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Fairness-aware hybrid NOMA/OFDMA for bandlimited multi-user VLC systems

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Abstract: In this paper, we for the first time propose and experimentally demonstrate a fairness-aware hybrid non-orthogonal multiple access/orthogonal frequency division multiple access (NOMA/OFDMA) scheme for practical bandlimited multi-user visible light communication (VLC) systems. The proposed fairness-aware hybrid NOMA/OFDMA scheme using discrete Fourier transform-spread-orthogonal frequency division multiplexing (DFT-S-OFDM) modulation can efficiently guarantee both the fairness of users within each user pair and the fairness of different user pairs. Specifically, an interleaved subcarrier multiplexing approach is proposed to mitigate user pair unfairness caused by the low-pass frequency response of bandlimited VLC systems, and a two-dimension (2D) power allocation strategy is further proposed to ensure both the fairness of users within each user pair and the fairness of user pairs with different channel conditions. Experimental results show that, in a bandlimited four-user VLC system applying the proposed fairness-aware hybrid NOMA/OFDMA scheme, the transmission distance at a target bit error rate (BER) of 3.8×10^{-3} can be extended by 12.3% in comparison to that employing the conventional hybrid NOMA/OFDMA scheme.

1. Introduction

Recently, visible light communication (VLC) using white light-emitting diodes (LEDs) has been attracting ever-increasing interest from both academia and industry [1]. Compared with traditional radio frequency (RF)-based communications, VLC has many inherent advantages such as abundant and unregulated spectrum resources, low-cost front-ends, electromagnetic interference-free operation, and high physical-layer security [2]. As a result, VLC has been widely considered as one of the key enabling technologies for the sixth generation (6G) mobile networks and the Internet of Things (IoT) systems [3–5].

The LED access point (AP) in a typical VLC system usually needs to communicate with multiple users within its serving coverage, and hence an efficient multiple access technique is of great significance to design and deploy a practical VLC system [1,6]. So far, many multiple access techniques have already been proposed and investigated in VLC systems, which can be generally divided into two categories: one is orthogonal multiple access (OMA) and the other is non-orthogonal multiple access (NOMA). In OMA-based VLC systems, users are allocated with orthogonal time or frequency resources, and hence there is no mutual interference between different users [7,8]. However, in NOMA-based VLC systems, different users utilize all the time and frequency resources via power domain superposition coding (SPC) and successive interference cancellation (SIC), under the condition of inter-user interference (IUI) [9,10]. Although the use of NOMA can enhance the resource utilization efficiency in VLC systems, it is usually only feasible to multiplex a pair of users in the power domain due to the IUI, the decoding complexity and the time delay [11]. Therefore, to accommodate a larger number of users, a hybrid NOMA/OMA scheme is generally adopted in multi-user VLC systems [5,12]. In

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the hybrid NOMA/OMA-based VLC system, all the users are divided into user pairs, and NOMA and OMA are applied for intra-pair and inter-pair multiple access, respectively. Specifically, the channel gain-based user pairing approach is generally utilized to pair the users in hybrid NOMA/OMA-based VLC systems [13].

In practical VLC systems, the available modulation bandwidth is usually limited due to the use of LEDs and the overall system frequency response exhibits a typical low-pass profile [14,15]. As a spectral-efficient modulation technique, orthogonal frequency division multiplexing (OFDM) has been widely used in bandlimited VLC systems [16]. Hence, OFDM-based multiple access, i.e., orthogonal frequency division multiple access (OFDMA), is a very popular OMA scheme for multi-user VLC systems [8]. Nevertheless, classical OFDM is not an ideal modulation technique for low-pass VLC systems, as the received power of a high-frequency subcarrier can be much lower than that of a low-frequency subcarrier, leading to unfairness between different subcarriers. To ensure subcarrier fairness, digital pre-equalization can be performed at the transmitter side by utilizing the estimated channel information. However, since the high-frequency subcarriers might be allocated with an excessively high power, they become much more vulnerable to LED nonlinearity [15]. In order to avoid subcarrier unfairness without the influence of nonlinear distortion, discrete Fourier transform-spread-OFDM (DFT-S-OFDM) can be a suitable method for bandlimited low-pass VLC systems with LED nonlinearity [17,18].

