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Channel-Aware Subcarrier Allocation for Hybrid NOMA/OFDMA-Based Bandlimited Multi-User VLC Systems

Yuru Tang
School of Microelectronics and Communication Engineering
Chongqing University.
Chongqing 400044, China
202012131116@cqu.edu.cn

Chen Chen
School of Microelectronics and Communication Engineering
Chongqing University.
Chongqing 400044, China
c.chen@cqu.edu.cn

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***Abstract*—In this paper, we propose a novel channel-aware subcarrier allocation scheme for hybrid non-orthogonal multiple access/orthogonal frequency division multiplexing access (NOMA/OFDMA)-based bandlimited multi-user visible light communication (VLC) systems. In the proposed channel-aware subcarrier allocation scheme, low-frequency (LF) subcarriers are allocated to the user pairs with worse channel conditions, while high-frequency (HF) subcarriers are allocated to the user pairs with better channel conditions. By using the proposed channel-aware subcarrier allocation scheme, the low-pass (LP) frequency response-induced power difference and the diverse channel conditions-induced power difference can be efficiently mitigated. Simulation results show that, in a bandlimited four-user VLC system applying the proposed channel-aware subcarrier allocation scheme, a remarkable 3.3-dB transmitted signal-to-noise (SNR) reduction at an overall bit error rate (BER) of 10^{-3} can be obtained in comparison to the benchmark schemes.**

***Index Terms*—Visible light communication (VLC), orthogonal frequency division multiplexing access (OFDMA), non-orthogonal multiple access (NOMA).**

I. Introduction

Visible light communication (VLC) employing commercially available light emitting diodes (LEDs) has been considered as an essential enabling technology for the sixth generation (6G) mobile networks and the Internet of Things (IoT) systems [1]–[3]. Although VLC has many merits such as low-cost front-ends, abundant and license-free spectrum resources, enhanced physical-layer security and no electromagnetic interference (EMI) radiation, the modulation bandwidth of off-the-shelf LEDs is only typically about a few MHz [4].

To improve the capacity of bandlimited multi-user VLC systems, loads of capacity-enhancing techniques have been proposed in the literature, including pre-equalization [5], spectral-efficient multiple access [6], multiple-input multiple-output (MIMO) transmission [7], and so on. Among them, multiple access is very important for VLC systems to support multiple users, which can be generally categorized into two parts. One part is orthogonal multiple access (OMA) where different users are assigned with orthogonal time or frequency resources. Specifically, orthogonal frequency division multiple access (OFDMA) is prominent as to be an OMA scheme for multi-user VLC systems [8], [9]. The other is non-orthogonal multiple access (NOMA) in which different users employ all the time and frequency resources via power domain superposition coding (SPC) and successive interference cancellation (SIC) [10], [11]. To accommodate numerous users and improve the spectral efficiency, a hybrid NOMA/OFDMA scheme is ordinarily proposed in multi-user VLC systems [12]. In the hybrid NOMA/OFDMA-based multi-user VLC system, users are divided into user pairs. NOMA is applied for intra-pair multiple access between different users in one user pair, while OFDMA is applied for inter-pair multiple access among different user pairs. Moreover, as a simple but efficient user pairing, channel gain-based user pairing has been widely adopted to pair the users in a hybrid NOMA/OFDMA-based multi-user VLC system [13].

Generally, the overall system frequency response exhibits a typical low-pass (LP) profile in practical VLC systems. The LP frequency response might cause power difference among different user pairs, due to a more severe power attenuation to the user pair occupying a high-frequency (HF) subcarriers block than that occupying a low-frequency (LF) subcarriers block. Moreover, owing to the use of channel gain-based user pairing, the user pairs also inevitably suffer from power difference caused by their diverse channel conditions. As a result, the fairness of user pairs might be degraded due to the power difference induced by both the LP frequency response of the VLC system and the diverse channel conditions of different user pairs. For the sake of fairness among different user pairs, we have previously proposed a fairness-aware hybrid NOMA/OFDMA scheme by using subcarrier interleaving and two-dimension (intra-pair and inter-pair) power allocation [12]. Nevertheless, the inter-pair power allocation is probably much more vulnerable to LED nonlinearity due to the unbalanced power allocation between different user pairs, and the two-dimension power allocation inevitably exhibits a

