PERFORMANCE ANALYSIS OF MULTI-HOP VEHICULAR VLC NETWORKS

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Abstract— Vehicular Visible Light Communication (V2LC) is a promising technology that enables our dream of having automated vehicles. V2LC helps vehicles to share data and information to run properly on road. In our paper, we have analyzed the performance of V2LC by using a simplified road model that contains only one way and one lane. Vehicles are installed with two Light-Emitting Diodes (LED) headlamps and a photodetector (PD) that are transmitters and a receiver respectively. Bit Error Ratio (BER) is evaluated while changing the distance between two vehicles. Moreover, we have considered how the attached position of PD and the horizontal gap between two vehicles affect BER. Finally, multi-hop among vehicles in the network is taken into account to have a clear view of the whole transmission performance.

Keywords— Vehicular visible light communication (V2LC), multi-hop performance, LED headlamp.

I. INTRODUCTION

Under the quarantine of the Covid 19 pandemic, our lives have changed totally and more than ever we appreciate how technology affects and supports our living and working. Technology enables us to continue to work from home and study online for months and even couple of years. We will have bright future to put our belief in the more advanced technologies that assist all aspects of human's life including transportation. Transportation is just like blood vessels to connect people in different parts of the world. From 1980s, we have heard the term of an intelligent transportation system (ITS). This term now become more vivid and being replaced by some others such as autonomous vehicles or driverless cars. Many researchers, companies and organizations have paid much attention to develop and bring that idea to life. In order to be automated or driverless, we have to think firstly about how vehicles communicate with each others to share information to run on the right routes and avoid collisions. The network among those vehicles must be created to enable them to talk and share essential information to at least run well. Because of the dynamic in movement of vehicles, the only promising solution should be via wireless communication. Unfortunately, wireless communications have been suffering the lack of available frequencies while many new applications and users have over-exploited the current radio frequencies. So, coping with the permanent and tricky issue, we try to figure out which frequency that has not used before to transmit data and now is it possible to take advantage from it. And the answer is Visible Light Communication (VLC). VLC uses the frequency at the visible light to transmit data. The visible light frequency is from 380nm to 780nm (400-800THz), offers around 1000 times greater bandwidth compared to the RF communications.

VLC can enable ITS come to life due to following reasons [1]. Firstly, it is economical because the visible frequency range is free without any requirement of registering and paying for. Secondly, it is safer and harmless to human, especially human's eyes. We have reached two goals at the same time, transferring data and providing lights [1]. Thirdly, the lighting industry has transformed itself from traditional light bulbs to LEDs. LEDs become popular due to characteristics of cheap, long-life, compact and low power consumption. Many vehicles are equipped with LEDs lighting. Moreover, many transportation signals, traffic lights as well as lighting road system use LEDs. Consequently, it is obvious for us that the implementation of VLC would be easier and economical.

In a vehicular network, there are two typical communications: vehicle-to-vehicle (V2V) and vehicle-to-roadside unit (V2R). Roadside units can be transportation signals, traffic lights and lighting road system. A vehicle can get data if it runs over a roadside unit. In the other hand, vehicle-to-vehicle connection is more flexible. A car can carry information or data and transfer it to any neighbor cars while running on a road. An ideal network should combine both V2V and V2R connections. However, in our research, we have tried to concentrate on V2V and multiple hops first.

Some remarkable researches that we can take into consideration are shown in following explanations. In [2], a path loss expression for V2V connection is introduced. The path loss varies based on distance between vehicles and weather conditions. With a given BER and data rate, a transmission distance can be calculated. In the same approaching, [3] considers Light-of-sight (LOS) communication between vehicles using two taillights and two headlights which mean 2x2 Multiple-Input Multiple-

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Output (MIMO) configuration at T-junction on road. The system performance is evaluated on average BER versus average SNR for three different types Multiple-Input Single-Output (MISO), Single-Input Single-Output (SISO) and MIMO. Both the above researches are limited to consider performance under only LOS communication. A further research is in [4]. Both LOS and Non-LOS (NLOS) are take into account for single hop between two vehicles. The relationship between communication distance and BER is shown. The performance is also related to the different values of placing a photodetector in vertical axis.

In this paper, we concentrate on system performance of multi hop vehicular VLC network. The channel combines both LOS and NLOS communications. The values of BER for multiple hops are varied by communication distance among vehicles. When vehicles run in a lane, they maybe not in perfect alignment. So, we consider not only the position of attaching PD but also the positioning of vehicles. That means the system performance is evaluated by different positions of Tx and Rx in both vertical and horizontal axis.

