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Performance Improvement of M-QAM OFDM-NOMA Visible Light Communication Systems

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***Abstract*—Visible light communication (VLC) system is a great candidate for indoor downlink access. Due to the limitation of light-emitting diode (LED)'s bandwidth, orthogonal frequency division multiplexing (OFDM) is used to enhance the transmission capacity of VLC system. Non-orthogonal multiple access (NOMA) can support multiple users in VLC system by sharing time and spectrum resources. The combination of OFDM and NOMA improves the overall channel capacity and spectral efficiency of a multi-user VLC system. In order to increase the data rate further, high order modulation formats are often applied. However, for the superposition of multiple high order modulation signals such as 16-quadrature amplitude modulation (QAM) and 64-QAM, it is hard to recover each user's signal under traditional successive interference cancellation (SIC) method, which is usually used in NOMA scheme. In this paper, we proposed a novel method to decode the superposed signals. This method is called ergodicity and comparison (EAC). By applying the EAC method, the bit error rate (BER) performance of two-user OFDM-NOMA VLC system is investigated under different power allocation conditions. In this system, the modulation formats for both the two users' signals are 4-QAM, 16-QAM and 64-QAM. Peak clipping effect on the received superposed signals is also considered. Numerical results demonstrate that the EAC method can improve significantly the BER performance of OFDM-NOMA VLC system, when high order M-QAM (M> 4) signals are applied to the two users.**

I. Introduction

With the rapid development of communication network, the radio frequency (RF) communication cannot meet the requirement of high-volume data traffic [1]. In recent years, the applications of optical communication via light emitting diode (LED) are becoming widespread, which is called visible light communication (VLC). The VLC has attracted a lot of attentions because of its following advantages in indoor communication [2], [3]. VLC is an energy-efficient and environment-friendly communication approach [4], due to the characteristics of LED. VLC can provide high bandwidth and license-free access. In addition, VLC is immune to RF interference [5]. Many techniques are proposed to further enhance the communication ability of VLC, such as multiple-input multiple-output (MIMO) and WiFi-light fidelity (LiFi) hybrid architecture [6], [7]. Due to the rapid increasing requirement on high data rate indoor wireless access, more and more techniques are considered to be applied in VLC system.

Non-orthogonal multiple access (NOMA) is a promising communication technique, which superposes multiple users' signals. As a special case of superposition coding, NOMA can integrate multiple users in the power domain, providing massive connectivity, high spectral efficiency and low latency [8]–[11]. In NOMA system, multiple users share the same time-frequency resources. Proper power allocation coefficients are assigned to different users according to the corresponding channel state information, in order to ensure the fairness and improve the transmission performance. Successive interference cancellation (SIC) method is exploited at the receiver to remove the decoded users' signals. Hence, when the signal with lower power is decoded, the interferences from high power users are reduced [12].

Being an improvement of orthogonal multiple access technique, NOMA can be combined with orthogonal frequency division multiplexing (OFDM) to further increase the spectral efficiency [13], [14]. The OFDM-NOMA scheme has been studied intensively [15]–[17], which can improve significantly the overall transmission capacity of VLC system. In such a system, the intensity of modulated light has a large peak-to-peak (PTP) value. At the receiver, the overall intensity of received signal is with an increased PTP value for multiuser VLC system, compared with the single-user VLC system. For the procedure of photo-detection, when the incident optical power is too high, some of the received signal with high power will be clipped, which leads to severe signal distortion and performance deterioration. Therefore, the adverse effect of peak clipping cannot be neglected when studying the OFDM-NOMA VLC system performance.

High order modulation formats such as 16-quadrature amplitude modulation (QAM) and 64-QAM are used to improve the spectral efficiency. However, it is difficult to decode the superposed signal with traditional SIC method due to the complex constellations. In this paper, we propose a novel method to decode the multiple users' signals from the superposed signal, where high order M-QAM signals are used. This decoding method is called ergodicity and comparison (EAC). Different from SIC method, the EAC method can recover the signals for multiple users simultaneously, instead of decoding them one by one. In the simulation, two-user NOMA scheme under particular power allocation coefficients is applied and the peak clipping effect is considered. Based on this, we study the bit error rate (BER) performance improvement of OFDM-NOMA VLC system. Three modulation formats are considered, including 4-QAM, 16-QAM, and 64-QAM. The simulation results illustrate that the OFDM-NOMA VLC system performance is improved significantly by using the EAC method.