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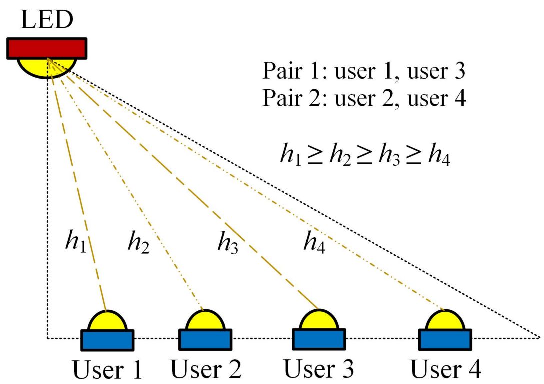


Fig. 1. Illustration of a four-user VLC system using hybrid NOMA/OFDMA.

relatively high complexity. Hence, in this paper, we propose a novel channel-aware subcarrier allocation scheme to address the above-mentioned issues for hybrid NOMA/OFDMA-based bandlimited multi-user VLC systems. The superiority of the proposed channel-aware subcarrier allocation scheme over the benchmark schemes has been successfully verified by simulation results.

II. System Model

In this section, we first introduce the channel model of the VLC systems, and then discuss the principle of user pairing and power allocation when applying hybrid NOMA/OFDMA. Finally, we present our proposed channel-aware subcarrier allocation scheme for hybrid NOMA/OFDMA-based bandlimited multi-user VLC systems.

A. Channel Model

Fig. 1 illustrates a four-user case as an example of the multi-user VLC system using hybrid NOMA/OFDMA. Without loss of generality, we consider $2K$ users in the system. Moreover, h_k ($k = 1, 2, \cdots, 2K$) denotes the line-of-sight (LOS) channel gain between the LED and the photodetector (PD) of the k-th user, which is calculated by

$$h_k = \frac{(l+1)\rho A}{2\pi d_k^2} \cos^m(\psi_n) T(\phi_k) g(\phi_k) \cos(\phi_k), \tag{1}$$

where $l = -\ln 2 / \ln(\cos(\Psi))$ denotes the order of Lambertian emission and Ψ is the semi-angle at half power of the LED; ρ is the PD responsivity and A is the PD active area; d_k denotes the distance between the LED and the PD of the k-th user; ψ_k is the emission angle and ϕ_k is the incident angle; $T(\phi_k)$ and $g(\phi_k) = \frac{r^2}{\sin^2 \Phi}$ represent the gain of the optical filter and the gain of the optical lens, respectively. Specifically, r is the refractive index and Φ is the half-angle field-of-view (FOV) of the optical lens. Note that if the incident light is outside the FOV of the receiver, h_k becomes zero.

Moreover, since the additive noise in the VLC system typically includes both shot and thermal noises, a real-valued zero-mean additive white Gaussian noise (AWGN) with power $Pn = N_0 B$ can be a general model, where N_0 denotes the noise power spectral density (PSD) and B denotes the total available modulation bandwidth.

B. User Pairing and Power Allocation

In hybrid NOMA/OFDMA-based multi-user VLC systems, users are usually first divided into pairs and channel gain-based user pairing is adopted [13]. Generally, the channel gains of the $2K$ users can be sorted in the descending order:

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

The $2K$ users can be firstly divided into two groups based on the above user ordering: the first group G_n and the second group G_f. Specifically, G_n consists of the high-channel-gain users starting from user 1 to user K, and G_f contains the low-channel-gain users starting from user $K + 1$ to user $2K$ [12]. Subsequently, user pairing can be performed in the following manner: $U^i_{\text{pair}} = [G_n(i), G_f(i)]$. In Fig. 1, we define the user pair with better channel conditions as pair 1 and the user pair with worse channel conditions as pair 2. Moreover, we assume equal bandwidth allocation among different user pairs. Given a modulation bandwidth B and K user pairs, the achievable bandwidth of each user pair is given by $B_{\text{pair}} = B/K$.

SPC can be performed with the two users within each user pair. The near and far users in the i-th ($i = 1, 2, \cdots, K$) user pair can be denoted by x^i_n and x^i_f, respectively. The superposed electrical signal of the i-th user pair can be expressed by

$$x_i = \sqrt{P^i_n} x^i_n + \sqrt{P^i_f} x^i_f, \tag{3}$$

where P^i_n and P^i_f represent the allocated electrical powers to the near and far users in the i-th user pair, respectively. And $P_e = P^i_n + P^i_f$ represents the total allocated electrical power to the i-th user pair.

