Application of NOMA in Vehicular Visible Light Communication Systems

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Abstract—In the context of an increasing interest toward reducing the number of traffic accidents and of associated victims, communication-based vehicle safety applications have emerged as one of the best solutions to enhance road safety. In this area, visible light communications (VLC) have a great potential for applications due to their relatively simple design for basic functioning, efficiency, and large geographical distribution. Vehicular Visible Light Communication (V VLC) is preferred as a vehicle to everything (V2X) communications scheme. Due to its highly secure, low complexity, and radio frequency (RF) interference-free characteristics, exploiting the line of sight (LoS) propagation of visible light and usage of already existing vehicle light-emitting diodes (LEDs). This research is addressing the application of the Non-Orthogonal Multiple Access (NOMA) technique in VLC based Vehicle-to-Vehicle (V2V) communication. The proposed system is simulated in almost realistic conditions and the performance of the system is analyzed under different scenarios.

Keywords—Visible light communication, Vehicular, NOMA, Modulation

I. INTRODUCTION

In recent years, the application potential of visible light communication (VLC) technology as an alternative and supplement to radio frequency (RF) technology has attracted people's attention. Vehicular visible light communication (V VLC) is one of most attractive outdoor applications of VLC. V- VLC aiming simultaneous data transmission and illumination through vehicle LED lights. V-VLC is considered as a secure complementary technology to RF vehicular communications, to support safety critical applications such as platooning due to its RF interference, jamming, and spoofing resiliency, with license free wide spectrum availability and directional LoS communication characteristics [1]. V-VLC is mainly considered to be a line-of-sight (LoS) technology due to its directional propagation characteristics. However, non-line-of-sight (NLoS) V-VLC transmissions are also demonstrated to increase received signal strength (RSS) of LoS V-VLC link through object reflections [2, 3]. Therefore, NLoS V-VLC can be considered to support close proximity V2V safety and high data rate demanding applications such as blind spot warning, lane change warning and intention sharing by taking advantage of nearby vehicle reflected optical signals.

Regardless of the outdoor conditions, a V-VLC system is supposed to provide reliable communication. This is particularly important for safety-related applications, which typically have stringent latency and reliability requirements. To meet these requirements under challenging communication conditions, a V-VLC system should have a carefully designed physical layer, especially with respect to the choice of robust and efficient modulation and coding schemes [4].

Power domain multiple access, known as non-orthogonal multiple access (NOMA), has been proposed as a promising candidate for cellular networks. In NOMA, users are multiplexed in the power domain using superposition coding at the transmitter side and successive interference cancellation (SIC) at the receivers. In NOMA, each user can exploit the entire bandwidth for the whole time. As a result, significant enhancement in the sum rate can be achieved [5]. There are some literature addressing application of NOMA in VLC. Lin et al in [6] propose a convolutional neural network based demodulator for NOMA-VLC for both signal compensation and recovery. In [7], Shi et al investigated the performance of offset quadrature amplitude modulation (OQAM) orthogonal frequency division multiplexing (OFDM) based multiple input multiple output (MIMO) NOMA VLC system, and studied its advantages over conventional MIMO system. In [5], a gain ratio power allocation (GRPA) strategy that considered users’ channel conditions to ensure efficient and fair power allocation was proposed, whereas in [8] optimal power allocation schemes for both static and mobile users were proposed.

In V-VLC sometimes a vehicle needs to communicate with more than one vehicle simultaneously. In this work we address the application of NOMA to create a real time multiple access in V-VLC system. The channel impulse response (CIR) for the proposed model is produced based on ray tracing model. The modulation formats for two users are On-Off-Keying (OOK) and Binary Phase Shift Keying (BPSK). The Bit Error Rate (BER) values are extracted for both links versus different values of Optical Signal-to-Noise Ratio (OSNR). Besides, the performance of the system is analyzed considering different bit rates.

The rest of this paper is organized as follows. Section II presents the principle of two-user NOMA V-VLC system model. Furthermore, channel model for both LOS and NLoS is discussed in this section. Simulation setup and results are included in section III. Finally, conclusions are drawn in section IV.