When applying conventional hybrid NOMA/OFDMA in practical bandlimited multi-user VLC systems, the low-pass frequency response of the system might cause unfairness among different user pairs, since the user pair occupying a higher-frequency subcarrier block suffers from a more severe power attenuation than that occupying a lower-frequency subcarrier block. Moreover, considering that different users might be located at different positions within the system coverage, the channel conditions of different user pairs are also different due to the channel gain-based user pairing, which further leads to user pair unfairness. Although user fairness within each user pair can be ensured by adopting a proper power allocation ratio between two users, user fairness among different user pairs has been barely considered in hybrid NOMA/OFDMA-enabled bandlimited multi-user VLC systems. To ensure both the fairness of users within each user pair and the fairness of different user pairs, in this paper, we for the first time propose a novel fairness-aware hybrid NOMA/OFDMA scheme using DFT-S-OFDM for practical bandlimited multi-user VLC systems. The superiority of the proposed fairness-aware hybrid NOMA/OFDMA scheme over the conventional hybrid NOMA/OFDMA scheme has been successfully verified by the obtained experimental results.

2. System model

Figure 1 illustrates the schematic diagram of a multi-user VLC system using conventional hybrid NOMA/OFDMA by taking the four-user case as an example. For a $2K$-user VLC system applying hybrid NOMA/OFDMA, the $2K$ users are first ordered based on their channel gains and then divided into K user pairs. Without loss of generality, we assume that the channel gains of the $2K$ users are sorted in the descending order as follows:

$$h_1 \geq \cdots \geq h_k \geq \cdots \geq h_{2K}, \tag{1}$$

where h_k $(k = 1, 2, \ldots, 2K)$ denotes the channel gain between the LED and the k-th user.

Based on the above user ordering, the sorted $2K$ users are first divided into two groups: the first group G_n contains the first half of the sorted users which have high channel gains starting from user 1 to user K, while the second group G_f consists of the second half users which have low channel gains starting from user $K + 1$ to user $2K$. Subsequently, user pairing can be performed in the following manner: $U^i_{\text{pair}} = [G_n(i), G_f(i)]$, i.e., the i-th user pair U^i_{pair} contains the i-th user in the first group G_n as the near user and the i-th user in the second group G_f as the far user, where $i = 1, 2, \ldots, K$. As shown in Fig. 1, we assume that the total system bandwidth B is equally

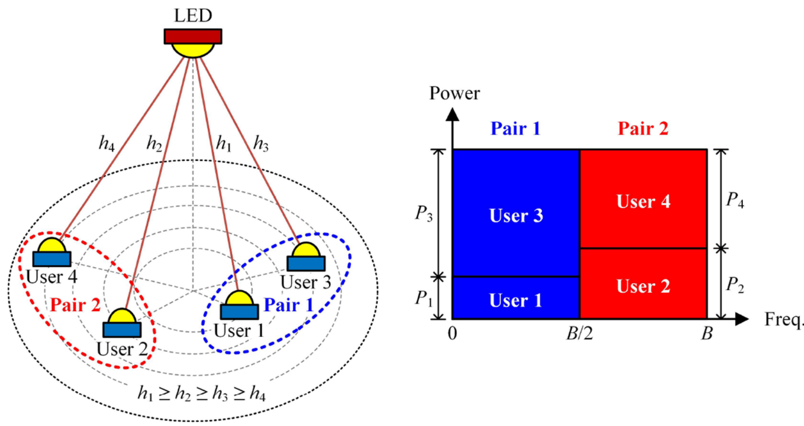

Fig. 1. Illustration of a four-user VLC system using conventional hybrid NOMA/OFDMA.

allocated to all the K user pairs and hence the achievable bandwidth of each user pair is given by $B_{\text{pair}} = B/K$. When applying conventional hybrid NOMA/OFDMA in multi-user VLC systems, all the data-carrying subcarriers are divided into blocks and each user pair is allocated with a corresponding block of subcarriers.

For the two users within each user pair, power domain superposition via SPC is performed to generate a superposed signal for transmission. Letting x_n^i and x_f^i respectively denote the modulated message signals intended for the near and far users in the i-th user pair, the superposed electrical signal of the i-th user pair can be expressed by

$$x_i = \sqrt{P_n^i} x_n^i + \sqrt{P_f^i} x_f^i, \tag{2}$$

where P_n^i and P_f^i represent the allocated electrical powers to the near and far users in the i-th user pair, respectively, and $P_{\text{pair}}^i = P_n^i + P_f^i$ denotes the total allocated electrical power to the i-th user pair. For the i-th user pair at the receiver side, the far user decodes its message signal directly by treating the intended message signal for the near user as noise, while the near user needs to decode the intended message signal for the far user first and then apply SIC to decode its own message signal.

3. Fairness-aware hybrid NOMA/OFDMA for bandlimited VLC

In order to guarantee both user fairness within each user pair and user pair fairness among different user pairs, a novel fairness-aware hybrid NOMA/OFDMA scheme employing DFT-S-OFDM with interleaved subcarrier multiplexing and 2D power allocation is for the first time proposed for bandlimited multi-user VLC systems. The fundamental idea of the fairness-aware hybrid NOMA/OFDMA scheme using DFT-S-OFDM is first introduced, and then the detailed principles of interleaved subcarrier multiplexing and 2D power allocation are discussed, respectively.