The rest of the paper is organized as follows. Section II describes the schematic of OFDM-NOMA VLC system and the algorithm of EAC method. Section III illustrates the BER performance improvement of two-user OFDM-NOMA VLC system, where the peak clipping effect and different power allocation coefficients are considered. Finally, the concluding remarks are summarized in Section IV.

II. System Model

The framework of two-user OFDM-NOMA VLC system is shown in Fig. 1. At the transmitter, Hermitian symmetry is used to guarantee the real output of OFDM signal [18]. Therefore, only half of the spectrum is used to transmit the information. α_1 and α_2 denote the power allocation coefficients for two users, respectively. Without loss of generality, we assume that $\alpha_1 < \alpha_2$ in this paper. At the receiver, if the PTP value of optical signal is large, peak clipping occurs due to the nonlinear transfer characteristic of photo-detector (PD). After photo-detection, the converted electrical signals pass through the decoding module, where proper decoding algorithm is used to recover the two users' signals. For the commonly used SIC method, U_1's receiver decodes U_2's signal first, and then decodes its own signal, while U_2's receiver decodes its own signal directly. For the proposed EAC method, both the two receivers decode their own signals directly.

A. VLC System

In a single-user VLC system, the transmitted data i and direct current (DC) bias I_0 drive the LED. The power of LED's output light is

$$P_{\mathrm{T}} = K\left(I_0 + i\right) = P_0 + Ki, \tag{1}$$

where K is the ratio of LED launching power to its driving signal, and $P_0 = KI_0$ is the average LED launching power.

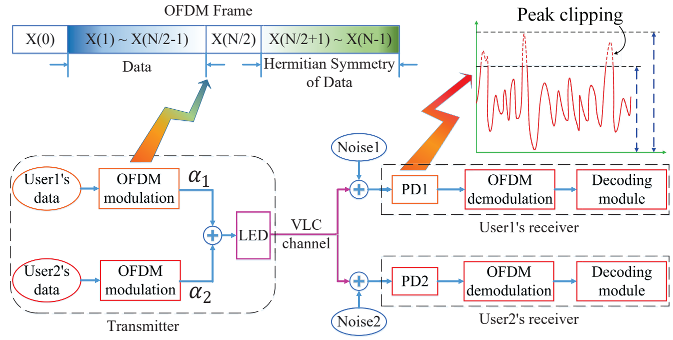

Fig. 1. Two-user OFDM-NOMA VLC system.

The light propagates through the indoor channel G, which is given by [19]

$$G = \frac{(m+1)\,A}{2\pi d^2}\cos^m(\phi)\cos(\psi)\,. \tag{2}$$

In Eq. (2), m is the order of Lambertian radiation pattern, d is the transmission distance, ϕ is the radiation angle, ψ is the incidence angle, and A is the area of PD. The PD collects light and converts it to electrical domain, which is given by

$$y = \rho GKi + n, \tag{3}$$

where n is the zero-mean additive white Gaussian noise (AWGN) with variance σ^2, and ρ is the responsivity of PD. Note that the DC component of converted signal y is removed by DC block.

B. NOMA Scheme

NOMA allows multiple users to share the same time-frequency resources, by superposing multiple users' signals with proper power allocation coefficients. Hence, the spectral efficiency of VLC systems is increased greatly. Combined with OFDM, NOMA can further improve the overall spectrum efficiency of VLC systems.

Based on the NOMA VLC system described above, we assume that the transmitter sends information to N users $(U_1, U_2, ..., U_N)$. The converted electrical signal of $U_k (k = 1, 2, ..., N)$ is given by [10]

$$y_k = \rho G_k K \sum_{q=1}^{N} \sqrt{\alpha_q}\; i_q + n, \tag{4}$$

where i_k (when $q = k$) is the OFDM signal for U_k, G_k is the VLC channel gain between LED and U_k, and α_k is the power allocation coefficient for i_k among the superposed signal under the constraint $\sum_{q=1}^{N} \alpha_q = 1$. Note that α_k is properly allocated according to the value order of G_k. The SIC method is usually adopted for decoding. When one signal is decoded, the other users' signals can be regarded as interferences. The user with higher power is always decoded first, and then the decoded signal is removed.

