Experimental Demonstration of Cooperative NOMA in Visible Light Communications

Geyang Wang [1], Shuhua Song[1], Lian-Kuan Chen[2], Jian Zhao[1]

[1] School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China, zhaojian@scut.edu.cn

[2] Department of Information Engineering, the Chinese University of Hong Kong, Shatin, Hong Kong

Abstract *We propose a cooperative NOMA VLC scheme and demonstrate in 1.84-Gbit/s experiments that the performance and coverage of cooperative OFDM-NOMA is better than conventional OFDM-NOMA, DFT-S-OFDM-NOMA and OCT-P-OFDM-NOMA regardless of the user's receiving angles when the far user has either poor performance or communication interruption.*

Introduction

Orthogonal frequency division multiplexing non-orthogonal multiple access (OFDM-NOMA) has been widely investigated in visible light communication (VLC) due to its higher throughput and better flexibility for multi-user access[1],[2]. For the sake of simplicity, most NOMA VLC works are based on scenarios where users have stable channel conditions and are within the line-of-sight (LOS)[1],[2]. However, in an actual VLC system, some users may have poor performance or even communication interruption due to severe path loss, occlusion in the link or limited field-of-view (FOV)[3]. In this case, we can take advantage of the NOMA signal that the near users (NUs) have the information of the far users (FUs) and can be used as the relay to send the NOMA signals to the FUs[4]. On the other hand, receiving angles of users in VLC can significantly affect the performance and the scheme where the receiving angle of users can be adjustable to optimize the performance has attracted more and more attention[5]. To the best of our knowledge, reusing NU as a relay in NOMA VLC systems with either fixed or adjustable receiving angles of users has not been experimentally studied yet.

In this paper, we propose and demonstrate a cooperative OFDM-NOMA VLC system. By reusing the NU as a relay for the FU, this scheme outperforms conventional NOMA, DFT-S-OFDM-NOMA and OCT-P-OFDM-NOMA regardless of the receiving angle of the FU. It can also improve the coverage when the FU has communication interruption due to occlusion in the link.

Principle

Fig.1 shows the principle of a two-user OFDM-NOMA VLC system. We assume that user 1 and user 2 represent the NU and FU, respectively. At the transmitter, 4QAM OFDM signals are generated for both users and combined using superposition coding:

$$S_t = \sqrt{p_{t,1}}\ S_{t,1} + \sqrt{p_{t,2}}\ S_{t,2} \qquad (1)$$

where $p_{t,1}$ and $p_{t,2}$ are the power allocated to users 1 and 2, respectively. $S_{t,1}$ and $S_{t,2}$ are the frequency-domain 4QAM-OFDM signals of two users. After transmission, the receiver for the NU (user 1) employs successive interference cancellation (SIC) for signal demodulation while that for the FU (user 2) regards the signal of the NU as the noise.

Due to the high path loss or the limited FOV, the FU may have poor performance or outside the LOS of the transmitter. In this paper, we will propose cooperative OFDM-NOMA to improve the performance and communication coverage. As shown in Fig. 1, because the NU knows the information of the FU via SIC of the NOMA signal, an additional LED/LD is used at the NU to transmit the reconstructed OFDM-NOMA $S_{r,DF}$ or the reconstructed FU signal $S_{r,Coop}$ to the FU:

$$S_{r,DF} = \sqrt{p_{r,1}}\ S_{r,1} + \sqrt{p_{r,2}}\ S_{r,2} \qquad (2)$$

$$S_{r,Coop} = \sqrt{p_{r,2}}\ S_{r,2} \qquad (3)$$

where $p_{r,1}$ and $p_{r,2}$ are the power reallocated to users 1 and 2 at the NU. $S_{r,1}$ and $S_{r,2}$ are the reconstructed frequency-domain signals for $S_{t,1}$ and $S_{t,2}$. We define Eqs. (2)-(3) as decoding and forwarding NOMA (NOMA-DF) and cooperative NOMA (NOMA-Coop), respectively. Eq. (3) is a special case of Eq. (2) where $p_{r,1}$=0, and as shown later, is also an optimal solution of Eq. (2).