3.1. Principle

Figures 2(a) and (b) illustrate the modulation and demodulation diagrams of the proposed fairness-aware hybrid NOMA/OFDMA scheme using DFT-S-OFDM with K user pairs, respectively. For the fairness-aware hybrid NOMA/OFDMA modulation using DFT-S-OFDM, as shown in Fig. 2(a), the input bit streams $b_{i,\text{n}}$ and $b_{i,\text{f}}$ for the near and far users in the i-th user pair are first mapped into quadrature amplitude modulation (QAM) constellation symbols. Then, intra-pair power allocation is performed to ensure user fairness for two users within each user pair before

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power-domain SPC. After that, DFT spreading is executed with respect to the superposed electrical signal of each user pair. For the obtained K DFT-spread signals, inter-pair power allocation is further conducted to mitigate the user pair unfairness caused by the channel gain-based user pairing. Subsequently, interleaved subcarrier multiplexing is performed to mitigate the user pair unfairness induced by the low-pass frequency response of the VLC system. After performing inverse fast Fourier transform (IFFT) with the Hermitian symmetry (HS) constraint and the parallel-to-serial (P/S) conversion, the transmitted hybrid NOMA/OFDMA signal x is generated. For the fairness-aware hybrid NOMA/OFDMA demodulation using DFT-S-OFDM, as shown in Fig. 2(b), the received serial signals $y_{i,\mathrm{n}}$ and $y_{i,\mathrm{f}}$ of the i-th user pair are first converted to parallel via serial-to-parallel (S/P) conversion. After fast Fourier transform (FFT) and subcarrier extraction, frequency-domain equalization (FDE) is carried out. Subsequently, IDFT is performed with respect to the equalized signal of each user pair. Finally, the bit stream for the far user in each user pair can be recovered directly through QAM demapping, while the bit stream for the near user can be obtained after SIC and QAM demapping.

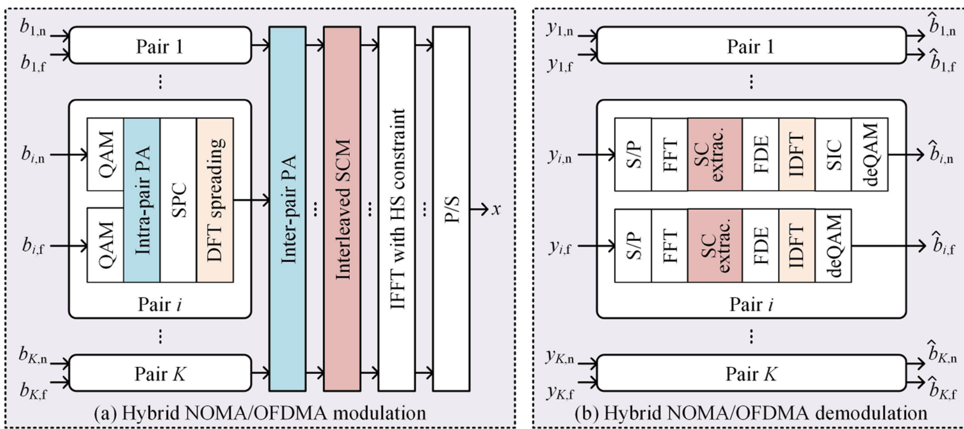

Fig. 2. Block diagram of the proposed fairness-aware hybrid NOMA/OFDMA scheme using DFT-S-OFDM with K user pairs: (a) modulation and (b) demodulation. PA: power allocation, SCM: subcarrier multiplexing, SC extrac.: subcarrier extraction.

3.2. Interleaved subcarrier multiplexing

The low-pass frequency response of a practical bandlimited multi-user VLC system inevitably causes user pair unfairness, when applying the conventional hybrid NOMA/OFDMA scheme where the subcarriers allocated to different user pairs are multiplexed in a block-by-block manner. To address this issue, we propose to use DFT-S-OFDM modulation with an interleaved subcarrier multiplexing approach for hybrid NOMA/OFDMA, where the subcarriers allocated to different user pairs are multiplexed in an interleaved manner. Figures 3(a) and (b) illustrate the transmitted OFDM spectra without and with interleaving for $K = 2$, respectively. As we can see, when interleaved subcarrier multiplexing is performed, the subcarriers allocated to each user pair are distributed across the whole frequency band. After passing through the low-pass VLC channel, the received OFDM spectra without and with interleaving for $K = 2$ are shown in Figs. 3(c) and (d), respectively. It can be clearly observed from Fig. 3(c) that the user pair 2 which is allocated with high-frequency subcarriers suffers from much more severe power attenuation than the user pair 1 which is allocated with low-frequency subcarriers. In contrast, when adopting interleaved subcarrier multiplexing, the low-pass frequency response-induced user pair unfairness can be efficiently mitigated, since the two adjacent subcarriers from two different user pairs experience comparable power attenuation when the total number of subcarriers is relatively large. Moreover, due to DFT spreading with respect to the subcarriers allocated to each user pair, subcarrier unfairness within each user pair can also be avoided.