Under the condition of $\alpha_1 < \alpha_2 < ... < \alpha_N$, when U_k's receiver decodes U_j's $(k < j < N)$ signal, the signal to interference plus noise ratio (SINR) is given by [20]

$$\gamma_{j \to k} = \frac{\rho^2 G_k^2 K^2 \alpha_j}{\rho^2 G_k^2 K^2 \sum_{q=1}^{j-1} \alpha_q + \sigma^2}. \tag{5}$$

After decoding U_j's signal, U_k decodes its own signal. The SINR becomes

$$\gamma_k = \frac{\rho^2 G_k^2 K^2 \alpha_k}{\rho^2 G_k^2 K^2 \sum_{q=1}^{k-1} \alpha_q + \sigma^2}. \tag{6}$$

For the two-user OFDM-NOMA VLC system as shown in Fig. 1, the converted signal at $U_j\ (j = 1, 2)$ before decoding can be denoted as

$$y_{\text{sum},j} = \text{DFT}\left[\rho G_j K \left(\sqrt{\alpha_1}\ i_1 + \sqrt{\alpha_2}\ i_2\right) + n\right], \tag{7}$$

where DFT $[\cdot]$ represents the discrete Fourier transform (DFT) operation. Let $\beta_1 = \rho G_j K \sqrt{\alpha_1} i_1$, $\beta_2 = \rho G_j K \sqrt{\alpha_2} i_2$ denote the converted signals for U_1 and U_2, respectively. The two users' signal-to-noise ratio (SNR) can be denoted as $\text{SNR}_1 = \beta_1^2/\sigma^2$ and $\text{SNR}_2 = \beta_2^2/\sigma^2$, respectively. Therefore, the SINR is given by

$$\begin{aligned} \text{SINR} &= \frac{\beta_2^2}{\beta_1^2 + \sigma^2} = \frac{\text{SNR}_2}{\text{SNR}_1 + 1} \\ &= \frac{1}{\alpha_1/\alpha_2 + 1/\text{SNR}_2}. \end{aligned} \tag{8}$$

where the transmitted data i_1 and i_2 are normalized. As shown in Eq. (8), since SNR_2 can reflect the variation of SINR directly, we use SNR_2 instead of SINR to investigate the BER performance. For the sake of convenience, the channel gains G_1 and G_2 are assumed to be identical, and the product ρK is assumed to be unity.

C. PD Transfer Characteristics

PD can convert linearly the received optical signal into electrical signal. However, the linear response region of PD is limited by the factors such as reverse bias voltage, load resistance and temperature [21]. When the power of incident optical signal is large, some parts of signal that are with high power cannot be converted to electrical signal linearly, or even be clipped. Due to the large PTP value of OFDM signals and the superposition operation in NOMA scheme, the peak value of specific locations in OFDM frame are often inphase and then summed to generate an even larger peak value. Hence, peak clipping of signal is more likely to occur in OFDM-NOMA VLC system. This adverse effect will deteriorate the BER performance.

D. EAC Decoding Algorithm

In a NOMA system, SIC is a commonly used decoding method. This method decides one converted signal based on specific thresholds that are determined by the structure of constellation points. For two-user NOMA system, to decode the superposed signal with SIC method correctly, a necessary condition is that the signs of real and imaginary parts of superposed signal are the same as that of the user with larger power. For 4-QAM, each quadrant has only one point. When two 4-QAM signals are superposed, such necessary condition can be satisfied. Hence, the 4-QAM superposed signals is decoded perfectly. However, when M is larger than 4, the necessary condition mentioned above cannot be satisfied for all superposed signal's constellation points, which deteriorates the BER performance. In order to solve this problem, we propose a novel method, which is called EAC. It can decode the superposed signal that is composed by multiple signals with high order modulation formats.

For one point in the constellation of M-QAM signal, its location is denoted as (R, I), where R, I are the real and imaginary parts of the constellation point, respectively. Thus, for two-user NOMA VLC system, we can use four variables to represent the constellation points. More specifically, R_1 and I_1 represent the real and imaginary parts of U_1's signal, which corresponds to the original transmitted binary data s_1; meanwhile, R_2 and I_2 denote the real and imaginary parts of U_2's signal, which corresponds to the original transmitted binary data s_2. The values of R_1, R_2, I_1, and I_2 are in the constellation point set $\mathcal{C} = \left\{-\left(\sqrt{M} - 1\right), -\sqrt{M} + 3, \ldots, \sqrt{M} - 1\right\}$. For example, when $M = 16$, the possible values of real and imaginary parts of 16-QAM's constellation points form the set $\{-3, -1, 1, 3\}$. Let $(\text{Re}\{y_{\text{sum}}\}, \text{Im}\{y_{\text{sum}}\})$ denote the constellation location of converted signal y_{sum} before decoding. According to Eq. (7), we have the following equations,

