, no. 1, pp. 30–39, Feb. 2009.

20. A. Chaaban and S. Hranilovic, "Capacity of optical wireless communication channels," Philos. Trans. R. Soc. Math. Phys. Eng. Sci., vol. 378, no. 2169, p. 20190184, Apr. 2020.
21. A. Gupta, N. Sharma, P. Garg, and M.-S. Alouini, "Cascaded FSO-VLC Communication System," IEEE Wirel. Commun. Lett., vol. 6, no. 6, pp. 810–813, Dec. 2017.
22. J.-Y. Wang, Y. Qiu, S.-H. Lin, J.-B. Wang, M. Lin, and C. Liu, "On the Secrecy Performance of Random VLC Networks With Imperfect CSI and Protected Zone," IEEE Syst. J., vol. 14, no. 3, pp. 4176–4187, Sep. 2020.
23. S.-A. Avătămăniței, C. Beguni, A.-M. Căilean, M. Dimian, and V. Popa, "Evaluation of Misalignment Effect in Vehicle-to-Vehicle Visible Light Communications: Experimental Demonstration of a 75 Meters Link," Sensors, vol. 21, no. 11, Art. no. 11, Jan. 2021.