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A Power and Spectrum Efficient NOMA Scheme for VLC Network Based on Hierarchical Pre-Distorted LACO-OFDM

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ABSTRACT Recently, a hybrid multiple access (MA) scheme, non-orthogonal MA (NOMA) combined with orthogonal frequency-division MA (OFDMA), has attracted significant attention in the fifth-generation (5G) wireless communication due to its superior spectrum efficiency. However, the advantage of the hybrid MA scheme cannot be fully realized in visible light communication (VLC) networks, since current optical orthogonal frequency-division multiplexing (OFDM) technologies are unable to provide high spectrum efficiency and power efficiency at the same time. In this paper, a hierarchical pre-distorted layered asymmetrically clipped optical OFDM (HPD-LACO-OFDM) scheme is proposed for NOMA, which offers superior spectrum efficiency as well as high optical power efficiency. In HPD-LACO-OFDM, multiple layers of asymmetrically clipped optical OFDM (ACO-OFDM) signals are generated to fill the odd subcarriers successively, and the inter-layer interference is eliminated with successive signal pre-distortion. A comparison of the bit-error-rate (BER) performance between the traditional dc-biased optical OFDM (DCO-OFDM), the layered ACO-OFDM (LACO-OFDM), and the proposed HPD-LACO-OFDM scheme is experimentally performed. The results show that with the same signal power, the HPD-LACO-OFDM-based NOMA-VLC network shows the best BER performance, whereas the demand for direct current voltage is reduced by half of the signal voltage compared to the traditional DCO-OFDM-based NOMA-VLC network.

INDEX TERMS Visible light communication (VLC), non-orthogonal multiple access (NOMA), orthogonal frequency division multiplexing (OFDM).

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) has recently attracted significant attention as a promising multiple access scheme for visible light communication (VLC) networks due to its superior spectrum efficiency [1], [2]. Different from traditional orthogonal multiple access (OMA) networks, users in NOMA networks are superposed in the power-domain at the transmitter, and successive interference cancellation (SIC) decoding is required at the receiver to separate the signals of different users. Thus, multiple users can share the same time-frequency (TF) resources [3]. However, it is not realistic to provide all users network access solely through NOMA technology since the power resources are limited. Thus, NOMA is always applied in combination with an orthogonal multiplexing technology. In the hybrid multiple access scheme, the users are always divided into multiple groups, to which orthogonal resources are allocated, and the NOMA is implemented within each group [4]. The orthogonal frequency division multiplexing (OFDM) is commonly selected due to its advantages of high spectrum efficiency, resistance to inter symbol interference (ISI) and flexible bandwidth allocation [5]–[7]. However, conventional OFDM technology cannot be directly applied to VLC systems since the transmitted signal has to be real-valued and non-negative. Several optical OFDM technologies have been designed for optical communication system, e.g. DC-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), asymmetrically clipped DC-biased optical OFDM (ADO-OFDM) [8], hybrid

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ACO-OFDM (HACO-OFDM) [9] and layered ACO-OFDM (LACO-OFDM) [10]. However, the optical power efficiency and the signal to noise ratio (SNR) are limited in DCO-OFDM and ADO-OFDM scheme since a large part of the optical power is wasted in DC-biasing, and the spectrum efficiency of HACO-OFDM is only 75% compared to DCO-OFDM. LACO-OFDM offers superior spectrum efficiency as well as optical power efficiency by generating multiple layers of ACO-OFDM signals with different size of IFFT to fill the odd subcarriers successively. However, a SIC receiver is required in LACO-OFDM scheme due to the signal of the higher layer is contaminated by the clipping distortion of the lower layer, leading to a complex receiver and error propagation (EP) problem [10], [11]. Unfortunately, such problems also exist in NOMA system [12], [13], which means the receiver complexity and the EP problem would be extremely serious in LACO-OFDM based NOMA-VLC networks.

