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Flexible-Rate SIC-Free NOMA for Downlink VLC Based on Constellation Partitioning Coding

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***Abstract*—Visible light communication (VLC) systems utilizing conventional superposition coding/successive interference cancellation (SPC/SIC)-based non-orthogonal multiple access (NOMA) suffer from the error propagation effect due to imperfect SIC. In this letter, we propose a flexible-rate SIC-free NOMA technique for downlink VLC systems, based on constellation partitioning coding (CPC) and uneven constellation demapping (UCD). By using CPC/UCD, SIC is not required and hence error propagation can be eliminated in NOMA-based VLC systems. Moreover, by selecting a proper bit allocation scheme, flexible-rate multiple access can be supported in the VLC system applying CPC/UCD-based NOMA. Proof-of-concept two-user VLC experiments verify that, compared with conventional SPC/SIC-based NOMA, the bit error rate performance of the near user can be greatly improved by using CPC/UCD-based NOMA, and hence the effective power allocation ratio range can be substantially extended.**

***Index Terms*—Visible light communication, non-orthogonal multiple access, constellation partitioning coding.**

I. Introduction

In recent years, visible light communication (VLC) using white light-emitting diodes (LEDs) has gained tremendous attention, due to the dual use of white LEDs for simultaneous illumination and communication in indoor environments [1]. As a complementary technology to traditional radio-frequency technologies such as Wi-Fi, VLC, also known as Li-Fi [2], has many inherent advantages such as huge and unregulated spectrum, low-cost front-ends and no electromagnetic interference emission [3]. Nevertheless, the achievable capacity of VLC systems is far beyond the expectations, due to the limited modulation bandwidth of off-the-self white LEDs [4]. To overcome the bandwidth limitation, many capacity-enhancing techniques have been proposed so far, such as bandwidth extension based on pre- or post-equalization in the frequency domain [5], [6], spectral efficiency improvement using orthogonal frequency division multiplexing (OFDM) with high-order quadrature amplitude modulation (QAM) constellations [7], diversity or multiplexing gain achievement via multiple-input multiple-output (MIMO) transmission [8]–[10], etc.

As a promising candidate for 5G systems, power-domain non-orthogonal multiple access (NOMA) has been considered for capacity improvement in downlink VLC systems. In [11], Marshoud *et al*. applied NOMA in VLC systems and proposed a gain ratio power allocation strategy. Advanced power allocation strategies were proposed for NOMA-based VLC systems by considering user fairness and the quality of service (QoS) constraint [12], [13]. An in-depth evaluation of NOMA in VLC systems was further performed by Yin *et al*. in [14]. In [15], NOMA was applied in MIMO VLC systems. In these works, superposition coding and successive interference cancellation (SPC/SIC) are adopted and perfect SIC is generally assumed. However, perfect SIC cannot always be guaranteed in practical NOMA-based VLC systems. It has been shown that imperfect SIC might cause error propagation and hence degrade the bit error rate (BER) performance [16]. To address this issue, Li *et al*. proposed symmetric SPC with symmetric SIC for error propagation mitigation [17]. Nevertheless, the error propagation effect cannot be completely eliminated since SIC is still required and only fixed-rate multiple access can be supported.

Moreover, NOMA has also been considered in uplink VLC systems. In [18], phase pre-distortion was applied to improve the BER performance of uplink NOMA-based VLC systems. In [19], a joint detection scheme was presented, which is SIC-free and maximum likelihood optimal. Nevertheless, according to [20], joint detection requires bit-level joint maximum likelihood calculations and hence has relatively high complexity.

In this letter, for the first time, we propose and demonstrate a novel NOMA technique based on constellation partitioning coding (CPC) and uneven constellation demapping (UCD) for downlink VLC systems. By using CPC/UCD, user decoding can be realized without SIC and hence the error propagation effect due to imperfect SIC can be eliminated, resulting in improved BER performance. Moreover, by selecting a proper bit allocation scheme, flexible-rate multiple access can also be achieved. The feasibility of applying the proposed flexible-rate SIC-free NOMA technique in practical VLC systems has been successfully verified through two-user VLC experiments.

