Non-Orthogonal Multiple Access for Visible Light Communications

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Abstract—The main limitation of visible light communication (VLC) is the narrow modulation bandwidth, which reduces the achievable data rates. In this paper, we apply the non-orthogonal multiple access (NOMA) scheme to enhance the achievable throughput in high-rate VLC downlink networks. We first propose a novel gain ratio power allocation (GRPA) strategy that takes into account the users’ channel conditions to ensure efficient and fair power allocation. Our results indicate that GRPA significantly enhances system performance compared to the static power allocation. We also study the effect of tuning the transmission angles of the light emitting diodes (LEDs) and the field of views (FOVs) of the receivers, and demonstrate that these parameters can offer new degrees of freedom to boost NOMA performance. Simulation results reveal that NOMA is a promising multiple access scheme for the downlink of VLC networks.

Index Terms—Multiple access, NOMA, power allocation, power domain multiple access, visible light communication.

I. INTRODUCTION

Visible light communication (VLC) is rapidly evolving as a promising candidate to support and complement traditional radio frequency (RF) communication. Advances in VLC technology can enable wireless data communication in various settings, where RF signals are considered hazardous or undesired, such as healthcare, aviation and military applications. Moreover, VLC can be used in public areas like museums, libraries and malls for broadcasting information. Another potential application for indoor VLC is to provide a means of communication in places with poor RF coverage [1].

VLC links can be realized by using light emitting diodes (LEDs) as transmitters and photo detectors (PDs) as receivers. The LEDs modulate the amplitude of the optical signals at sufficiently high frequencies that cannot be perceived by the human eye. This process is known as intensity modulation (IM). At the receiver, direct detection (DD) of the arriving signals is performed to reconstruct the transmitted data.

The main drawback of VLC systems is the narrow modulation bandwidth of the light sources, which forms a barrier to achieving rival data rates. Recently, the development of high-rate VLC systems has been an active research area. To this end, equalization techniques [2], adaptive modulation schemes [3], and multiple-input-multiple-output (MIMO) technology [4], [5] have been considered for achieving higher data-rates in VLC systems. Orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) schemes have also attracted attention in VLC systems due to their high spectral efficiency [6], [7]. However, conventional OFDM and OFDMA techniques cannot be directly applied to VLC systems, due to the restriction of positive and real signals imposed by IM and the illumination requirements. For this reason, DC-biasing and clipping techniques have been proposed to adapt OFDM and OFDMA to VLC systems, but such techniques degrade the spectral efficiency and the bit error rate (BER) performance [8].

Power domain multiple access, also known as non-orthogonal multiple access (NOMA), has been recently proposed as a promising candidate for 5G wireless networks [9]. 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. Recent investigations on NOMA for RF systems are shown to yield substantial enhancement in throughput [10].

In this paper, we propose NOMA as an efficient and flexible multiple access protocol for boosting spectral efficiency in VLC downlink systems because of the following main reasons:

- Multiplexing in the power domain fits perfectly in VLC systems, where the detection of the signals is directly related to the received power.
- NOMA is more effective in multiplexing a few number of users. This is in line with VLC systems, which depend on transmitting LEDs that act as small cells to accommodate a small number of users in room environments.
- SIC requires channel state information (CSI) at both the receivers and the transmitters to assist the functionalities of user demultiplexing, decoding order, and power allocation. This is a major limitation in RF but not in a VLC system, thanks to the deterministic nature of its channel.
- NOMA performs better in high signal-to-noise ratio (SNR) scenarios [10]. This is the case in VLC links, which inherently offer high SNRs due to the short LED-PD separation and the dominant line of sight (LOS) path.
VLC system performance can be optimized by tuning the transmission angles of the LEDs and the field of views (FOVs) of the PDs. These two degrees of freedom can enhance the channel gain differences among users, which is critical for the performance of NOMA.