In this paper, a hierarchical pre-distorted LACO-OFDM (HPD-LACO-OFDM) scheme is proposed for NOMA-VLC network, in which a hierarchical pre-distortion technology is utilized to eliminate the inter-layer interference (ILI) of LACO-OFDM caused by clipping distortion at the transmitter. With pre-distortion operation, there will be no interference between all the layers and the signals of all the layers can be directly recovered. Thus, the SIC demodulation is no longer required, and the problems of receiver complexity and EP no longer exist. In addition, the proposed HPD-LACO-OFDM scheme shows a better PAPR performance than LACO-OFDM scheme due to most of the interference signals caused by clipping distortion are subtracted. The results of the Monte Carlo simulations show that the proposed HPD-LACO-OFDM scheme shows 0.86 dB PAPR gain over the LACO-OFDM scheme at average in 2 layers case, 1.28 dB PAPR gain in 3 layers case and 1.68 dB PAPR gain in 4 layers case. In addition, such hierarchical pre-distortion scheme could also be applied to layered/enhanced asymmetrically clipped optical single-carrier frequency-division multiplexing (L/E-ACO-SCFDM) for better PAPR performance [14], [15]. Furthermore, the BER performance of DCO-OFDM, 3-layers LACO-OFDM and HPD-LACO-OFDM based NOMA-VLC network with 2 users are experimentally compared. The results show that with the same signal power, the HPD-LACO-OFDM based NOMA-VLC network shows the best BER performance while the demand for DC voltage is reduced by half of the signal voltage compared to traditional DCO-OFDM based NOMA-VLC network.

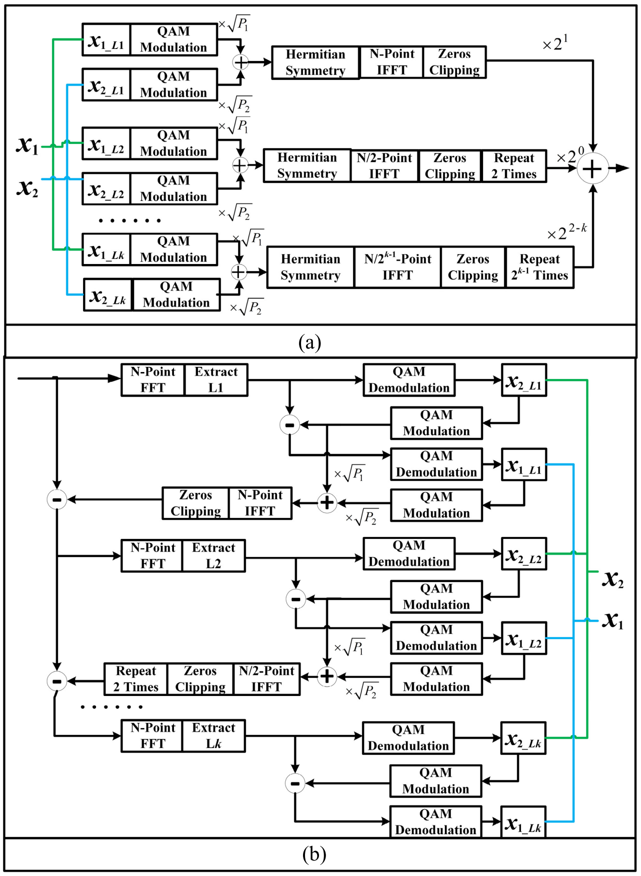
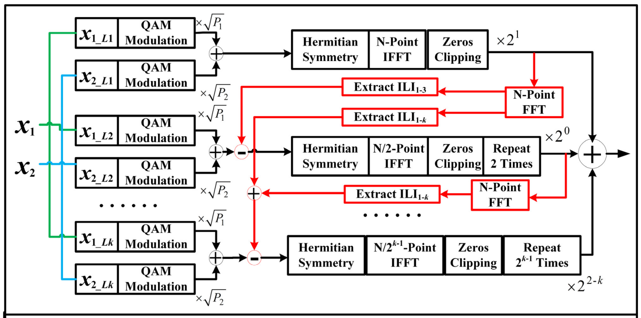
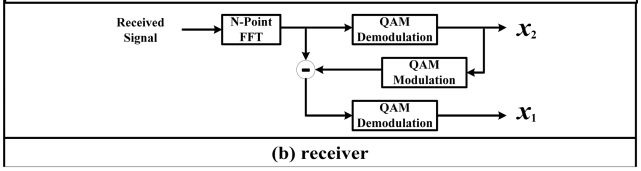


FIGURE 1. Schematic diagram of LACO-OFDM based NOMA-VLC network.



