On the Sum Rate of Precoded Multi-User SDMA VLC System with Limited Dynamic Range

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Abstract: We investigate the sum rate performance of a precoded multiuser MIMO-VLC system under the constraint of LED's limited dynamic range. Simulation results verify the superiority of SVD-precoded SDMA for practical dynamic-range-limited multiuser MIMO-VLC systems. © 2021 The Author(s)

1. Introduction

Due to the rapid development of solid-state lighting (SSL) technology, light-emitting diodes (LEDs) have been widely deployed for lighting in general indoor and outdoor environments [1]. Visible light communication (VLC) utilizing existing illumination LEDs has been considered as a key enabling technology for both 6G and Internet of Things (IoT) communications, owing to its inherent advantages including huge and unregulated spectrum, low-cost front-ends and no electromagnetic interference [2,3]. Nevertheless, the bottleneck for the development of practical high-speed VLC systems is the small -3dB bandwidth of commercial off-the-shelf LEDs. So far, many techniques have been proposed to enhance the capacity of VLC systems, among which multiple-input multiple-output (MIMO) transmission built on existing LED fixtures has been widely recognized as a promising solution [4].

Practical MIMO-VLC systems are usually required to support multiple users simultaneously and hence an efficient multiple access scheme should be considered. Conventional multiple access schemes such as orthogonal frequency division multiple access (OFDMA) can be applied in MIMO-VLC systems, but the spectrum utilization of OFDMA is not efficient. Recently, we have proposed a space division multiple access (SDMA) scheme for multiuser MIMO-VLC systems [5]. Nevertheless, zero forcing (ZF) postequalization-based MIMO demultiplexing was adopted in the system, which might cause severe noise amplification and hence reduce system capacity. In order to avoid the adverse effect of noise amplification, in this paper, we apply precoding techniques for MIMO demultiplexing in SDMA VLC systems where the constraint of LED's limited dynamic range is also taken into consideration. Numerical simulations are conducted to evaluate the sum rate performance of the precoded dynamic-range-limited multiuser MIMO-VLC system using both OFDMA and SDMA.

2. Precoded multi-user SDMA VLC system with limited dynamic range

Fig. 1 depicts the block diagram of a precoded K-user $N \times N$ MIMO-VLC system using the proposed SDMA technique, where only the k-th ($k = 1, 2, \cdots, K$) user is shown for illustration. As we can see, the input data of the k-the user is only transmitted by a single LED when using SDMA, whereas all the N LEDs are used to transmit the input data of the k-th user in conventional OFDMA. Specifically, distributed user grouping (DUG) approaches can be adopted to divide all the users into groups based on their signal-to-noise ratio (SNR) conditions with respect to different LEDs. In this work, SDMA with the basic DUG approach is considered for performance evaluation. For more details about the fundamental principle of SDMA with DUG, please refer to our previous work [5].

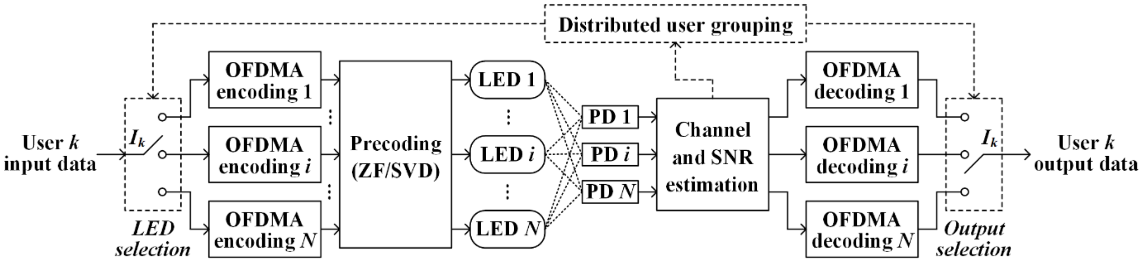


Fig. 1. Block diagram of a precoded SDMA-based K-user $N \times N$ MIMO-VLC system.

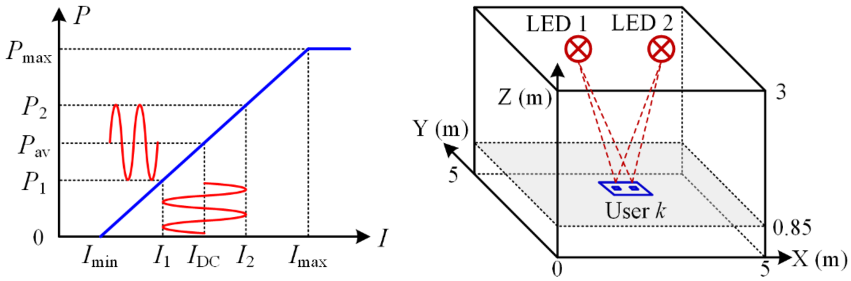
To mitigate the adverse effect of noise amplification caused by ZF postequalization-based MIMO demultiplexing as adopted in [5], here we consider to apply precoding techniques for MIMO demultiplexing at the transmitter side.