The rest of the paper is organized as follows. Section II introduces the system and channel model. Section III provides BER performance of multi-hop V2LC in equation as well as simulation results. All the research will be summarized in section IV.

II. SYSTEM AND CHANNEL MODEL

This section describes two main models that are applied to our research. The first system model will introduce about type of the road, specific characteristic of our particular vehicles, and some main angles of transmitter (Tx), two headlamps, and a receiver (Rx), a photodetector (PD), attached behind a vehicle. Then, the channel model will introduce in details about LOS and NLOS communications for V2LC.

2.1. System model

In our research, we try to simplify the road patterns by using the most simple road, one way and one lane. We assume that vehicles run on the road will create multi-hop connection, shown in Fig. 1. However, running vehicles may not in perfect alignment. That behavior of drivers also affects to the transmission that will be considered in our research by using the term, horizontal gaps between vehicles. In fig. 2, the information is transmitted by using two headlamps of a behind vehicle and received by a PD, installed back of a front vehicle. The headlamps and PD will have some technical angles that show the ability of transmitting and receiving VLC. We assumed the headlamps have the angle of irradiance ϕ and half-power semiangle of LED $\Phi_{1/2}$. h_t and d_t are the position of headlamp compared to the road surface and the distance between two headlamps respectively. At a receiver, there are three angles that are the vertical inclination θ, the field of view (FOV) Ψ_c, and the instant angle of incidence ψ. h_r is the installed position of a PD above the road surface. All the important parameters are listed in Table 1.

TABLE 1. ROAD AND VEHICLE PARAMETERS

Width of vehicle	1.4 m
Width of lane	3.5 m
Height of vehicle	1.4 m
Height of headlamps *ht*	0.7 m
Height of receiver h_r	0.9-1.2 m
Distance between two headlamps d_t	1.2 m
Half-power semiangle $\Phi_{1/2}$	70^0
FOV of receiver Ψ_c	70^0

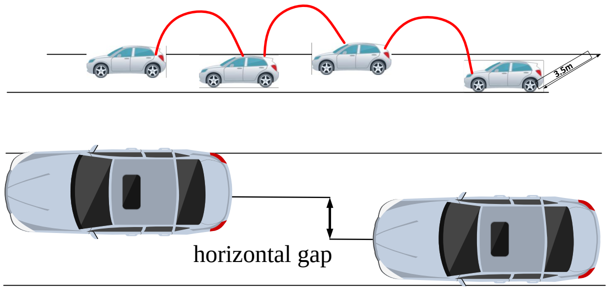

Fig 1 Road pattern and multi-hop connection

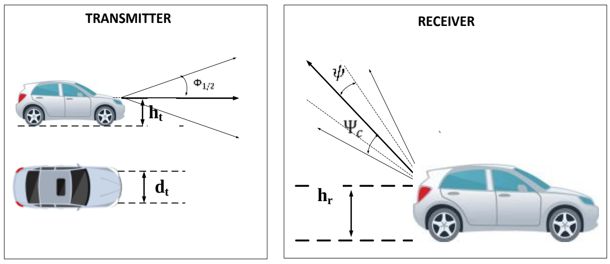

Fig 2 Transmitter and receiver parameters

2.2. Channel model

In the research, both LOS and NLOS are analyzed. However, we consider only the first reflection of NLOS which happens on road surface between two vehicles.

At the transmitter, LEDs in headlamps are optical transmitters that follow the Lambertian model [5]. In the model, LED radiant intensity P_{tr} on each headlamp is given by

$$P_{tr}(\phi) = \frac{m+1}{2\pi} P_t \cos^m(\phi), \tag{1}$$

where P_t is the transmitted optical power and the order m is related to $\Phi_{1/2}$ by

$$m = -\frac{\ln 2}{\ln \cos \Phi_{1/2}}. \tag{2}$$

Considering the VLC link, a receiver with an optical band-pass filter of transmission $T_S(\psi)$, a non-imaging concentrator of gain $g(\psi)$ and the detection area of the PD A_r , the DC gain for a receiver located at a distance of d can be approximated as

$$H_{LOS}(0) = \begin{cases} \dfrac{(m+1)A_r}{2\pi d^2}\cos^m(\Phi)T_s(\psi)g(\psi)\cos(\psi), & 0 \le \psi \le \Psi_c. \\ 0, & \psi > \Psi_c \end{cases} \quad (3)$$

