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Visible Light V2V Cooperative Communication Under Environmental Interference

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***Abstract*— Robust, efficient, secure, and low-cost vehicle-to-vehicle (V2V) visible light communication (VLC) protocols, with high transmission rates, are very appealing to alleviate high traffic and to diminish air pollution in high vehicle density environments. In contrast to radio frequency (RF) protocols, where a stable communication cannot be ensured in highly dense road scenarios, VLC has emerged as a revolutionary alternative for the control of road traffic and prevention of accidents. Although last years have witnessed an increasing interest in this subject, VLC is still considered to be in the early phase of research (with several drawbacks to be faced). In this paper is analyzed a cooperative dual-hop visible light network operating with half-duplex and full-duplex protocols in a scenario subject to environmental interference of other vehicle. In particular, we considered four vehicles being the source, the destination, a relay and a potential interferer. The system performance is evaluated considering the bit error rate (BER), and throughput metrics. The results show that the cooperative communication is an effective solution for scenarios where it is not possible a direct transmission between source and destination. Numerical results are compared for the cases with and without interferences in order to show the impacts of interference in the proposed cooperative VLC schemes.**

***Keywords*— Visible light communication (VLC); Vehicle to vehicle (V2V) Communication; Wireless communication; Full-duplex (FD).**

I. Introduction

Due to their improved energy consumption, long lifespan, physical robustness, smaller size and switching speed, light emitting diodes (LEDs) are replacing the conventional incandescent and fluorescent bulbs for applications as diverse as aviation lighting, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper and medical devices [1–4]. LED intensity can also be modulated easily and quickly, without any risk to human eyes, motivating their application for dual purpose of cost-effective data transmission as well as illumination [5], of very high relevance for the future of the internet of everything (IoE), where people, processes, things, data and everything would require permanent internet connectivity with low-power consumption [6]. On the other hand, the visible light spectrum (400 THz-800 THz) offers a 10^3 times wider and unlicensed (low-cost of implementation) bandwidth compared to the radio frequency (RF) communication [7–9]. These advantages made the visible light communication (VLC) technology emerged as a revolutionary wireless communication paradigm [10–12], with operation rates on the order of gigabits per second (Gbps) for short and medium distances [13]. These data rates can also be boost through the implementation of multiple input multiple output (MIMO) communication techniques [14–17], promising for future 5G technologies, and allows the implementation of hybrid VLC-RF heterogeneous networks with improved communication performances [17, 18].

Although the VLC technology was initially intended for fast internet connection links in indoor environments, last decade has witnessed an increasing interest in its application for autonomous vehicles and intelligent transportation systems (ITSs), under an ever increasing number of vehicles per year, to provide safety and improved highway traffic flows [19–21]. In the context of vehicular communication, data is transferred from vehicle-to-vehicle (V2V) and from vehicle-to-infrastructure (V2I) [22]. Most recent studies on VLC applied to V2V and V2I communication have been devoted to consider the effects of road moisture [22, 23], measure the power of the signal quantified by the received signal strength indicator (RSSI) and the packet delivery ratio (PDR) [24], as well as their low spreading outside the target to avoid information theft and interception techniques [10]. In [25], a more deep analysis was performed taking into account diffuse and specular light combined reflection instead of using an ideal lambertian mode.

Another interesting possibility is the integration with cooperative schemes[26], with the objective of improving the communication between the source and destination through the use of one or more relay vehicles. This communication system could work in half-duplex (HD) or full-duplex (FD) modes. In the first case, communication occurs in two time slots, the relay just receives or transmits at each time, while for FD the relay concurrently transmit with the source. Due to the directional line-of-sight (LOS), associated to the visible light, there is no self-interference for VLC-FD, in contrast to RF communications. The bit error rate (BER) was modeled in cooperative V2V-VLC with half-duplex communication in [27], the analysis take into account the position and posture of the vehicles. In [28], a MAC protocol based on FD

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communication was proposed with enhanced throughput in relation to HD through reduced packet collisions.

In the present work, we aims to evaluate the performance of VLC cooperative schemes in a scenario subject to the interference of other vehicle. In this paper is considered a dual-hop cooperative network with an intermediary relay operating in FD and HD modes. The analysis is performed in terms of BER and throughput for different positions of relay and interferer vehicles.

The manuscript is organized as follows, the system model is presented in Section II. The mathematical analysis of the V2V cooperative schemes are presented in III. Numerical results are given in Section IV. Finally, conclusions are presented in Section V.

II. System Model

We investigate an ad-hoc VLC vehicular network, referred to as V2V-VLC, see Fig 1, composed of a transmitting vehicle (S), a relay vehicle (R), a destination vehicle (D), and a potential interferer vehicle (I).