In this work, two types of precoding techniques are considered, i.e., ZF precoding and singular value decomposition (SVD) precoding. As shown in Fig. 1, ZF/SVD precoding is performed after parallel OFDMA encoding, which requires the channel state information as the prior information. Letting $\mathbf{x} = [x_1, x_2, \cdots; x_N]^T$ be the transmitted electrical signal vector before precoding, the received signal vector of the *k*-the user can be expressed as follows:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{W}_k \mathbf{x} + \mathbf{n}_k, \tag{1}$$

where $\mathbf{H}_k$ is the $N \times N$ MIMO channel matrix of the *k*-the user, $\mathbf{W}_k$ is the adopted precoding matrix, and $\mathbf{n}_k$ is the additive noise vector. The calculation of $\mathbf{H}_k$ is omitted here for brevity, which can be found in [5].

For ZF precoding, the precoding matrix of the *k*-the user is the pseudo inverse of the channel matrix $\mathbf{H}_k$, which can be expressed by $\mathbf{W}_{k,\mathrm{ZF}} = \mathbf{H}_k^{\dagger} = \mathbf{H}_k^T(\mathbf{H}_k \mathbf{H}_k^T)^{-1}$, where $\mathbf{H}_k^{\dagger}$ denote the pseudo inverse of $\mathbf{H}_k$, while $(\cdot)^T$ and $(\cdot)^{-1}$ represent the transpose and the inverse of a matrix, respectively [6]. For SVD precoding, the precoding matrix is explored by the SVD of the channel matrix, i.e., $\mathbf{H}_k = \mathbf{U}_k \mathbf{\Lambda}_k \mathbf{V}_k^T$, where $\mathbf{U}_k$ and $\mathbf{V}_k$ are two unitary matrices and $\mathbf{\Lambda}_k$ represents the nonnegative diagonal matrix [7]. By applying SVD precoding, the transmitted electrical signal vector $\mathbf{x}$ after parallel OFDMA encoding is multiplied by the precoding matrix $\mathbf{V}_k$, and meanwhile the received signal vector $\mathbf{y}_k$ is multiplied by the combining matrix $\mathbf{U}_k^T$. Therefore, the precoded signal vector $\mathbf{x}_{\mathrm{SVD}}$ and the equivalent received signal vector $\mathbf{y}_{k,\mathrm{SVD}}$ are given by $\mathbf{x}_{\mathrm{SVD}} = \mathbf{V}_k \mathbf{x}$ and $\mathbf{y}_{k,\mathrm{SVD}} = \mathbf{U}_k^T \mathbf{y}_k$, respectively.



(a) **(b)**

Fig. 3. (a) The P-I characteristic of a linear LED and (b) the geometric setup of a 2 × 2 MIMO-VLC system.

Although precoding techniques can efficiently realize MIMO demultiplexing at the transmitter side without noise amplification, the performance of precoding might be severely degraded due to the limited dynamic range of practical LED transmitters [8]. Fig. 3(a) illustrates the power-current (P-I) characteristic of a typical linear LED, where the LED has a turn-on current of $I_{\min}$ and there will be no light generated if the driven current of the LED is smaller than $I_{\min}$. Moreover, the LED also has a saturation current $I_{\max}$, indicating that the output optical power will not be increased and remain to be $P_{\max}$ when the driven current of the LED is larger than $I_{\max}$. Hence, the available dynamic range of the LED is within ($I_{\min}$, $I_{\max}$). In order to ensure stable illumination, the LED is usually driven by a constant DC bias current I_{DC}, which is generally assumed to the midpoint of the dynamic range, i.e., $I_{\mathrm{DC}} = (I_{\min} + I_{\max})/2$. As a result, the input AC signal and the DC bias are combined together to jointly drive the LED. Here, modulation index (MI) can be employed to describe the modulation level of the AC signal with respect to the LED's dynamic range. According to Fig. 3(a), assuming the minimum and maximum currents of the input AC signal are respectively denoted by I_1 and I_2, the MI of the LED can be defined by

$$\mathrm{MI} = \frac{I_2 - I_1}{I_{\max} - I_{\min}}. \tag{2}$$

3. Simulation Results

In this section, we investigate the performance of the precoded multiuser SDMA VLC system with limited dynamic range through numerical simulations, where both ZF precoding and SVD precoding are applied and compared. In the simulations, we consider an indoor 2 × 2 MIMO-VLC system with multiple users. Fig. 3(b) depicts the geometric setup of the 2 × 2 MIMO-VLC system, which is configured in a typical indoor room with a dimension of 5m × 5m × 3m. The two LEDs are located at (1.5 m, 2.5 m, 3 m) and (3.5 m, 2.5 m, 3 m), respectively. The height of the receiving plane is 0.85 m and the users are randomly distributed over the receiving plane. The semi-angle at half power of LED is 70 °, the gain of the optical filter is 0.9, while the refractive index and the half-angle field-of-view (FOV) of optical lens are 1.5 and 70 °, respectively. Each photodetector (PD) is assumed to have a responsivity of 0.53 A/W and an active area of 1 cm^2. The spacing between two PDs of each user is 5 cm. The overall modulation bandwidth and the noise power spectral density are set to 20 MHz and 10^{-22} A^2/Hz, respectively.