An idealized nonimaging concentrator having an internal refractive index n achieves a gain

$$g(\psi) = \begin{cases} \dfrac{n^2}{\sin^2 \Psi_c}, & 0 \le \psi \le \Psi_c \,. \\ 0, & \psi > \Psi_c \end{cases} \quad (4)$$

In each headlamp, if we consider only the first refection inside the S area, the road surface between two vehicles, the DC channel gain is given by [6]

$$H_{NLOS}(0) = \begin{cases} \dfrac{(m+1)A_r}{2\pi^2 d_1 d_2}\rho dA_{road}\cos^m(\Phi_r)\cos(\alpha_{ir}) \\ \times\cos(\beta_{ir})T_s(\psi_r)g(\psi_r)\cos(\psi_r) & ,0 \le \psi_r \le \Psi_c, \\ 0, & \psi_r > \Psi_c \end{cases} \quad (5)$$

where d_1 and d_2 are the distances between a headlamp and a reflection point, and between that reflection point and the PD, ρ is the reflection factor, dA_{road} is the reflection area of small region, Φ_r is the angle of irradiance to a reflection point, α_{ir} and β_{ir} are angles of incidence and irradiance at the reflection point, Ψ_r is the angle of incidence from the first reflection at PD. Fig 3 illustrates those important angles at a reflection point on road surface.

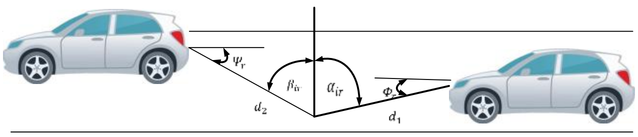

Fig 3 The reflection model of NLOS on each headlamp

III. BER PERFORMANCE OF MULTI-HOP V2LC

This section is an in-depth introduction of performance metrics such as the signal-to-noise ratio, BER of single hop and multiple hop in the considering system. Finally, some mathematical simulation results will be shown to evaluate clearly our research.

3.1. BER performance

Considering both LOS and NLOS channels, the received power from each headlamp at the PD can be given by

$$P_r = P_{tr}H_{LOS}(0) + \int_S P_{tr}\, dH_{NLOS}, \quad (6)$$

where S is the area refection on the road surface between two considering vehicles. There are two headlamps. Therefore, P_{Rtotal} will be the sum of the received power from the both headlamps.

In optical wireless communication, noise mainly comes from the ambient light, also called the background solar radiation, and the artificial light, such as street lights, traffic lights and lighting road system. The shot noise is mostly the dominant noise created by solar radiation for C2C VLC system during the daytime [7,8]. In our research, we consider the system noise composed of shot noise σ_{shot} and thermal noise $\sigma_{thermal}$, known as the additive white Gaussian noise (AWGN). The system noise can be calculated as

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2. \quad (7)$$

We can have shot noise σ_{shot} and thermal noise $\sigma_{thermal}$ in following equations [9]

$$\sigma_{shot}^2 = 2q\gamma P_{Rtotal}B + 2qI_{bg}I_2 B, \quad (8)$$

$$\sigma_{thermal}^2 = \frac{8\pi k T_K}{G}\eta A_r I_2 B^2 + \frac{16\pi^2 k T_K \Gamma}{g_m}\eta^2 A_r^2 I_3 B^3, \quad (9)$$

where, q is the electronic charge ($1.602x10^{-19}$ C), γ is the responsivity of the PD, B is the system bandwidth, I_{bg} is the received background noise current, k is Boltzmann's constant, T_K is absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of PD per unit area, Γ is the field-effect transistor (FET) channel noise factor, g_m is the FET trans-conductance, and the noise bandwidth factors $I_2 = 0.562$ [10] and $I_3 = 0.0868$ [11].

In our system, an on-off keying (OOK) modulation is used. Therefore, the value of signal-to-noise and BER can be achieved by the following two equations [12]

$$SNR = \frac{(\gamma P_{Rtotal})^2}{\sigma^2}, \quad (10)$$

$$BER = Q(\sqrt{SNR}), \quad (11)$$

where $Q(.)$ is Q function.

