

NOMA for MIMO Visible Light Communications: A Spatial Domain Perspective

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Abstract—In this paper, we propose a novel non-orthogonal multiple access (NOMA) technique from a spatial domain (SD) perspective for indoor multiple-input multiple-output visible light communication (MIMO-VLC) systems. By fully exploiting the spatial distributions of light-emitting diode (LED) transmitters in the ceiling and users over the receiving plane, SD-NOMA is achieved by assigning all the users to different LEDs in the MIMO-VLC system. Hence, each user only receives data from a specific LED and users assigned to the same LED can use the overall modulation bandwidth of the system. Moreover, a signal-to-noise ratio (SNR) based LED selection scheme is further proposed for each user to efficiently select its desired LED. The achievable rates of a general indoor MIMO-VLC system using conventional MIMO orthogonal frequency division multiple access (MIMO-OFDMA) and the proposed SD-NOMA are analytically derived. The superiority of SD-NOMA over conventional MIMO-OFDMA for multi-user MIMO-VLC systems is successfully verified by detailed analytical results.

Index Terms—Visible light communication (VLC), multiple-input multiple-output (MIMO), non-orthogonal multiple access (NOMA), spatial domain, LED selection

I. INTRODUCTION

Due to the wide application of white light-emitting diodes (LEDs) for indoor illumination, visible light communication (VLC) relying on the existing LED light fixtures has attracted ever-increasing interest in recently years [1], [2]. Compared with traditional radio-frequency (RF) technologies, VLC has many exiting advantages such as huge and unregulated spectrum, potentially high data rate, low-cost front-ends and no electromagnetic interference (EMI) [3]. Therefore, VLC has been considered as a very promising technology for high data rate short-reach wireless communications [4]. Although white LEDs have abundant spectrum, the available 3-dB modulation bandwidth of the commercial off-the-shelf illuminating LEDs is relatively small, which greatly limits the achievable rate of practical VLC systems using white LEDs [5].

So far, many techniques have been proposed for white LEDs enabled VLC systems, such as the extension of LED modulation bandwidth via frequency domain equalization [6]–[8], the enhancement of spectral efficiency using high-order

quadrature amplitude modulation (QAM) constellations aided orthogonal frequency division multiplexing (OFDM) modulation [9], [10], the multiple-input multiple-output (MIMO) transmission based on an array of LED transmitters [11], [12], and so on. In practical indoor environments, multiple LEDs are usually mounted in the ceiling to obtain sufficient and uniform illumination. Hence, MIMO transmission is a very natural and efficient way to improve the achievable rate of practical indoor VLC systems [12].

Since there might be more than one user within the coverage of a practical indoor MIMO-VLC system, an efficient multiple access scheme should be adopted to simultaneously support multiple users. In [13]–[15], precoding techniques have been applied in multi-user MIMO-VLC systems in order to separate the received signals for different users. However, practical implementation of precoding in MIMO-VLC systems might be challenging since white LEDs usually suffer from a limited dynamic range and severe nonlinearity [16]. In [17] and [18], conventional orthogonal frequency division multiple access (OFDMA) has been applied in multi-user VLC systems, where the system modulation bandwidth is divided and shared by all the users. MIMO-OFDMA, as a combination of MIMO and OFDMA, has been conventionally adopted to support multiple users in RF MIMO systems [19]. However, due to spectrum partitioning, the available bandwidth of each user becomes relatively small, resulting in reduced achievable rate, especially when there are a large number of users in the MIMO system. Recently, power domain non-orthogonal multiple access (NOMA) has also been considered in both VLC systems [20]–[24] and MIMO-VLC systems [25], [26]. Nevertheless, the performance of power domain NOMA largely depends on the specific user pairing/grouping and power allocation strategies adopted [27], and it might be very difficult to achieve optimal performance in practical cost-sensitive MIMO-VLC systems due to the high implementation complexity.