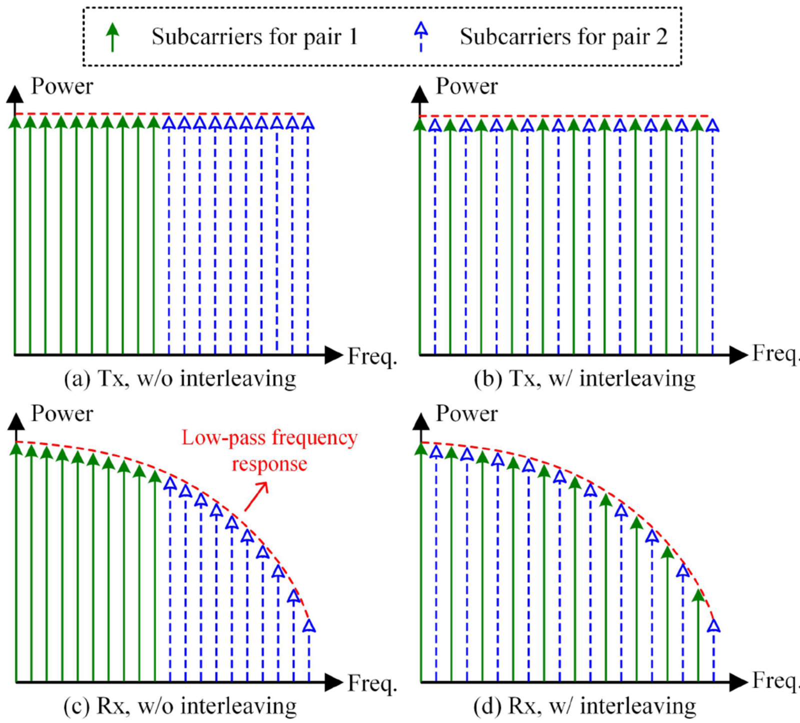

Fig. 3. Illustration of transmitted OFDM spectrum (a) without interleaving and (b) with interleaving, and received OFDM spectrum (c) without interleaving and (d) with interleaving for $K = 2$.

3.3. 2D power allocation

Besides the low-pass frequency response, the channel gain-based user pairing is another factor that can generate user pair unfairness in a practical bandlimited multi-user VLC system applying conventional hybrid NOMA/OFDMA. To ensure user fairness within each user pair and eliminate user pair unfairness due to the channel gain-based user pairing, we further propose a 2D power allocation strategy. As illustrated in Fig. 2(a), the proposed 2D power allocation strategy includes both intra-pair power allocation within each user pair and inter-pair power allocation among different user pairs. Figure 4 illustrates the transmitted OFDM spectrum with interleaved subcarrier multiplexing and inter-pair power allocation for $K = 2$.

Specifically, intra-pair power allocation is performed to guarantee user fairness within each user pair. For the i-th user pair, letting $\alpha_i = P_n^i/P_f^i$ denote the power ratio between the near and far users, the allocated powers of the near and far users can be given by

$$\begin{cases} P_n^i = \dfrac{\alpha_i P_{\text{pair}}^i}{1+\alpha_i} \\ P_f^i = \dfrac{P_{\text{pair}}^i}{1+\alpha_i} \end{cases}. \tag{3}$$

Considering that the far user is usually allocated with more power than the near user, we can have $0<\alpha_i<1$ with $i = 1, 2, \ldots, K$. Moreover, inter-pair power allocation can be further

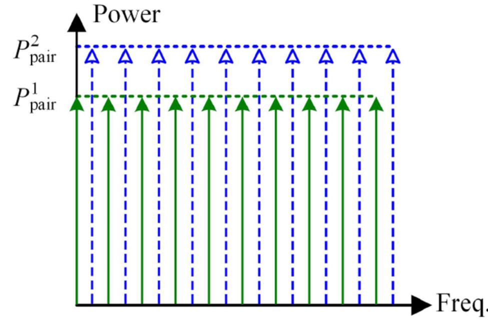

Fig. 4. Illustration of transmitted OFDM spectrum with interleaved subcarrier multiplexing and inter-pair power allocation for $K = 2$.