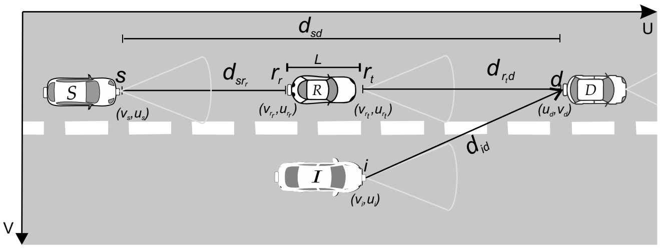

Fig. 1. V2V-VLC cooperative network with an relay and an interfering vehicle.

The channel, $H_{k,l}(0)$, denoting the direct current gain, is one of the most important characteristics in VLC to estimate the achievable signal-to-noise ratio (SNR) for a fixed transmit power. Subindex $k \in \{s, r_t, i\}$ is used to denote each one of the possible transmitters in the system, while subindex $l \in \{r_r, d\}$ is used to represent the possible receivers (relay or destination vehicle). Before to show an expression for $H_{k,l}(0)$, we need to perform a complementary geometrical analysis. In Figure 2 it is shown a pictorial representation of VLC-V2V mechanism for two vehicles along a road. Having into account that the lane runs along the u-axis, and its width along the v-axis, $\hat{n}_1$ and $\hat{n}_2$ are used to represent the transmitter and receiver axis, i.e., are normal to the LEDs surfaces, which are inclined by α (γ_1) and β (γ_2) respect to the v-axis (w-axis). ϕ_s and ψ_d are the irradiance and the incident angles respect to $\hat{n}_1$ and $\hat{n}_2$, respectively. Considering the distance between k and l along the u-axis (v-axis) as $\overline{u_{k,l}}$ ($\overline{v_{k,l}}$), and (v_k, u_k) $[(v_l, u_l)]$ as the coordinates of the transmitter (k) (receiver, l) in v-axis and u-axis, respectively. The angles ϕ_s and ψ_d are obtained as [27]

$$\phi_s = \arccos\left(\sin(\gamma_1)\cos\left[\alpha - \arctan\left(\frac{\overline{v_{k,l}}}{\overline{u_{k,l}}}\right)\right]\right), \quad (1)$$

$$\psi_d = \arccos\left(-\sin(\gamma_2)\cos\left[\beta - \arctan\left(\frac{\overline{v_{k,l}}}{\overline{u_{k,l}}}\right)\right]\right) \quad (2)$$

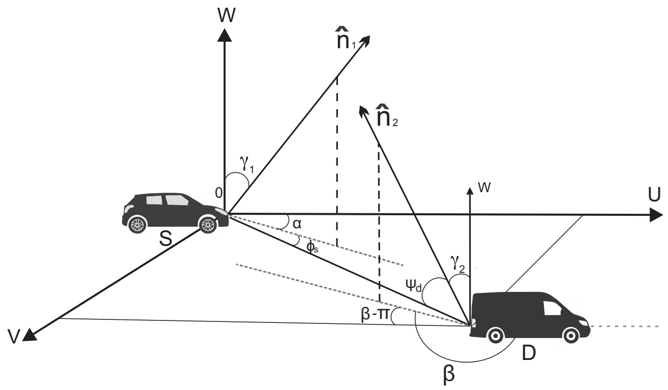

Fig. 2. Pictorial representation of two vehicles using VLC-V2V communication along a road. Parameters γ_1, γ_2, and ϕ_s depict the vertical inclination angles of the corresponding photoreceivers and the irradiance angle respect to $\hat{n}_1$. α and β are used to denote the horizontal inclination angles for $\hat{n}_1$ and $\hat{n}_2$, respectively. ψ_d denotes the incidence angle respect to $\hat{n}_2$, with $\hat{n}_1$ and $\hat{n}_2$ being the transmitter and receiver axis.

