Study on Multi-Users Interference in Vehicle to Vehicle Visible Light Communications

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Abstract—**Visible Light Communications (VLC) can play an important role in the Cooperative Intelligent Transport Systems (C-ITS) by enabling vehicles to communicate with nearby vehicles (V2V) and infrastructure (V2I) by offering virtually unlimited and unregulated spectrum. Whereas extensive R&D efforts have been made on physical layer techniques, almost no study has been made on Multi-Users Interference (MUI), consequently Medium Access Control (MAC), in VLC. This work sheds light on the impacts of MUI on VLC performances for V2V communications. We first develop an analytical model that formulates the Packet Delivery Ratio (PDR) performances of VLC communication in presence of MUI. We then conduct simulation evaluations to confirm the analytical model and evaluate the VLC performance when there is one or more interfering nodes. The obtained results clearly show that, in an absence of MAC, VLC can suffer from MUI in medium to dense traffic density even when message generation rate at each node is relately low.**

Keywords–Visible Light Communication (VLC); Multi-Users Interference (MUI), Vehicle to Vehicle (V2V) communication; mathematical modeling, MATLAB

I. Introduction

The key objective of C-ITS is to improve road safety and traffic efficiency by enabling vehicles and infrastructure to exchange information via Vehicle to Vehicle/Infrastructure communication (V2X). Radio communications technologies, particularly 802.11p and 4G/5G are considered to be the key players by providing omni-directional medium to long distance communications, allowing vehicles and roadside infrastructure communicate directly with each other (V2V or V2I) or through a network (V2N). Whereas radio communication technologies are probably the *de-facto* choice for a great number of C-ITS applications, due to the limited radio resource and their vulnerability against security attacks, there is a need for complementary technology especially for applications that require 100% of reliability and strong cyber-security protection. Indeed applications particularly those for automated driving have extremely strict requirements in terms of reliability and security. One of such applications having such stringent requirements is vehicle platooning in which, V2V communication between platoon members are required for longitudinal and lateral controls avoiding chain instability problem. Because the information is to control vehicles, the information exchange has to be extremely reliable and secure. Targeting applications, such as vehicles platooning, a great number of researchers suggest VLC for V2V as a complementary solution to radio communications as shown in Figure 1, [1]–[5]. VLC uses the visible light spectrum (wavelengths between 780 nm to 375 nm) as communication media. VLC is a fast, safe and cheap technology, since it is implemented directly using vehicle headlights and taillights. Moreover, the usage of Light Emitter Diodes (LED) instead of a xenon or halogen bulb, has a number of benefits such as long useful life, low power consumption, high tolerance to environmental conditions, and high efficiency [6]. Finally, since radio and light communications do not interfere with each other, and hence VLC can perfectly co-exist and complement radio communications.

Indeed, IEEE provides the possibility to deploy VLC by specifying VLC standards: 802.15.7 [7] and 802.15.7r1 [8], which are published in 2011 and in 2018, respectively, and the ongoing work on IEEE 802.11bb [9]. The standard IEEE 802.15.7 and its revision 802.15.7r1 have a strong focus physical layer configurations of VLC for both indoor and outdoor LED to photodiode (PD) or LED to camera VLC communications. Concerning the MAC, the standards basically carried over the solutions of Wireless Personal Area Networks (WPAN). On the other hand, the aim of IEEE 802.11bb [9] is to integrate Wireless Local Area Network (WLAN) solutions to Light Fidelity communication (LiFi). In adding to the above-mentioned standardisation efforts, a great number of R&D studies have been carried out proposing VLC as a candidate technology for enhanced reliability and security for V2X communications. The majority of the efforts however focuses on the physical layer design of VLC proposing modulation schemes, filtering strategies, etc. [10]–[12]. Some real-world demonstrations of VLC prototypes for V2V communication have been also made [1], [2], [12]. In contrast to the voluminous literature on physical layer solutions, very few efforts

Figure 1. Visible Light Communication for V2V information exchange.

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are made on medium access control for VLC [13]–[16]. Most importantly, because VLC is directional and requiring Line Of Sight (LOS) condition, one may even doubt about MUI in VLC, and hence neglecting the importance of MAC.

To the best of our knowledge, the current work is the only work that studies the impact of MUI in VLC. In this paper, we first develop analytical models that formulate the size of MUI zone in V2V VLC. We then further develop a model of PDR in VLC in presence of MUI, when vehicles' density follows the Poisson distribution. Finally, by using computer simulations, we validate the correctness of the theoretical model and evaluate the VLC performance in presence of MUI. The results clearly show that PDR can quickly degrade down to few % for medium to dense roads.

