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Experimental Demonstration of a Novel OFDM-NOMA Bit and Power Loading Algorithm for Hybrid Unicast and Broadcast Transmission in Cooperative VLC Systems

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Abstract *We propose a novel OFDM-NOMA bit and power loading algorithm for hybrid unicast and broadcast downlink and demonstrate in 1.1~1.9-Gbit/s cooperative VLC experiments that the proposed algorithm outperforms conventional OFDM-NOMA, DFT-S OFDM-NOMA, and OCT-P OFDM-NOMA regardless of the unicast/broadcast data rates and channel conditions. ©2022 The Author(s)*

Introduction

Orthogonal frequency division multiplexing non-orthogonal multiple access (OFDM-NOMA) is a very promising technology for visible light communication (VLC) networks, because it combines the multi-user access capability of NOMA and the advantage of OFDM to maximize the capacity of frequency-selective VLC systems [1]. However, the conventional OFDM-NOMA algorithms employ the same format and a fixed power ratio between users for all subcarriers, because adaptive loading algorithms in OFDM cannot be migrated to OFDM-NOMA due to the multi-user scenario and the power-superposed interference that needs successive interference cancellation (SIC) at the receiver. Recently, for the first time, we propose a practical adaptive loading algorithm for OFDM-NOMA passive optical networks, which considers both the interference and the data rate fairness between users [2]. However, the services in VLC, e.g. IoT, are more diverse and there are many scenarios where both unicast and broadcast information are required by end users [3-5]. To the best of our knowledge, there is no OFDM-NOMA loading algorithm that can allocate both the unicast and broadcast information at not only the subcarrier level but also the user level.

On the other hand, practical VLC systems are vulnerable to path loss, occlusion in the link, and limited field-of-view (FOV). Cooperative communication is a promising solution to break the limitation of line-of-sight (LOS) and extend the reach [6]. Combining NOMA with cooperative communication is particularly advantageous, because the near user (NU) of the NOMA signal intrinsically contains the information of the far user (FU) and can be re-used as a relay to improve the performance of the FU.

In this paper, for the first time, we propose a novel adaptive loading algorithm, named hybrid greedy OFDM-NOMA bit and power loading (hGONBP), for systems with both unicast and broadcast information. We demonstrate in 1.1~1.9-Gbit/s cooperative VLC experiments that the proposed algorithm outperforms conventional, DFT-S, and OCT-P OFDM-NOMA, regardless of the unicast/broadcast data rates, the FU's receiving angles, and the position of the relay.

Principle

We will describe the principle based on two users for simplicity. Fig. 1 shows the setup of an OFDM-NOMA cooperative VLC system. The source sends the downlink signal to both user 1 (NU) and user 2 (FU). Three kinds of information are contained in the OFDM-NOMA downlink signal: the unicast information to the two users, and the shared broadcast information. At the NU, a part of the received signal is processed to extract the broadcast information and its unicast information, while the other part is amplified and sent to the FU. The FU receives two copies of the signal from the source and the relay, whose delay is compensated by cyclic prefix (CP) in OFDM.

The principle flow of the proposed hGONBP algorithm is depicted in Fig. 2. We define the unicast bits and powers of the two users as $b_{1,n,u}$, $b_{2,n,u}$, $p_{1,n,u}$, $p_{2,n,u}$ respectively, where $n = 1\ldots N$ is the index of OFDM subcarriers. The broadcast bits are shared by the two users but physically they are still carried by the constellation of either user 1 or user 2 of the NOMA signal. Therefore, we still use $b_{1,n,b}$, $b_{2,n,b}$, $p_{1,n,b}$, $p_{2,n,b}$ to represent the broadcast bits and powers carried on the constellation of user 1 and user 2. Note that the actual broadcast bits on the n^{th} subcarrier is $b_{1,n,b} + b_{2,n,b}$. We also define $b_{m,n} = b_{m,n,u} + b_{m,n,b}$ and $p_{m,n} = p_{m,n,u} + p_{m,n,b}$, where $m = 1$ or 2.