performed to ensure user pair unfairness among different user pairs. Letting $\beta_i = P^i_{\text{pair}}/P^{i+1}_{\text{pair}}$ denote the power ratio between the i-th user pair and the $(i+1)$-th user pair, since the i-th user pair generally has better channel conditions than the $(i+1)$-th user pair, it is reasonable to allocate more power to the $(i+1)$-th user pair and hence we can have $0<\beta_i<1$. Taking the VLC system with two pairs of users as an example, i.e., $K = 2$, the allocated powers of two user pairs are expressed by

$$\begin{cases} P^1_{\text{pair}} = \dfrac{\beta_1 P_{\text{tot}}}{1+\beta_1} \\ P^2_{\text{pair}} = \dfrac{P_{\text{tot}}}{1+\beta_1} \end{cases}, \tag{4}$$

where $P_{\text{tot}} = \sum_{i=1}^{K} P^i_{\text{pair}}$ is the total transmitted power of all the user pairs in the VLC system.

4. Experiments and results

In this section, we conduct experiments to investigate the performance of the proposed fairness-aware hybrid NOMA/OFDMA scheme in practical bandlimited multi-user VLC systems. The experimental setup of the multi-user VLC system is shown in Fig. 5(a), where the transmitted hybrid NOMA/OFDMA signal using DFT-S-OFDM modulation is first generated offline by MATLAB and then uploaded to an arbitrary waveform generator (AWG, Tektronix AFG31102) with a sampling rate of 10 MSa/s. The length of IFFT in digital OFDM modulation is 256 and a total of 88 (i.e., 2[nd] to 89[th]) subcarriers are utilized to modulate 4QAM symbols. Therefore, the bandwidth of the hybrid NOMA/OFDMA signal is about 3.4 MHz.

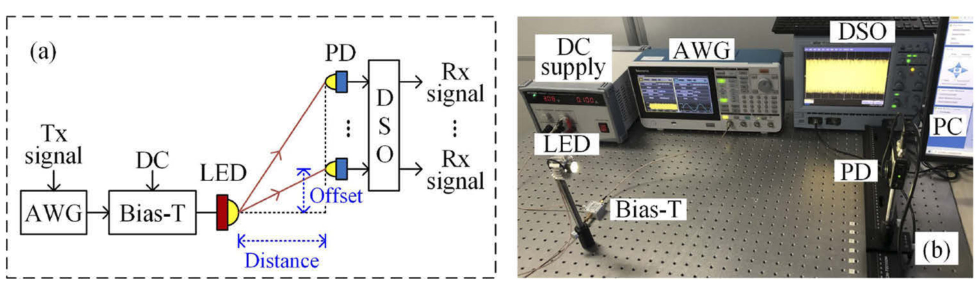

Fig. 5. (a) Experimental setup of the multi-user VLC system and (b) the photo of the testbed.

Subsequently, the AWG output signal is added with a 100-mA DC bias current via a bias-tee (bias-T, MiniCircuits, ZFBT-6GW+) and the resultant signal is used to drive a commercially

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available white LED (Luxeon Star). After free-space propagation, $2K$ users are located within the coverage of the VLC system. For simplicity and without loss of generality, we consider a four-user case in the proof-of-concept experiments, i.e., $K = 2$. Each user is equipped with a photodiode (PD, Thorlabs PDA36A2) to detect the optical signal, and we put the PD at various positions to emulate different users. Specifically, the first user is assumed to face directly towards the LED, while the rest three users have different offsets from the first user. The detected electrical signal of each user is recorded by a digital storage oscilloscope (DSO, LeCroy WaveSurfer 432) with a sampling rate of 50 MSa/s and all the recorded digital signals are further processed offline via MATLAB.

Figure 6(a) shows the measured frequency response of the VLC system using an off-the-shelf white LED. As we can see, the VLC system exhibits a typical low-pass frequency response and the corresponding -3dB bandwidth is about 1.5 MHz. As we can see, the experimental VLC system suffers from severe low-pass effect and the corresponding power attenuation at the frequency of 3.4 MHz is about 11 dB. Moreover, the received average signal-to-noise ratio (SNR) versus receiver offset at a distance of 60 cm is given in Fig. 6(b), where four receiver positions with respect to four users are considered and the corresponding receiver offsets are ranged from 0 to 9 cm with a step of 3 cm. It can be clearly observed from Fig. 6(b) that the received average SNR gradually decreases with the increase of receiver offset. In the following experiments, according to the channel gain-based user pairing approach, user 1 with a receiver offset of 0 cm and user 3 with a receiver offset of 6 cm are paired in user pair 1, while user 2 with a receiver offset of 3 cm and user 4 with a receiver offset of 9 cm are paired in user pair 2.