This paper is organized as follows. Section II highlights the related work. We develop an analytical model on impacts of MUI on V2V VLC in Section III. Section IV validates the analytical model and evaluates the PDR performance of VLC up to 3- and 7-lanes of highway scenarios with sparse to dense traffic density. Finally, Section V concludes the paper.

II. Related Work

The majority of the existing standardisation and R&D efforts on VLC are to advance physical layer design of VLC. IEEE 802.15.7 standard specified three PHY modes PHY-I, II, and III, where PHY-I is intended to outdoor applications utilizing On-Off Keying (OOK) and Variable Pulse Position Modulation (VPPM) coding schemes, which are relatively robust in harsh outdoor environments. The authors of [10], [11] demonstrated different modulation schemes for transmission (Manchester, Orthogonal Frequency Division Multiplexing (OFDM), Miller, etc.), and complex filtering strategies for reception. *A. Belle et al.* [17] presented a VLC prototype of IEEE 807.15.7 that extending their previous work [18] on IEEE 802.15.4 [19]. The authors developed software libraries for PHY and *zigbee* MAC, which is not specifically designed for VLC. *Q. Wang et al.* [20] evaluated VLC performances, using a VLC platform, in terms of communication speed, communication distance, and low power LED/PD saturation in outdoor/indoor environments for different types of VLC systems: high/low power LED to PD or LED to LED. The authors of [1], proposed to use visible light not only for V2V communications but also for inter-vehicle distance measurement. Finally, a number of demonstrations using VLC for V2V communications have been made [1], [2].

In contrast to the great number of efforts made on PHY, very few works on MAC can be found in the literature. The authors of [13] studied Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) on top of the physical layer of specified by IEEE 802.15.7 [7] with different priority levels setting (High, Medium, and Low Priorities), which result in differentiated settings of back-off time, back-off exponent and contention window sizes. *P. Shams, et al.* [15] presented a performance evaluation of throughput, delay, power consumption, collision probability, transmission probability, access probability and packet discard probability based on Markov modelling and MATLAB simulations of IEEE 802.15.7 VLC standard. The authors of [21] evaluated the service time distribution of the IEEE 802.15.7 standard using Markov chain model. The authors also proposed an analytic and semi-analytic approach of queue modeling. *S. Ishihara et al.* [14] proposed a radio and visible light hybrid communication for platooning applications implementing IEEE 1609.4/802.11p standard for radio frequency and ALOHA MAC protocol for VLC. None of the above efforts are based on studies on MUI in VLC, demonstrating the needs of MAC. Furthermore, the rational behind the usages of CSMA/CA or ALOHA for VLC, which is naturally half-duplex and directional communication, is not clear. This paper is to fill the missing gap, studying MUI in VLC, presenting the need of MAC, which shall take into account the VLC properties.

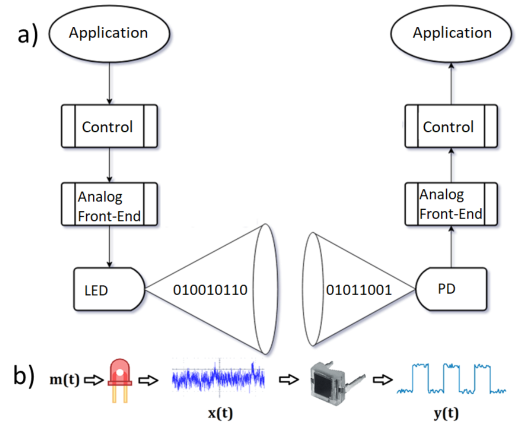

Figure 2. VLC System, a) VLC Schematic b) Conceptualization of the VLC channel.

Concerning VLC evaluation tools, *Q. Wang et al.* [20] presented a low cost, flexible and open source VLC platform enabling researchers to develop and test their own VLC systems. Besides prototyping, researchers can also conduct simulations. Veins VLC [22], [23] is a simulation framework that integrates VLC transmitter, receiver, and channel models. Nevertheless, it misses several important functionalities including that transmission power ($10mW$) cannot be reconfigured, and the noise takes into account only the thermal noise ignoring environmental noises. For this reasons, in this paper, we have developed own VLC models using Simulink tool.

To summarize, motivated by the fact that there is no work studying MUI in VLC, this paper is dedicated to study on MUI and presents the need of MAC that takes into account the VLC properties.

III. Modeling Impact of VLC Multi-users Interference

In this Section, we first present a VLC channel model and then develop an analytical model of a zone, from which no interference is allowed such that an ongoing VLC communication is protected. Note that for the sake of simplicity, the model does not take into account weather condition, sun light direction and intensity.

