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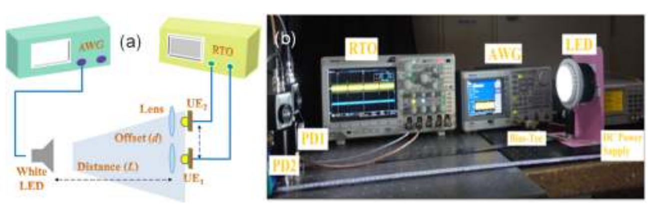

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Demonstration of Non-Hermitian Symmetry (NHS) IFFT/FFT Size Efficient OFDM Non-Orthogonal Multiple Access (NOMA) for Visible Light Communication

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Abstract: We propose and experimentally demonstrate a non-orthogonal multiple access (NOMA) visible light communication (VLC) system using non-Hermitian symmetry (NHS) inverse-fast-Fourier-transform (IFFT)/FFT size efficient (SE) orthogonal frequency division multiplexing (OFDM). Fix power allocation and successive interference cancellation (SIC) algorithms are realized. The power ratio between different users, transmission distance, network cell coverage are investigated. The proposed scheme is also compared with the HS based direct-current optical (DCO)-OFDM NOMA-VLC system.

Index Terms: Light emitting diode (LED), visible light communication (VLC), non-orthogonal multiple access (NOMA).

1. Introduction

White-Light light emitting diode (LED) based visible light communication (VLC) has attracted much attention recently [1]–[4]. Although VLC offers many attractive features, only intensity modulation/direct detection (IM/DD) can be used in LED based VLC. Besides, white-light phosphor-based LED for illumination has a limited modulation bandwidth of ∼1 MHz [5]. Different approaches have been reported to enhance the VLC transmission capacity, including using multiple-input and multiple-output (MIMO), or spectral efficient modulation, such as orthogonal frequency division multiplexing (OFDM) [6]. During the encoding of OFDM, Hermitian symmetry (HS) is required for the input of inverse fast Fourier transform (IFFT) to generate real-valued signals to drive the LED. However the HS doubles the IFFT/FFT size and increase the transceiver (TRx) complexity. Non-Hermitian symmetry (NHS)-OFDM were proposed, such as the fast Hartley transform (FHT) [7]; separated transmission of real (Re) and imaginary (Im) parts of the OFDM using red/green/blue (RGB) LEDs [8] or separated transmission by MIMO white LEDs [9]. However, these NHS OFDM

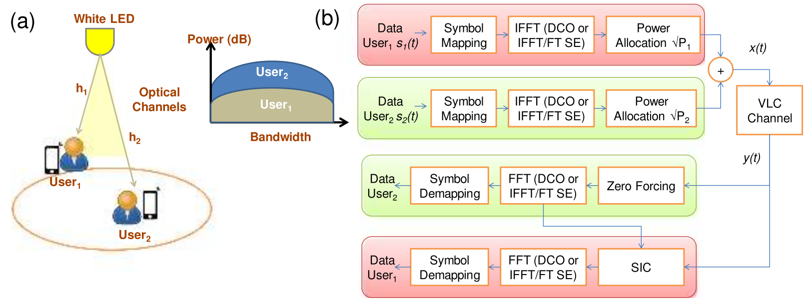

Fig. 1. (a) Conceptual diagram of the NOMA-VLC system for 2 users. (b) NOMA algorithm implementation.

have different limitations, for example, the FHT approach only accept real constellation signals, and the separated transmission schemes require multiple LED transmitters (Txs) and receivers (Rxs). An IFFT/FFT size efficient (SE) approach is proposed to transmit the Re and Im parts of OFDM in time domain sequentially [10], and experimentally demonstrated in [11]. This scheme does not complicate the TRx by doubling the IFFT/FFT size and only requires one set of LED TRx.

Another challenge of the VLC network is that it should support different users simultaneously. Time division multiple access (TDMA), wavelength division multiple access (WDMA), code division multiple access (CDMA) were reported for VLC systems [12]. Recently, power division multiple access (PDMA), also known as non-orthogonal multiple access (NOMA) was proposed to enhance the spectral efficiency [13]. Users can use the entire spectrum by deploying power allocation and superposition technique inside the Tx. At the Rx, successive interference cancellation (SIC) algorithm can be used to remove other user signals. Fixed power allocation (FPA) can also be used to allocate different powers to different users [13]. In 2017, B. Lin *et al.* demonstrated a two users HS-OFDM NOMA-VLC system with transmission distance of 30 cm and user-equipment (UE) offset of 7 cm [14]. Besides, they also reported a single-carrier NOMA-VLC using MIMO with 30 cm transmission distance [15]. In 2019, C. Chen *et al.* reported a SIC-free NOMA-VLC using constellation partitioning coding with transmission distance of 100 cm and UE offset of 10 cm [16]. J. Shi *et al.* demonstrated a NOMA-VLC using subcarrier pair-wise coding with transmission distance of 40 cm [17]. In the same year, H. Li *et al.* illustrated a NOMA-VLC using pre-distorted layered asymmetrically clipped OFDM with transmission distances of 40 cm and 70 cm for UE_1 and UE_2 respectively [18]. In 2020, Y. Wang *et al.* demonstrated a three users NOMA-VLC with transmission distance of 120 cm [19].