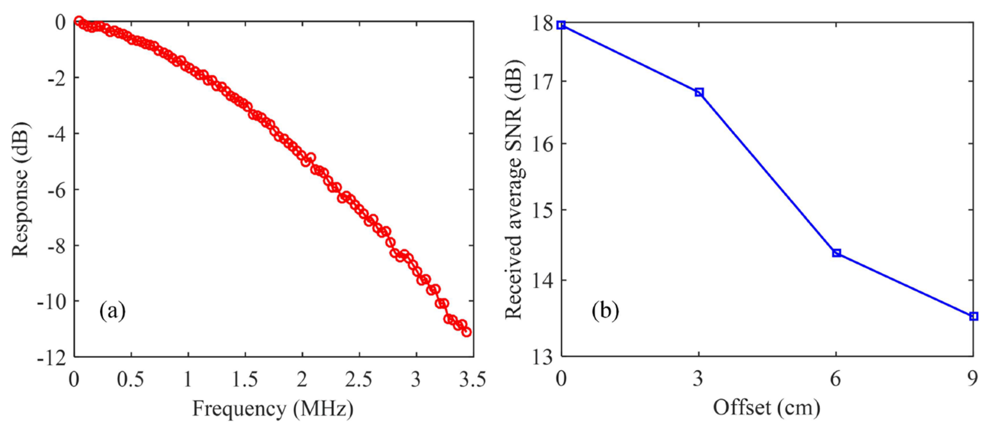

Fig. 6. (a) System frequency response and (b) received average SNR vs. receiver offset.

We first evaluate the feasibility of applying interleaved subcarrier multiplexing to address the user pair unfairness issue caused by the low-pass frequency response of the bandlimited VLC system, where the 88 data-carrying subcarriers are divided into two groups. Figure 7 shows the measured received average SNR of each subcarrier group versus the length of IFFT/FFT without and with interleaving in a point-to-point setup, where the signal bandwidth is maintained at about 3.4 MHz, the distance is 60 cm and the receiver offset is 0 cm. As can be seen, the received average SNR of each subcarrier group first rapidly increases when the IFFT/FFT length is increased from 16 to 128, which then becomes stable when the IFFT/FFT length reaches 256. This is mainly because the low-pass effect experienced by each subcarrier becomes negligible when the IFFT/FFT length reaches 256 and the received average SNR cannot be further improved by further increasing the IFFT/FFT length. Particularly, for the case without interleaving, the received average SNRs of two subcarrier groups with the IFFT/FFT length of 256 are 21.3 and 18.1 dB, respectively. Hence, an SNR difference of 3.2 dB is obtained due to the low-pass system

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frequency response. In contrast, for the case with interleaving, the two interleaved subcarrier groups have comparable SNRs when the IFFT/FFT length is relatively large, which indicates that user pair unfairness caused by the low-pass system frequency response can be efficiently mitigated by applying the proposed interleaved subcarrier multiplexing approach. Hence, the length of IFFT/FFT is set to 256 in our following experiments.

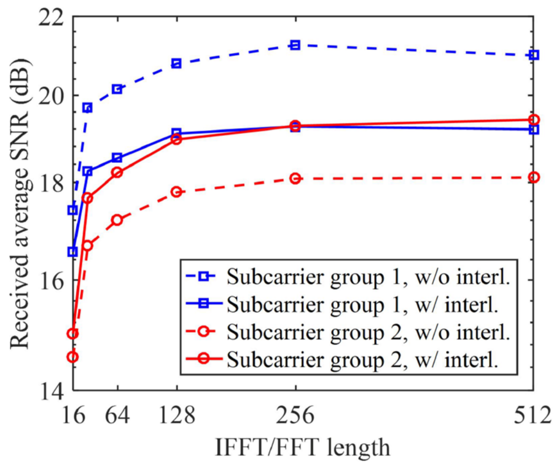

Fig. 7. Received average SNR vs. IFFT/FFT length. Interl.: interleaving.

In the next, we investigate the average BER performance of the four-user VLC system. Since intra-pair power allocation can be performed to ensure user fairness within each user pair, we first obtain the optimal intra-pair power allocation ratios for two user pairs in the four-user VLC system. Figures 8(a), (b), (c) and (d) depict the BER versus intra-pair power allocation ratio α for the far and near users in user pair 1 without interleaving, user pair 2 without interleaving, user pair 1 with interleaving and user pair 2 with interleaving, respectively, where the distance is 60 cm. As we can see, for all the four cases, the BER of the far user gradually increases with the increase of α, while the BER of the near user first decreases and then increases. Moreover, both the minimum average BER and the minimum BER difference of the far and near users are achieved when $\alpha = 0.2$. Hence, the user fairness within each user pair can be guaranteed when the intra-pair power allocation ratio α is set to 0.2 for all the four cases.