In this paper, we extend the NOMA concept to the spatial domain (SD) and for the first time propose a novel SD-NOMA technique for multi-user MIMO-VLC systems. According to

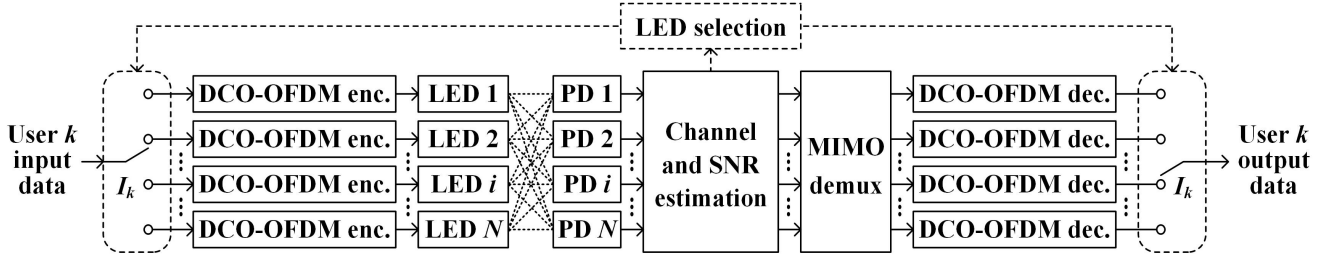


Fig. 1. Schematic diagram of an indoor K -user $N \times N$ MIMO-VLC system using SD-NOMA. Only the k -th user is shown for illustration.

the distinctive spatial positions of the ceiling LEDs and the relative positions of users with respect to different LEDs, all the users can be assigned to different LEDs in the MIMO-VLC system and each user only receives data from a specific LED. As a result, the users assigned to the same LED can utilize the overall modulation bandwidth of the MIMO-VLC system and hence the available bandwidth of each user can be substantially increased compared with that using conventional MIMO-OFDMA. In order to select to a desired LED for each user, we further propose a signal-to-noise ratio (SNR) based LED selection scheme. The achievable rate of MIMO-VLC systems employing SD-NOMA is analytically derived and the obtained analytical results successfully verify the superiority of SD-NOMA over conventional MIMO-OFDMA for multi-user MIMO-VLC systems.

II. MIMO-VLC USING SD-NOMA

In this section, we first describe the mathematical model of indoor multi-user MIMO-VLC systems. Then, the principle of the proposed SD-NOMA technique is introduced, where an SNR-based LED selection scheme is also described. Finally, the achievable rate of SD-NOMA enabled MIMO-VLC systems is analytically derived.

A. System Model

The schematic diagram of an indoor MIMO-VLC system using SD-NOMA is illustrated in Fig. 1, where N LEDs are mounted in the ceiling and K users are randomly located over the receiving plane. Each user is assumed to be equipped with N photodiodes (PDs) which are vertically oriented towards the ceiling. For simplicity and without loss of generality, the system is assumed to have a flat frequency response with an overall modulation bandwidth of B . Moreover, DC-biased optical OFDM (DCO-OFDM) modulation is adopted in the K -user $N \times N$ MIMO-VLC system [28].

Letting $\mathbf{x} = [x_1, x_2, \dots, x_N]^T$ be the transmitted electrical OFDM signal vector with a power of P_s , the received OFDM signal vector after free-space propagation at the k -th user, i.e. $\mathbf{y}_k = [y_{k,1}, y_{k,2}, \dots, y_{k,N}]^T$, can be expressed by

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k, \quad (1)$$

where $\mathbf{H}_k$ is the $N \times N$ MIMO channel matrix for the k -th user and $\mathbf{n}_k = [n_{k,1}, n_{k,2}, \dots, n_{k,N}]^T$ is the corresponding

additive noise vector. The pre-estimated channel matrix $\mathbf{H}_k$ can be represented by

$$\mathbf{H}_k = \begin{bmatrix} h_{k,11} & \cdots & h_{k,1N} \\ \vdots & \ddots & \vdots \\ h_{k,N1} & \cdots & h_{k,NN} \end{bmatrix}, \quad (2)$$

where the element $h_{k,ji}$ is the channel gain between the i -th ($i = 1, 2, \dots, N$) LED and the j -th ($j = 1, 2, \dots, N$) PD of the k -th user.

