Optical Beam Steerable and Flexible Data Rate Orthogonal Frequency Division Multiplexing Non-Orthogonal Multiple Access (OFDM-NOMA) Visible Light Communication

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Abstract: We propose and demonstrate visible-light-communication (VLC) system using spatial-light-modulator (SLM) and orthogonal-frequency-division-multiplexing non-orthogonal-multiple access (OFDM-NOMA), illustrating the flexibilities of optical-beam steering and data-rate allocation for multiple users. © 2023 Author(s)

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1. Introduction

Optical wireless communication (OWC) has attracted much attention recently since it can provide extra wireless communication spectrum for the highly congested radio-frequency (RF) communication spectrum [1]. As optical signal does not interference with RF signal, OWC can be used to augment RF transmission to provide additional capacity without degrading the performance of the RF signal. One realization of OWC is visible light communication (VLC), which can provide both communication and lighting simultaneously. VLC is also considered as one of the potential candidates for the 6G networks [2]. Recently, 40 Gbit/s high-speed VLC systems using red/green/blue (R/G/B) wavelengths and spectral efficient orthogonal frequency division multiplexing (OFDM) has been reported [3]. Most OWC links reported in the literatures are based on direct line-of-sight (LOS) or diffused channels; and they have several limitations. The LOS channel requires precise optical alignment and suffers from light blocking by objects. Although diffused channel can support non-LOS transmission, the performance is limited by low power efficiency, and inter-symbol interference (ISI) caused by pulse spreading issue. To solve these deficiencies, optical beam steerable OWC systems utilizing optical phased array (OPA) [4], micro-electromechanical system (MEMS) [5] or spatial light modulator (SLM) [6] have been demonstrated. Among them, SLM could be promising due to its low power consumption, lightweight and the agile optical beam redirection.

Besides the high capacity requirement, future network also needs to support multiple users with satisfactory performance. To accommodate these demands, a combination of multiple approaches, for example, spectral efficient modulation (e.g. OFDM), as well as advanced multiple access technology (e.g. non-orthogonal-multiple access, NOMA) is crucial. In this work, we propose and demonstrate an optical beam steerable VLC system using bit-loaded OFDM and NOMA. NOMA can enhance the spectral efficiency by allowing multiple users to share the transmission channel simultaneously [7]. Experiment results show the proposed VLC system can provide the flexibilities of optical-beam steering and data-rate allocation for multiple users.

2. Bit-load OFDM-NOMA Algorithm and Experimental Setup

Fig. 1(a) shows the experimental setup of the optical beam steerable bit-loaded OFDM and NOMA VLC system. Before describing the experimental detail, the NOMA encode and decode (i.e. green blocks) algorithms in channel estimation phase and data transmission phase, as shown in Figs. 1(b) and (c), respectively, will be discussed first. The successful NOMA implementation is based on the utilization of superposition code and successive interference cancellation (SIC). Prior to the data transmission, the channel estimation is applied to obtain the full channel state information (CSI) as shown in Fig. 1(b). Thus, in the stage of the channel estimation, the transmitted data is generated through the addition of two independent normalized power 4-quadrature amplitude modulation (QAM) data sequences with the specific power ratio (PR). Without loss of generality, it is assumed that in this stage, the power used for the data-2 (i.e. P_{large}) is larger than that of the data-1 (i.e. P_{small}). At the receiver (Rx) side, the channel coefficients for user-1 and user-2 (i.e. h_1 and h_2) will be estimated. Besides, in order to acquire the signal-to-noise ratio (SNR), the received data will be decoded and compared with the transmitted data. During the decoding process, the data-2 will be firstly considered for both user-1 and user-2 since data-2 is encoded with larger power. Here, the data-1 is regarded as the noise and the maximum likelihood (ML) detection is employed. Then, with the decoded data-2, SIC is performed and we can therefore obtain the data-1. This means that the data-2 will be multiplied with the power used for encoding (i.e. P_{large}) and subtracted from the received data for both user-1 and user-2. After both the data-1 and data-2 are known, four SNRs (i.e. SNR_{user1}^{1st}, SNR_{user1}^{2nd}, SNR_{user2}^{1st} and SNR_{user2}^{2nd}) can be thereby calculated. In the stage of the data transmission and unchanged PR as shown in Fig. 1(c), h_1 and h_2 are compared with each other to determine which data sequence can be encoded with larger power. The principle is that the better channel can be decoded with more SIC iterations, and hence the corresponding data sequence should be encoded with smaller power. Besides, the bit-loading can be also applied according to SNR obtained from the channel estimation. The decoding process is similar to the stage of the channel estimation while it is not necessary to decode twice for those data sequence encoded with large power.