A. VLC Channel Model

Intensity Modulation with Direct Detection (IM/DD) is a commonly used method for optical communications. As illustrated in Figure 2, the LED emits the modulated signal $m(t)$, whose intensity is varied in accordance with the data. After propagating through the wireless channel, the signal $x(t)$ is collected by the photo-diode (PD) of the receiver. The latter generates a current, $y(t)$, which is proportional to the power of the light incident on the active area of the PD.

In order to model such a VLC [1], [2], [24], we first need to express the angular distribution ($R_o(\phi)$) or intensity pattern generated by the LED:

$$R_o(\phi) = \begin{cases} \frac{(m_i+1)}{2\pi} \cos^{m_i}(\phi) & \phi \in [\frac{-\pi}{2}\frac{\pi}{2}]. \\ 0 & \phi \geq \frac{\pi}{2}, \end{cases} \quad (1)$$

Here, m_i is the Lambert coefficient related to the LED semi-angle at half-power $\phi_{\frac{1}{2}}$ (see Figure 3):

$$m_i = \frac{-\ln 2}{\ln(\cos\phi_{\frac{1}{2}})} \quad . \quad (2)$$

For the receiver side, its effective reception area ($A_{eff}(\psi)$) is modeled:

$$A_{eff}(\psi) = \begin{cases} A_r \cos(\psi) & 0 \leq \psi \leq \frac{\pi}{2}, \\ 0 & \psi > \frac{\pi}{2} \end{cases} \quad (3)$$

where, A_r is the active area, collecting the light beams at angles ψ (see Figure 3).

The wireless optical channel then, can be modeled considering the wireless link with an array of several LEDs without optical lenses as the transmitter and a PD as the receiver. The DC gain ($H(\phi,\psi)$) is expressed as follows for a PD placed at d distance with an irradiance (ϕ) and an incidence (ψ) angles [1], [2], [24] (see Figure 3):

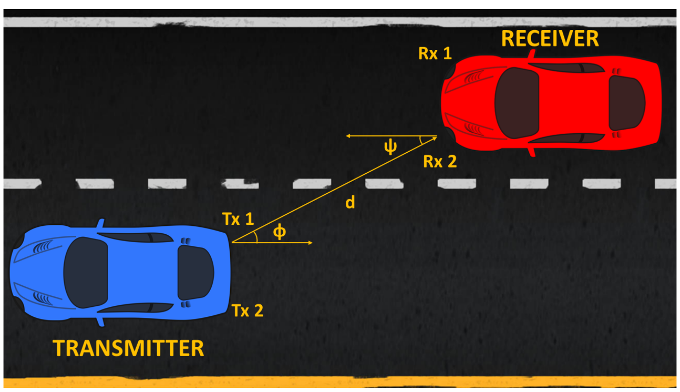

Figure 3. Relative positioning of a transmitter (blue vehicle) and a receiver (red vehicle).

$$H(\phi,\psi) = R_o(\phi) \cdot Aeff(\psi) 0 \leq \psi \leq \psi_c \quad , \quad (4)$$

$$H(\phi,\psi) = \begin{cases} \frac{A_r(m_i+1)}{2\pi d^2} \cos^{m_i}(\phi)\cos\psi & 0 \leq \psi \leq \psi_c, \\ 0 & \text{elsewhere} \end{cases} \quad . \quad (5)$$

The receiver power P_r, is hence

$$P_r = H(\phi,\psi)P_t = \frac{H_0(\phi,\psi)}{d^2} \quad , \quad (6)$$

where, P_t is the transmission power and $H_0(\phi,\psi)$ is

$$H_0(\phi,\psi) = \begin{cases} \frac{A_r(m_i+1)P_t}{2\pi} \cos^{m_i}(\phi)\cos\psi & 0 \leq \psi \leq \psi_c, \\ 0 & \text{elsewhere} \end{cases} \quad . \quad (7)$$

For the sake of simplicity, we assume that no error-correction coding applied. In such a case, as one can neglect the multipath fading in VLC [25], the ability of correctly decoding the received signal at the receiver, PDR, depends on the Bit-Error Rate (BER) and the packet size, L bits [26]:

$$PDR = (1 - BER)^L \quad . \quad (8)$$

The relation between BER and the Signal to Interference Noise Ratio (SINR) for OOK is expressed as follows [24]

$$BER = Q(\sqrt{SINR}) = Q(\sqrt{\frac{P_r}{MUI + N}}) \quad , \quad (9)$$

where Q function is defined as

$$Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} \mathrm{d}y \quad . \quad (10)$$

In (9), N is the noise power, which consists of shot noise and thermal noise, and MUI is the total interference power. It is obvious that in order to correctly receive the transmitted data, the received SINR must be higher than a given threshold ($SINR_{th}$), which is determined by the modulation scheme.