In this work, we propose and experimentally demonstrate a NOMA-VLC system using NHS IFFT/FFT SE OFDM format. This NHS-OFDM NOMA-VLC system is based on FPA and SIC to serve two users. Experimental results show that the required power ratio in serving two UEs is 4.5 dB, transmission distance of $>$100 cm and UE offset of 7.5 cm are achieved satisfying the forward error correction (FEC; bit-error-ratio, BER $<$3.8 $\times$ 10^{-3}) threshold. The proposed scheme is also compared with the HS based DCO-OFDM NOMA-VLC system.

2. Algorithm and Experiment

The NHS-OFDM IFFT/FFT SE approach was proposed in [10]. In this approach, Re and Im parts of the complex-valued OFDM signals are extracted and time-serial multiplexed them in OFDM symbol. Here, we will also compare the proposed scheme with the conventional HS-OFDM system. One typical example of HS-OFDM is the direct-current optical (DCO)-OFDM [6]. Fig. 1(a) shows the conceptual diagram of the NOMA-VLC system having 2 users. UE_1 has a higher SNR due to having shorter line-of-sight (LOS) distance with the LED; while UE_2 has a lower SNR. Fig. 1(b) shows the NOMA algorithm implementation in the VLC system. Suppose $s_1(t)$ and $s_2(t)$ are the signals for UE_1 and UE_2 respectively, and P_1 and P_2 are the corresponding transmission power.

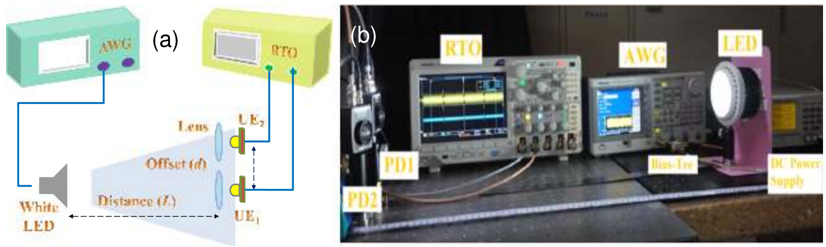

Fig. 2. (a) Experiment of the NOMA-VLC system using the proposed NHS based IFFT/FFT SE OFDM and the HS based DCO-OFDM; (b) photograph of the experiment.

The transmitted signal *x(t)* can be written as Eq. (1).

$$x\,(t) = \sqrt{P_1} s_1\,(t) + \sqrt{P_2} s_2\,(t) \tag{1}$$

The total power is $P = P_1 + P_2$. We define $\alpha = P_2 \,/\, P_1$ as power ratio between user 1 and user 2 in dB. Here, α is obtained by experiment with the goal to achieve FEC requirements for all users. The received signal at UE_i ($i = 1, 2$) is represented by Eq. (2),

$$y_i\,(t) = h_i x\,(t) + n_i \tag{2}$$

where h_i is the channel response between the Tx and the UE_i; while n_i is the noise. In the NOMA implementation, SIC is employed at the UE Rx to remove the interference of other user signals. As shown in Fig. 1(b), UE_2 does not need the SIC, and it can directly decode $s_2(t)$ via zero forcing (ZF) algorithm by considering $s_1(t)$ as noise. In UE_1, SIC is used to decode $s_2(t)$ and then subtract it from $y_1(t)$ to obtain $s_1(t)$. In fact, both UE_1 and UE_2 are equipped with the same SIC module as shown in Fig. 1(b). Each UE will recover the stronger signal first while treating the weaker signal as noise. Since in this scenario, the power for UE_2 is higher; when UE_2 recovers its own signal, it will stop. For UE_1, after reconstructing the stronger signal, UE_1 will subtract it from the total received signal to recover its weaker signal based on SIC algorithm.

Fig. 2(a) shows the experiment of the NOMA-VLC system. The NHS based IFFT/FFT SE OFDM and the HS based DCO-OFDM are encoded using MATLAB program. The signal is applied to a white-light LED via an arbitrary waveform generator (AWG; Tektronix AFG3252C) with sampling rate of 12.5 MS/s. Two PIN photo-detectors (PDs) are used as UE_1 and UE_2, where UE_1 is aligned with LED (i.e., cell-center user); while UE_1 is located with different offsets with respect to UE_1 (i.e., cell-edge user). They are connected to a 4-channel real-time oscilloscope (RTO; Tektronix MDO3024) with sampling rate of 2.5 GS/s. The IFFT size used is 256. The number of effective subcarriers for proposed IFFT/FFT SE OFDM and DCO-OFDM are 256 and 127; while the symbols per frame are 18 and 36 respectively. The received illuminance by the cell center user at 100 cm is about 70 lux. Fig. 2(b) shows the photograph of the experiment.