Other important term for the calculation of $H_{k,l}(0)$ is the field of view (FOV) (limiting the gain), or aperture angle of the concentrator (ψ_c) (generally this is less than $\pi/2$), which depends on the refractive index (n) of the photodetector for computing the gain $g(\psi_d)$ and is modeled by [29]

$$g(\psi_d) = \begin{cases} \frac{n^2}{\sin^2(\psi_c)} & , 0 \leq \psi_d \leq \psi_c, \\ 0 & , \psi_d \geq \psi_c. \end{cases} \quad (3)$$

Since the LED surface is considered as an ideal Lambertian surface, the radiant intensity can be described by

$$\mathrm{R} = \left[\frac{(m+1)}{2\pi}\right]\cos^m(\phi_s), \quad (4)$$

The order-index, m, is given by $m = -\ln 2/\ln(\cos(\phi_{1/2}))$, where $\phi_{1/2}$ is a half value angle of an LED. Hence, $H_{k,l}(0)$ can be calculated as

$$H_{k,l}(0) = \left\{ \frac{\mathrm{R}A_{\mathrm{p}}T}{d_{k,l}^2} g(\psi_d)\cos(\psi_d) \quad , \quad 0 \leq \psi_d \leq \psi_c, \right. \quad (5)$$

where $d_{k,l}$ is the separation distance between the transmitter k and the receiver l, A_{p} is the area of incidence of the receiver (photodiode) and T is the filter transmission coefficient.

III. Cooperative Communication Analysis

In this section, we introduce the analysis of the cooperative schemes in a VLC network operating under the half-duplex and full-duplex protocols. For a full-duplex V2V-VLC network, the self-interference is neglected because the receiver and transmitter sensors are isolated. The received signals at the relay and at the destination can be expressed, respectively, as

$$y_{s,r_r} = \zeta P_s H_{s,r_r}(0)x_s + N_{s,r_r} + \zeta\delta_r P_i H_{i,r}(0), \quad (6)$$

$$y_{r_t,d} = \zeta P_{r_t} H_{r_t,d}(0)x_{r_t} + N_{r_t,d} + \zeta\delta_d P_i H_{i,d}(0), \quad (7)$$

where P_k and x_k are the power and the message sent by the transmitter k, respectively. $N_{k,l}$ represents the Gaussian additive noise at the node l, with variance σ^2, ζ is the responsivity of the photodiode, in A/W, for a certain wavelength (λ) and δ_l gives account of the interference by

$$\delta_l = \begin{cases} 1, & u_i < u_l, \\ 0, & \text{otherwise}, \end{cases} \tag{8}$$

where $\delta_l = 1$ represents the case in which the interferer vehicle causes interference to the receiver l.

The SINR is calculated for both channels, $s \rightarrow r$ and $r \rightarrow d$, by having into account the presence of an interferer vehicle as

$$\text{SINR}_{s,r_r} = \frac{[\zeta P_s H_{s,r_r}(0)]^2}{[\zeta \delta_r P_i H_{i,r_r}(0)]^2 + \sigma^2}, \tag{9}$$

$$\text{SINR}_{r_t,d} = \frac{[\zeta P_{r_t} H_{r_t,d}(0)]^2}{[\zeta \delta_d P_i H_{i,d}(0)]^2 + \sigma^2}, \tag{10}$$

where the noise variance σ^2 is the sum of the shot noise variance (σ^2_{shot}) shot and the thermal noise variance ($\sigma^2_{\text{thermal}}$). The shot noise variance is calculated by

$$\sigma^2_{\text{shot}} = 2q\zeta P_k H_{k,l}(0)B + 2q\zeta P_{bg} I_2 B, \tag{11}$$

where q represents the electron charge, B is the bandwidth considered, P_{bg} represents the background noise power and I_2 is noise bandwidth factor for the background noise. The thermal noise is generated within the transimpedance receiver circuitry [30] and its variance ($\sigma^2_{\text{thermal}}$) is expressed by:

$$\sigma^2_{\text{thermal}} = \left(\frac{8\pi K_b T_{\text{A}}}{G}\right) \eta A_{\text{p}} I_2 B^2 + \left(\frac{16\pi^2 K_b T_{\text{A}} \Gamma}{g_{\text{m}}}\right) \eta^2 A_{\text{p}} I_3 B^3, \tag{12}$$

where K_{b} is the Boltzman constant, in J/K, T_{A} is the absolute temperature, G is the voltage gain in open loop, η is the capacitance per unit area of the photodetector, Γ is the noise factor of the FET channel, I_3 is the noise bandwidth factor and g_{m} is the FET transconductance. For On-Off-Keying (OOK) modulation, the BER of each link can be calculated as [31]

$$\text{BER}_{s,r_r} = Q(\sqrt{\text{SINR}_{s,r}}), \tag{13}$$

$$\text{BER}_{r_t,d} = Q(\sqrt{\text{SINR}_{r,d}}), \tag{14}$$

where the Q($\cdot$) function represents the probability of a normal (Gaussian) random variable having a value grater than x standard deviations and is given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{\frac{-a^2}{2}} da. \tag{15}$$