At the FU, the signals from both the transmitter and the NU are received. The demultiplexed signal in the frequency domain is written as:

$$R_{FU} = H_{t\to FU} S_t + H_{r\to FU} S_{r,DF/Coop} \qquad (4)$$

where $H_{t\text{->}FU}$ (or $H_{r\text{->}FU}$) is the frequency response from the transmitter (or the NU) to the FU. $S_{r,DF/Coop}$ represents $S_{r,DF}$ or $S_{r,Coop}$. The delays between the signals from the transmitter and the NU are different but if the length of cyclic prefix (CP) in OFDM is longer than the delay difference, the DSP of conventional OFDM-NOMA can still be used for channel equalization and decoding.

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

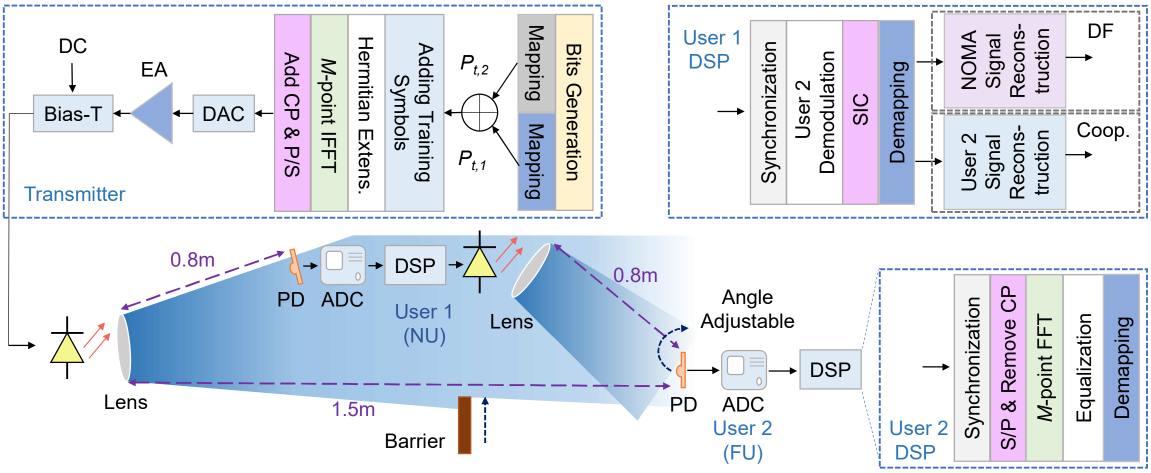

Fig. 1: Principle and experimental setup. Two scenarios are investigated: 1) the FU (user 2) can receive the signals from both the transmitter and the NU (user 1); 2) Only the signal from the NU can be received in the FU due to a barrier between the transmitter and the FU. In both scenarios, different receiving angles of the FU, as shown in Tab. 1, are studied.

We will investigate two scenarios. In the first scenario, the FU is within the FOV of the transmitter. That is, the FU can receive the signals from both the transmitter and the NU. The receiving angle of the NU is optimized while that of the FU is adjustable for investigation. Three cases are studied, as shown in Tab. 1. In the first case, the receiving angle of the FU is between the transmitter and the NU. In the second and third cases, the receiver of the FU points directly to the transmitter and the relay, respectively.

Tab. 1: Investigated receiving angles of the FU

	$H_{t\text{->}FU}$	$H_{r\text{->}FU}$
Case 1	Moderate	Moderate
Case 2	Best	--
Case 3	--	Best

In the second scenario, there is a barrier between the transmitter and the FU so that only the signal from the NU can be received. The angle of the receiver for the FU is also adjustable to investigate the performance of different cases.

Experimental Setup

Fig. 1 shows the experimental setup. The bits of two users were mapped into 4QAM symbols and combined with a power ratio. Training symbols were inserted for synchronization and channel estimation. Hermitian extension and a 256-point IFFT were employed to generate a real time-domain signal. The number of modulated subcarriers varied from 82 to 124. CP was added to mitigate the effects of channel impairments and different delays of received signals from the transmitter and the NU in the FU. After P/S, the signal was fed into a 1-GS/s arbitrary waveform generator. The gain of the electrical amplifier (EA) was 25 dB and the bias voltage was 5.8V. The amplified signal drove a blue laser and a planoconvex len was placed at the transmitter to enhance the power. The distances from the transmitter to users 1 and 2 were 0.8 m and 1.5 m, respectively. User 1 detected the signal using a 400-MHz optical receiver and recorded it in a 4-GS/s digital storage oscilloscope (DSO) with a 3-dB bandwidth of 200 MHz. DSP was used for SIC, decoding of user 1, and reconstruction of OFDM-NOMA or the signal of user 2. The reconstructed signal was then sent to user 2. After another 0.8-m transmission, the optical signals from user 1 and the transmitter were both received by user 2. The signals were recorded by a DSO and demodulated as described in Fig. 1.