$$\frac{P_r}{MUI + N} \geq SINR_{th} \quad . \quad (11)$$

B. Impact of MUI

For a given pair of intended transmitter and receiver, we are now interested in determining the geographical zone from where no interference is allowed, i.e., MUI zone. In another words, we will calculate the distance from an interfering node to the intended receiver (d_{ir}) that fulfills the following condition

$$P_i(d_{ir}) \geq \frac{P_r(d_{tr})}{SINR_{th}} - N \quad , \quad (12)$$

where d_{tr} is the distance between the intended transmitter and the receiver. P_i is the interference power, i.e., the receive power from the interfering node. Since VLC is directional, the transmitter and the interfering node (LEDs) have to be in the Field of View (FoV) of the receiver (PD), respecting the conditions of irradiance and incidence angles (see Figure 3).

As (12) suggests, we now need to determine the SINR threshold ($SINR_{th}$), which depends on the desired communication quality i.e., the PDR requirement. Since PDR=1 - PER, we can easily calculate the SINR threshold, using the equations (8) and (9) for a binary modulation scheme:

$$SINR_{th} = \left(Q^{-1}(1 - \sqrt[L]{PDR_{req}})\right)^2 \quad . \quad (13)$$

Here, Q^{-1} is the inverse Q function. Calculating (13) for the packet size of 1000 Bits, we can draw Figure 4, which shows $SINR_{th}$ (in dB) for different PDR requirements. As can be seen in the Figure, the SINR threshold sharply increases with the increase of the PDR threshold, taking 12.47 dB for the PDR requirement of 90%. We are now ready to determine the MUI zone for communication between an intended transmitter and a receiver. Because $\frac{P_r}{SINR_{th}} \gg N$ (indeed, we can observe $\frac{P_r}{SINR_{th}} = 1\mu W$ while $N = 50nW$), we can safely ignore N in (12).. Furthermore, since P_r and P_i are both expressed by

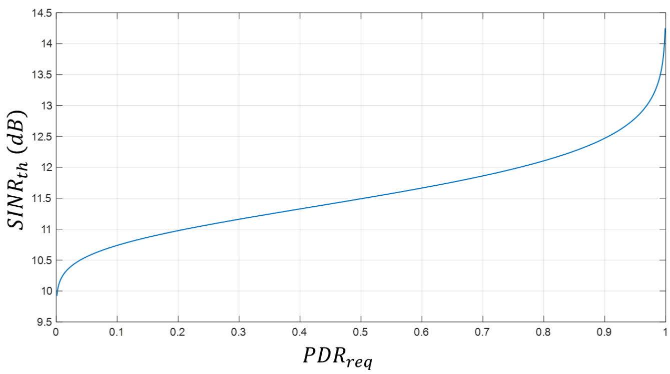

Figure 4. $SINR_{th}(dB)$ vs. PDR_{req}. Mathematical computation of the SINR threshold as a function of the PDR requirement. Here L=1000 Bits.

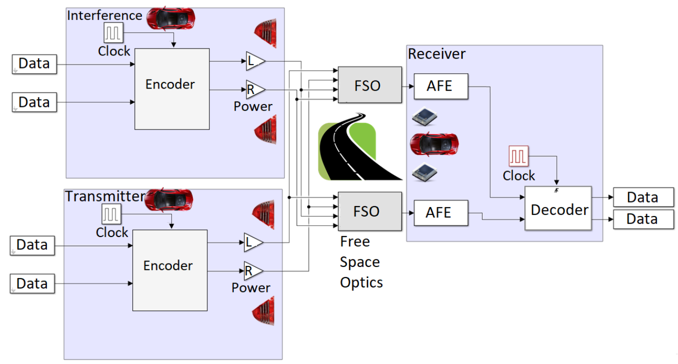

Figure 6. Simulink models for simulation evaluations.

(6) using d_{tr} and d_{ir}, respectively, the maximum d_{ir} satisfying the condition (12) is found as

$$d_{ir} = d_{tr}\sqrt{SINR_{th}} \quad . \tag{14}$$

Since the interfering nodes (as well as the intended transmitter) have to be in the FoV of the receiver, for a given pair of an intended transmitter (Tx) and receiver (Rx), the MUI zone is the circular sector with the radius d_{ir} and the central angle 2ψ as shown in orange in Figure 5. If we consider V2V