II. Two-User VLC Using CPC/UCD-Based NOMA

In this section, we introduce a downlink VLC system with two users using the proposed flexible-rate SIC-free NOMA technique based on CPC and UCD. Fig. 1 illustrates the block diagram of the system. As we can see, the input bits of both the near and far users are fed into the CPC block to generate the CPC-coded constellation and the detailed principle of CPC is described in Section II.A. Subsequently, inverse fast Fourier transform (IFFT) is executed and Hermitian symmetry (HS) is imposed to obtain a real-valued OFDM signal. The resultant digital signal is converted to an analog signal via digital-to-analog conversion (DAC) and a direct-current (DC) bias is added to ensure the non-negativity of the LED-driving signal.

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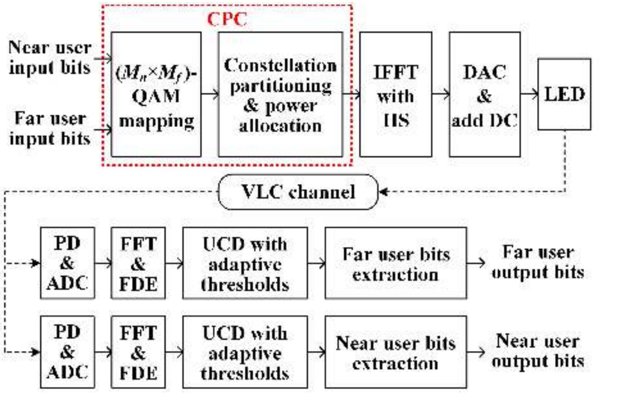

Fig. 1. Block diagram of a downlink two-user VLC system using CPC-based flexible-rate SIC-free NOMA.

After propagation over the indoor VLC channel, the light is converted into an electrical analog signal via photodetection (PD) at each user. The obtained analog signals are converted back to digital signals via analog-to-digital conversion (ADC). In the following, fast Fourier transform (FFT) and frequency-domain equalization (FDE) are performed to obtain the respective constellations of both users. At each user, uneven Gray-coded QAM demapping is first performed and then the desired bits for each user are extracted. The principle of UCD with adaptive thresholds is discussed in Section II.B.

A. Constellation Partitioning Coding (CPC)

As shown in Fig. 1, the general rule of CPC for two-user NOMA consists of two parts. The first part is Gray-coded $(M_n \times M_f)$-QAM mapping, where M_n and M_f denote the orders of QAM constellations desired by the near user and the far user, respectively. The second part includes two steps: one is constellation partitioning which is performed to adaptively partition a Gray-coded QAM constellation into multiple sub-constellations according to a pre-defined bit allocation scheme, and the other is power allocation which is executed according to a pre-defined power allocation strategy. In the following, without loss of generality, we introduce CPC by taking the 8-QAM constellation as an example, i.e. $M_n \times M_f = 8$.

The Gray-coded 8-QAM constellation for CPC is depicted in Fig. 2(a), where there is only a one-bit difference between any two adjacent constellation points. However, for the non-Gray-coded 8-QAM constellation generated by SPC, as shown in Fig. 2(b), there is a two-bit difference between the constellation points representing bits “010” and “100”, and the ones representing bits “011” and “101”. Therefore, the near user using SPC/SIC-based NOMA might suffer from the adverse effect of severe error propagation due to the non-orthogonality of the superposed constellation [17].

When using 8-QAM constellation, totally three bits ($b_1 b_2 b_3$) can be transmitted per 8-QAM symbol. For a two-user VLC system, the three bits are allocated to the near user and the far user. Specifically, two bit allocation schemes can be adopted according to users' data rate requirements: (1) the near user is allocated with two bits while the far user is allocated with one bit, i.e., $M_n = 4$ and $M_f = 2$; (2) the near user is allocated

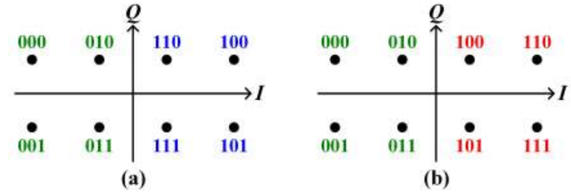

Fig. 2. Comparison of (a) Gray-coded 8-QAM constellation for CPC and (b) non-Gray-coded 8-QAM constellation generated by SPC.