For comparison, conventional OFDM NOMA was implemented. We also applied DFT-S and orthogonal circulant transform precoding (OCT-P)[6] to OFDM-NOMA. The setup was similar to Fig. 1 but user 1 was not employed as a relay.

Experimental Results

We first investigate case 1 in scenario 1, in which the FU receives signals from both the transmitter and the NU. Fig. 2 shows the average BER of users 1 and 2 versus the power ratio of NOMA at 1.47 Gbit/s. In conventional OFDM-NOMA, DFT-S-OFDM-NOMA and OCT-P-OFDM-NOMA, the NU does not act as the relay and the optimal power ratio at the transmitter $p_{t,2}/p_{t,1}$ is 8 dB. In the proposed cooperative NOMA, because the performance of the FU is improved by further utilizing the signal from the NU, the power required by user 2 at the transmitter is reduced and the optimal $p_{t,2}/p_{t,1}$ is 6 dB. On the other hand, the curves for NOMA-DF with $p_{t,2}/p_{t,1}$ of both 8 dB and 6 dB indicate that if a NOMA signal is sent from the relay, the power of user 2 in this signal should be as high as possible. In fact, given a $p_{t,2}/p_{t,1}$, the BER of NOMA-Coop is the minimal BER of NOMA-DF when the power ratio $p_{r,2}/p_{r,1}$ is infinite, or all power is on $p_{r,2}$.

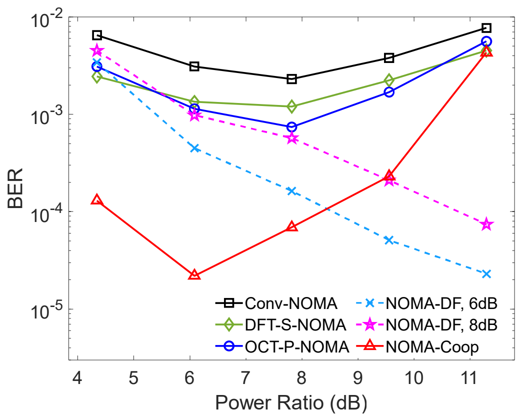

Fig. 2: Average BER of users 1&2 versus power ratio in case 1 of scenario 1 at 1.47 Gbit/s. In all schemes except NOMA-DF, the power ratio in the *x*-axis is $p_{t,2}/p_{t,1}$. In NOMA-DF, the *x*-axis is $p_{r,2}/p_{r,1}$ while $p_{t,2}/p_{t,1}$ is set as 6 or 8 dB.

Fig.3 shows the average BER of users 1 and 2 versus data rate in case 1 of scenario 1. The power ratios are optimized for all schemes. It can be seen that the performance of OCT-P-OFDM-NOMA is better than conventional OFDM-NOMA and DFT-S-OFDM-NOMA for a BER below 10^{-2}. At all data rates, the proposed scheme has the best performance.

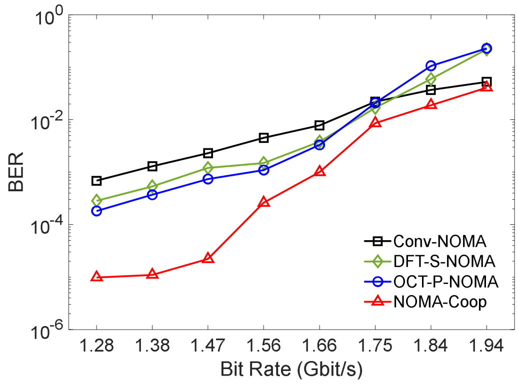

Fig. 3: Average BER of users 1&2 versus bit rate in case 1 of scenario 1. The power ratios of all schemes are optimized.

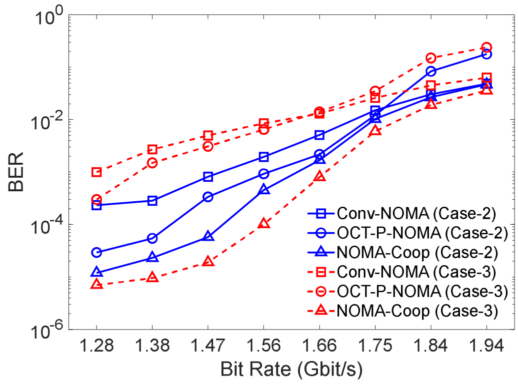

Fig. 4: Average BER of users 1&2 versus bit rate in cases 2 and 3 of scenario 1 when the power ratios are optimized.