Moreover, better user fairness within each user pair can be assured by performing power allocation. For the i-th user pair, the power ratio between the near and far users can be denoted by $\alpha_i = P^i_n / P^i_f$ and the allocated electrical powers of near and far users can be obtained by

$$\begin{cases} P^i_n = \dfrac{\alpha_i P_e}{1+\alpha_i} \\ P^i_f = \dfrac{P_e}{1+\alpha_i} \end{cases}, \tag{4}$$

since more power is usually allocated to the far user, we can have $0 < \alpha_i < 1$.

C. Subcarrier Allocation

Figs. 2(a), (b) and (c) illustrate the received orthogonal frequency division multiplexing (OFDM) spectra with different subcarrier allocation schemes for $K = 2$. In Scheme 1, as shown in Fig. 2(a), pair 1 is allocated with LF subcarriers and pair 2 is allocated with HF subcarriers. Pair 2 with Scheme 1 has less allocated power since subcarriers allocated to the HF band suffer much more severe power attenuation. For Scheme 1, the power difference between two user pairs is

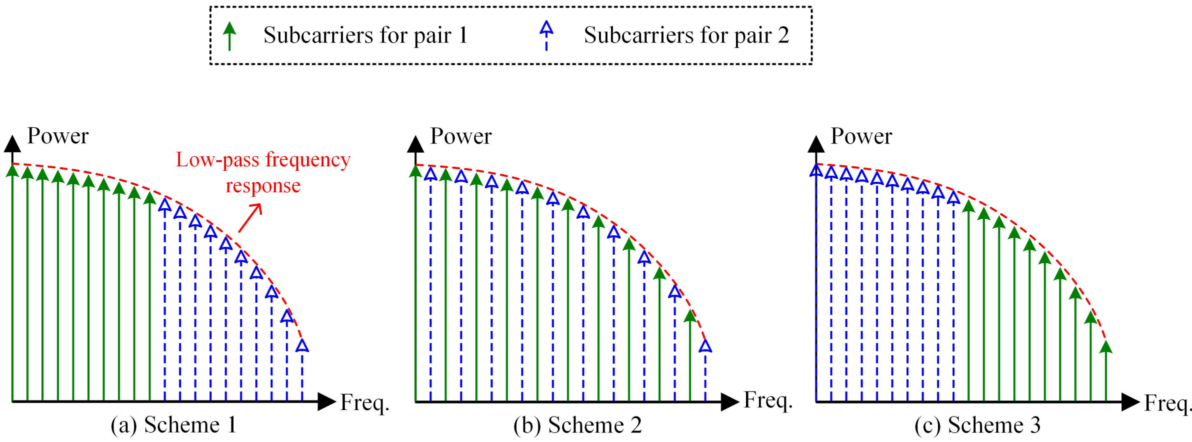


Fig. 2. Illustration of transmitted OFDM spectrum: (a) Scheme 1: LF subcarriers allocated to pair 1 and HF subcarriers allocated to pair 2, (b) Scheme 2: interleaved subcarrier allocation for pair 1 and pair 2, and (c) Scheme 3: LF subcarriers allocated to pair 2 and HF subcarriers allocated to pair 1 for $K = 2$.

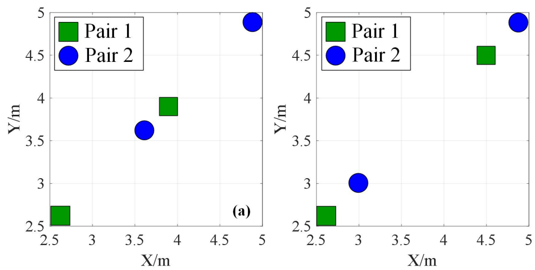


Fig. 3. User pairs in different channel conditions: (a) distinctive and (b) similar channel conditions.

comparatively large. While in Scheme 2, as shown in Fig. 2(b), different user pairs are allocated with interleaved subcarriers. When the total number of subcarriers is considerably large, LP frequency response-induced power difference can be alleviated since the adjacent subcarriers of two user pairs experience comparable power attenuation. However, the diverse channel conditions-induced power difference caused by different user locations is not concerned. To mitigate LP frequency response-induced power difference and the diverse channel conditions-induced power difference, Scheme 3 with LF subcarriers allocated to pair 2 and HF subcarriers allocated to pair 1 as shown in Fig. 2(c) is adopted. By exchanging the subcarrier locations of each user pair from Fig. 2(a), it can efficiently mitigate the power difference of each user pair since pair 2 with worse channel condition obtains more allocated power with better frequency response.