Assuming each LED follows a Lambertian radiation pattern and only considering the line-of-sight (LOS) components [11], the LOS channel gain is calculated by

$$h_{k,ji} = \frac{(m+1)\rho A}{2\pi d_{k,ji}^2} \cos^m(\varphi_{k,ji}) G_f G_l \cos(\theta_{k,ji}), \quad (3)$$

where m is the order of Lambertian emission which is defined by $m = -\ln 2 / \ln(\cos(\Psi))$ with Ψ being the semi-angle at half power of each LED transmitter; ρ and A are the responsivity and the active area of the PD, respectively; $d_{k,ji}$ is the distance between the j -th PD of the k -th user and the i -th LED; $\varphi_{k,ji}$ and $\theta_{k,ji}$ are the corresponding emission angle and incident angle, respectively; G_f and G_l are the gains of the optical filter and the optical lens, respectively. The gain of the optical lens is given by $G_l = \frac{n^2}{\sin^2 \Phi}$, where n and Φ are the refractive index and the half-angle field-of-view (FOV) of the optical lens, respectively [1]. Note that the LOS channel gain becomes zero if the incident light is outside the FOV of the receiver.

Moreover, the additive noise consists of both thermal and shot noises which can be generally modeled as a real-valued zero-mean additive white Gaussian noise (AWGN) with power $P_n = N_0 B_m$, where N_0 is the power spectral density (PSD) of the additive noise and B_m is the modulation bandwidth [29].

To successfully decode the intended signal for the k -th user, MIMO de-multiplexing is usually first performed by utilizing the pre-estimated channel matrix $\mathbf{H}_k$. Due to its simplicity and low computational complexity, zero forcing (ZF) is adopted to perform MIMO de-multiplexing in the following analysis [30]. Therefore, the estimate of the transmitted OFDM signal vector at the k -th user, i.e., $\hat{\mathbf{x}}_k$, can be obtained by multiplying the pseudo inverse (PI) of $\mathbf{H}_k$ with $\mathbf{y}_k$:

$$\hat{\mathbf{x}}_k = \mathbf{H}_k^* \mathbf{y}_k = \mathbf{x} + \mathbf{H}_k^* \mathbf{n}_k, \quad (4)$$

where the PI of $\mathbf{H}_k$, i.e. $\mathbf{H}_k^*$, is given by

$$\mathbf{H}_k^* = (\mathbf{H}_k^* \mathbf{H}_k)^{-1} \mathbf{H}_k^*. \quad (5)$$

In (5), $\mathbf{H}_k^*$ denotes the conjugated transpose of $\mathbf{H}_k$ and $(\cdot)^{-1}$ represents the inverse of a matrix. As a result, the estimate of the transmitted data in the i -th channel corresponding to the i -th LED for the k -th user is obtained by

$$\hat{x}_{k,i} = x_i + \sum_{j=1}^N \tilde{h}_{k,ij} n_{k,j}, \quad (6)$$

where $\tilde{h}_{k,ij}$ is the element in the i -th row and the j -th column of $\mathbf{H}_k^*$.

B. Principle of SD-NOMA

When conventional MIMO-OFDMA is employed to support multiple users in the MIMO-VLC system [17]–[19], the desired data of the k -th user is first split into N streams which are then simultaneously transmitted in N channels using all N LEDs. However, when adopting SD-NOMA, as shown in Fig. 1, the input data of the k -th user is only transmitted by a single LED. The selection of a specific LED to transmit the input data of the k -th user is the key to successfully implement the SD-NOMA technique. In this work, an SNR-based LED selection scheme is proposed which is described as follows.