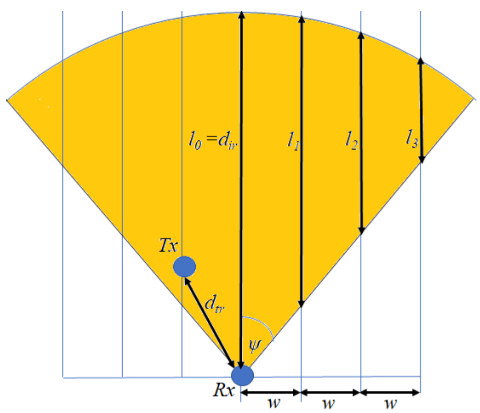

Figure 5. The MUI zone for a given pair of transmitter (Tx) and receiver of VLC (Rx).

communication on multi-lane straight road, vehicles can be only on individual lanes. For such a scenario, we now calculate the lengths of each lane belonging to the MUI zone (see Figure 5). As d_{ir} is the distance from the receiver to the limit of the MUI zone (see (14)), we can assume $d_{ir} \gg w$, where w is the lane width, the lengths of individual lanes l_k in the MUI zone (see Figure 5) are

$$l_k = d_{ir} - k \cdot w \cdot \cot\psi \quad , \quad 0 \le k \le n \quad , \tag{15}$$

where n is the number of lanes on the right or left side of the receiver. The total length of lanes in the MUI zone is then

$$l = d_{ir} + \sum_{k=1}^{n_l} l_k + \sum_{k=1}^{n_r} l_k \quad . \tag{16}$$

Here n_l (resp. n_r) is the number of adjacent lanes on left (resp. right) side of the receiver.

Targeting an intended transmitter and a receiver are at d_{tr} distance with the LOS condition, we now calculate the probability of having interfering vehicles on the lanes in the MUI zone. More specifically, we assume that vehicles on a highway follow Poisson distribution, which is widely used for highway traffic [27], the probability of finding i vehicles on the l length of the road is [28]

$$P(i,l) = \frac{(\beta l)^i e^{-\beta l}}{i!} \quad . \tag{17}$$

The communication between the intended transmitter and receiver will be successful only if none of the interfering vehicles in the MUI zone accesses the channel at the same time, i.e.,

$$P_s = \sum_{i=0}^{\infty} P(i,l)(1-\tau)^i \quad . \tag{18}$$

Here τ is the channel access probability at individual vehicles. Assuming that vehicles periodically generate messages (beacons) and letting T_{tx} be the average packet transmission time, τ is found as

$$\tau = \frac{T_{tx}}{T_{interval}} \quad . \tag{19}$$

Here $T_{interval}$ is the message generation interval. It should be noted that, since we ignore shadowing induced by vehicles, (18) is the minimum success probability.

IV. Performance Evaluation

In this Section, we evaluate the impact of MUI on VLC using both the theoretical and simulation evaluations. For simulation evaluations, we have developed the models of VLC transmitter, receiver, and interfering nodes using Matlab/SimuLink. As illustrated in Figure 6, the transmitter and interfering nodes have a message generator, a Digital to Analog Converter (DAC), and LEDs. They periodically generate sequences of bits, encode them using the Manchester modulation, and emit the signal using the LEDs. The receiver node has a PD and an Analog to Digital Converter (ADC), and hence tries to decode the received VLC signals. The simulation parameters are listed in Table I that are typical values of VLC based on LEDs to PDs. We first evaluate PDR for VLC communications from the intended transmitter to the receiver in absence of interfering nodes. Specifically, the simulations are carried out targeting on a 7-lane straight road, where the receiver (Rx) is

TABLE I. SIMULATION PARAMETERS.

Parameter	*Value*
PD reference	$S6967$ Hamamatsu [29]
A_{eff}	$100mm$ x $100mm$
PD efficiency	$0.5(A/W)$
FoV (ψ)	$55°$
PD capacitance	$1.12\mu F/m^2$
Transmission frequency	$500kHz$
Transmission power	1 Watt (car taillight)
Transmitter Semi-angle ($\phi_{1/2}$)	$20°$
Inter-PD separation distance	$1.2meters$
Road lane width (w)	$2.5meters$
Data size (L)	$1000Bytes$

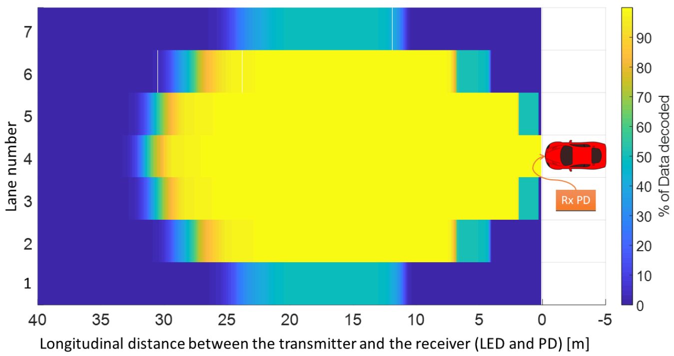

Figure 7. Communication range (PDR) of vehicle to vehicle VLC when transmitter and receiver are on a 7-lanes road.