When considering the intermediary node r, the overall error performance of the cooperative communication scheme is then given by

$$\text{BER}_{\text{coop}} = 1 - (1 - \text{BER}_{s,r_r})(1 - \text{BER}_{r_t,d}). \tag{16}$$

The corresponding throughput ($\mathcal{T}$) is limited by the cooperative BER (previously calculated) and the number of bits (N) used in the frame, for a given time slot, hence

$$\mathcal{T}_{\text{FD}} = R(1 - \text{BER}_{\text{coop}})^{\text{N}}, \tag{17}$$

where R represents the code rate. In the case of HD, the analysis is similar but as the transmission occurs within two time slots, the throughput of HD is reduced by a factor of $1/2$ in relation to the FD communication, i.e., $\mathcal{T}_{\text{HD}} = (1/2)\mathcal{T}_{\text{FD}}$.

TABLE I
SYSTEM PARAMETERS.

Parameter	Symbol	Value
FOV of the receiver	ψ_c	$\pi/6$ rad
Half value angle of an LED	$\phi_{1/2}$	$\pi/12$ rad
Internal refractive index	n	1.5
Area of incidence at receiver	A_p	1 cm^2
Filter Transmission Coefficient	T	1
Detector Responsivity	ζ	0.56 A/W
Ambient Temperature	T_A	300 K
Open loop channel gain	G	10
FET Transconductance	g_m	30 mS
Fixed PD Capacitance/area	η	112 pF/cm^2
Noise Bandwidth Factor	I_2, I_3	$0.562, 0.0868$
Background Noise Power	P_{bg}	16 dBm
LED Power	P_k	0.3 W
Horizontal Inclination angle	α	0 rad
Horizontal Inclination angle	β	π rad
Vertical Inclination angle	γ_1, γ_2	$\pi/2$ rad
Code Rate	R	20 Mbps
Electronic Charge	q	1.6021×10^{-19} C
FET Channel noise factor	Γ	1.5
Boltzmann Constant	K_b	1.3806×10^{-23} J/K
System Bandwidth	B	20 MHz
Number of bits	N	2400 bits

IV. NUMERICAL RESULTS AND DISCUSSIONS

This section presents a numerical study of the performance of the proposed V2V-VLC cooperative communication schemes. The input parameters used in the calculations are presented in Table I, in accordance to [25, 27]. A relay vehicle is considered between the source and destination vehicles on a straight line. The vehicles move at constant speed and each vehicle has a length L of 5 meters. The source vehicle transmits beacons with length of 300 Bytes (N $=$ 2400 bits) [32].

Fig. 4 shows the BER versus the distance between the source and destination (d_{sd}) for the cases with/without the presence of interferer vehicle. Considering the source transmitter (s) as a reference at $(0,0)$, the relay receiver (r_r) at $(0, \frac{d_{sd}-L}{2})$, the relay transmitter (r_t) at $(0, \frac{d_{sd}+L}{2})$ and the interferer transmitter (i) at $(3, \frac{d_{sd}-L}{2})$, as depicted in Fig. 3 for a particular case of $d_{sd} = 21$ meters.

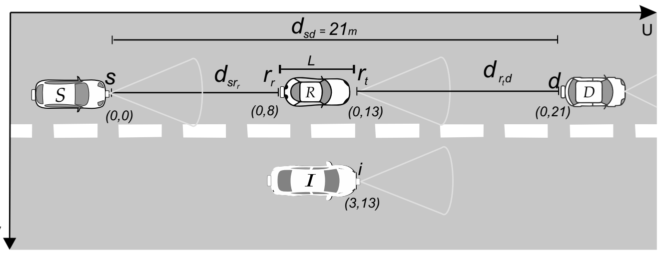

Fig. 3. Location of vehicles for the scenario of Figs. 4 and 5 .

The Fig. 4 shows that the performance in terms of BER degrades with the presence of an interferer. For instance, the maximum d_{sd} in which BER $< 10^{-3}$ is 23 meters for the

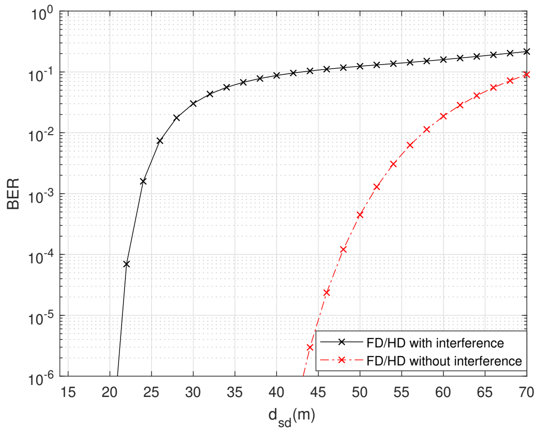

Fig. 4. BER as function of the distance source-destination for two different scenarios.

case with the presence of interferer, while the maximum d_{sd} is equal 51 meters for the case without interference.