According to (6), the SNR of the estimated data in the i -th channel corresponding to the i -th LED for the k -th user, i.e., $\hat{x}_{k,i}$, can be calculated by

$$\gamma_{k,i} = \frac{P_s}{\sum_{j=1}^N \tilde{h}_{k,ij}^2 P_n} = \frac{\gamma_{tx}}{\sum_{j=1}^N \tilde{h}_{k,ij}^2}, \quad (7)$$

where $\gamma_{tx} = \frac{P_s}{P_n}$ denotes the transmit SNR.

In order to select the desired LED for the k -th user, we first obtain the following SNR vector $\mathbf{\Gamma}_k$:

$$\mathbf{\Gamma}_k = [\gamma_{k,1}, \gamma_{k,2}, \dots, \gamma_{k,N}], \quad (8)$$

where the element $\gamma_{k,i}$ is with respect to the i -th LED. Based on (8), the index of the desired LED for the k -th user, i.e., I_k , can be identified by finding the index of the largest element of $\mathbf{\Gamma}_k$, i.e., the index of the specific LED with respect to which a maximum SNR can be achieved by the k -th user:

$$I_k = \arg \max_i \gamma_{k,i}, \quad i \in \{1, 2, \dots, N\}. \quad (9)$$

By utilizing (9), a specific LED can be selected for each user in the K -user $N \times N$ MIMO-VLC system.

After LED selection, DCO-OFDM encoding (enc.) is performed to transform the input data to be transmitted by each LED into an OFDM signal, which is subsequently utilized to drive the corresponding LED. At the receiver side, channel and SNR estimation is first executed and then MIMO demultiplexing (demux) is followed to separate different channels.

After that, DCO-OFDM decoding (dec.) is conducted in each channel to recover the respective transmitted data. The output data of the DCO-OFDM decoder which is corresponding to the specific LED assigned to the k -th user is selected as the output data of the k -th user. As shown in Fig. 1, successive interference cancellation (SIC) is not required in SD-NOMA which is generally adopted in power domain NOMA systems [20], [21], [31]. Therefore, SD-NOMA will not suffer from error propagation caused by imperfect SIC [32], [33].

C. Achievable Rate

The key difference between conventional MIMO-OFDMA and SD-NOMA is that each user receives data from all the LEDs when using conventional MIMO-OFDMA, while each user only receives data from its desired LED when employing SD-NOMA. As a result, the overall modulation bandwidth of the system is shared by all users when adopting conventional MIMO-OFDMA, while the overall modulation bandwidth of the system can be utilized by the users which are assigned to the same LED when employing SD-NOMA. For the k -th user which is assigned to the I_k -th LED, assuming that there are totally K_{I_k} ($\sum_{i=1}^N K_i = K$) users assigned to the I_k -th LED and the overall modulation bandwidth B is equally allocated to these K_{I_k} users, the achievable bandwidth of the k -th user is then given by

$$B_{k,I_k} = \frac{B}{K_{I_k}}. \quad (10)$$

It should be noted that if the i -th LED is assigned with no users, i.e., $K_i=0$, the i -th LED will be deactivated for signal transmission and only the DC bias is applied to maintain its illumination function.