$$\begin{aligned} \text{Re}\{y_{\text{sum}}\} &= \beta_1 R_1 + \beta_2 R_2 + n_1, \\ \text{Im}\{y_{\text{sum}}\} &= \beta_1 I_1 + \beta_2 I_2 + n_2. \end{aligned} \tag{9}$$

where n_1 and n_2 are the AWGN.

In the EAC method, we assume that the power allocation coefficients and channel state information are known at the receiver. First, the EAC method selects an element from the constellation point set $\mathcal{C}$ as the first trial value of R_1. Similarly, an element is chosen from $\mathcal{C}$ as the first trial value of I_1. Then the corresponding real and imaginary parts of U_2 can be expressed as

$$\begin{aligned} \tilde{R}_2 &= \frac{\text{Re}\{y_{\text{sum}}\} - \beta_1 \hat{R}_1}{\beta_2}, \\ \tilde{I}_2 &= \frac{\text{Im}\{y_{\text{sum}}\} - \beta_1 \hat{I}_1}{\beta_2}. \end{aligned} \tag{10}$$

In Eq. (10), $\hat{R}_1$ and $\hat{I}_1$ denote the chosen trial values of R_1 and I_1, respectively. $\tilde{R}_2$ and $\tilde{I}_2$ denote the detected values of R_2 and I_2 with noise. Second, the EAC method calculates the differences between $\tilde{R}_2$ and all the possible values in $\mathcal{C}$. The minimal difference value d_{V} and its corresponding location d_{L} in $\mathcal{C}$ are recorded. Two vectors, $\boldsymbol{d}_{\text{V}}$ and $\boldsymbol{d}_{\text{L}}$, are used to store the minimal difference values and corresponding locations based on different values of $\hat{R}_1$. The same procedure of calculation is carried out for $\tilde{I}_2$. As a result, the calculation on first trial value is completed. Later, the rest elements in $\mathcal{C}$ are selected as the trial values of R_1 and I_1 one by one, repeating the operations of first and second steps. After the ergodic selection for $\hat{R}_1$ from the set $\mathcal{C}$, the two vectors $\boldsymbol{d}_{\rm V}$ and $\boldsymbol{d}_{\rm L}$ are filled with the minimal difference values and corresponding locations, respectively. Last, we find the minimal value in $\boldsymbol{d}_{\rm V}$. The location of such minimum corresponds the optimal trial value, which is chosen as the decision value of R_1. Based on the same procedure, the decision value of I_1 is also obtained. According to $\boldsymbol{d}_{\rm V}$ and $\boldsymbol{d}_{\rm L}$, R_2 and I_2 are detected simultaneously. Then, the original binary data s_1 and s_2 can be recovered. The decoding process is shown in **Algorithm 1**. The complexity of the EAC method is $\mathcal{O}(M)$.

Algorithm 1 Algorithm for decoding superposed M-QAM signals by using the EAC method

1: Given $y_{\rm sum}$, β_1, β_2, and C_k is an element of $\mathcal{C}$;
2: **for** $k = 1$ to $\sqrt{M}$ **do**
3: Let $\hat{R}_1 = \hat{I}_1 = C_k$, and obtain $\tilde{R}_2$ and $\tilde{I}_2$ based on Eq. (10);
4: Store $d_{\rm V}$ and $d_{\rm L}$ into $\boldsymbol{d}_{\rm V}$ and $\boldsymbol{d}_{\rm L}$, respectively;
5: **end for**
6: Find the location of the minimum in $\boldsymbol{d}_{\rm V}$;
7: Based on $\boldsymbol{d}_{\rm V}$ and $\boldsymbol{d}_{\rm L}$, obtain the optimal estimation of R_1, I_1, R_2 and I_2;
8: Obtain the decoded data of U_1 and U_2;
9: **return** binary data s_1 and s_2.