(a) Transmitter



(b) receiver

FIGURE 2. Schematic diagram of HPD-LACO-OFDM based NOMA-VLC network. ILI_{i_j} : inter-layer interference between layer *i* and layer *j*.

II. TECHNIQUE PRINCIPLE

Figures 1 and 2 show the schematic diagrams of LACO-OFDM based NOMA-VLC network and HPD-LACO-OFDM based NOMA-VLC network respectively, with parameters as N subcarriers, *k* layers and a group factor of 2 (i.e. there are 2 users in each group to perform NOMA jointly). At the transmitter of LACO-OFDM based NOMA-VLC network, as shown in Fig. 1(a), the original data of user 1 and user 2 (i.e. x_1 and x_2) are divided into *k* parts to generate *k* ACO-OFDM signals. In each layer, take layer *l* as example, the data of the part *l* of user 1 and user 2 (i.e. x_{1-Ll} and x_{2-Ll} are QAM modulated and superimposed according

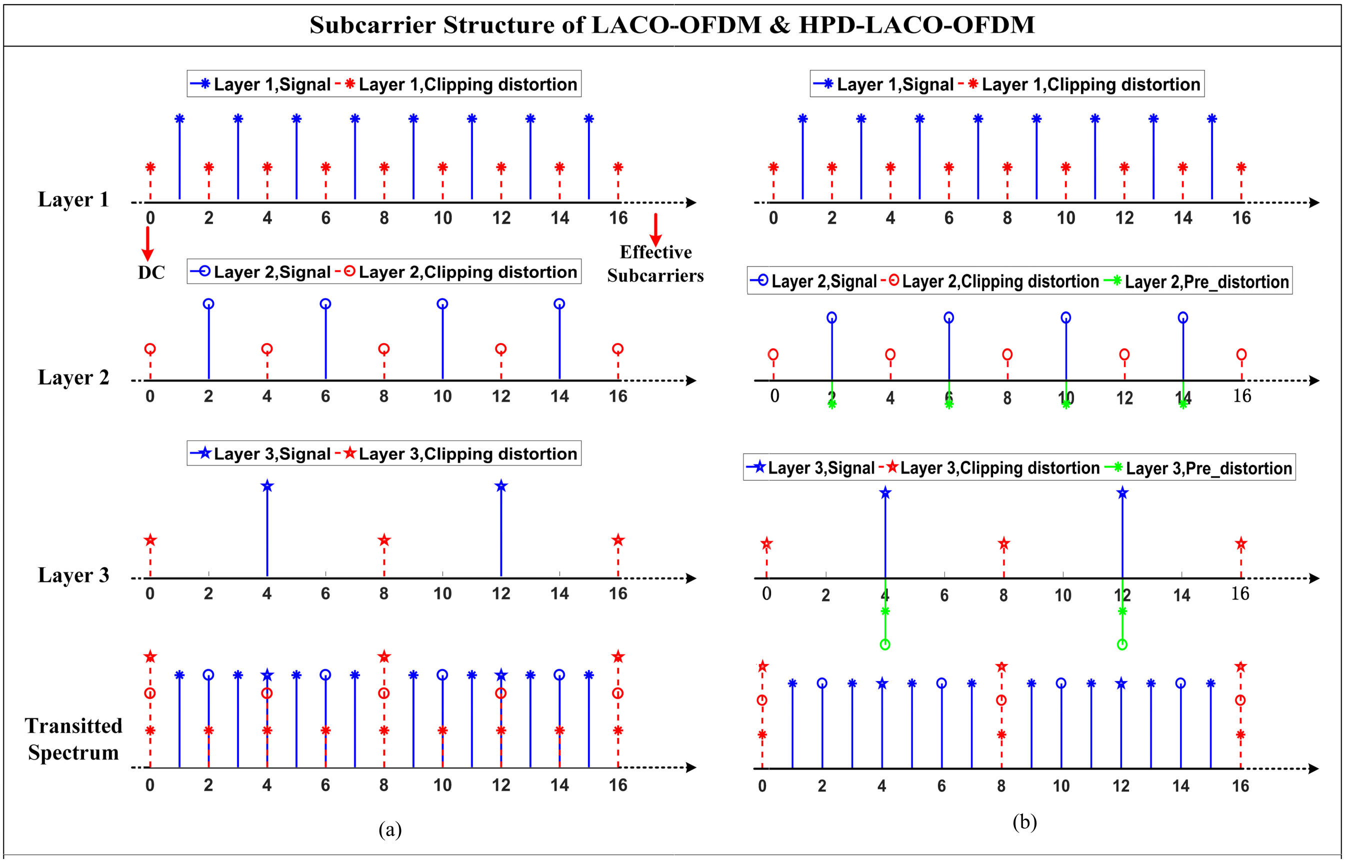


FIGURE 3. Subcarrier distribution of. (a) LACO-OFDM. and (b) HPD-LACO-OFDM.

to the power allocation ratio (PAR, user 2 is allocated with more power in this paper). The superimposed signal is then N/2^{l-1}-point OFDM modulated and clipped at zero. Since the superimposed signal of user 1 and user 2 is modulated only on the odd effective subcarriers (subcarrier $2m + 1$), the clipping distortion only falls on the direct current component and even subcarriers (subcarrier $2m$). Then the clipped ACO-OFDM signal is repeated 2^{l-1} times to get a N-point signal. After the repeating operation, the effective signal will be moved to subcarrier $2^{l-1}\times(2\text{m} + 1)$ and the clipping distortion will be moved to subcarrier $2\text{m}\times 2^{l-1}$. Figure 3(a) shows the subcarrier distribution of a 3-layer ACO-OFDM signal. Before superimposed with the other layers of signals, the ACO-OFDM signal of layer l needs to be multiplied by 2^{2-l} since the clip operation will reduce the signal energy (frequency domain) by half and the repeat operation will double the signal energy (frequency domain). Since all the layers are clipped at zero independently, the final signal is nonnegative in time domain, and only $1/2^{k}$ of the effective subcarriers are unutilized.

However, the signals of different layers cannot be directly recovered at the receiver due to the ILI. As shown in Fig. 3(a), in the spectrum of the transmitted signal, only the first layer of the signal is uncontaminated by ILI. Thus, the subcarriers of layer 1 is required to be extracted and demodulated at first as shown in Fig. 1(b). During the demodulation process of layer 1, the signal of user 2 