At a given distance between two vehicles, we can estimate the value of BER by using the equation (10). If we assume that at any hops of V2LC, all drivers share the same behavior that leads to the same distance between two any vehicles. While the BER is for a single hop, the final BER of n hops $BER_{multi-hop}$ can be calculated as below

$$BER_{multi-hop} = 1 - (1 - BER)^n. \quad (12)$$

3.2. Numerical results

Performance analysis is carried out to evaluate some specific cases of our road model. The numerical results firstly concentrate on the single-hop transmission to analyze some factors that could influence the performance of network. Then the next step, we will have a total view of the multi-hop vehicular network. The transmitters here are two LED headlamps ready-to-use at the front part of a vehicle. These two headlamps are 1.2 m apart from each other. The transmit power of each headlamps is 1 W. All other important parameters are listed in details in Table 2.

TABLE 2
SIMULATION PARAMETERS

Detection area of the PD A_r [cm^2]	1
Reflection factor n	0.8
Gain of optical filter $T_s(\psi)$	1
Absolute temperature T (K)	300
Responsivity of the PD γ (A/W)	0.54
Received background noise current I_{bg} (μA)	5100
Open-loop voltage gain G	10
Fixed capacitance of PD per unit area η (pF/cm^2)	112

FET channel noise factor Γ	1.5
FET trans-conductance g_m (mS)	30
System bandwidth B (Mhz)	1

In the first result, our assumption is that vehicles run in a straight line and in the middle of the road. The height of the PD attached on the receiver h_r is equal to the height of headlamps $h_t = 0.7\ m$. We try to test how FOV affects the quality of received signal along with different distances between two vehicles. The qualities of received signal are reflected by BER. As shown in Fig. 4, BER gets worse when the distance increases because the received power reduces. The broader of FOV will provide better BER at a certain value of the distance.

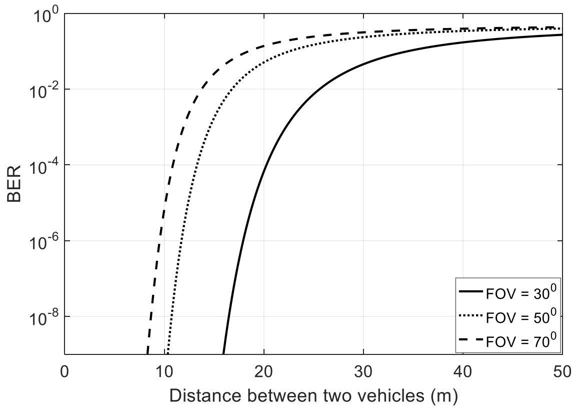

Fig 4 BER at different FOVs while changing the distance between two vehicles.

From this time, FOV is set at 70^0. Then, we try to evaluate whether or not the changes in vertical and horizontal directions of transmitter and receiver will affect the system performance, in particular BER between the two vehicles. The evaluation will be carried on two different cases: (1) the attached position of the PD h_r will be varied on vertical direction at the receiver; (2) the positioning of vehicles will change that leads to multiple values of horizontal gap between that two vehicles. In the first case, Fig. 5 shows that at all attached positions of the PD, BER will increase if the vehicles are going far away from each other. At a particular h_r , value of BER fluctuates when the vehicles are about 10m from each other. The reason here is at close by position, the FOV will influent

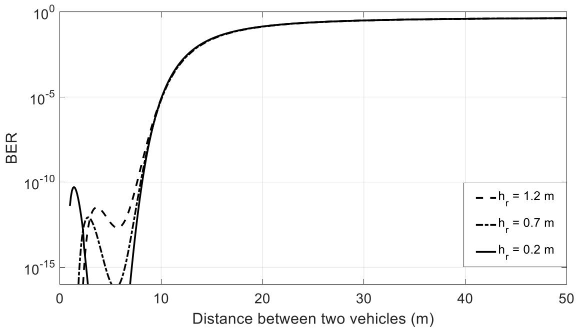

Fig 5 BER at different attached positions of the PD h_r while changing the distance between two vehicles.

the ability of receiving signal at the PD that causes dramatic changes of BER. The result of the second case is clearly depicted in Fig. 6 where h_r is set to 0.7 m. The horizontal gap between two vehicles is set with three values 0 m, 1 m and 2 m. All share the same pattern which is worse BER if the distance increases. If the two vehicles are in perfect alignment, BER gets the best value. The increasing of horizontal gap causes the worse performance of BER.