III. Simulation Results

In this section, we evaluate our proposed channel-aware subcarrier allocation scheme and compare the benchmark schemes in hybrid NOMA/OFDMA-based bandlimited four-user VLC systems. In our simulations, we consider an indoor room with a dimension of 5 m $\times$ 5 m $\times$ 3 m, where the LED is located in the center of the ceiling and the receiving plane is 0.85 m above the floor. We assume two different channel

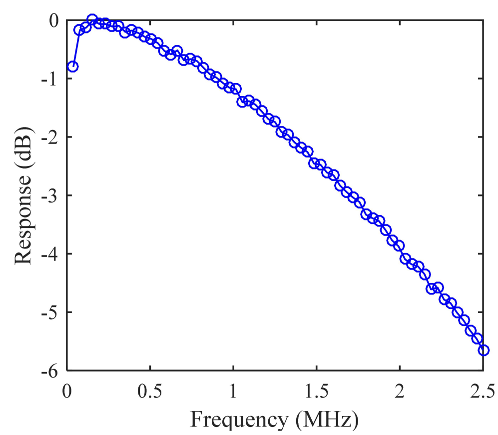
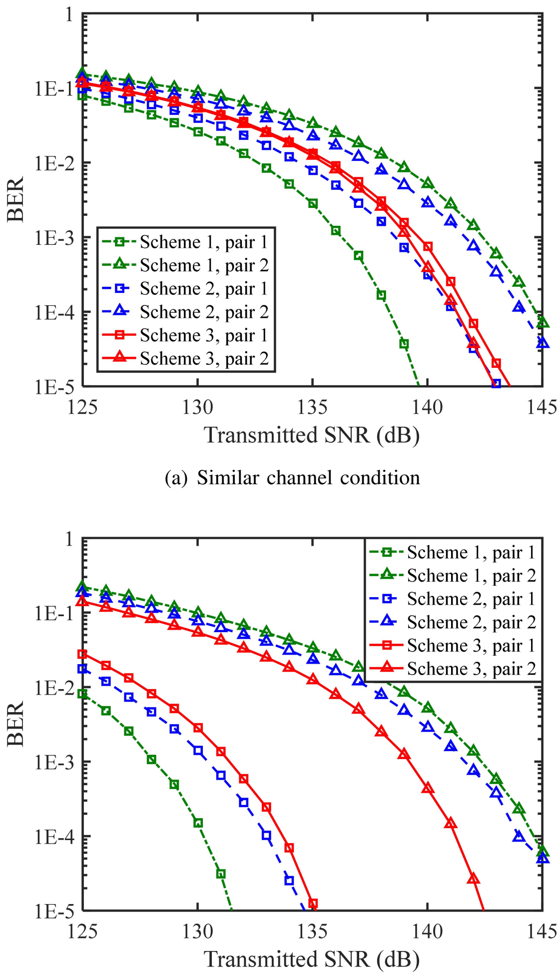


Fig. 4. LP frequency response of the system.

conditions: one is the distinctive channel condition as shown in Fig. 3(a), and the other is the similar channel condition as shown in Fig. 3(b). The LED has the 70° semi-angle at half power and each user has equipped a photodiode (PD) with 0.53 A/W responsivity and 1 cm^2 active area. Meanwhile, the refractive index is 1.5 and the half-angle FOV of the optical lens is 70°. The signal bandwidth and the noise PSD are 2.5 MHz and 10^{-22} A^2/Hz, respectively. Figs. 4 shows a typical LP frequency response by using an off-the-shelf white LED in the VLC system. Moreover, the corresponding -3dB bandwidth is about 1.5 MHz.