The contribution of this paper is two-fold; first, to the best of our knowledge, this is the first work suggesting NOMA as a potential multiple access scheme for high-rate VLC systems, and second, we develop a complete framework for indoor NOMA-VLC multi-LED downlink networks by adopting a novel channel-dependent power allocation strategy called gain ratio power allocation (GRPA). GRPA maximizes the users’ sum rate, thus significantly enhancing the system performance compared to the static power allocation approach. Moreover, the proposed framework can adjust the transmission angles of the LEDs and the FOVs of the PDs. These two degrees of freedom can be exploited to maximize system throughput.

II. SYSTEM MODEL

In this section, we discuss the concept of NOMA and its application to VLC downlink systems. We consider a realistic scenario with multiple LEDs in an indoor environment, such as a library or a conference room, with the beams formed by adjacent LEDs being slightly overlapped, as shown in Fig. 1. In this way, users located at the cell boundary may be receiving data streams from two adjacent LEDs. In our setup, we assume that user \( U_1 \) is associated or connected to LED1, since it lies in the coverage of its beam. Similarly, \( U_2 \) is associated or connected to LED2. Finally, \( U_3 \), located in the intersection area of the two beams, can receive data from both LEDs.

Using NOMA, LED1 transmits the real and positive signals \( x_1 \) and \( x_3 \) with power values \( P_{11} \) and \( P_{13} \), where \( x_1 \) and \( x_3 \) carry information intended for \( U_1 \) and \( U_3 \), respectively. Likewise, LED2 transmits \( x_2 \) to \( U_2 \) and \( x_3 \) to \( U_3 \) with power values \( P_{22} \) and \( P_{23} \), respectively. For each LED, the transmitted signal is a superposition of the signals intended for its users. Let us now denote by \( G_l \) the index set of users connected to the \( l \)th LED, which defines the LEDl users group. Then, the signal transmitted from LEDl, \( l = 1, 2 \), is given by

\[
z_l = \sum_{j \in G_l} P_{lj} x_j,
\]

while the total power transmitted from the \( l \)th LED is

\[
P_l = \sum_{j \in G_l} P_{lj},
\]

The received signal at \( U_i \) is formed by the contribution of all signals transmitted from the LEDs in the network, written as

\[
y_i = \sum_{l=1}^{L} \sum_{j \in G_l} h_{li} P_{lj} x_j + n_i,
\]

where \( L \) is the total number of LEDs and \( n_i \) denotes additive white Gaussian noise (AWGN) of zero mean and total variance \( \sigma_i \), which is the sum of contributions from shot noise and thermal noise at \( U_i \). The LOS path gain from LEDl to \( U_i \) is

\[
h_{li} = \frac{A_i}{d_{li}^2} R_o(\varphi_{li}) T_s(\phi_{li}) g(\phi_{li}) \cos \phi_{li}, \quad 0 \leq \phi_{li} \leq \Phi_i,
\]

where \( h_{li} = 0 \) for \( \phi_{li} > \Phi_i \). In (4), \( A_i \) is the \( i \)th user PD area, \( d_{li} \) the distance between LED \( l \) and \( U_i \), \( \varphi_{li} \) is the angle of irradiance, \( \phi_{li} \) is the FOV of \( U_i \), \( T_s(\phi_{li}) \) is the gain of the optical filter, and \( g(\phi_{li}) \) represents the gain of the optical concentrator given by

\[
g(\phi_{li}) = \frac{n^2}{\sin^2 \Phi_i}, \quad 0 \leq \phi_{li} \leq \Phi_i,
\]

while \( g(\phi_{li}) = 0 \) for \( \phi_{li} > \Phi_i \) and \( n \) is the refractive index. Also, \( R_o(\varphi_{li}) \) is the Lambertian radiant intensity of the LED

\[
R_o(\varphi_{li}) = \frac{m + 1}{2\pi} \cos^m \varphi_{li},
\]

where \( m \) is the order of Lambertian emission, expressed as

\[
m = \frac{\ln 2}{\ln \cos \varphi_{1/2}}
\]

with \( \varphi_{1/2} \) being the transmitter semi-angle at half power.