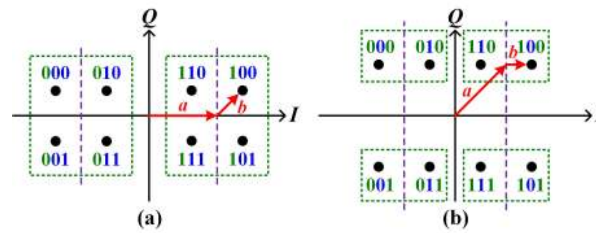

Fig. 3. Flexible-rate partitioning of Gray-coded 8-QAM constellation by CPC for (a) $b_n = b_2 b_3$, $b_f = b_1$ and (b) $b_n = b_2$, $b_f = b_1 b_3$.

with one bit while the far user is allocated with two bits, i.e., $M_n = 2$ and $M_f = 4$. Hence, flexible-rate multiple access can be achieved by employing CPC/UCD-based NOMA.

Let b_n and b_f denote the bit/bits allocated to the near and far users, respectively. Fig. 3(a) illustrates the first bit allocation scheme with $b_n = b_2 b_3$ and $b_f = b_1$, where the 8-QAM constellation is divided into two 4-QAM subconstellations. Fig. 3(b) shows the second bit allocation scheme with $b_n = b_2$ and $b_f = b_1 b_3$, where the 8-QAM constellation is partitioned into four binary phase-shift keying (BPSK) subconstellations. As shown in Figs. 3(a) and (b), for both bit allocation schemes, the electrical powers allocated to the far user and the near user are a^2 and b^2, respectively. Hence, the power allocation ratio between the electrical powers allocated to the far user and the near user for both bit allocation schemes is obtained by

$$\rho = \frac{a^2}{b^2}. \tag{1}$$

Therefore, the resultant $(M_n \times M_f)$-QAM symbol after CPC can be represented by

$$x_{CPC} = \sqrt{\frac{P}{1+\rho}} x_n + \sqrt{\frac{\rho P}{1+\rho}} x_f, \tag{2}$$

where x_n and x_f are the symbols desired by the near and far users, respectively, and P is the total input electrical power for the two users at the LED transmitter.

Although only 8-QAM constellation is considered here as an example, the general rule of CPC for two-user NOMA is applicable to a QAM constellation with an arbitrary order, i.e., the values of M_n and M_f can be arbitrary.

B. Uneven Constellation Demapping (UCD)

Due to the use of CPC, the transmitted constellation remains to be Gray-coded and hence maintains the quasi-orthogonality.

Therefore, UCD can be performed to recover the output bits for both the near and far users. Unlike the conventional even Gray-coded QAM demapping which uses fixed thresholds, adaptive thresholds are required when performing UCD. It can be observed from Fig. 3 that the adaptive thresholds can be obtained by slightly modifying the fixed thresholds of conventional even Gray-coded QAM constellation. Specifically, the threshold sets adopted to decode the CPC-coded 8-QAM constellation are given as follows:

$$\mathcal{T}=\begin{cases}\{I=0;Q=0,\pm a\}, & \text{if } b_n=b_2b_3, b_f=b_1\\ \{I=0;Q=0,\pm\frac{a}{\sqrt{2}}\}, & \text{if } b_n=b_2, b_f=b_1b_3\end{cases}. \quad (3)$$

Since three bits can be obtained from each input symbol, bit extraction is required by users to recover their desired output bits. Similarly, the principle of UCD can be easily generalized to a QAM constellation with an arbitrary order.

It can be found that SIC is no longer required when adopting CPC with UCD. Consequently, the adverse error propagation effect induced by imperfect SIC can be successfully eliminated due to the quasi-orthogonality of the received constellation.