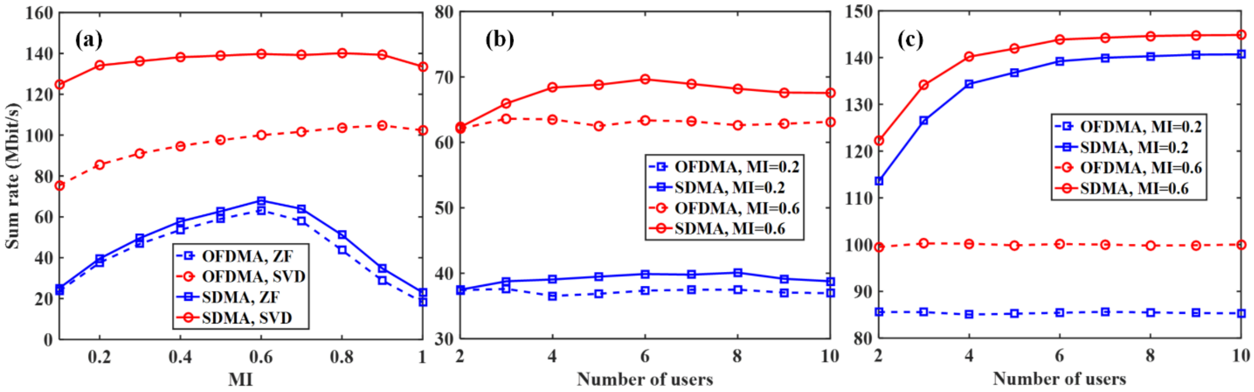


Fig. 3. (a) Sum rate vs. MI for 4 users, and sum rate vs. number of users for (b) ZF and (c) SVD precoding.

We first evaluate the average sum rate versus the MI for totally four random users and the corresponding results are shown in Fig. 3(a). As we can see, when applying ZF equalization, the sum rate first increases and then decreases with the increase of MI for both OFDMA and SDMA. Specifically, the maximum data rates of 63.2 and 68.1 Mbit/s are obtained at MI = 0.6 for OFDMA and SDMA, respectively. It can be found that ZF-precoded SDMA VLC systems experience sum rate fluctuations, which is mainly due to the fact that the ZF precoding matrix, i.e., the pseudo inverse of the channel matrix, might allocate substantially different powers to different LEDs. As a result, the LED which is allocated with a much higher power might suffer from severe signal clipping due to the limited dynamic range of the LED, especially for a large MI. Moreover, it is also revealed that SDMA slightly outperforms OFDMA when using ZF precoding. For the case of SVD precoding, the sum rate is gradually increased with the increase of MI for both OFDMA and SDMA, and only a slight decrease occurs when MI is increased from 0.9 to 1. It clearly suggests that the limited dynamic range of LEDs has a negligible impact on the performance of SVD-precoded SDMA VLC systems, and hence the LED’s dynamic range can be fully explored to achieve a large system capacity. Furthermore, it is also shown that SDMA achieves a much higher sum rate than OFDMA. For example, when MI = 0.6, the sum rates of OFDMA and SDMA are 99.9 and 139.8 Mbit/s, respectively, indicating a sum rate improvement of 39.9% by applying SDMA in comparison to OFDMA. The sum rate versus the number of users for ZF precoding and SVD precoding are shown in Figs. 3(b) and (c), respectively. For ZF precoding, the sum rate of OFDMA remains the same given an MI, which is not affected by the number of users. In contrast, the sum rate of SDMA first slightly increases and then remains stable with the increase of the number of users. For SVD precoding, the sum rate of OFDMA also remains constant, but the sum rate of SDMA gradually increases when the number of user is increased from 2 to 6. With more than 6 users, the sum rate of SDMA becomes stable. It can be observed from Figs. 3(b) and (c) that SDMA performs slightly better than OFDMA when employing ZF precoding, while SDMA significantly outperforms OFDMA when applying SVD precoding.

4. Conclusion

In this paper, we have investigated the performance of a dynamic-range-limited multiuser MIMO-VLC system using SDMA with both ZF and SVD precoding. Simulation results show that the achievable sum rate of ZF-precoded SDMA VLC systems is largely affected by the limited dynamic range of the LED, while SVD-precoded SDMA VLC systems can fully explore the LED’s dynamic range to achieve high sum rates. Moreover, SDMA can achieve a significantly higher sum rate than OFDMA when utilizing SVD precoding. Therefore, SDMA with SVD precoding might be a very promising candidate for high-speed dynamic-range-limited multiuser MIMO-VLC systems.

5. References

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