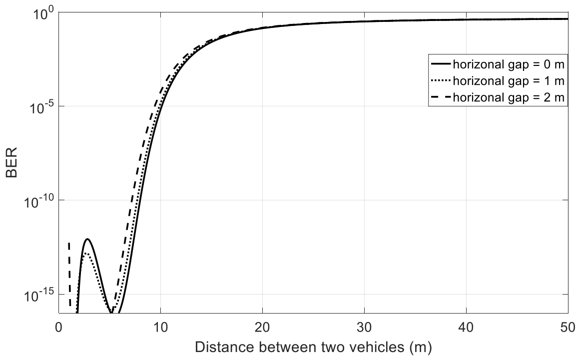

Fig 6 BER at different horizontal gaps while changing the distance between two vehicles.

The last numerical result, we pay attention to multi-hop vehicles. If all vehicles on the road share the same characteristics of the attached position of the PD h_r 0.7 m, horizontal gap 0 m and distance between two adjacent vehicles 13.7 m , what will be the BER at each hop. We apply the equation (11) and get Fig. 7. Based on Fig. 7, the more hops we transfer signal, the worse BER we receive. Furthermore, the result is shown that maximum of hops would be 4. It guarantees that the whole performance of the multi-hop transmission is smaller than 10^{-3}.

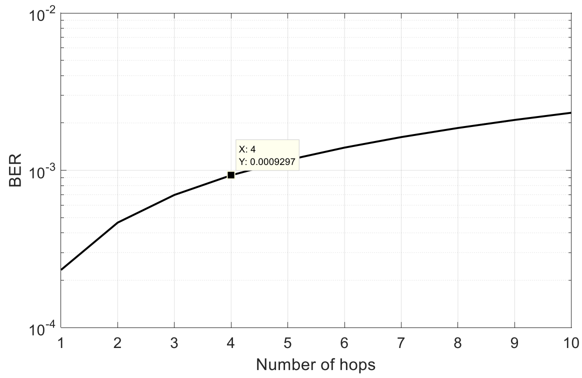

Fig 7 BER of multi-hop connection.

IV. CONCLUSION AND FUTURE WORK

In the paper, we have analyzed the performance of vehicular VLC network based on value of BER in some particular situations. In order to simplify the traffic model, we have introduced our road model with one way and one lane. Vehicles transfer information based on VLC with two headlamps as transmitters and one PD as receiver. The VLC channel includes both LOS and NLOS. The values of BER prove that if vehicles go away from each other, BER will reduce. Both the position of attaching PD and the horizontal gap between two vehicles affect the received signal that causes the chances of BER value. Moreover, when the distance between vehicles is smaller than 10 m, BER seems to have a high fluctuation. Finally, BER with multi-hop will reduce along with the increasing number of hops.

V2LC networks are an interesting topic that contains so many rooms that researchers can engage themselves to develop it. Our work can easily improved if we consider more complex road models as well as plug in some traffic models. The application of some advanced technologies like MIMO, the mixture of VLC and radio and learning machine also can be promising further steps.

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PHÂN TÍCH HIỆU NĂNG MẠNG VLC ĐA CHẶNG CHO PHƯƠNG TIỆN GIAO THÔNG

Tóm tắt- Truyền thông bằng ánh sáng nhìn thấy cho phương tiện giao thông (V2LC) là một công nghệ tiềm năng nhằm hiện thực hóa phương tiện giao thông tự động. V2LC giúp phương tiện giao thông chia sẻ thông tin và dữ liệu để chạy chính xác trên đường. Trong bài báo này, chúng tôi phân tích hiệu năng của V2LC bằng cách sử dụng một mô hình đường một chiều và một làn đường. Các phương tiện giao thông được lắp đặt hai đèn pha sử dụng điốt phát quang (LEDs) và một bộ tách sóng quang (PD) đóng vai trò lần lượt là thiết bị phát và thiết bị thu. Tỷ số lỗi bit (BER) được đánh giá khi thay đổi khoảng cách giữa hai phương tiện giao thông. Thêm vào đó, chúng tôi cũng xem xét vị trí lắp đặt PD và khoảng cách di chuyển lệch theo chiều ngang giữa hai phương tiện giao thông ảnh hưởng đến BER như thế nào. Cuối cùng, mạng truyền thông đa chặng các phương tiện giao thông cũng được xem xét để có cái nhìn rõ ràng về hiệu năng truyền dẫn xuyên suốt.

Từ khóa- Truyền thông bằng ánh sáng nhìn thấy cho phương tiện giao thông (V2LC), hiệu năng đa chặng, đèn pha LED.

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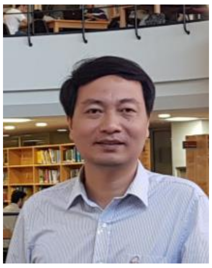

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