can be demodulated directly by treating the signal of user 1 as noise since user 2 is allocated with much more power than user 1. Then the signal of user 2 are re-modulated and subtracted, so the signal of user 1 could be demodulated. After the signal demodulation of layer 1, the demodulation results of user 1 and user 2 are utilized to reconstruction the time-domain signal of layer 1. The reconstructed signal of layer 1 is then subtracted by received signal. Due to the lower layer will not be contaminated by the clipping distortion of the higher layers as shown in Fig. 3, the signal of layer 2 can be demodulated after the subtraction of layer 1, and the signal of the other layers can be demodulated in the same way.

Although the signal of user 1 and user 2 in each layer can be successfully demodulated by SIC receiver, the receiver complexity and latency performance for the user with less power is intolerable. On the other hand, the EP problem caused by SIC receiver will have serious effect on system BER performance, i.e. if the signals of lower layers cannot be correctly demodulated and subtracted, the demodulation of higher-layer signals will be affected, and in the same layer, the demodulation error of the user with more power will affect the demodulation of the user with less power.

Thus, a hierarchical pre-distortion scheme is proposed to eliminate the ILI at the transmitter. As shown in Fig. 2(a), the pre-distortion part of the transmitter is marked red. Before superimposed with the other layers of signals, the time-domain signal of each layer (except the last layer) is converted to the frequency domain by fast Fourier transform (FFT), so the clipping distortion signal could be acquired, whose inverse signal will be utilized as the pre-distortion signal for higher layers. Take layer l as example, the clipping distortion from layer 1 to layer l-1 that falls on layer l(i.e. subcarrier $2^{l-1}\times(2\mathrm{m}+1)$) is extracted and subtracted by layer l in frequency domain. Then the pre-distorted signal is processed in the same way as the traditional transmitter. Thus, when these signals of different layers are superimposed, as shown in Fig. 3(b), the clipping distortion signal that falls on the subcarriers carrying the effective signal will be offset by the pre-distortion signal, i.e. signals between different layers are orthogonal in HPD-LACO-OFDM. So the signal of different layers can be directly recovered at the receiver, as shown in Fig. 2(b), since the ILI has been eliminated at the transmitter.