We firstly obtain the SNR of the two users, $\text{SNR}_{1,n}$ and $\text{SNR}_{2,n}$, where $\text{SNR}_{2,n}$ is the one combining the paths of source $\rightarrow$ user 2 and source $\rightarrow$ user 1 $\rightarrow$ user 2. The allocation is realized iteratively based on the greedy criterion. In each iteration, we calculate the required power to add one bit to the m^{th} user's constellation on

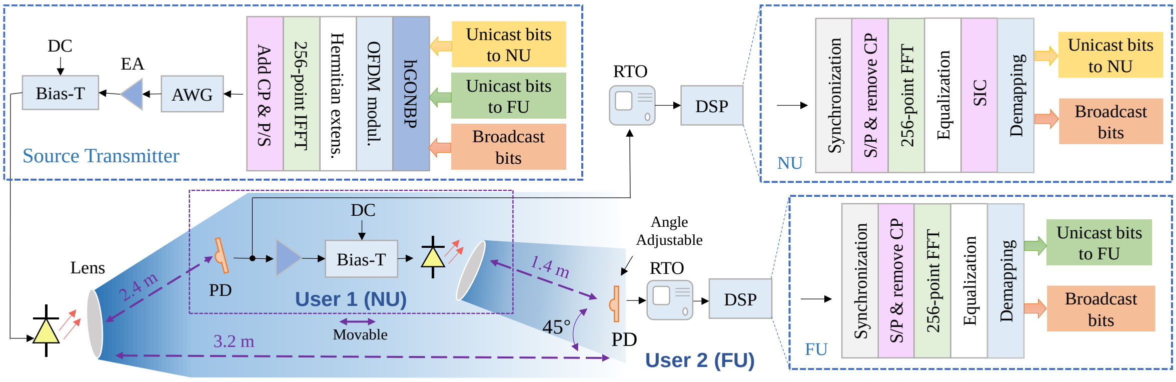

Fig. 1: Principle and experimental setup. The user 1 (NU) also acts as a relay for user 2 (FU). The source sends both unicast and broadcast information, which are allocated at both the subcarrier and the user levels. The position of the NU is movable.

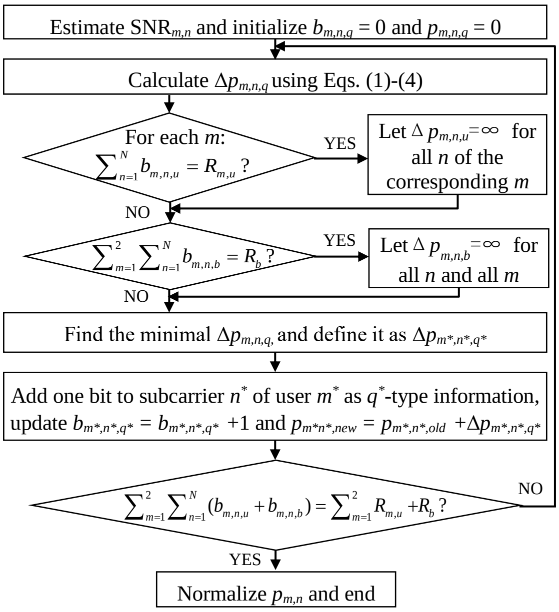

Fig. 2: Flow of the proposed hGONBP algorithm

the n^{th} subcarrier as the unicast or broadcast information using Eqs. (1)-(4):

$$\Delta p_{1,n,u} = 2^{b_{1,n,old}} (\Gamma / SNR_{1,n}) \tag{1}$$

$$\Delta p_{2,n,u} = 2^{b_{2,n,old}} \Gamma (p_{1,n,old} + 1 / SNR_{2,n}) \tag{2}$$

$$\Delta p_{1,n,b} = \max[\Delta p_{1,n,u},\ 2^{b_{1,n,old}} (\Gamma / SNR_{2,n})] \tag{3}$$

$$\Delta p_{2,n,b} = \max[\Delta p_{2,n,u},\ 2^{b_{2,n,old}} \Gamma (p_{1,n,old} + 1 / SNR_{1,n})] \tag{4}$$

where $\Gamma = -\ln(5\times BER_{target})/1.5$ with BER_{target} as the target bit error rate (BER). $b_{m,n,old} = b_{m,n,u,old} + b_{m,n,b,old}$ and $p_{m,n,old}$ are the already allocated bits and powers to the n^{th} subcarrier of the m^{th} user, respectively, both of which are initialized as zero and updated iteratively. In Eqs. (3)-(4), in contrast to the unicast bit whose power only needs to achieve the target BER for its own channel, the power of the broadcast bit carried on the constellation of either user 1 or user 2 should meet the requirement of both channels so that the max(·) function should be used.

