Optical Beam Steerable and Beam Dividable of Non-Orthogonal Multiple Access (NOMA) Signal with Low-Density Parity-Check (LDPC) for Multi-User Optical Wireless Communication System

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Abstract: We propose a spatial-light-modulator (SLM)-enabled optical beam steerable and beam dividable optical-wireless-communication (OWC) using orthogonal-frequency-division-multiplexing non-orthogonal-multiple-access (OFDM-NOMA) and low-density-parity-check (LDPC). Three-layer successive-interference-cancellation (SIC) is experimentally demonstrated.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications

1. Introduction

With the ever-increasing demand on the wireless traffic, optical wireless communication (OWC) has attracted much attention since it can offer extra communication spectrum for the highly congested radio-frequency (RF) spectrum [1]. OWC can be a viable option in electromagnetic-sensitive areas and to provide high security communication link owing to the narrow beam divergence. In order to reduce optical blocking or support movable users, optical beam steering techniques are essential for the OWC systems. The micro-electromechanical system (MEMS), the optical phased array (OPA) [2] and the spatial light modulator (SLM) [3] have been proposed to support the beam steering function. Among them, the SLM-based OWC system is not only beam steerable but also beam dividable, which enables the user equipments (UEs) reconfigurability in terms of user locations and user numbers.

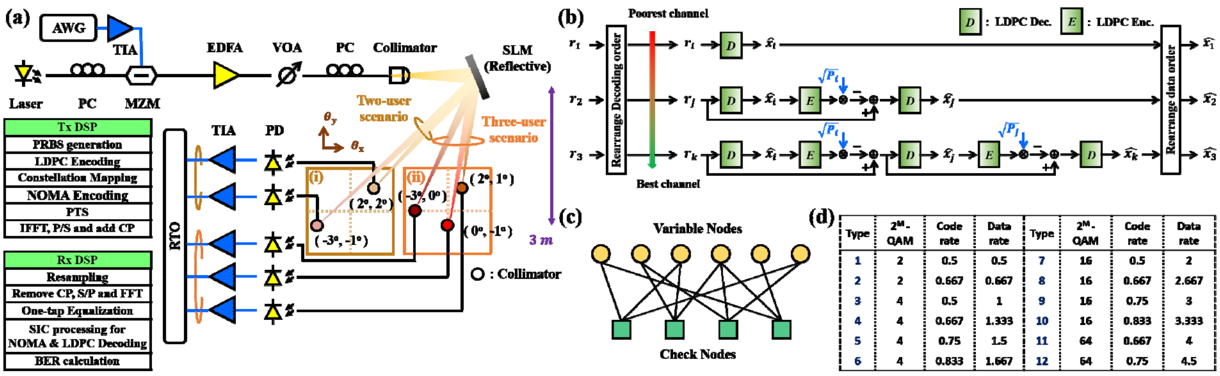
To pursue higher spectrum efficiency, besides the orthogonal multiple access (e.g. orthogonal frequency division multiple access, OFDMA), power-domain non-orthogonal-multiple access (NOMA) is a critical technique in 5G era to enhance data rates in multi-user scenarios. There have been many works of adopting NOMA in OWC systems [4-6]. However, these experimental demonstrations are focus on two-user scenario with the implementation of two-layer successive-interference-cancellation (SIC) [7]. Our previous demonstration [6] showed that a SLM steering enabled OWC system can achieve flexible data rate allocation for two users at different locations simultaneously. The hindrance of scaling user numbers results from the non-optimal power utilization. For example, despite the fact that the capacity of 2 bits can be transmitted with the signal-to-noise ratio (SNR) of 5 dB according to the Shannon's theory, the decoder with the hard-decision (HD) forward error correction (FEC) for the un-coded quadrature-phase-shift-keying (QPSK)-format takes that of roughly 9 dB, indicating the power utilization is inefficient, and what's worse is that the interferences influencing other users become more severe, shrinking the achievable capacity region. Fortunately, the situation can be relaxed if the soft-decision (SD) FEC is employed. For example, the low-density parity check (LDPC), which is one of the low-complexity and structural channel encoder/decoders [8], can be adopted to improve the efficiency of the power utilization, which is needed to support more NOMA users.