The complexity analysis of LACO-OFDM and HPD-LACO-OFDM based NOMA-VLC are given as follows.

We use K to indicate the number of users and L to indicate the number of layers. In LACO-OFDM based NOMA-VLC network, $K \times L$ times QAM modulation operations and L times IFFT operations are required at the transmitter, and $K \times L - 1$ times QAM modulation operations, $K \times L$ times QAM demodulation operations, L times FFT operations and $L - 1$ times IFFT operations are required at the receiver. The other operations such as signal superposition and zero clipping are not compared here since these operations are relatively simple.

In HPD-LACO-OFDM based NOMA-VLC network, $K \times L$ times QAM modulation operation, L times IFFT operations and $L - 1$ times IFFT operations are required at the transmitter, and $L - 1$ times QAM modulation operations, L times QAM demodulation operations and one FFT operations are required at the receiver.

In summary, the receiver of HPD- LACO-OFDM based NOMA-VLC network requires $(K - 1) \times L$ times QAM modulation operations, $(K - 1) \times L$ times QAM modulation operations, $L - 1$ times FFT operations and $L - 1$ times IFFT operations less than that of LACO-OFDM based NOMA-VLC network, and the cost is that $L - 1$ times additional FFT operations is required at the transmitter.

In addition to low complexity, the EP between different layers is resolved since the signals of each layer of HPD-LACO-OFDM are orthogonal. HPD-LACO-OFDM also shows better PAPR performance than LACO-OFDM due to most of the clipping distortion signal are subtracted at the transmitter, which is closely related to the signal PAPR [16].

III. SIMULATIONS AND EXPERIMENTS

The PAPR performance of HPD-LACO-OFDM and LACO-OFDM with 2 layers, 3 layers and 4 layers are compared by Monte-Carlo simulations. In each comparison, 200,000 HPD-LACO-OFDM signals and LACO-OFDM signals are generated with 200,000 sets of data, which are randomly generated by MATLAB. The FFT size is 512, containing 112 effective subcarriers, and the constellation size is 16. The complementary cumulative distribution function (CCDF) of PAPR is calculated by these signals and the simulation results are shown in Fig. 4. As shown in Fig. 4, HPD-LACO-OFDM and LACO-OFDM with more layers show better PAPR performance for the reason that the peak power increases slower than the average power upon combining more layers [16]. On the other hand, the PAPR gain of HPD-LACO-OFDM over LACO-OFDM increases as the number of layers increases for the reason that more clipping distortion signal will be generated with the increase of the number of layers, which will have a greater impact on the PAPR performance of LACO-OFDM than that of HPD-LACO-OFDM since most of the clipping distortion is subtracted in HPD-LACO-OFDM scheme. The simulation results is demonstrated that the HPD-LACO-OFDM shows 0.86 dB PAPR gain over the LACO-OFDM at average in 2 layers case, shows 1.28 dB PAPR gain in 3 layers case and 1.68 dB PAPR gain in 4 layers case.

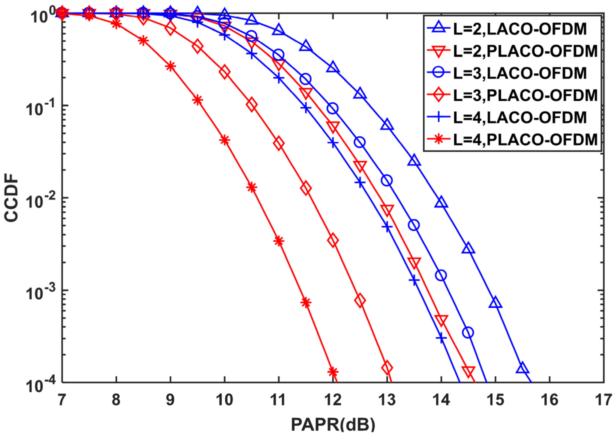


FIGURE 4. CCDF of the PAPR for LACO-OFDM and HPD-LACO-OFDM.