fixed on the central lane (lane 4) and the intended transmitter (Tx) takes different positions. Figure 7 shows the obtained results, where horizontal and vertical axis are the longitudinal (i.e., longitudinal distance from the receiver) and the lateral (i.e., lane number) positions of Tx. The obtained PDR result for each position of Tx is expressed by the color plate. As

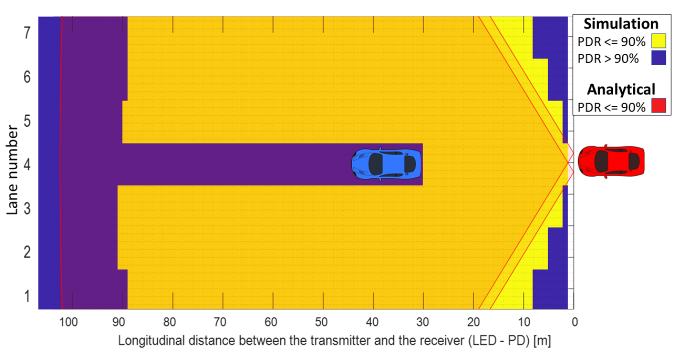

Figure 8. MUI zone for 90% of PDR requirement. Blue and yellow zones are simulation results, Red transparent area is the results of the analytical model.

expected, the longest communication distance is obtained when the transmitter is on the same lane as the receiver (i.e., the lateral distance is 0 meters). Specifically, 90% of PDR can be obtained up to 30 meters of longitudinal distance. On the other hand, when the transmitter is on the right or the left adjacent lanes, 90% of PDR can be obtained for 2 to 28 meters of longitudinal distances. When the transmitter is on a second adjacent lane, 90% of PDR can be obtained for

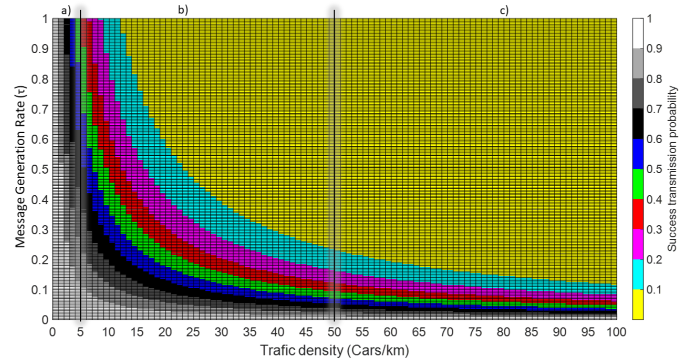

Figure 9. PDR performances of VLC in 3-lanes highway scenario ($l = 203m$). a) Low Density - maximum 1 vehicles on the road, b) Medium Density - maximum 10 vehicles on the road, and c) High Density - maximum 20 vehicles on the road.

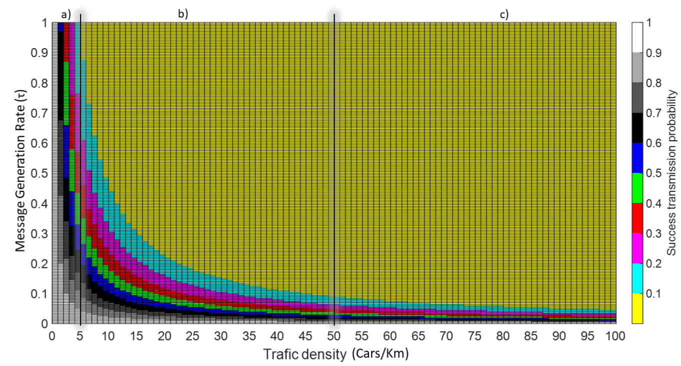

Figure 10. PDR performances of VLC in 7-lanes highway scenario ($l = 529m$). a) Low Density - maximum 2 vehicles on the road, b) Medium Density - maximum 26 vehicles on the road, and c) High Density - maximum 53 vehicles on the road.