In this work, we propose and demonstrate a SLM-enabled optical beam steerable and beam dividable OWC system combing the spectral efficient orthogonal frequency division multiplexing (OFDM), the NOMA scheme and the LDPC algorithm. Experiment results show that the data rates for two-user scenario can increase up to 28% with the LDPC algorithm. Moreover, we also experimentally demonstrate a three-layer SIC in NOMA OWC supporting three users simultaneously, for the first time up to the authors' knowledge.

2. OFDM-NOMA with LDPC Algorithm and Experimental Setup

Fig. 1(a) shows the proposed SLM-based optical beam steerable and beam dividable OWC system. The laser at wavelength of 1550 nm is operated at 13 dBm. The digital signal is offline generated by a transmitter (Tx) digital signal process (DSP) and converted to the analog one via an arbitrary waveform generator (AWG, Tektronix® AWG 70001). The Tx DSP includes the generation of pseudorandom binary sequence (PRBS) sequences, LPDC encoding, constellation mapping, NOMA encoding, partial transmit sequence (PTS) and OFDM processing. The optical beam passes through the polarization controller (PC) and is modulated with the analog signal via the 40 GHz Mach-Zehnder modulator (MZM). After the modulation, the optical signal is amplified to 13 dBm, passes through the second PC and is coupled into the free space via the collimator. The incident beam is launched at the center of the SLM. The SLM can split the optical beam into two or three optical spots, providing a specific steering angle for each one. For the two-optical-spot case, as shown in inset (i), the steering angles of ($\theta_{1,x}$, $\theta_{1,y}$, $\theta_{2,x}$, $\theta_{2,y}$) = (2°, 2°, -3°, -1°) is demonstrated, where the subscript denotes the user index and the steering direction. In this scenario, the power ratio (PR) of 1: 4 are tested in the NOMA scheme. Besides, the data rates without and with the LDPC will be compared. As can be seen in inset (ii), we present the steering angles of ($\theta_{1,x}$, $\theta_{1,y}$, $\theta_{2,x}$, $\theta_{2,y}$, $\theta_{3,x}$, $\theta_{3,y}$) = (2°, 1°, -3°, 0°, 0°, -1°) for the three-optical-spot case, wherein the power ratios of 1: 4: 9 and 1: 4: 16 in the NOMA scheme with the LDPC are adopted. For both cases, the collimators are placed at the corresponding locations. They are 3-meter away from the SLM, which is the typical distance for indoor applications. The signals are detected by the 40 GHz photodetectors (PDs) and captured by a real-time oscilloscope (RTO, Teledyne LeCroy® 816ZI-B) at the same time. The Rx DSP includes the resampling, the OFDM processing, the equalization, the SIC processing for the NOMA and the LPDC decoding and the BER counting.

The SIC processing with the three-user scenario is illustrated in Fig. 1(b). The received OFDM symbols (i.e. r_1, r_2 and r_3, where the subscript is the user index) are arranged based on the channel states. The principle is that the better channel can experience more SIC iteration. Let r_i, r_j and r_k be the received symbols with the poorest, middle and the best channels. During the first SIC iteration, the log-likelihood ratios (LLRs) of the user-i's symbols are calculated and sent as the input of the LDPC decoder. The output of the decoder is the information bits of user-i. Then, user-j and user-k continue to the next iteration, and user-i waits for the end of the whole process. During the second SIC iteration, the decoded user-i's information bits should be encoded and mapped into the constellation again, scaled by the specified power of user-i, and subtracted from the user-j's and user-k's symbols. Afterwards, the LLRs of the user-j's symbols are calculated and LDPC decoding for the user-j's information is processed. Following the same procedure, the SIC processing completes until all of the users' information bits are decoded. Last, the users' orders are rearranged reversely. The LDPC has a simple generator matrix as the encoder. The outstanding correction ability comes from the message passing (MP) iterative decoding. As shown in Fig. 1(c), during each round of the LDPC decoder, the LLRs are measured along all paths connected with corresponding variable nodes (VNs) and sent to the check nodes (CNs), and the LLRs will be re-evaluated at each CN, sending back to VNs. After several rounds, the decoder can more convinced of what the information bits are. The prototype matrices of the parity-check matrices adopted in this work follow the IEEE 802.11 standard [8], which has four distinct code rates. Fig. 1(d) shows the combination of QAM orders and code rates, where there are twelve types with the data rates ranging from 0.5 to 4.5.