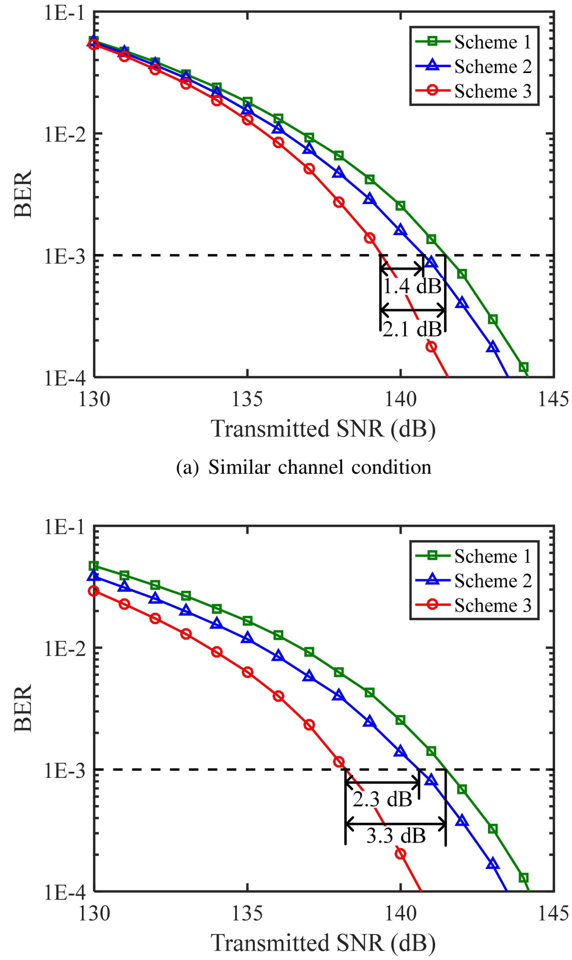
Figs. 5(a) and (b) show the user pair BER versus the transmitted SNR for different subcarrier allocation schemes with similar and distinctive channel conditions, respectively. It can be observed from Fig. 5(a) that SNR gaps of each user pair in the similar channel condition for Scheme 1, Scheme 2 and Scheme 3 at BER = 10^{-3} are 6.1, 3 and 0.5 dB, respectively. Specifically, a smaller SNR gap implies better fairness of each user pair, and our proposed Scheme 3 obtains the minimum SNR gap. Likewise, the BER performance in the



(a) Similar channel condition

(b) Distinctive channel condition

Fig. 5. User pair BER vs. transmitted SNR with two different channel conditions: (a) similar channel condition and (b) distinctive channel condition.



(a) Similar channel condition

(b) Distinctive channel condition

Fig. 6. Overall BER vs. transmitted SNR with two different channel conditions: (a) similar channel condition and (b) distinctive channel condition.

distinctive channel condition has a similar conclusion as shown in Fig. 5(b). SNR gaps of each user pair in the distinctive channel condition for Scheme 1, Scheme 2 and Scheme 3 at BER = 10^{-3} are 14.3, 11.1 and 7.8 dB, respectively. As a result, the minimum SNR gap of user pairs can be ensured by applying Scheme 3 with each user pair under both similar and distinctive channel conditions.

Figs. 6(a) and (b) show the overall BER of user pairs versus the transmitted SNR for different subcarrier allocation schemes with similar and distinctive channel conditions, respectively. Specifically, compared with Scheme 1, the required transmitted SNR of Scheme 3 to achieve an overall BER of 10^{-3} is reduced by 2.1 dB and 3.3 dB in similar and distinctive channel conditions, respectively. While compared with Scheme 2, the required transmitted SNR of Scheme 3 to achieve an overall BER of 10^{-3} is reduced by 1.4 dB and 2.3 dB in similar and distinctive channel conditions, respectively. It can be observed that Scheme 3 outperforms other benchmark schemes in both similar and distinctive channel conditions.

IV. Conclusion

In this paper, we have proposed and evaluated a novel channel-aware subcarrier allocation scheme for hybrid NOMA/OFDMA-based bandlimited multi-user VLC systems. In the proposed channel-aware subcarrier allocation scheme, the LF subcarriers are allocated to user pairs with worse channel conditions and the HF subcarriers are allocated to user pairs with better channel conditions. Compared with the benchmark schemes, the proposed channel-aware subcarrier allocation scheme mitigates both the LP frequency response-induced power difference and diverse channel conditions-induced power difference. Simulation results verify that the proposed channel-aware subcarrier allocation scheme can efficiently improve the BER performance of a bandlimited four-user VLC system. Therefore, the proposed hybrid NOMA/OFDMA-based on channel-aware subcarrier allocation scheme can be a promising candidate for bandlimited multi-user VLC systems.

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