III. Simulation Results

In the simulation, we investigate the performance of two-user OFDM-NOMA VLC system. Two power allocation conditions are studied as follows: 1) the power allocation coefficients for U_1 and U_2 are $\alpha_1 = 0.4$ and $\alpha_2 = 0.6$, respectively; 2) the power allocation coefficients for U_1 and U_2 are $\alpha_1 = 0.3$ and $\alpha_2 = 0.7$, respectively. In addition, three peak clipping scenarios are also considered as follows: 1) no peak clipping; 2) 2% peak clipping, *i.e.*, the instantaneous amplitude that is higher than 98% of the signal's peak is clipped; 3) 5% peak clipping, *i.e.*, the instantaneous amplitude that is higher than 95% of the signal's peak is clipped. Both the EAC and SIC methods are used to decode the superposed signal. For the SIC method, we assume that the decoded signal of U_2 are removed completely based on the channel state information, when decoding the signal of U_1. Monte-Carlo simulation is carried out, where 10000 OFDM frames are used and the number of subcarriers in each OFDM frame is 64.

A. 4-QAM signals

We study the performance of EAC and SIC decoding methods in OFDM-NOMA VLC system, when the modulation format for the two users' signals are both 4-QAM. The BER performances under the three peak clipping scenarios are shown in Figs. 2 and 3, for the cases of $\alpha_1 = 0.3$, and $\alpha_1 = 0.4$, respectively. For the case of $\alpha_1 = 0.3$, the required SNR_2 to achieve BER of 10^{-3} are 18.5 dB, 18.6 dB and 19.2 dB, respectively, under the scenarios of no peak clipping, 2% peak clipping and 5% peak clipping, respectively.

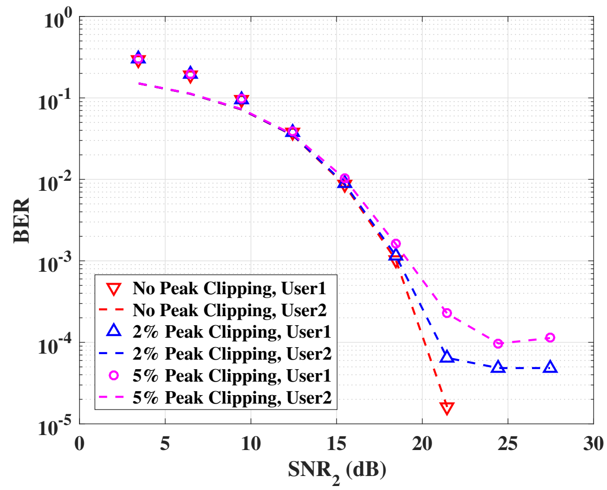

Fig. 2. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 4-QAM-OFDM signals are superposed and $\alpha_1 = 0.3$.

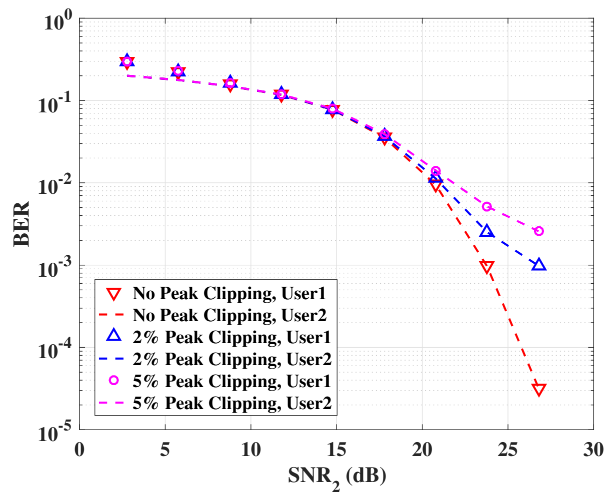

Fig. 3. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 4-QAM-OFDM signals are superposed and $\alpha_1 = 0.4$.

Furthermore, error floor is found when the SNR_2 is larger than 24.5 dB under the peak clipping scenarios when $\alpha_1 = 0.3$, as shown in Fig. 2. For the case of $\alpha_1 = 0.4$, the BER of 10^{-3} is achieved for the scenarios of no peak clipping and 2% peak clipping, respectively, when the SNR_2 are 23.7 dB and 26.7 dB, respectively. In addition, the difference between the BERs under the cases with and without peak clipping are increased as the SNR_2 rises, and the BER deterioration is more significant when peak clipping becomes severer. Note that in Figs. 2 and 3, the BER curves of the SIC decoding method are overlapped with those of the EAC decoding method, *i.e.*, the SIC method has the same performance as the EAC method when 4-QAM signals are applied to the two users.