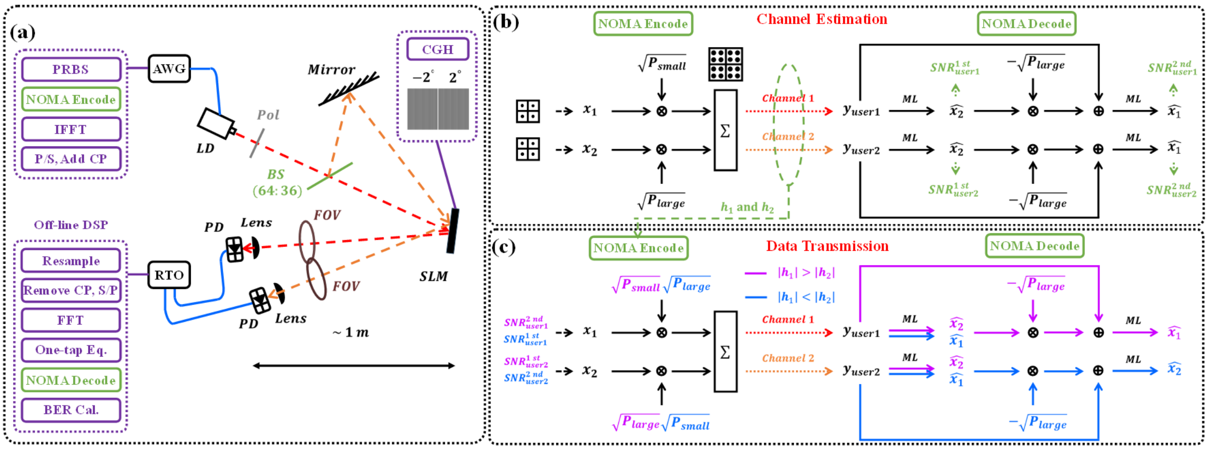

Fig. 1. (a) Experiment of the optical beam steerable bit-loaded OFDM and NOMA VLC system. LD: laser diode; AWG: arbitrary waveform generator; Pol: polarizer; BS: beam splitter; CGH: computer generated hologram; SLM: spatial light modulator: PD: photodiode; RTO: real time oscilloscope. The NOMA algorithms in (b) channel estimation phase and (c) data transmission phase.