The multi-user interference is eliminated by means of SIC and the decoding is performed in the order of increasing channel gain. Based on this order, \( U_l \) can correctly decode the signals of all users with lower decoding order. The interference from users of higher decoding order (i.e., from \( U_k \) with \( k > i \)) is not eliminated and is treated as noise. The instantaneous signal-to-interference-plus-noise ratio (SINR) for \( U_i \) reads

\[
\gamma_i = \sum_{l=1}^{L} \frac{h_{li} P_{li}}{\sum_{k \neq i} h_{lk} P_{lk} + \sigma_i^2},
\]

where \( U_k \) is higher than \( U_i \) in the decoding order. Evidently, the strategy adopted for the allocation of the transmitted power among users is critical for the performance of the VLC system.

III. POWER ALLOCATION FOR NOMA-VLC NETWORKS

In this section, we present the NOMA-VLC framework with the gain ratio power allocation (GRPA) scheme. The goal is to implement NOMA in a realistic multi-LED scenario...
for achieving the highest possible throughput. We consider the existence of a central control unit (CCU) that collects the necessary information about users’ locations and their associated channel gains. Thanks to its deterministic nature, the VLC channel remains constant for a fixed receiver location, which simplifies channel estimation.\footnote{We can assume that an RF uplink channel is utilized for obtaining CSI.}

A. Users Association

Each user associates with the LED that is covering its location. If the user is located in the overlapping area of two adjacent LEDs, it will be associated with both of them. In this way, diversity gain can be achieved to enhance the performance of the cell edge users. To gain more insight, we investigate the effect of adjusting the LEDs transmission angles at half power $\phi_{l/2}$ in order to eliminate inter-beam interference. Increasing $\phi_{l/2}$ extends the coverage area of the LED beam and vice versa. Thus, by shrinking the beam coverage of LED$_2$ in Fig. 1 U$_3$ will only observe the signals transmitted by LED$_1$. In order to consider practical feasibility, we assume that each LED has two different transmission angle tunings.

B. Decoding Order

The SIC decoding order among the UG of the LED is decided based on the channel gain of each user, $h_{lj}$. By substituting (3) and (4) into (5) and substituting $\cos \phi_{lj}$ with $\frac{1}{d_{lj}}$, where $z$ is the height between the PDs and the LEDs (which is assumed to be fixed, i.e., at table level), and assuming vertical alignment of LEDs and PDs, the channel gain $h_{lj}$ can be expressed as

$$h_{lj} \propto \frac{1}{d_{lj}^{1-m_j} \sin^2 \Phi_j}. \tag{9}$$

From (9), it can be seen that the channel gain depends on two parameters; the distance and the FOV of the PD.

1) Fixed FOVs: If the FOVs of the PDs are fixed (i.e. not tunable), then the SIC ordering can be easily made in the decreasing order of the distance. Users in the UG of LED$_i$ are sorted in the order of decreasing distance $d_{lj}$. Then, users existing at the cell boundary (if any), are moved to the end of the decoding order. In this way, cell boundary users can decode their signals after subtracting the signals components intended for other users in both cells. Thus, if the decreasing order of the users’ distances from the LED is

$$d_{lc1} > d_{lc2} > .... > d_{lcn},$$

for users in the cell centre, and

$$d_{le1} > d_{le2} > .... > d_{leen},$$

for cell edge users, then the decoding order is set to

$$\tilde{d}_{lc1} < \tilde{d}_{lc2} < .... < \tilde{d}_{lcn} < \tilde{d}_{le1} < \tilde{d}_{le2} < .... < \tilde{d}_{leen},$$

where $\tilde{d}_j$ denotes the SIC decoding order for user U$_j$.

2) Tunable FOVs: As a further step, we examine the effect of changing the FOVs of the users. As shown in [5], the gain of the optical concentrator of the PD can be increased by reducing the FOV. Thus, FOV tuning can be utilized to enhance channel gain differences among users, which is beneficial for the success of the NOMA technique. However, if the FOV is smaller than it should be, the PD will no longer be able to observe the required LED beam.