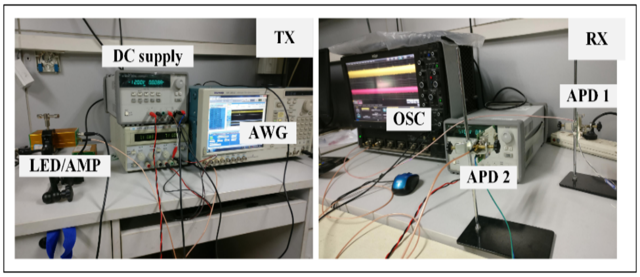


FIGURE 5. Experimental setup of our NOMA-VLC network.

The BER performance of DCO-OFDM, LACO-OFDM and HPD-LACO-OFDM scheme are further compared by experiments. The experimental setup is shown in Fig. 5 and the experimental parameters are provided in Table 1.

TABLE 1. Experimental parameters.

OFDM parameters	Value	Circuit parameters	Value
FFT	512	Sampling rate	10 M/S
Effective subcarriers	112	Vpp for DCO scheme	-3V~+3V
CP	8	Vpp for LACO scheme	0~6V
Modulation format	16 / 4x4	Bias for DCO scheme	7V
layers	3	Bias for LACO scheme	4V

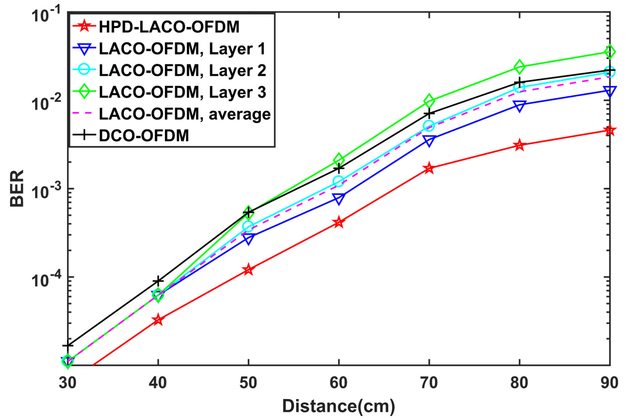


FIGURE 6. BER performance for DCO-OFDM, LACO-OFDM and HPD-LACO-OFDM.

The signal is firstly generated by MATLAB and transmitted by an arbitrary waveform generator (AWG, Tektronix AWG5012) operating at 10 M/S, then amplified and superposed onto the LED (OSRAM LUW W5SM) by aid of Bias-T. The same size of the voltage amplitude is provided to the three types of OFDM signal, i.e. -3V∼3V for DCO-OFDM signal, 0∼6V for both types of LACO-OFDM signal. The bias voltage is fixed at 7V for DCO-OFDM signal and 4V for both types of LACO-OFDM signal, which move the signal voltage to the linear area of the LED. The optical signal is received and converted back into the electrical signal by a commercially available avalanche photodiode (Hamamatsu C12702-12), and then captured by an oscilloscope (LeCroy SDA760Zi).

We first performed a point-to-point transmission experiment with 16QAM modulation to compare the BER performance of the three types of OFDM scheme under different transmission distance, and the experimental results are shown in Fig. 6. The BER performance of HPD-LACO-OFDM is better than LACO-OFDM since HPD-LACO-OFDM is free of EP problem between different layers and has a better PAPR performance. On the other hand, the BER performance of HPD-LACO-OFDM is not offered in layers since all the layers have similar BER performance. However, in LACO-OFDM scheme, the lower layers show better BER performance than higher layers in long distance condition while all the layers show similar performance in short distance condition. This can be explained as follows. At short distance, the lower layers can be recovered more accurate, leading to perfect cancellation. While the cancellation is imperfect at long distance since there are more demodulation errors in lower layers. Thus, the EP problem of LACO-OFDM is getting worse when the transmission distance is greater than 40cm in this experiment. In addition, compared with DCO-OFDM, HPD-LACO-OFDM shows better BER performance while the demand for DC voltage is reduced by half of the signal voltage.