Due to the average and peak power constraints and the non-negativity of the modulated optical signal, the classic Shannon equation is not applicable for achievable rate calculation in the typical VLC systems and the exact capacity calculation of the VLC channel still remains a challenging open question. Nevertheless, several upper and lower bounds have been derived in literature. Here, we adopt the lower bound derived in [34] as an approximation of the capacity of the VLC channel. Therefore, the achievable rate of the k -th user in the $N \times N$ MIMO-VLC system using SD-NOMA is obtained by

$$R_{k,SD-NOMA} = \frac{1}{2} B_{k,I_k} \log_2 \left(1 + \frac{e}{2\pi} \gamma_{k,I_k} \right), \quad (11)$$

where γ_{k,I_k} is the SNR with respect to the selected LED, i.e., the I_k -th LED, of the k -th user. Referring to (7) and (10), we have:

$$R_{k,SD-NOMA} = \frac{B}{2K_{I_k}} \log_2 \left(1 + \frac{e \gamma_{tx}}{2\pi \sum_{j=1}^N \tilde{h}_{k,I_k j}^2} \right), \quad (12)$$

Finally, the achievable sum rate of all the K users applying SD-NOMA is given by the summation of the achievable rates

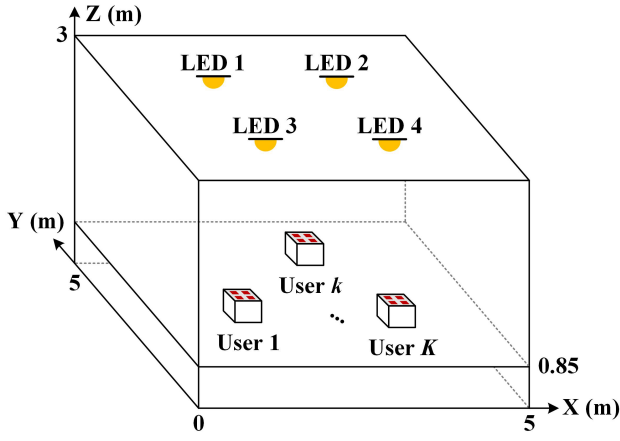


Fig. 2. Geometric setup of an indoor multiuser 4×4 MIMO-VLC system with K users randomly distributed over the receiving plane.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Room dimension	$5 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$
Height of the receiving plane	0.85 m
LED spacing	$0.5 \sim 4.5 \text{ m}$
Semi-angle at half power of LED	70°
Transmit SNR	$150 \sim 170 \text{ dB}$
Gain of optical filter	0.9
Refractive index of optical lens	1.5
Half-angle FOV of optical lens	70°
PD spacing	$0.01 \sim 0.1 \text{ m}$
Responsivity of PD	0.53 A/W
Active area of PD	1 cm^2
Overall modulation bandwidth	20 MHz
Noise power spectral density	$10^{-22} \text{ A}^2/\text{Hz}$

of all the K users:

$$\begin{aligned} \mathbb{R}_{\text{SD-NOMA}} &= \sum_{k=1}^K R_{k,\text{SD-NOMA}} \\ &= \frac{B}{2} \sum_{k=1}^K \frac{1}{K_{I_k}} \log_2 \left(1 + \frac{e\gamma_{\text{tx}}}{2\pi \sum_{j=1}^N \tilde{h}_{k,I_{kj}}^2} \right). \end{aligned} \quad (13)$$

For the purpose of comparison, the achievable rate of the k -th user in the K -user $N \times N$ MIMO-VLC system utilizing conventional MIMO-OFDMA is given by

$$R_{k,\text{MIMO-OFDMA}} = \frac{B}{2K} \sum_{i=1}^N \log_2 \left(1 + \frac{e\gamma_{\text{tx}}}{2\pi \sum_{j=1}^N \tilde{h}_{k,ij}^2} \right), \quad (14)$$

and the achievable sum rate of all the K users is obtained by

$$\mathbb{R}_{\text{MIMO-OFDMA}} = \frac{B}{2K} \sum_{k=1}^K \sum_{i=1}^N \log_2 \left(1 + \frac{e\gamma_{\text{tx}}}{2\pi \sum_{j=1}^N \tilde{h}_{k,ij}^2} \right). \quad (15)$$