The location of the user with respect to the transmitting LED determines the optimal FOV adjustment. We assume that each PD has three tunable FOV settings. The FOVs of cell edge users are tuned to receive the beam of one LED only (if possible) to reduce beam overlapping and enhance spectral efficiency. This is done by tuning the FOV to the lowest setting that allows reception from the nearest LED. Moreover, the FOVs of users in the center of the cell are set to the lowest setting to enhance channel gain. After adjusting the FOVs of the users, SIC decoding order is done based on the distance.

C. Gain Ratio Power Allocation (GRPA)

Based on the previous step, each LED transmits the signals of its UG using NOMA. To do so, different power values are allocated to the users based on their channel gains. The sum of the assigned power values is equal to the LED transmitting power. We propose a novel gain ratio power allocation strategy, and compare it to the static power allocation. Using static power allocation, the transmission power of the $j$th sorted user is set to

$$P_j = \alpha P_{j-1}, \tag{10}$$

where $\alpha$ is the power allocation factor ($0 < \alpha < 1$). According to GRPA, power allocation depends on the user gain compared to the gain of the first sorted user as well as the decoding order $j$. After setting the decoding order, the power allocated to the $j$th sorted user is

$$P_j = \left(\frac{h_1}{h_j}\right)^{\frac{1}{\alpha}} P_{j-1}. \tag{11}$$

Thus, the assigned power decreases with the increase of $h_j$, since lower power levels will be sufficient for users with good channel conditions to decode their signals, after subtracting the signals of users with lower decoding order. Moreover, the ratio $\frac{h_1}{h_j}$ is raised to the power of the decoding order $j$, to ensure fairness; as users with low decoding order will need much higher power due to the large interference they receive.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we evaluate the performance of the NOMA-VLC framework proposed in Section [III]. Specifically, we consider a $6 \times 6 \times 3$ m$^3$ room with two transmitting LEDs. In the cases with no tuning, we set the LED transmission angles and the FOVs to fixed values, i.e., $\varphi_i = 45$ and $\Phi_i = 50$. The tunable transmission angles and FOVs are (45,60) and (15,30,50) respectively. We used the same LEDs and PDs characteristics as in [11].

First, we compare the average BER performance for the GRPA and the static power allocation. It was found by
simulations that static power allocation gives its best BER performance at ($\alpha = 0.3$ and $\alpha = 0.4$). At these values, the power allocated to users experiencing bad channel conditions is high enough to enable correct signal decoding. As $\alpha$ increases, more power is allocated to users with good channel conditions. As a result, high BER will exist in the first stages which leads to bad BER performance. Fig. 2 shows the average BER for all users for the two power allocation schemes. The proposed GRPA strategy performs better than static power allocation as it compensates for channel differences among users. For example, at BER = $10^{-2}$, GRPA was able to serve 7 users, while static power allocation can only accommodate 4 users to maintain the same BER performance.

Next, the effect of transmission angles and FOVs tuning on system performance is studied. We primarily compare the following scenarios: 1) no tuning, 2) transmission angles tuning, and 3) FOVs tuning. Figs. 3 and 4 show the users' sum rate for the three scenarios under static power allocation ($\alpha = 0.4$) and the proposed GRPA, respectively. As it can be seen, for a small number of users, transmission angles and FOV tuning increases the sum data rate. This is because the interference between the two beams is completely eliminated.

However, as the number of users increases, less power is allocated to each user, which makes it better for cell edge users to receive their signals from both LEDs. Thus, transmission angles tuning will degrade system throughput, as it limits cell edge users to receive from one LED only. On the other hand, FOV tuning will have the best performance as it allows each user to optimize reception according to its position. As expected, the performance improvement induced by FOV tuning is significantly increased when GRPA is adopted, as the latter accounts for channel gain variations.

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