In Fig. 1(a), two independent data sequences are generated and combined using the NOMA encoding algorithm. It is followed by the traditional OFDM encoding, including the Inverse Fast Fourier Transform (IFFT), parallel-to-serial (P/S) and the addition of the cyclic prefix (CP). The signal drives the laser diode (LD) via an arbitrary waveform generator (AWG, Tektronix® AWG 70001). The green LD at wavelength of 532 nm is used in the proof-of-concept experiment. RGB LDs can be used to further increase the capacity. The optical signal passes through a polarizer to match the alignment angle of the SLM, and then splits into two different paths via a beam splitter (BS). The measured power after the polarizer is fixed at 7.27 dBm. The BS has the measured splitting ratio of 64:36 and the beam with less power is reflected by the mirror with 1.64 dB loss. These two paths are separately adjusted to launch at the different positions of the SLM, and it can reflect the lights in a controlled manner by uploading the computer-generated holograms (CGHs). In this experiment, two CGHs are uploaded and tested. One is a single zero pattern, representing (θ_1, θ_2) = (0^0, 0^0), and the other one is a blaze grating, representing (θ_1, θ_2) = (2^0, -2^0). It is worth to mention that the steering angles for two users can be separately controlled to support moving users. The two photodiodes (PD, EOT ET-2030A) are located ~ 1 m away from the SLM, and lenses are placed in front of the PDs for focusing. The received signals are simultaneously captured by a real-time oscilloscope (RTO, Teledyne LeCroy® 816ZI-B) for bit-loaded OFDM NOMA signals decoding. It involves signal resampling, removal of CP, serial-to-parallel (S/P), Fast Fourier Transform (FFT), one-tap equalization and the NOMA decoding algorithm as mentioned. Finally, the bit error rate (BER) is calculated to evaluate the VLC system performance.

3. Results and Discussion

The powers of user-2 and user-1 prior to detection are measured to be 3.77 dBm and 0.86 dBm respectively at the steering angle of (θ_1, θ_2) = (0^0, 0^0). They are reduced to -0.09 dBm and -3.28 dBm respectively at the beam steering angle of (θ_1, θ_2) = (2^0, -2^0). The significant steering loss results from the low steering efficiency of our SLM available at the laboratory. We hope to report lower steering loss results in the conference with another new SLM, which will be available later. It is observed that user-2 processes a better channel and the SIC should be applied. User-1 experiences a poor channel and only one decoding is performed. In this experiment, two data sequences are encoded with the power ratio (i.e. P_{large} / P_{small}) of 2.5 and 4.0 in the NOMA scheme, and this implies it achieves different locations on the boundary of the capacity region. Figs. 2(a) and (b) show the SNR distributions for user-1 and user-2, and the corresponding bit loading for the different PRs as the steering angle is (θ_1, θ_2) = (0^0, 0^0), where the red curves stand for the PR of 2.5 and the blue curves stand for the PR of 4.0. Since user-1 decodes only once, its data sequence is encoded with P_{large} and we can observe the rise in the user-1 SNR distribution from PR = 2.5 to PR = 4.0. Similarly, the drop of the SNR distribution of user-2 can be explained in the same manner. The constellations for user-1and user-2 are included. In the user-1 constellations, as shown in Fig. 2(a), 'small' 8-QAM data around the origin 4-QAM data when PR = 2.5. Also, 'small' 4-QAM data around the origin 4-QAM and 8-QAM data at PR = 4.0. They are typically observed in NOMA. The user-2 constellations, as shown in Fig. 2(b) are condensed because of the implementation of SIC. Figs. 2 (c) and (d) show the SNRs for user-1 and user-2, and the corresponding bit-loadings at the steering angle of (θ_1, θ_2) = (2^0, -2^0). They trends are similar to that in the 0^0 steering case in Figs. 2(a) and (b) except for the SNR drops in all curves. This can be explained by the steering loss introduced by the SLM.