the longitudinal distances between 7 to 26 meters. Finally, 90% of PDR cannot be obtained if the transmitter is a third adjacent lane. We now evaluate the impact of interference for the VLC communication. We fix the intended transmitter on the same lane as the receiver at 29 meters and evaluate PDR for varying positions of the interfering node. The obtained results are shown in Figure 8, in which two areas are depicted: yellow and blue. When the interfering node is in the yellow area, the PDR performance higher than 90% is not achieved. In contrast, when the interfering node is in the blue area, the communication between the intended Tx and Rx is succeeded having higher than 90% of PDR. The Figure also shows the analytical result by the red transparent area, which the MUI zone corresponds to PDR_{req} = 90% (see 13). As the figure shows, the simulation and analytical results match pretty well. Nevertheless, 10 meters of shift in the longitudinal direction is observed for the analytical results w.r.t that of the simulations. This is probably because a bit wider the FoV angle is used for the simulations. We now evaluate PDR results between the intended transmitter and the receiver, targeting the possibility of having more than one interfering vehicle on the road, and the vehicles density follows the Poisson distribution. Figures 9 and 10 show the results for 3- and 7-lanes highway scenarios, respectively. The horizontal axis of the figures is the traffic density, β in (17), and the vertical axis is the message generation rate, τ in (18). Finally, PDR results are depicted using the color plate. The results clearly show that, if there is no MUI control, i.e., no MAC, sufficient PDR performances are achievable only for extremely low traffic density and very low message generation rate. Particularly, in order to obtain 90% of PDR for the message generation rate of 0.9, the traffic density has to be lower than 1 and 2 cars/Km for 3-lanes and 7-lanes scenarios respectively. Otherwise, in order to obtain higher than 90% PDR in 50 cars/km density, the message generation rate has to be lower than 0.05 and 0.01 for 3- and 7-lanes scenarios, respectively. Although the obtained results are rather pessimistic figures, they clearly present a strong need of MAC protocol for VLC.

V. CONCLUSION

In this paper, we have developed an analytical model determining MUI zone, from which no interference is allowed for protecting an ongoing visible light V2V communication. Furthermore, we analytically formulated the PDR performance of a VLC when the interfering nodes follow the Poisson distribution. Finally, we have conducted simulation evaluations using a Simulink model. The model integrates, in adding to an intended transmitter, one or several interference vehicles, all of them with the possibility to generate, encode, and send random messages over the same VLC channel to the target receiver. Using the channel model for Free Space Optical (FSO) communications, and integrating the physical and electrical properties of a typically used PD, we have compared the results obtained by simulation and the developed analytical model. The simulation results first confirm the correctness of the analytical model on MUI zone. The results further show that even with low traffic densities and low message generation rates, the vehicles in the MUI zone can significantly degrade the PDR performance of the target VLC communication and presenting the inherent necessity of a MAC protocol for V2V communications. The future work includes an improvement of the theoretical model by taking into account shadowing effect by bodies of vehicles. We also conduct study on MAC that is aware of the presences of vehicles in the MUI zones by e.g., introducing two-hop beacons.

REFERENCES

[1] B. Béchadergue, "Visible light range-finding and communication using the automotive led lighting," Ph.D. dissertation, 2017.

[2] M. Abualhoul, "Visible light and radio communication for cooperative autonomous driving: applied to vehicle convoy," Ph.D. dissertation, MINES ParisTech, 2016.

[3] J.-H. Yoo et al., "Demonstration of vehicular visible light communication based on led headlamp," International journal of automotive technology, vol. 17, no. 2, 2016, pp. 347–352.

[4] H.-Y. Tseng et al., "Characterizing link asymmetry in vehicle-to-vehicle visible light communications," in 2015 IEEE Vehicular Networking Conference (VNC). IEEE, 2015, pp. 88–95.

[5] M. D. Hina, H. Guan, A. Ramdane-Cherif, and N. Deng, "Secured data processing, notification and transmission in a human-vehicle interaction system," in 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC). IEEE, 2016, pp. 1277–1284.

[6] R. D. Dupuis and M. R. Krames, "History, development, and applications of high-brightness visible light-emitting diodes," Journal of lightwave technology, vol. 26, no. 9, 2008, pp. 1154–1171.

[7] 802.15.7-2011 - IEEE Standard for Local and Metropolitan Area Networks–Part 15.7: Short-Range Wireless Optical Communication Using Visible Light, IEEE Std., Sep. 2011, [Retrieved: May, 2020]. [Online]. Available: https://standards.ieee.org/standard/802_15_7-2011.html

[8] 802.15.7-2018 - IEEE Standard for Local and metropolitan area networks–Part 15.7: Short-Range Optical Wireless Communications, IEEE Std., Apr. 2019, [Retrieved: May, 2020]. [Online]. Available: https://standards.ieee.org/standard/802_15_7-2018.html

[9] 802.11 Light Communications Amendment - Task Group "bb", IEEE Std., [Retrieved: May, 2020]. [Online]. Available: http://www.ieee802.org/11/Reports/tgbb_update.htm

[10] M. Uysal, F. Miramirkhani, O. Narmanlioglu, T. Baykas, and E. Panayirci, "Ieee 802.15. 7r1 reference channel models for visible light communications," IEEE Communications Magazine, vol. 55, no. 1, 2017, pp. 212–217.