Type	2^M-QAM	Code rate	Data rate	Type	2^M-QAM	Code rate	Data rate
1	2	0.5	0.5	7	16	0.5	2
2	2	0.667	0.667	8	16	0.667	2.667
3	4	0.5	1	9	16	0.75	3
4	4	0.667	1.333	10	16	0.833	3.333
5	4	0.75	1.5	11	64	0.667	4
6	4	0.833	1.667	12	64	0.75	4.5

Fig. 1. (a) Experimental setup of the proposed SLM-based optical beam steerable and dividable OWC system. (b) SIC processing for the NOMA and the LPDC decoding. (c) Diagram of the iterative decoding in LPDC decoders. (d) The combination of QAM orders and code rates.

3. Results and Discussion

For the two-user scenario, the received powers prior to the PD are -2.3 dBm and -4.5 dBm for user-1 and user-2, respectively. This implies user-1 will experience the SIC processing. Fig. 2(a) reveals the SNR distributions of both users. The SNR distribution of user-2 is almost flat since the noise is dominated by the interference that comes from user-1. On the other hand, the SNR distribution of user-1 looks normal as the the frequency response of the channel owing to the SIC. The carrying bits on each subcarrier are shown in Fig. 2(b), where the results without and with the LDPC are presented as the dotted lines and the solid lines, respectively. It is observed that the carrying bits can increase as the LDPC is included, indicating both users make better use of the allocated power. To be specific, the data rates of (user-1, user-2) are (32.8 Gbps, 12.65 Gbps) without the LDPC, and they are able to be enhanced to (37.26 Gbps, 21.31Gbps) when applying the LDPC. Up to 28% improvement is obtained in terms of the sum rate. For the three-user scenario, the optical powers of -3.7 dBm, -4 dBm and -6.9 dBm for user-1, user-2 and user-3 are measured at the receiver, respectively. The respective received power implies user-1, user-2 and user-3 will experience twice, once and zero-times SIC iteration. The top and the bottom of Fig. 2(c) present the SNR distributions of three users as the PRs are 1: 4: 9 and 1: 4: 16. It can be seen that the SNR of user-3 arise by 2.4 dB as the PR change from 1: 4: 9 to 1: 4: 16 since more power is allocated to user-3. However, due to the total power conservation, the SNR of user-1 accordingly drops by 2 dB. The carrying bits on each subcarrier for each user and for two PRs are shown in Fig. 2(d). The data rates of (user-1, user-2, user-3) are (18.97 Gbps, 18.85 Gbps, 12.81 Gbps) as the PR is 1: 4: 9, and they become (14.68 Gbps, 17.75 Gbps, 19.19 Gbps) when the PR of 1: 4: 16 is used. The results can verify the flexible data rate allocation among users via adjusting the PR in the NOMA scheme.