3. Results and Discussions

First, the power ratio α for each UE to achieve a satisfactory BER performance is investigated. Fig. 3(a) shows the experimental BER performance of different power ratios UE_2/UE_1 using the IFFT/FFT SE OFDM. When $\alpha = 2.5$ dB is applied, both users cannot achieve FEC requirement. This is because the signal power for UE_2 is not high enough to neglect the UE_1 signal as noise. Then, the power ratio is increased gradually. When the $\alpha = 4.5$ dB, both users have nearly the same performance and satisfy the FEC requirement. When the power ratio is further increased, much higher power is allocated for the UE_2; hence its performance is further enhanced as shown in Fig. 3(a). However, as the total transmitted power *P* is constant; allocating more power to UE_2 will reduce the power to UE_1; hence the BER performance of UE_1 is getting worse when $\alpha >$ 6 dB. Based on above investigation, the experiment was performed using $\alpha = 4.5$ dB. Besides, to investigate the cell coverage of NOMA VLC system, the cell-edge user UE_2 is moved along the

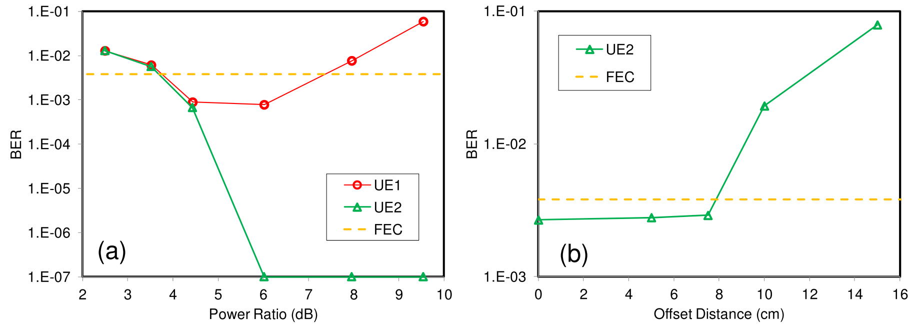

Fig. 3. Experimental BER of (a) different power ratios α using IFFT/FFT SE OFDM; (b) cell edge user UE_2 moving along the perpendicular direction with respect to UE_1.

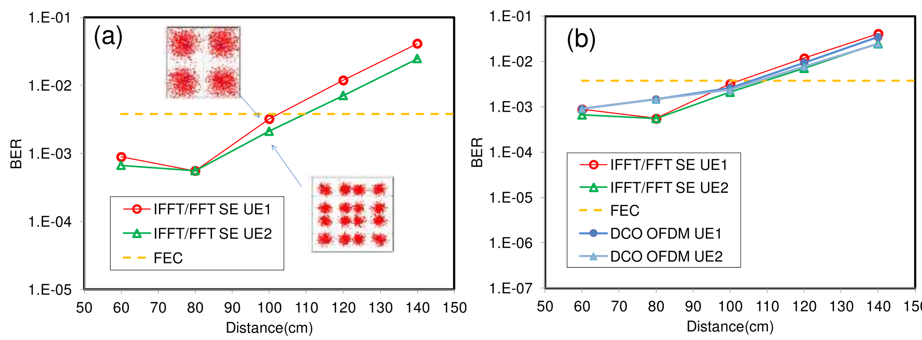

Fig. 4. Experimental BER of UE_1 and UE_2 (a) at different LOS transmission distance; (b) by comparing the proposed IFFT/FFT SE OFDM and the DCO-OFDM approaches.

perpendicular direction with respect to UE_1 with distance $d = 0$, 5, 7.5, 10 and 15 cm. Fig. 3(b) shows that its maximum offset distance is $d = 7.5$ cm, satisfying the FEC requirement. At $d = 7.5$ cm, the received illuminance is about 55 Lux. The cell radius could be increased by using higher power LED Tx or using higher sensitivity Rx at the UE, such as avalanche PD instead of PIN-PD.

After the investigation of the cell coverage, both UE_1 and UE_2 are moved to the cell-center position to investigate the ZF and SIC algorithm performances under the same received optical illuminance (70 lux). Fig. 4(a) shows the BER performance of UE_1 and UE_2 when the direct LOS transmission distance L is increased from 60 to 140 cm. Using the power ratio of 4.5 dB can provide both UE_1 and UE_2 to have similar BER performances as shown in Fig. 4(a). Constellation diagrams of UE_1 and UE_2 are included. Both users have nearly the same performance showing that both the ZF and SIC algorithms are functioning properly, and the power ratio α is a proper choice. The data rate of the NOMA VLC system is 7.2 Mbit/s. Finally, the proposed scheme is compared with the DCO-OFDM as shown in Fig. 4(b). Similar experimental settings are employed in the comparison. Based on the simulation work reported in [10], both the IFFT/FFT SE OFDM and the DCO-OFDM approaches have similar performance; and we have experimentally verified here in the BER curves shown in Fig. 4(b).

4. Conclusion

We proposed and demonstrated a NOMA-VLC system using NHS IFFT/FFT SE OFDM format. Experimental results showed that the required power ratio in serving two UEs was 4.5 dB, transmission distance of >100 cm and cell coverage diameter of 7.5 cm were achieved. The proposed scheme was also compared with the HS based DCO-OFDM NOMA-VLC system.

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