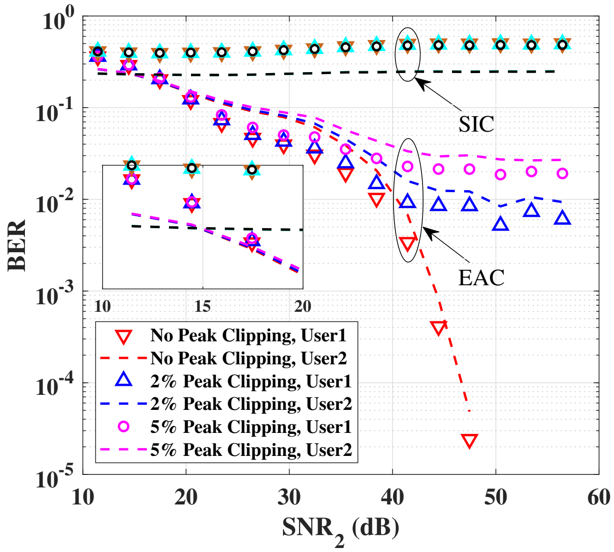

Fig. 4. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 16-QAM-OFDM signals are superposed and α_1 = 0.3.

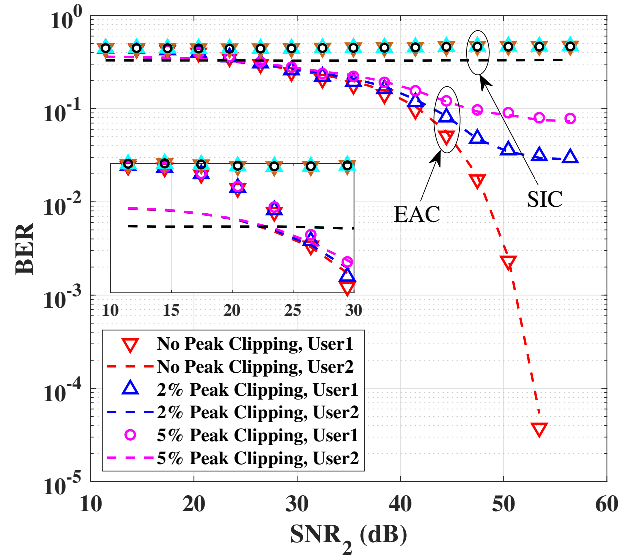

Fig. 6. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 64-QAM-OFDM signals are superposed and α_1 = 0.3.

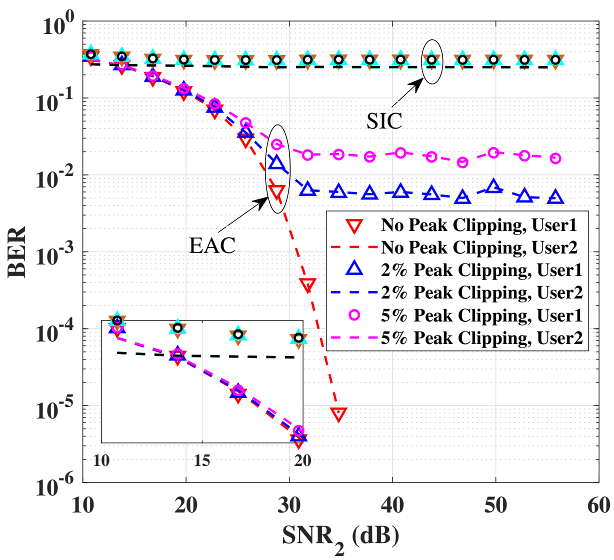

Fig. 5. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 16-QAM-OFDM signals are superposed and α_1 = 0.4.