III. Experimental Setup and Results

To verify the feasibility of applying the CPC/UCD-based NOMA technique in practical downlink VLC systems, a proof-of-concept experimental demonstration is conducted here and the experimental setup of a two-user VLC system is depicted in Fig. 4. The transmitted two-user OFDM-NOMA signal with a power allocation ratio ρ as defined by (1) is generated offline by MATLAB and uploaded to an arbitrary waveform generator (AWG, Tabor WW2074) with a sampling rate of 50 MSa/s. Subsequently, the obtained signal is added with a 300-mA DC bias current via a bias-tee (bias-T) and the resultant signal is then used to drive a white LED (Luxeon SR-12 Rebel Star/O). After 100-cm free-space propagation, the light is detected by two users, where the near user is assumed to face towards the LED while the far user has an position offset of 10 cm from the near user. Each user is individually equipped with a blue filter (BF) and an avalanche photodiode (APD, Hamamatsu S8664-50K). The APD has a responsivity of about 15 A/W at 450 nm and an active area of 19.6 mm^2. Due to the hardware limitation, we adjust the position of the receiver to detect the signals of two users. The detected signals are recorded by a mixed domain oscilloscope (MDO, Tektronix MDO3104) with a sampling rate of 250 MSa/s and further processed offline.

The OFDM-NOMA signal is generated offline with an IFFT size of 512, where totally 154 (2$^{\text{nd}}$ to 155$^{\text{th}}$) subcarriers are utilized to modulate valid data. Therefore, the bandwidth of the OFDM-NOMA signal is 15 MHz. When using 8-QAM constellation, the sum data rate of the two users is 45 Mbit/s. No cyclic prefix (CP) is used and a total of 200 symbols are transmitted through the VLC system for BER measurement. Inset (a) in Fig. 4 shows the electrical spectrum of the received signal. The photos of the transmitter part and the receiver part are shown by insets (b) and (c), respectively.

In the following, we evaluate the BER performance of the two-user VLC system using the conventional SPC/SIC-

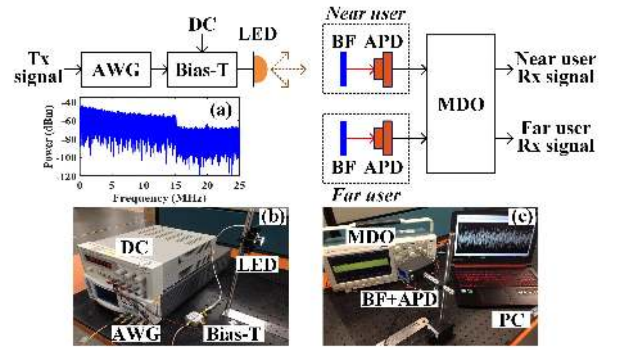

Fig. 4. Experimental setup of the two-user VLC system. Insets: (a) electrical spectrum of the received OFDM-NOMA signal, (b) photo of the transmitter part, and (c) photo of the receiver part.

based NOMA and the proposed CPC/UCD-based NOMA. Moreover, to demonstrate that flexible rates can be achieved for the two users, two bit allocation schemes as discussed in Section II.A are investigated. Fig. 5(a) shows the measured BER as a function of power allocation ratio ρ for 8-QAM constellation with $b_n = b_2b_3$, $b_f = b_1$, where the input peak-to-peak voltage of AWG is set to 2.4 V and ρ is in the range from 1.4 to 2.6. As can be observed, nearly the same BER can be achieved for the far user using either conventional SPC/SIC-based NOMA or CPC/UCD-based NOMA, which is gradually reduced with the increase of ρ. However, for the near user, the BER is first reduced and then increased with the increase of ρ when using conventional SPC/SIC-based NOMA. More specifically, the BER is below the 7% forward error correction (FEC) overhead limit of 3.8×10^{-3} only when the value of ρ is around 1.8. The deteriorated BER performance at small ρ values, i.e., $\rho < 1.8$, is mainly due to the adverse error propagation effect caused by imperfect SIC. In contrast, when applying the proposed CPC/UCD-based NOMA, SIC is no longer required and hence error propagation can be eliminated. As a result, the BER is gradually reduced with the decrease of ρ, suggesting that the BER performance of the near user is robust against the interference from the signal intended for the far user. Moreover, when ρ becomes relatively large, the near user can achieve almost the same BER performance using either conventional SPC/SIC-based NOMA or CPC/UCD-based NOMA, which is because the interference caused by the far user's signal becomes negligible. The measured BER performance versus the power allocation ratio ρ for 8-QAM constellation with $b_n = b_2$, $b_f = b_1b_3$ is shown in Fig. 5(b), where the input peak-to-peak voltage of AWG is 3.1 V and ρ is in the range from 5 to 11. Similarly, the BER performance of the near user can be substantially improved by applying the proposed CPC/UCD-based NOMA, when ρ is relatively small. In addition, the insets in Figs. 5(a) and (b) show the corresponding constellation diagrams.