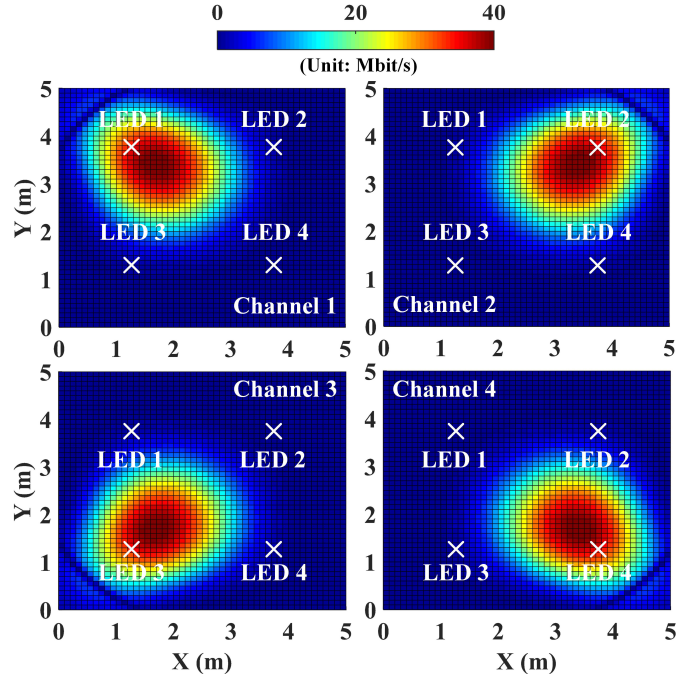


Fig. 3. Achievable rate distribution with $K=1$, $\gamma_{\text{tx}}=160 \text{ dB}$, $d_{\text{LED}}=2.5 \text{ m}$ and $d_{\text{PD}}=0.05 \text{ m}$ for four different channels.

III. RESULTS AND DISCUSSIONS

Based on the analytical expressions derived above, we evaluate the achievable rate of the proposed SD-NOMA technique in a typical indoor MIMO-VLC system. Here, without loss of generality, we consider an indoor 4×4 MIMO-VLC system with K users. Fig. 2 depicts the geometric setup of the indoor multi-user 4×4 MIMO-VLC system configured in a practical indoor environment with a dimension of $5 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$. The four LEDs are placed in a square and located at the center of the ceiling. The detailed parameters of the system are listed in Table I. The height of the receiving plane is fixed at 0.85 m. The LED spacing d_{LED} is in the range from 0.5 to 4.5 m and the semi-angle at half power of the LEDs is 70° . The transmit SNR γ_{tx} is in the range from 150 to 170 dB. The gain of the optical filter is 0.9. The refractive index and the half-angle FOV of the optical lens are 1.5 and 70° , respectively. The PD spacing d_{PD} is in the range from 0.01 to 0.1 m. Each PD has a responsivity of 0.53 A/W and an active area of 1 cm^2 . The overall modulation bandwidth is set to 20 MHz and the noise PSD is assumed to be $10^{-22} \text{ A}^2/\text{Hz}$.

We first investigate the achievable rate distribution of each channel in the indoor 4×4 MIMO-VLC system with a single user, i.e., $K=1$. Fig. 3 shows the achievable rate distribution with $K=1$, $\gamma_{\text{tx}}=160 \text{ dB}$, $d_{\text{LED}}=2.5 \text{ m}$ and $d_{\text{PD}}=0.05 \text{ m}$ for four different channels. As can be seen clearly, the achievable rate of each channel varies significantly when the user is moving around the receiving plane. Specifically, taking channel 1 for example, the highest achievable rate is about 40 Mbit/s which is obtained near the projection point of LED 1 on the receiving plane, and meanwhile the lowest achievable rate is almost ap-