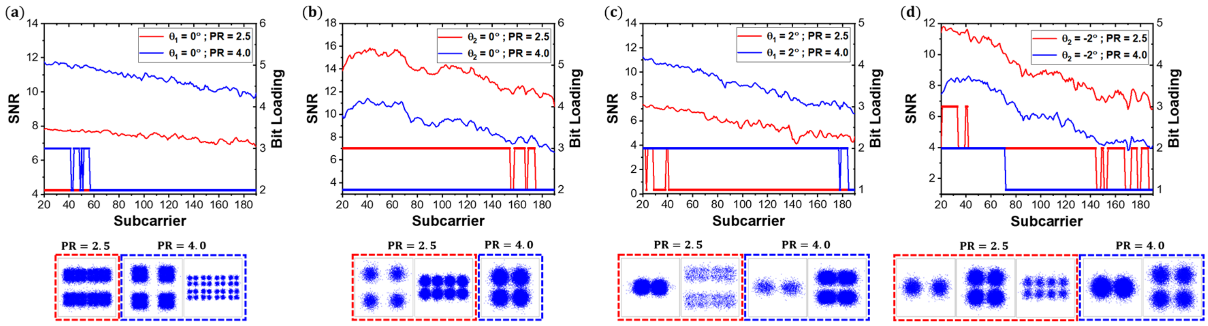

Fig. 2. The SNRs, bit-loadings and their realizations over different power ratios and different steering angles at (a) User-1 with 0^0 steering angle, (b) User-2 with 0^0 steering angle, (c) User-1 with 2^0 steering angle, and (d) User-2 with -2^0 steering angle.

For the steering angle of (θ_1, θ_2) = (0^0, 0^0), the data rates of user-1 and user-2 are 1.943 Gbit/s and 2.795 Gbit/s, respectively in the case of the PR = 2.5; and data rates of user-1 and user-2 are 2.131 Gbit/s and 1.943 Gbit/s, respectively in the case of PR = 4.0. For the steering angle of (θ_1, θ_2) = (2^0, -2^0), the data rates of user-1 and user-2 are 1.028 Gbit/s and 1.92 Gbit/s, respectively in the case of the PR = 2.5; and data rates of user-1 and user-2 are 1.903 Gbit/s and 1.267 Gbit/s, respectively in the case of PR = 4.0. Figs. 3(a)-(d) show the BER against the received powers of user-1 and user-2 for different PRs and steering angles. The results indicate that all of the data rate pairs can be simultaneously below the pre-forward error correction (FEC) BER (BER = 3.8 × 10^{-3}) threshold.

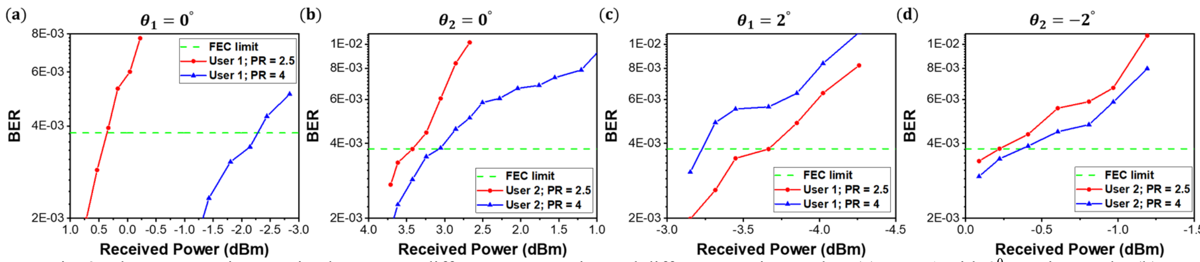

Fig. 3. The BERs against received powers at different power ratios and different steering angles: (a) User-1 with 0^0 steering angle, (b) User-2 with 0^0 steering angle, (c) User-1 with 2^0 steering angle, and (d) User-2 with -2^0 steering angle.

4. Conclusion

We proposed and demonstrated an optical beam steerable VLC system using bit-loaded OFDM and NOMA. The flexibilities of optical-beam steering and data rate allocation for user-1 and user-2 were demonstrated. The data rate pairs of (user-1: 1.943 Gbit/s; user-2: 2.795 Gbit/s) and (user-1: 2.131 Gbit/s; user-2: 1.943 Gbit/s) were achieved when the steering angle was 0^0; and the data rate pairs of (user-1: 1.028 Gbit/s; user-2: 1.92 Gbit/s) and (user-1: 1.903 Gbit/s; user-2: 1.267 Gbit/s) were achieved when the steering angle is 2^0.

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