Before bit allocation, we need to check if the total unicast bits for user m, m=1 or 2 has been assigned, and if true, set $\Delta p_{m,n,u} = \infty$ for all n of the corresponding m. Similarly, we check if all broadcast bits have been assigned, and if true, set $\Delta p_{m,n,b} = \infty$ for all n and all m. Then we traverse subcarriers, users, and information types to find the minimal $\Delta p_{m,n,q}$, where q is u (unicast) or b (broadcast), and define it as $\Delta p_{m^*,n^*,q^*}$. The broadcast bit is privileged when the unicast and broadcast bits have the same minimal Δp. Then, the bit is added to subcarrier n^*, user m^* as the information type q^*, and update $b_{m^*,n^*,q^*,new} = b_{m^*,n^*,q^*,old} + 1$, The iteration continues until the total unicast and broadcast bits $R_{1,u}$, $R_{2,u}$, and R_b are assigned. After allocation, the powers are normalized based on the principle in [1].

Experimental Setup

Fig. 2 shows the experiment setup. The bits and powers were allocated using the proposed algorithm. The generated OFDM-NOMA signal was Hermitian extended and transformed to the time domain using a 256-point IFFT. The CP was added to mitigate the multipath effect. After P/S, the digital signal was fed into a 1-GS/s arbitrary-waveform generator (AWG), whose output was amplified, biased at 4.5 V, and used to drive a blue laser. Planoconvex lenses were used to enhance the optical power. The distances between the source and two users were 2.4 m and 3.2 m respectively, unless otherwise stated. The receiving angle of the PD of user 2 pointed at user 1 and was 45° from that pointing at the source. The signals detected at both users were sampled with a 2-GS/s real-time oscilloscope (RTO). The digital signals were synchronized, transformed back to the frequency domain, and equalized using one-tap equalizers. SIC was used for NOMA decoding.

For comparison, conventional OFDM-NOMA, DFT-S OFDM-NOMA, and OCT-P OFDM-NOMA were implemented. The formats of two users were 4QAM for all subcarriers and were superimposed with the optimized power ratio.

Experimental Results

Fig. 3 shows the average BER of two users without and with cooperation, by turning off/on the amplifying-forwarding path in user 1. It is seen that cooperative communication greatly improves the performance of all schemes. The performances of DFT-S and OCT-P OFDM-NOMA are better than that of conventional OFDM-NOMA for the BER below 10^{-2} but poorer at higher BERs [7]. The proposed algorithm exhibits the best performance no matter whether cooperative communication is used.

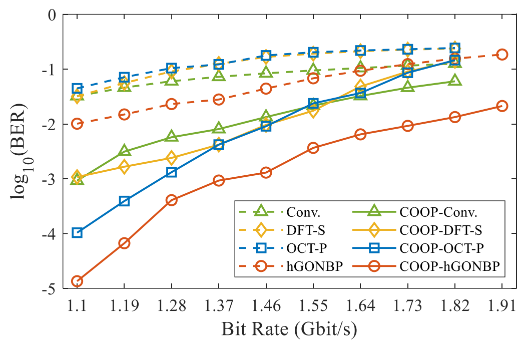

Fig. 3: Average BER versus the total unicast bit rate ($R_{1,u}$+ $R_{2,u}$) when there is no broadcast information (R_b=0).

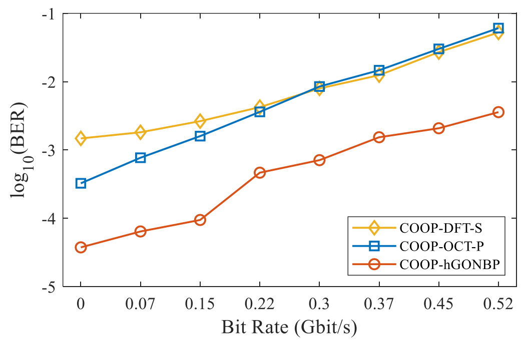

Fig. 4: Average BER versus the broadcast bit rate R_b when the total unicast rate ($R_{1,u}$+ $R_{2,u}$) is 1.19 Gbit/s.

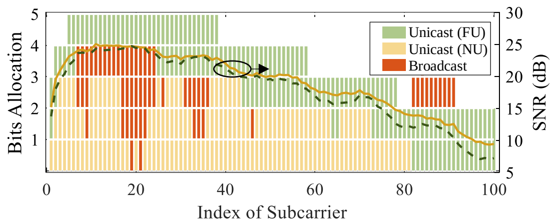

Fig. 5: Allocated bits using the proposed hGONBP at a 1.19-Gbit/s total unicast rate and 0.22-Gbit/s broadcast rate. The solid and dashed lines represent $SNR_{1,n}$ and $SNR_{2,n}$.