II. SYSTEM MODEL

In general, the V-VLC literature can be divided in two major categories, depending on the type of the employed receiver, which can be a Photo Diode (PD) or a camera image sensor. These two different ways of realizing V-VLC (and VLC, in general), have distinct properties. We rely on a PD, which is rather cheap, and supports higher switching frequencies, thus, higher bandwidth.
Fig. 1. VLC based V2V communication scenario

Fig. 1 shows the proposed scenario with one transmitter and two receiver vehicles. In this model, the headlights are considered as VLC transmitters and labeled as $T_1$ and $T_2$ for right and left lamps, respectively. A PD is placed at the back of each vehicle as a receiver, where named as $R_1$ for receiver vehicle 1 and $R_2$ for receiver vehicle 2. Considering a transmitter vehicle and a receiver one, there is a two downlink $T_k\rightarrow R_1$ and $T_L\rightarrow R_1$. Consequently, a Multiple-Input Single-Output (MISO) communication system is formed.

Considering Fig. 1, the received signal for $2\times1$ MISO system is given as

$$y = H\otimes s + z$$

(1)

where the symbol $\otimes$ denotes the convolution operation, $s$ and $y$ are transmitted and received signal vectors respectively, $H$ indicates the channel matrix comprising of LoS, and NLoS (diffuse) components [9]. Here, $z$ is the total noise vector with variance $\sigma_z^2$ given as

$$\sigma_z^2 = \sigma_n^2 + \sigma_{ISI}^2 + \sigma_c^2$$

(2)

where $\sigma_n^2$ is the sum of the shot noise, dark noise, and thermal noise, $\sigma_{ISI}^2$ is the ISI noise, $\sigma_c^2$ is the clipping noise. The random arrival of the incident photons from both LED light and sunlight result into shot noise. This type of noise can be modeled by Poisson process. Moreover, when the number of incident photons is large, shot noise is approximated by a Gaussian process (using central limit theorem).

For a $2 \times 1$ MISO, the channel matrix $H$ is given as

$$H = [h1 \ h2]$$

(3)

Each entry of matrix $H$ can be given as

$$h_{RT}(t) = h_{LOS}(t) + h_{NLOS}(t)$$

where $h_{LOS}(t)$ and $h_{NLOS}$ are the CIR for LoS and NLoS paths, respectively.

A. Channel Model

VLC channel models are currently investigated under two categories: deterministic and stochastic channel models. Deterministic channel models aim to predict the channel characteristics in a specific location considering transmitter and receiver locations, as well as the surrounding environment, with ray tracing, recursive algorithms and empirical methods. To date, ray tracing based V-VLC channel models are demonstrated to yield V-VLC channel parameters, such as channel delay profiles of vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) links in [10].

According to the geometry presented in Fig. 1, for the LoS path, CIR between Transmitter $T$ and a receiver $R$, $h_{RTLOS}$ is given as

$$h_{RTLOS} = \sum_{T=I, L} \sum_{q=1}^Q \frac{A_d(m_i + 1)}{\pi^2 d_{Tq}^2} \cos(m_i \phi_{Tq}) \cos(\theta_{Tq}) T_s(\theta_{Tq}) g(\theta_{Tq}) \rho_q$$

(4)

$$\times \delta\left(t - \frac{d_T}{c}\right)$$

$$0 \quad \text{if} \quad \theta_T > \psi_R$$

where $\phi_{Tq}$ denotes the emitting angle, $\theta_T$ denotes the incident angle from source T to receiver R respectively, $A_d$ denotes the area of the receiver R, $m_i$ is Lambert’s mode number expressing directivity of the source beam, the $T_s(\theta_{Tq})$ denotes the signal transmission coefficient of an optical filter, $c$ denotes the speed of light, $\delta(\cdot)$ is the Dirac function, and $\psi_R$ denotes the field of view of the receiver R with respect to the transmitter T, $g(\theta_{Tq})$ denotes the concentrator gain, $d_T$ is the distance between source T and receiver R. For instantaneous given a receiver vehicle 1, $d_L$ would be $d_{L1}$ and $d_{L2}$ for $T_1\rightarrow R_1$ and $T_L\rightarrow R_1$ LoS links [9, 11].

To avoid the more complexity in Fig. 1, we have shown the geometry of a VLC NLoS link in Fig. 2. Similarly, the NLoS impulse response Transmitter T and a receiver R, $h_{RTNLOS}$ is given as

$$h_{RTNLOS} = \sum_{T=I, L} \sum_{q=1}^Q \frac{A_d(m_i + 1)}{\pi^2 d_{Tq}^2} \cos(m_i \phi_{Tq}) \cos(\theta_{Tq}) T_s(\theta_{Tq}) g(\theta_{Tq}) \rho_q$$

$$\times \delta\left(t - \frac{d_{Tq}}{c}\right)$$

$$0 \quad \text{if} \quad \theta_T > \psi_R$$

(5)

where $q$ is the reflections, and $Q$ indicates the total number of reflectors, $\rho_q$ denotes the reflectivity coefficient.
B. NOMA Transmission

The performance of VLC system can be improved by using NOMA. NOMA is an attractive access means to let multiple terminals use the same time and frequency resources. It provides high spectral efficiency, high flexibility, and improved fairness.