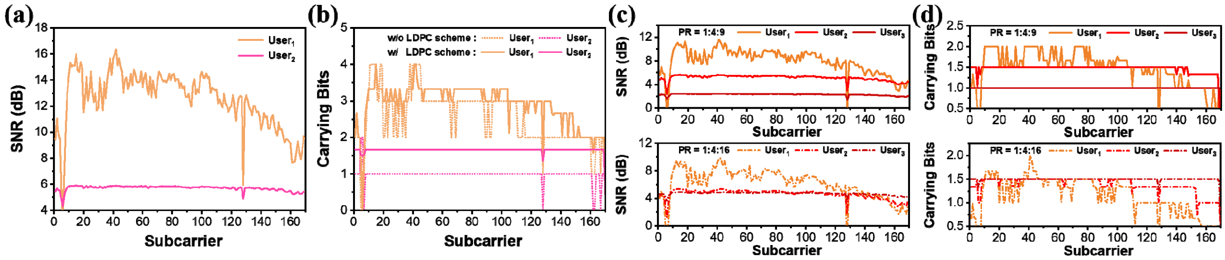


Fig. 2. (a) SNR distributions and (b) bit-loadings without and with the LDPC in the two-user scenario. (c) SNR distributions and (d) bit-loadings as the PR = 1: 4: 9 and 1: 4: 16 in the three-user scenario.

The realizations of the constellations for the two-user scenario are shown in Fig. 3(a), wherein the case without applying the LDPC is on the upper row, and the case with the LDPC is on the lower row. In the former case, we present the 8-QAM of user-1 and the 'corrupted' BPSK of user-2, while the 16-QAM of user-1 and the 'corrupted' QPSK of user-2 are shown in the latter case. The BER curves against the received power for both users and both cases are measured and presented in Fig. 3(b). It is noted that at the initial received power (i.e. without attenuating the transmitted power), none of the errors is detected at the output of the LDPC decoder. However, we can observe that with the application of the LDPC algorithm, the BER will rapidly arise as the SNR deteriorates, which is the typical phenomena in channel coding schemes. Fig. 3(c) shows the realizations of the constellations for the three-user scenario. The upper row and the lower row respectively stand for the cases of the PRs of 1: 4: 9 and 1: 4: 16. 16-QAM belonging to user-1 are presented, and the remained constellations in Fig. 3(c) are all with QSPK format. Finally, the BER curves with the previously claimed data rates for all users are shown in Fig. 3(d). The successful SIC decoding for the NOMA and the LDPC in our experiment validates the feasibility of scaling more user numbers.

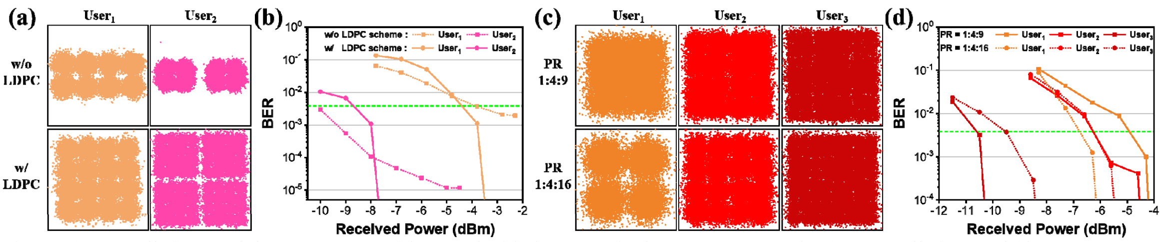


Fig. 3. (a) Constellations and (b) BER curves without and with the LDPC in the two-user scenario. (c) Constellations and (d) BER curves as the PR = 1: 4: 9 and 1: 4: 16 in the three-user scenario.

4. Conclusion

We proposed and demonstrated a SLM-based optical beam steerable and dividable OWC with OFDM-NOMA scheme. Experiment results showed that the total data rates for two-user scenario can increase up to 28% with the LDPC algorithm. Moreover, this is the first experimental demonstration of allowing three-layer SIC, simultaneously supporting three-user transmission with a total data rate > 50 Gbps. The results show the feasibility of scaling UEs with the optimal spectrum efficiency in NOMA, increasing the flexibility of the reconfigurability in OWC system.

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5. References

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