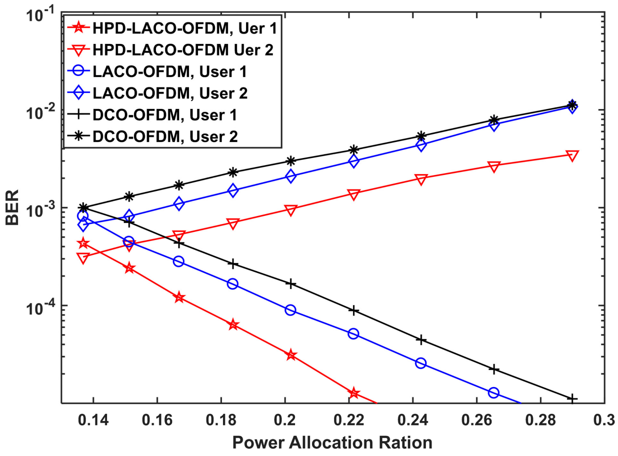


FIGURE 7. BER performance for DCO-OFDM, LACO-OFDM and HPD-LACO-OFDM based NOMA-VLC with 2 users.

Furthermore, the BER performance of DCO-OFDM, LACO-OFDM and HPD-LACO-OFDM based NOMA-VLC network with 2 users are experimentally compared under different PAR values (PAR = P1 / P2, P1 represents the power allocated for user 1). Both of the users are 4QAM modulated and the transmission distance between user 1 and the transmitter is 40cm while the transmission distance between user 2 and the transmitter is 70 cm.

As shown in Fig. 7, both of the users in HPD-LACO-OFDM based NOMA-VLC network show the best BER performance while the receiver is much simple than that of LACO-OFDM based NOMA-VLC network and the optical power efficiency is much higher than that of DCO-OFDM based NOMA-VLC network. Although the transmitter of HPD-LACO-OFDM is a bit more complicated than that of LACO-OFDM, and a small part of effective subcarriers are still unutilized (12.5% in 3 layers case), HPD-LACO-OFDM is still suitable for NOMA-VLC network.

IV. DISCUSSION

A. *OPTIMAL LAYER ANALYSIS*

As previously analyzed, the spectrum efficiency of HPD-LACO-OFDM will increase with the increase of the layer number. The subcarrier utilization η of L-layer HPD-LACO-OFDM satisfies:

$$\eta = 1 - (1/2)^L. \tag{1}$$

As shown in formula (1), the spectral efficiency gain for each additional layer decreases exponentially as L increases. However, the system complexity will continues to increase.

On the other hand, more layers mean less power allocated to each layers since the total power needs to be maintained within a certain range for lighting, which will lead to a higher BER. The optimal layer amount under different optical signal-to-noise ratio (SNR) scenarios is studied in [17], which suggests that small layer number is recommended in low SNR scenarios for better BER performance and large layer number is recommended in high SNR scenarios for higher spectral efficiency. However, system complexity and performance requirement should also be taken into consideration.

B. DIMMING CONTROL ANALYSIS

Dimming control is an import part of VLC system since there are different illumination requirements need to be satisfied in the practical VLC applications. Several dimming schemes have been proposed for LACO-OFDM based VLC system [18], [19], which could also been ultilized in HPD-LACO-OFDM based VLC system since the difference between the transmitter of HPD-LACO-OFDM and LACO-OFDM is small. For instance, dimming control is accomplished in [18] by changing the proportion of LACO-OFDM signals and negative LACO-OFDM signals. Negative HPD-LACO-OFDM could also be accomplished by applying hierarchical pre-distortion scheme into negative LACO-OFDM. Thus, dimming control could also be accomplished by changing the proportion of HPD-LACO-OFDM signals and negative HPD-LACO-OFDM signals.

V. CONCLUSION

In this paper, HPD-LACO-OFDM is proposed for NOMA-VLC network to overcome the optical power inefficiency problem of the traditional DCO-OFDM based NOMA-VLC network while the advantage of high spectrum efficiency is retained. In HPD-LACO-OFDM, multiple layers of asymmetrically clipped optical OFDM signals are generated to fill the odd subcarriers successively and the inter-layer interference is eliminated with successive signal pre-distortion. Thus, superior spectrum utilization can be obtained and the signal of different layers can be directly recovered at the receiver. The experimental results shows that with the same signal power, the HPD-LACO-OFDM based NOMA-VLC network with 3 layers shows a superior BER performance over DCO-OFDM based NOMA-VLC network while the demand for DC power is reduced by half of the signal voltage.

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