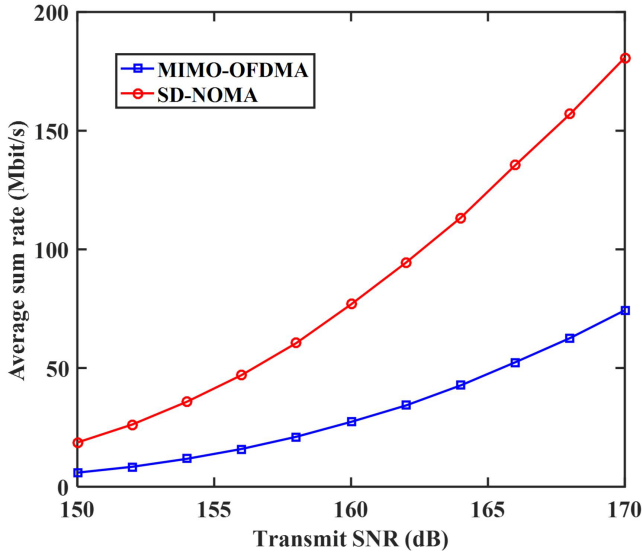


Fig. 4. Average sum rate versus transmit SNR γ_{tx} with $K=8$, $d_{LED}=2.5$ m and $d_{PD}=0.05$ m.

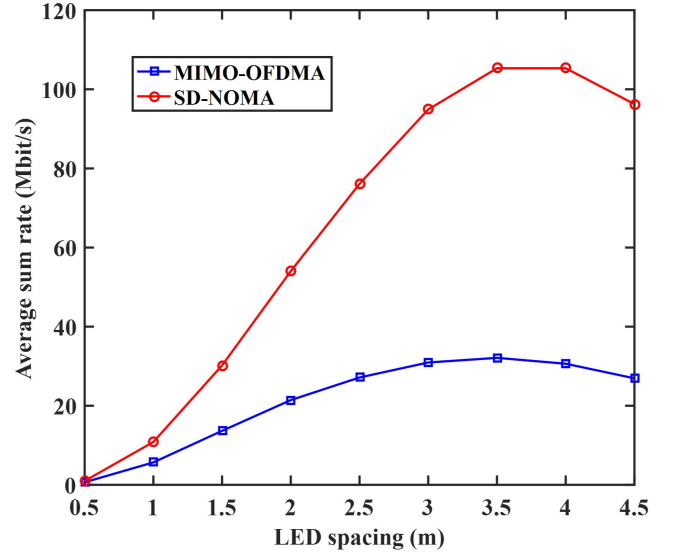


Fig. 5. Average sum rate versus LED spacing d_{LED} with $K=8$, $\gamma_{tx}=160$ dB and $d_{PD}=0.05$ m.

proaching zero which is obtained at the farthest corner from LED 1. Due to geometric symmetry, an achievable rate variation of 40 Mbit/s is observed for each channel in the indoor 4×4 MIMO-VLC system. When adopting conventional MIMO-OFDMA, each user will receive data via all the four channels and the achievable rates of these channels are the same only if the user is located at the center of the receiving plane. When the user is moving away from the central position, the achievable rates of the four channels will become significantly different. This observation indicates that the achievable rate difference of different channels is related to the position of the user, which is not taken into consideration when conventional MIMO-OFDMA is used. However, the SD-NOMA technique is proposed by fully exploiting the achievable rate difference to improve the achievable sum rate of the MIMO-VLC system.

In the next, we evaluate and compare the achievable sum rate performance of the indoor 4×4 MIMO-VLC system using conventional MIMO-OFDMA and the proposed SD-NOMA. Fig. 4 presents the achievable sum rate versus transmit SNR γ_{tx} with $K=8$, $d_{LED}=2.5$ m and $d_{PD}=0.05$ m. For both conventional MIMO-OFDMA and SD-NOMA, the achievable sum rate gradually increases with the increase of γ_{tx} . When $\gamma_{tx}=160$ dB, the achievable sum rates using conventional MIMO-OFDMA and SD-NOMA are 27.3 and 76.8 Mbit/s, respectively. Therefore, an achievable sum rate improvement of 181.3% can be obtained by applying the proposed SD-NOMA technique compared with conventional MIMO-OFDMA. Fig. 5 shows the achievable sum rate versus LED spacing d_{LED} with $K=8$, $\gamma_{tx}=160$ dB and $d_{PD}=0.05$ m. It can be seen that, for both conventional MIMO-OFDMA and SD-NOMA, the achievable sum rate gradually increases with the increase of d_{LED} if d_{LED} is less than 3.5 m. When d_{LED} is larger than 3.5 m, the achievable sum rate is decreased with the increase of d_{LED} . Evidently, the optimal d_{LED} to achieve