Fig. 5 shows the throughput versus the distance between the source and destination (d_{sd}) of HD/FD schemes for the cases with/without the presence of interferer node. Note that

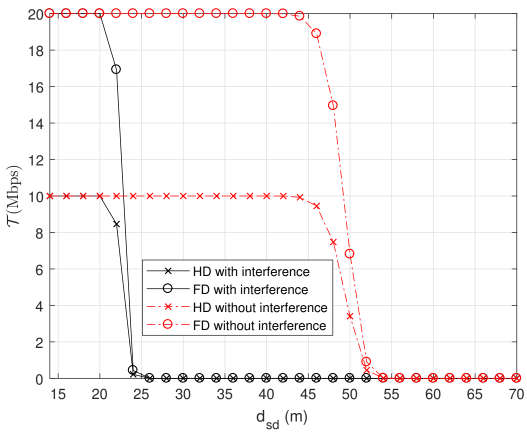

Fig. 5. Throughput as function of the distance source-destination of HD and FD schemes for two different scenarios.

the maximum throughput for $d_{sd} < 20$ meters for the scenario with interference and $d_{sd} < 42$ meters for the interference free case.

Fig. 7 evaluates the BER versus the distance between the source transmitter and relay receiver (d_{sr_r}). Considering the the source transmitter (s) as a reference at $(0, 0)$, destination (d) is at $(0, 50)$, the transmitter (i) is positioned at three different locations in the lane next to the dual-hop network at $(3, 10)$, $(3, 23)$ and $(3, 40)$. The proposed configuration is depicted in the Fig. 6.

It is possible to see by the Fig. 7, that the best location for the relay vehicle is in the middle of the distance between source and destination for the scenario without interference. When the interferer is present the best location of relay is repositioned to next the source or destination in order to

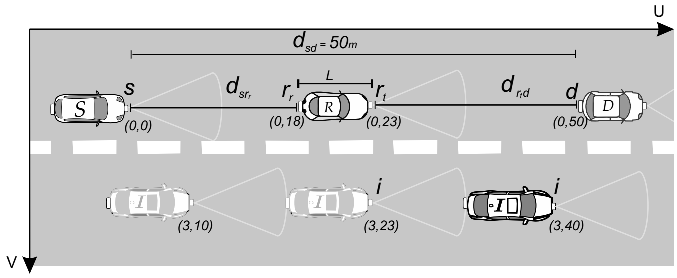

Fig. 6. Location of vehicles for the scenario of Fig. 7.

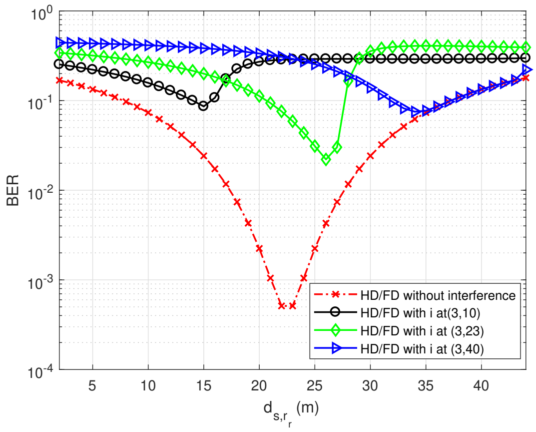

Fig. 7. BER as function of the distance source-relay for three different positions of interferer vehicle.

decrease the effect of interference. The optimal BER increases of $5{\cdot}10^{-4}$ to values in the order of 10^{-2}. Moreover, the scenarios with interference have little range with possible communication, for instance, when the interferer is located at $(3, 23)$, the communication can just occur for $20 < d_{sr_r} < 26$ meters, limiting the contribution of relay in the communication.

V. Conclusions

In this paper we analyzed the effect of a possible interferer in a dual-hop VLC network. The results show that the performance in terms of BER and throughput can be seriously affected by the presence of an interferer. For instance, the maximum separation between source and destination decreases from 42 to 22 meters for the particular scenario. Besides, the range of possibles locations to the relay is lower in comparison to the scenario without interference. However, even with the effects of interference, the results show that the cooperative communication is an effective solution for scenarios where it is not possible a direct transmission between source and destination, for instance with the presence of other vehicles among then. As a future works, we intend to analyse different selection relays schemes for a cooperative VLC network, with the objective of improving the performance in scenarios under the effect of interference.

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