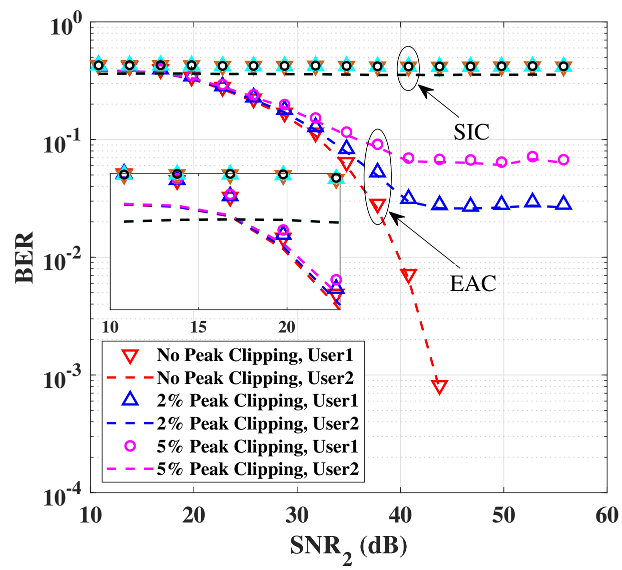

Fig. 7. The BER performance of OFDM-NOMA VLC system under different peak clipping scenarios, where two 64-QAM-OFDM signals are superposed and α_1 = 0.4.

B. 16-QAM signals

Now we investigate the performance of OFDM-NOMA VLC system, when 16-QAM is applied to both users' signals. The BER performances under the situations of α_1 = 0.3 and α_1 = 0.4 are shown in Fig. 4 and Fig. 5, respectively. In both figures, the BER curves obtained from the SIC method are colored by brown, cyan and black, which are for the scenarios of no peak clipping, 2% peak clipping and 5% peak clipping, respectively. For the SIC method, the BER curves are almost unchanged and are overlapped for a particular user. In addition, the BERs of U_2 are lower than those of U_1 under all the three peak clipping scenarios. Such BER performance is worse than that of the EAC method. While for the EAC method, the BER decreases as SNR_2 increases for the scenario of no peak clipping. In Fig. 4, error floor occurs when peak clipping exists, and the corresponding BER is higher than 10^{-3}. In Fig. 5, the BER performance under the case of α_1 = 0.4 is better than that under the case of α_1 = 0.3 as depicted in Fig. 4. The BER can reach 10^{-3} at SNR_2 of

30.8 dB under the scenario of no peak clipping. In addition, error floor occurs under the peak clipping scenarios when the SNR_2 is larger than 31.8 dB. Such error floor is still much lower than that of the SIC method. From Figs. 4 and 5, we can see that BER performance can be greatly improved by using the EAC method when 16-QAM signals are superposed.

C. 64-QAM signals

When 64-QAM signals are applied to both users, the BER curves under the cases of α_1 = 0.3 and α_1 = 0.4 are shown in Fig. 6 and Fig. 7, respectively. The BER curves obtained from the SIC method are colored by brown, cyan and black, which are for the scenarios of no peak clipping, 2% peak clipping and 5% peak clipping, respectively. Similar to Figs. 4 and 5, the BER curves of the SIC method are overlapped for a particular user under different peak clipping scenarios, and are worse than those of the EAC method. The BERs of U_2 are also lower than those of U_1 for all the three peak clipping scenarios. In addition, the BER curves in Figs. 6 and 7 have the same trends, and the BERs under the case of α_1 = 0.3 are higher than those under the case of α_1 = 0.4. As depicted in Figs. 6 and 7, under the scenario of no peak clipping, 51.2-dB and 43.5-dB SNR_2 are required to achieve the BER of 10^{-3} for the cases of α_1 = 0.3 and α_1 = 0.4, respectively. In Fig. 7, for the 2% and 5% peak clipping scenarios, error floors are found, when SNR_2 reaches 43.8 dB, *i.e.*, 12.0 dB higher than that for the 16-QAM signal as depicted in Fig. 5.

Figs. 4 to 7 indicate the effectiveness of the EAC method on the improvement of the BER performance under various peak clipping scenarios. As the SNR_2 rises, the BER difference between EAC and SIC methods is gradually increasing and the improvement on the BER performance becomes more significant. The EAC method is more effective for high order M-QAM ($M > 4$) signal under the scenario of no peak clipping, where no error floor is found.

IV. Conclusion

In this paper, we investigate the performance of two-user OFDM-NOMA VLC system. The traditional SIC decoding method does not work well for the signals with high order modulation formats. In order to improve the performance of OFDM-NOMA VLC system, we proposed a novel decoding method, which is called EAC. Under the EAC decoding method, the BER performance is investigated, where the modulation formats for each user are 4-QAM, 16-QAM and 64-QAM, respectively. The effects of power allocation coefficients and peak clipping on the BER performance are also studied. The simulation results indicate that the proposed EAC method can provide better BER performance than the SIC method, when high order M-QAM ($M > 4$) signals are applied to the two users.

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