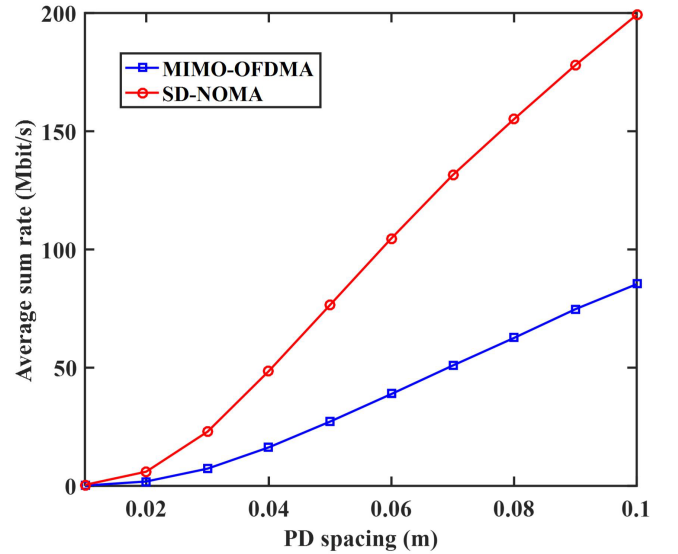


Fig. 6. Average sum rate versus PD spacing d_{PD} with $K=8$, $\gamma_{tx}=160$ dB and $d_{LED}=2.5$ m.

the highest sum rates for both conventional MIMO-OFDMA and SD-NOMA is around 3.5 m. Moreover, the achievable sum rate improvement becomes much more significant when d_{LED} becomes relatively large. Fig. 6 shows the achievable sum rate versus PD spacing d_{PD} with $K=8$, $\gamma_{tx}=160$ dB and $d_{LED}=2.5$ m. As we can observe, the achievable sum rate can be substantially improved by increasing the PD spacing, especially when using SD-NOMA, which is because enlarging PD spacing can effectively reduce channel correlation and thus improve multiplexing gain.

IV. CONCLUSION

In this paper, we have for the first time proposed a novel SD-NOMA technique for indoor multi-user MIMO-VLC systems.

By fully exploiting the spatial distributions of users over the receiving plane with respect to different LEDs in the ceiling, all the users can be assigned to different LEDs and each user only receives data from its corresponding LED. As a result, the users which are assigned to the same LED can utilize the overall modulation bandwidth of the MIMO-VLC system. To select to a desired LED for each user, an SNR-based LED selection scheme is proposed and the corresponding achievable rate expressions are analytically derived. The motivation to employ the proposed SD-NOMA technique in MIMO-VLC systems is justified through the observation of the achievable rate distributions of different channels over the receiving plane in an indoor 4×4 MIMO-VLC system with a single user. After that, we evaluate the achievable sum rates of the 4×4 MIMO-VLC system with eight users using both conventional MIMO-OFDMA and SD-NOMA, in terms of transmit SNR, LED spacing and PD spacing. The analytical results verify that the proposed SD-NOMA technique can substantially improve the achievable sum rate of the system in comparison to the widely used MIMO-OFDMA technique. Therefore, SD-NOMA can be a promising multiple access technique for future high-speed indoor multi-user MIMO-VLC systems.

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