We then investigate cases 2-3 in scenario 1, as shown in Fig. 4. For clear presentation, we do not show DFT-S-OFDM-NOMA in the figure, whose performance is worse than that of OCT-P-OFDM-NOMA. When the receiver of the FU points to the relay, the performance of the cooperative NOMA improves compared to that in case 1 while those of conventional schemes degrade. On the contrary, when the receiver of the FU points to the transmitter, the BER of the cooperative NOMA increases while those of conventional schemes reduce. In both cases, the proposed scheme outperforms conventional NOMA and OCT-P-OFDM-NOMA. At a BER of 2×10^{-2}, the achievable rate of NOMA-Coop is ~1.84 Gbit/s. The results of Figs. 3-4 also imply that the advantage of the proposed scheme maintains even when the receiving angle of the FU is adaptive, because it is better than conventional schemes regardless of the receiving angles of the FU.

Finally, we investigate scenario 2 in which the communication between the transmitter and the FU is interrupted by a barrier. Fig. 5 shows the BER versus data rate of NOMA-Coop in three cases. It can be seen that the proposed scheme can still maintain good performance and improve the communication coverage. The best case is that the FU receiver is pointed to the relay node.

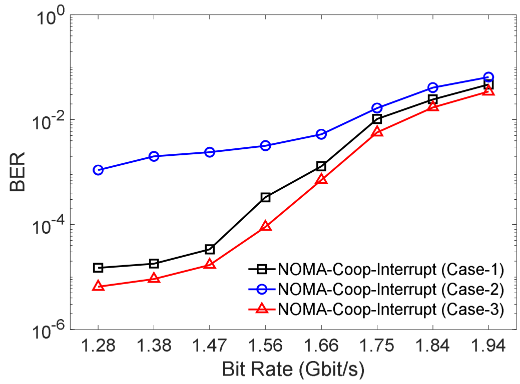

Fig. 5: Average BER versus bit rate in scenario 2 when there is a barrier between the transmitter and the FU. The power ratios are optimized, and the receiving angles are as Tab. 1.

Conclusions

We have proposed a cooperative NOMA scheme to improve the performance and coverage of the VLC system. Experiments of a 1.28~1.94-Gbit/s OFDM-NOMA VLC system show that the proposed scheme outperforms conventional OFDM-NOMA, DFT-S-OFDM-NOMA and OCT-P-OFDM-NOMA regardless of the receiving angle of the FU when the FU has either poor performance or communication interruption.

Acknowledgements

National Natural Science Foundation of China (61971199), Guangdong Science and Technology Plan Project (2019A050503003), and Natural Science Foundation of Guangdong Province (2021A1515012309).

References

[1] B. Lin, Q. Lai, Z. Ghassemlooy and X. Tang, “A machine learning based signal demodulator in NOMA-VLC”, *IEEE Journal of Lightwave Technology*, vol. 39, no. 10, pp. 3081-3087, May 2021.

[2] G. Wang, Y. Shao, L. Chen and J. Zhao, “Subcarrier and power allocation in OFDM-NOMA VLC systems”, *IEEE Photonics Technology Letters*, vol. 39, no. 10, pp. 3081-3087, 2021.

[3] W. Gheth, K.M. Rabie, B. Adebisi, M. Ijaz, and G. Harris, “Performance analysis of cooperative and non-cooperative relaying over VLC channels”, *Sensors*, vol. 20, no. 13, 3660, 2020.

[4] Z. Ding, M. Peng and H. V. Poor, “Cooperative non-orthogonal multiple access in 5G systems”, *IEEE Communications Letters*, vol. 19, no. 8, pp. 1462-1465, 2015.

[5] K. Mekonnen, Q. Pham, F. Huijskens, E. Tangdiongga, A. Mefleh and T. Koonen, “Circumventing LoS blocking in beam-steered optical-wireless systems with real-time tracking and handover”, *Optical Fiber Communications Conference and Exhibition (OFC)* 2020, paper M1J.3.

[6] J. Zhao, Y. Hong and L. K. Chen, “Discrete-circulant-transform spread OFDM for bandwidth-limited VLC systems”, *IEEE Journal of Lightwave Technology*, vol. 37, no. 20, pp. 5340-5353, 2019.