[11] A. Galisteo, D. Juara, and D. Giustiniano, "Research in visible light communication systems with openvlc1. 3," in 2019 IEEE 5th World Forum on Internet of Things (WF-IoT). IEEE, 2019, pp. 539–544.

[12] S.-A. Avătămăniţei et al., "Intensive testing of infrastructure-to-vehicle visible light communications in real outdoor scenario: Evaluation of a 50 meters link in direct sun exposure," in 2019 Global LIFI Congress (GLC). IEEE, 2019, pp. 1–5.

[13] V. Van Huynh, Y. M. Jang et al., "Priority mac based on multi-parameter for ieee 802.15. 7 vlc," in ICTC 2011. IEEE, 2011, pp. 257–260.

[14] S. Ishihara, R. V. Rabsatt, and M. Gerla, "Improving reliability of platooning control messages using radio and visible light hybrid communication," in 2015 IEEE Vehicular Networking Conference (VNC). IEEE, 2015, pp. 96–103.

[15] P. Shams, M. Erol-Kantarci, and M. Uysal, "Mac layer performance of the ieee 802.15. 7 visible light communication standard," Transactions on Emerging Telecommunications Technologies, vol. 27, no. 5, 2016, pp. 662–674.

[16] Q. Mao, P. Yue, M. Xu, Y. Ji, and Z. Cui, "Octmac: A vlc based mac protocol combining optical cdma with tdma for vanets," in 2017 International Conference on Computer, Information and Telecommunication Systems (CITS). IEEE, 2017, pp. 234–238.

[17] A. Bellè, M. Falcitelli, M. Petracca, and P. Pagano, "Development of ieee802. 15.7 based its services using low cost embedded systems," in 2013 13th International Conference on ITS Telecommunications (ITST). IEEE, 2013, pp. 419–425.

[18] R. Corsini et al., "Free space optical communication in the visible bandwidth for v2v safety critical protocols," in 2012 8th International Wireless Communications and Mobile Computing Conference (IWCMC). IEEE, 2012, pp. 1097–1102.

[19] 802.15.4-2015 - IEEE Standard for Low-Rate Wireless Networks, IEEE Std., Apr. 2016, [Retrieved: May, 2020]. [Online]. Available: https://standards.ieee.org/standard/802_15_4-2015.html

[20] Q. Wang, D. Giustiniano, and O. Gnawali, "Low-cost, flexible and open platform for visible light communication networks," in Proceedings of the 2nd International Workshop on Hot Topics in Wireless, 2015, pp. 31–35.

[21] K. A. Mehr, S. K. Nobar, and J. M. Niya, "Ieee 802.15. 7 mac under unsaturated traffic: Performance analysis and queue modeling," Journal of Optical Communications and Networking, vol. 7, no. 9, 2015, pp. 875–884.

[22] A. Memedi, H.-M. Tsai, and F. Dressler, "Impact of realistic light radiation pattern on vehicular visible light communication," in GLOBECOM 2017-2017 IEEE Global Communications Conference. IEEE, 2017, pp. 1–6.

[23] A. Memedi, C. Tebruegge, J. Jahneke, and F. Dressler, "Impact of vehicle type and headlight characteristics on vehicular vlc performance," in 2018 IEEE Vehicular Networking Conference (VNC). IEEE, 2018, pp. 1–8.

[24] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical wireless communications: system and channel modelling with Matlab®. CRC press, 2019.

[25] M. Kavehrad and R. Aminikashani, Visible Light Communication Based Indoor Localization. CRC Press, 2019.

[26] J. Zhang, L. Cheng, and I. Marsic, "Models for non-intrusive estimation of wireless link bandwidth," in IFIP International Conference on Personal Wireless Communications. Springer, 2003, pp. 334–348.

[27] R. J. Salter, Highway traffic analysis and design. Macmillan International Higher Education, 1996.

[28] O. Shagdar, F. Nashashibi, and S. Tohme, "Performance study of cam over ieee 802.11 p for cooperative adaptive cruise control," in 2017 Wireless Days. IEEE, 2017, pp. 70–76.

[29] Plastic Si PIN Photodiode, Hamamatsu, 11 2014, [Retrieved: May, 2020]. [Online]. Available: https://www.hamamatsu.com/resources/pdf/ssd/s2506-02_etc_kpin1048e.pdf