Fig. 4 shows the average BER when the unicast rate is 1.19 Gbit/s while the broadcast bit rate increases. It is shown that the proposed scheme outperforms the traditional precoding schemes regardless of the broadcast bit rate. Fig. 5 shows the SNR and allocated bits using the proposed algorithm. $SNR_{2,n}$ exhibits slightly higher attenuation at high frequencies than $SNR_{1,n}$ because the path source→user 1→user 2 experiences additional bandwidth limitation. The allocated unicast and broadcast bits are interleaved and match the SNR profile.

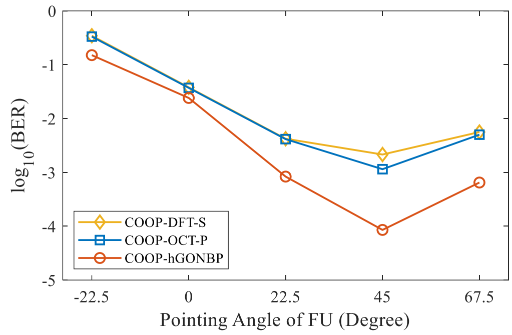

Fig. 6: Average BER versus the pointing angle of the FU at a 1.19-Gbit/s total unicast rate and 0.15-Gbit/s broadcast rate.

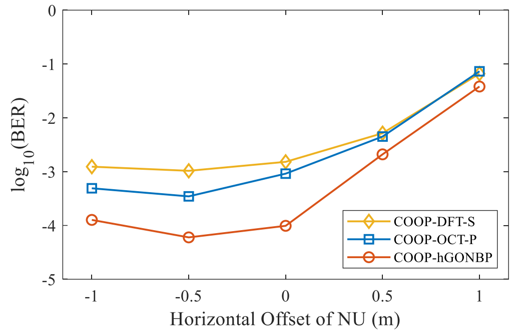

Fig. 7: Average BER versus the horizontal offset of the NU at a 1.19-Gbit/s total unicast rate and 0.15-Gbit/s broadcast rate. Zero offset represents the case of Fig. 1. Negative/positive offset represents moving the NU farther from the FU/source.

Finally, we investigate the performance when the channel conditions change. Fig. 6 shows the performance when the pointing angle of FU's PD changes. It is seen that the performance is optimal when the PD of user 2 points at user 1, i.e. at the angle of 45°. Fig. 7 shows the BER when the position of the NU changes. The performance deteriorates when the relay is farther from the source. When the relay moves closer to the source, there is an optimal offset where the loss in the path user 1→ user 2 is compensated by the gain at the relay. In both Figs. 6-7, the proposed algorithm is always the best regardless of the channel conditions.

Conclusion

For the first time, we have proposed a novel hGONBP algorithm, which can load bits and powers to multi-users with not only unicast but also broadcast information at both the subcarrier and the user levels. 1.1~1.9-Gbit/s cooperative VLC experiments show that the proposed algorithm outperforms conventional, DFT-S, and OCT-P OFDM-NOMA in all investigated cases.

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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, 2021, DOI: 10.1109/JLT.2021.3058591

[2] G. Wang, Z. Fan, and J. Zhao, "Experimental Demonstration of Adaptive Bit and Power Loading Algorithm for OFDM-NOMA PON," *Optical Fiber Communications Conference and Exhibition* (*OFC*), San Francisco, USA, 2021, paper Tu1J.4, DOI: 10.1364/OFC.2021.tu1j.4.

[3] T. Uday, A. Kumar and L. Natarajan, "NOMA for Multiple Access Channel and Broadcast Channel in Indoor VLC," *IEEE Wireless Communications Letters*, vol. 10, no. 3, pp. 609-613, 2021, DOI: 10.1109/LWC.2020.3040061

[4] M. Jani, P. Garg, and A. Gupta, "On the Performance of a Cooperative PLC-VLC Indoor Broadcasting System Consisting of Mobile User Nodes for IoT Networks," *IEEE Transactions on Broadcasting*, vol. 67, no. 1, pp. 289-298, 2021, DOI: 10.1109/TBC.2020.2989621

[5] H. B. Eldeeb and M. Uysal, "Visible Light Communication-Based Outdoor Broadcasting," *17th International Symposium on Wireless Communication Systems* (*ISWCS*), Berlin, Germany, 2021, DOI: 10.1109/ISWCS49558.2021.9562235

[6] G. Wang, S. Song, L. K. Chen, and J. Zhao, "Experimental Demonstration of Cooperative NOMA in Visible Light Communications," *European Conference on Optical Communication* (*ECOC*), Bordeaux, France, 2021, DOI: 10.1109/ECOC52684.2021.9606138

[7] 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, DOI: 10.1109/JLT.2019.2932568