Given the optimal intra-pair power allocation ratio α for each user pair, we further obtain the optimal inter-pair power allocation ratio β to address the user pair unfairness issue induced by channel gain-based user pairing for two user pairs. Figures 9(a) and (b) show the BER versus inter-pair power allocation ratio β for two user pairs without and with interleaving, respectively, where the distance is 60 cm. It can be observed that, for both cases, the BER of user pair 1 gradually decreases with the increase of β while the BER of user pair 2 gradually increases when β is increased. For the case without interleaving, both the minimum average BER and the minimum BER difference are achieved when $\beta = 0.4$. However, for the case with interleaving, both the minimum average BER and the minimum BER difference are obtained when $\beta = 0.9$. As a result, the optimal β becomes much larger when interleaved subcarrier multiplexing is applied. Note that a smaller β indicates a much unbalanced power allocation between two user pairs, while a larger β means that the two user pairs can have more comparable powers. Considering the LED nonlinearity in practical VLC systems, the system with a smaller β suffers from much more severe nonlinear distortion than that with a larger β. Therefore, the application of interleaved subcarrier multiplexing can enhance the system tolerance against LED nonlinearity.

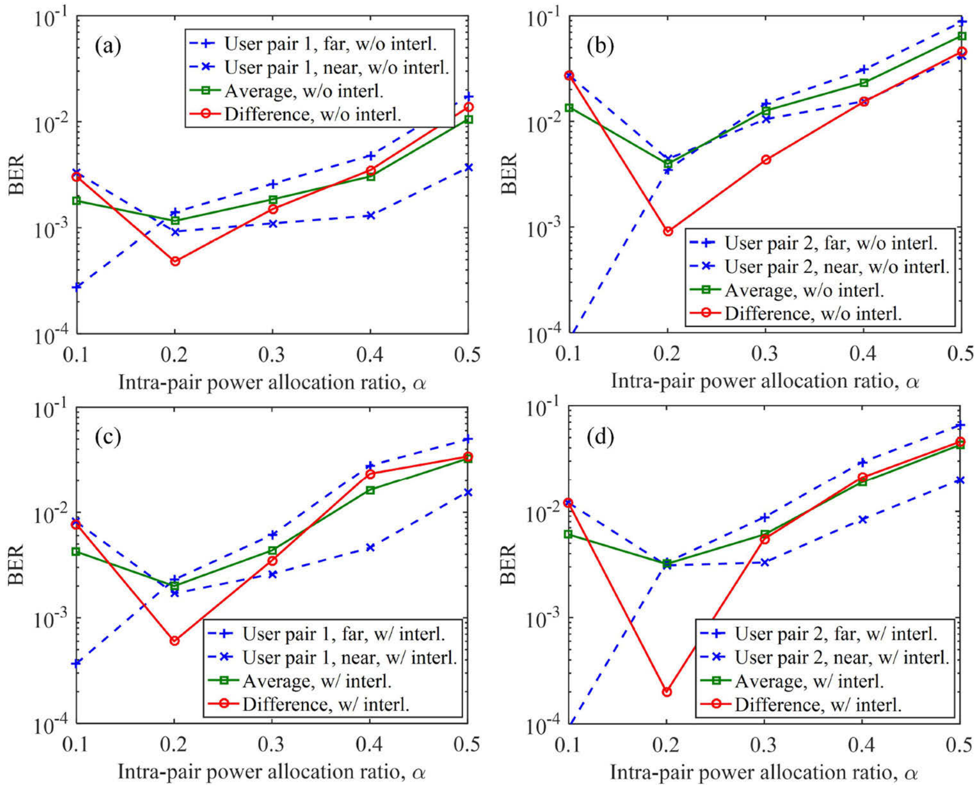

Fig. 8. BER vs. intra-pair power allocation ratio α for (a) user pair 1 without interleaving, (b) user pair 2 without interleaving, (c) user pair 1 with interleaving, and (d) user pair 2 with interleaving. Interl.: interleaving.

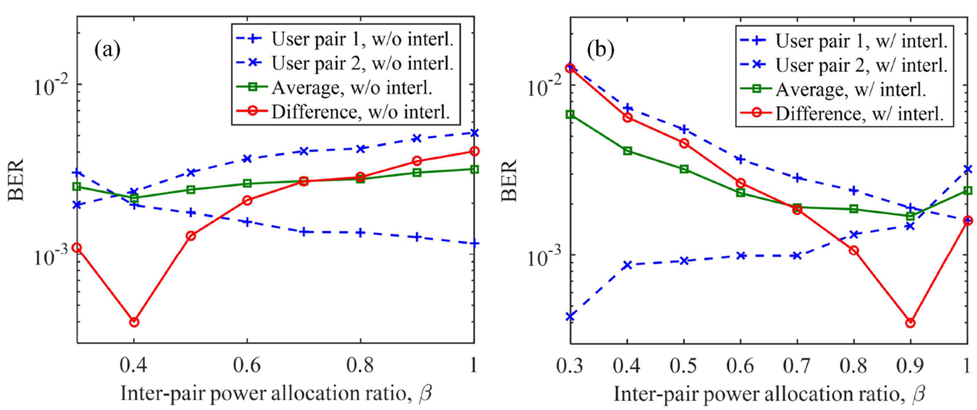

Fig. 9. BER vs. inter-pair power allocation ratio β for two user pairs (a) without interleaving and (b) with interleaving. Interl.: interleaving.