In order to achieve error-free downlink transmission in the two-user VLC system, the BERs of two users should both below the FEC overhead limit, i.e., 3.8×10^{-3}. Here, we define the effective power allocation ratio ρ_e as the value of ρ which guarantees that both the near and far users can achieve BERs

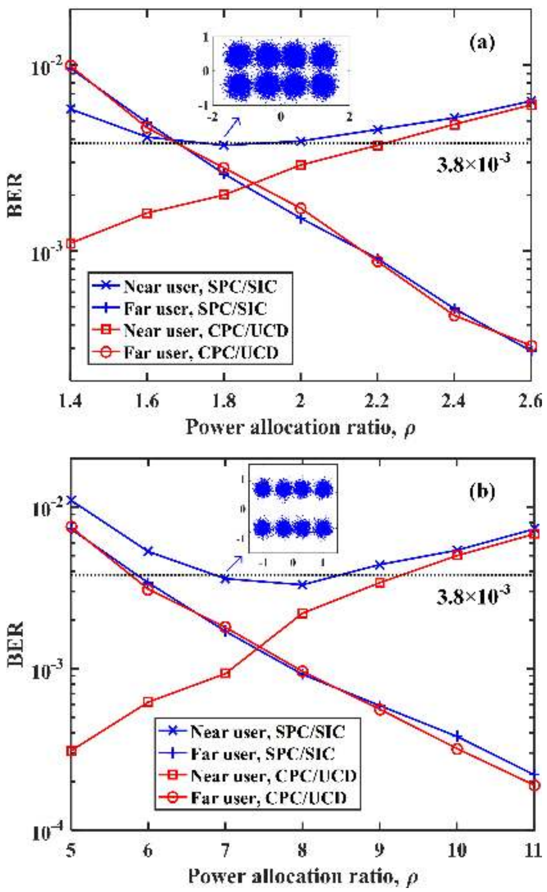

Fig. 5. Measured BER vs. power allocation ratio for 8-QAM constellation with (a) $b_n = b_2b_3$, $b_f = b_1$ and (b) $b_n = b_2$, $b_f = b_1b_3$.

below 3.8×10^{-3}. For 8-QAM constellation with $b_n = b_2b_3$, $b_f = b_1$, ρ_e is in a very small range between 1.75 and 1.9 when using conventional SPC/SIC-based NOMA. However, when CPC/UCD-based NOMA is applied, the range of ρ_e is extended to (1.68, 2.22). Similarly, for 8-QAM constellation with $b_n = b_2$, $b_f = b_1b_3$, the range of ρ_e is extended from (6.85, 8.51) to (5.81, 9.29) when conventional SPC/SIC-based NOMA is replaced by CPC/UCD-based NOMA. From the practical implementation point of view, a wider effective power allocation ratio range indicates the potential to support higher data rates and the flexibility of overall system design.

IV. Conclusion

In this letter, we have proposed and experimentally verified a novel CPC/UCD-based NOMA technique for downlink VLC systems. By applying CPC with UCD in NOMA, the desired signals for all users in the VLC system can be successfully decoded without SIC. Therefore, the error propagation effect induced by imperfect SIC can be efficiently mitigated. A two-user VLC system achieving a sum data rate of 45 Mbit/s has been experimentally demonstrated to verify the feasibility of the proposed CPC/UCD-based NOMA technique. The obtained results show that flexible rates can be achieved for both users by selecting a proper bit allocation scheme. Moreover, the BER performance of the near user can be substantially improved when the power allocation ratio is relatively small, by using CPC/UCD-based NOMA in comparison to conventional SPC/SIC-based NOMA. Meanwhile, the BER performance of the far user remains the same for both NOMA techniques. In consequence, an extended effective power allocation ratio range can be achieved by the VLC system using CPC/UCD-based NOMA, which enables the potential of higher data rate transmission and more flexible system design.

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