In the considered scenario we assume that the users R1 and R2 channels are as $h_1 \ll h_2$. Based on the proposed NOMA concept, the corresponding LED transmits the real and non-negative signals $s_1$ and $s_2$ with associated power values $P_1$ and $P_2$. It is also noted here that, unless otherwise stated, the term power refers to the corresponding optical power at the receiver.

At the PD site, direct detection of the received signal is performed based on the received optical power. In the NOMA system using SIC, the best decoding order is that the user with a better channel should be decoded later since it can decode all other users with the worse channel conditions [12]. It is recalled here that the multi-user interference at user U1 can be eliminated by means of SIC. Based on this, user2 decodes its own signal. But, user1 first needs to successfully decode and subtract the signals of user2. As a result, the residual interference from user2 becomes insignificant and can be treated as noise. Also, in order to facilitate SIC decoding, the LED allocates higher transmission power to users with poor channel gains. To this effect, the simplest power allocation scheme is the fixed power allocation (FPA). According to FPA in the context of the NOMA concept, the power allocated to user U1 is reduced at increase of $h_i$ because users with good channel conditions require lower power levels to successfully decode their desired signals, after canceling the interference from the signals of the users with lower decoding order. This is, in fact, the fundamental principle of NOMA, which has been also shown to provide considerable performance gains in conventional radio communications.

III. SIMULATION SETUP AND RESULTS

The OOK is one of the most common modulation formats employed in V-VLC due to its simplicity in implementation. Likewise, the different narrowband modulation techniques such as BPSK, and higher order QAM, in conjunction with OFDM, provide an efficient yet robust physical layer implementation. In this work, we implement the OOK scheme with BPSK mapper. The BPSK was chosen because of the most powerful of all types of PSK. It takes the highest distortion level to make the demodulator perform the wrong decision.

In simulations, we assume that the transmitters and the receivers are on the same horizontal level. The parameters and their values used in simulations are summarized in Table I. Multipath propagation with one reflection is considered. All the reflectors’ surfaces are assumed to have the same reflective factor. We do Monte Carlo simulation for simulating the proposed VLC channel. White light XM-L LED for the vehicle’s headlight is considered as a transmitter.

![Fig. 2. Geometry of transmitter, receiver, and reflector](image)

| Symbol | Description | Value |
|--------|-------------|-------|
| $T, R$ | Transmitter and receiver | - |
| $Q$ | reflections | 1 |
| $\phi_T$ | emitting angle | 30° |
| $\theta_T$ | incident angle from source to receiver | 45° |
| $\psi_R$ | field of view of the receiver | 75° |
| $A_d$ | area of the receiver | $1 \times 10^4 \text{m}^2$ |
| $m_1$ | Lambert’s mode number | 1 |
| $T_s(\theta_f)$ | signal transmission coefficient of an optical filter | 1 |
| $g(\theta_f)$ | concentrator gain | 5 |
| $\rho_o$ | reflectivity coefficient | 0.8 |
| $d$ | path length | 10 – 40 m |

The resulting V-VLC CIR for both downlinks i.e. T-R1 and T-R2 presented in Fig. 3 and Fig. 4, respectively. We can quickly notice that the CIR of the T-R2 component is lower than that of T-R1. The reason is that the travel distance of T-R2 is longer than that of T-R1, so the path loss of light is also larger, which is why T-R2 has a larger time delay than the other.

![Fig. 3. The CIR of T-R1 with $d_{R1} = 11 \text{m}$ and $d_{R1} = 12 \text{m}$](image)
data rate. As the time duration of symbols are shorter for higher data rate, the ISI due to CIR has. Fig. 6 repeats the results of Fig. 5 for BPSK modulation. Comparing the peer BER curves of OOK and BPSK modulations shows that BPSK results overcome OOK. On the other hand, OOK scheme is simple in implementation.

IV. CONCLUSION

In this paper, we studied the application of NOMA in V-VLC communication system. First, we proposed a model consisting of a transmitter vehicle and two receiver ones. Then we discussed channel impulse response for the proposed model and implementation aspects of NOMA over V-VLC. Our simulation results cover CIR, system performance with OOK and BPSK modulation formats under different data rates.

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