Finally, we evaluate the average BER versus transmission distance for four different schemes and the results are shown in Fig. 10. For simplicity, a fixed α value of 0.2 is applied for intra-pair power allocation of two user pairs for both the cases without and with interleaving. Moreover, a fixed β value of 0.4 is adopted for inter-pair power allocation without interleaving, while a fixed β value of 0.9 is used for inter-pair power allocation with interleaving. For the VLC system

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using conventional hybrid NOMA/OFDMA, i.e., only intra-pair 1D power allocation without interleaving, the maximum distance is about 58.6 cm to meet the 7% forward error correction (FEC) coding requirement of BER = 3.8×10^{-3}. For the hybrid NOMA/OFDMA scheme with intra-pair 1D power allocation and interleaving, the maximum distance is increased to 61.9 cm. For the hybrid NOMA/OFDMA scheme with 2D power allocation without interleaving, the maximum distance is further extended to 63.1 cm. Moreover, when the proposed fairness-aware hybrid NOMA/OFDMA scheme with 2D power allocation and interleaving is used, the maximum distance is further extended to 65.8 cm. As we can see, a remarkable 12.3% distance extension can be achieved by the proposed fairness-aware hybrid NOMA/OFDMA scheme with 2D power allocation and interleaving in comparison to the conventional hybrid NOMA/OFDMA scheme with 1D power allocation without interleaving. Furthermore, a slight distance extension of 4.3% is obtained by the hybrid NOMA/OFDMA scheme with 2D power allocation and interleaving in comparison to that without interleaving. Although a much smaller β can be adopted with interleaving, as can be seen from Fig. 9, the corresponding performance gain is not significant, which is mainly because the nonlinearity of our experimental system is not very severe. It is believed that a much more significant performance gain can be obtained when the system has much more severe nonlinearity.

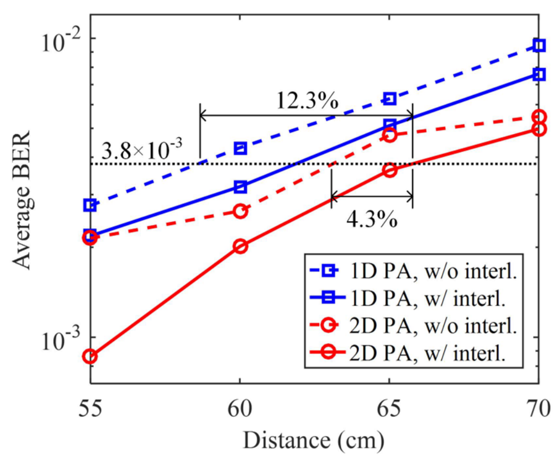

Fig. 10. Average BER vs. distance for four different schemes. Interl.: interleaving.

Although the proposed fairness-aware hybrid NOMA/OFDMA scheme has been evaluated in a simple four-user VLC system, it is generally applicable to a practical VLC system with an arbitrary number of users. When there are more than two user pairs in the VLC system, interleaved subcarrier multiplexing can also be performed, but a relatively large IFFT/FFT length might be used to ensure satisfactory interleaving performance. As our future work, more advanced interleaving schemes will be designed to guarantee the performance without using IFFT/FFT with a large size.

5. Conclusion

In this paper, we have proposed and experimentally demonstrated a novel fairness-aware hybrid NOMA/OFDMA scheme using DFT-S-OFDM for practical bandlimited multi-user VLC systems. Compared with conventional hybrid NOMA/OFDMA scheme, the proposed fairness-aware hybrid NOMA/OFDMA scheme not only adopts an interleaved subcarrier multiplexing approach to overcome the low-pass system frequency response-induced user pair unfairness among different user pairs, but also applies a 2D power allocation strategy to ensure both the fairness of users within each user pair and the fairness of user pairs. The obtained experimental results verify that the proposed fairness-aware hybrid NOMA/OFDMA scheme can efficiently improve the BER performance of a practical four-user VLC system using a commercially available white LED. It is also expected that a much more significant performance gain can be achieved by the proposed fairness-aware hybrid NOMA/OFDMA scheme when the system exhibits more severe nonlinearity. Therefore, the proposed fairness-aware hybrid NOMA/OFDMA scheme is promising for practical multi-user VLC systems.

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Data availability. The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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