Phase Pre-Distortion for Non-Orthogonal Multiple Access in Visible Light Communications

Xun Guan, Yang Hong, Qing Yang, and Calvin Chun-Kit Chan
Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
Author e-mail address: guanxun@ie.cuhk.edu.hk

Abstract: We propose a phase pre-distortion method to improve the symbol-error-rate performance of non-orthogonal multiple access in visible light communications. Both theoretical analysis and experimental evaluation have been performed to prove its effectiveness.
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1. Introduction

Visible light communication (VLC) is an emerging technique for optical wireless communication for its advantages of license-free, low cost, and easy integration with pervasive illustration devices [1]. To support optical wireless networks with multiple VLC transmitters/receivers, a specifically designed multiple access method is indispensable. Recently, non-orthogonal multiple access (NOMA), a potential candidate for the upcoming 5G standard, has drawn great attention due to its superior spectral efficiency [2]. In NOMA, multiple wireless users transmit their signals to a common receiver simultaneously thus result in an overlapped (non-orthogonal) signal; the receiver then decodes the users' data individually from the overlapped signal using multi-user detection. The non-orthogonal feature improves the system fairness and allows more flexible subcarrier allocation among multiple users [3,4]. Recently, NOMA was introduced into VLC to improve the downlink throughput in [5]. However, the practicality of NOMA is strictly restrained by the power ratio constraint among multiple users, which still remains unexplored. In this paper, we propose a phase pre-distortion method to improve the performance of NOMA in VLC. Theoretical study and experimental results show that our method improves the performance for different power ratios among users.

2. Principles

Fig. 1(a) depicts a VLC network with two light-emitting diodes (LEDs) as transmitters and three photodiodes (PDs) as receivers. The two LEDs provide VLC data service within their corresponding illuminative regions that are slightly overlapped. In this setup, PD_1 can only receive the signal from LED_1, while PD_3 can only receive the signal from LED_2. PD_2, which locates in the overlapping region of LED_1 and LED_2, is associated with both LEDs.

Specifically, PD_2 lies at the center area of the illumination region of LED_1, but at the edge of the coverage of LED_2. PD_2 receives a stronger signal S from LED_1 and a weaker signal W from LED_2, forming an overlapped signal C. For the ease of the investigation, we assume that both S and W are 4QAM-OFDM modulated with four constellation points $\sqrt{2}/2\{1+i, -1+i, -1-i, 1-i\}$. Without loss of generality, we only consider one subcarrier of the OFDM in the following analysis. The received baseband signal at PD_2 after OFDM demodulation and matched-filtering is

$$y_c = h_s x_s + h_w x_w + n,$$

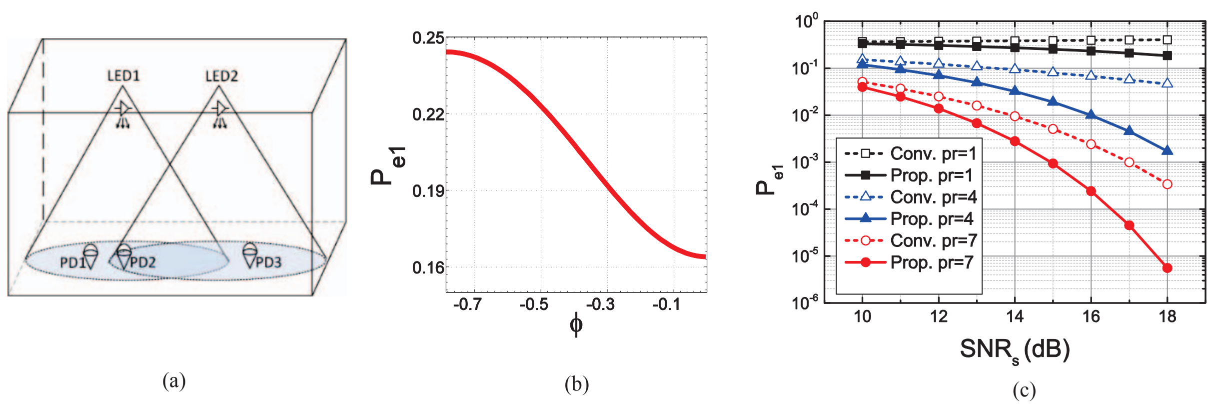

Fig. 1 (a) System model of visible light communication with NOMA; (b) SIC 1st step error probability vs. *S-W* relative phase, r=0.7, SNR of strong signal is 10dB; (c) SIC 1st step error probability vs. SNR of strong signal, pr: power ratio, conv: conventional, prop: proposed where x_s and x_w are transmitted signal of S and W from LED_1 and LED_2, respectively; h_s and h_w are the corresponding channel responses between LED_1 & PD_2 and LED_2 & PD_2; n is the complex additive white Gaussian noise (AWGN) with a power spectrum density of $N_0/2$. Let $h_w/h_s = re^{j\phi}$, where $0<r<1$ denotes the amplitude ratio of the two channel coefficients, and ϕ denotes the relative phase difference between h_w and h_s. Note that the phase difference ϕ depends on the channel conditions (e.g., transmission distance, angle of arrival, and multipath) thus ϕ is random in each transmission. Consider a noiseless case without pre-distortion, the received overlapped signal at PD_2 forms an irregular composite constellation.

Upon receiving the overlapped signal, PD_2 employs successive interference cancellation (SIC) [3] to detect the individual signals from LED_1 and LED_2. The SIC process consists of two steps: (1) decode the strong signal x_s while treating the weak signal x_w as noise; (2) subtract x_s from y_c and then decode the weak signal x_w. Let P_{e1} and P_{e2} denote the symbol error rate (SER) in step (1) and step (2), respectively. Owing to the error propagation of SIC, the decoding errors in step (1) would inevitably lead to decoding errors in step (2). Moreover, the SER in step (2) depends only on the weak signal, given that step (1) is correctly decoded. Therefore, in order to improve the overall performance of NOMA, we shall focus on reducing the SER in step (1). The constellation of the overlapped signal y_c is central-symmetric, with respect to the origin. The SER in step (1) is derived to be:

$$P_{e1} = \frac{1}{4}\sum_{n=1}^{4}\left(Q\left(\frac{\frac{\sqrt{2}}{2}+r\cos\left(\phi+\frac{n\pi}{2}-\frac{\pi}{4}\right)}{\sqrt{N_0/2}}\right) + Q\left(\frac{\frac{\sqrt{2}}{2}+r\sin\left(\phi+\frac{n\pi}{2}-\frac{\pi}{4}\right)}{\sqrt{N_0/2}}\right) - Q\left(\frac{\frac{\sqrt{2}}{2}+r\cos\left(\phi+\frac{n\pi}{2}-\frac{\pi}{4}\right)}{\sqrt{N_0/2}}\right)\cdot Q\left(\frac{\frac{\sqrt{2}}{2}+r\sin\left(\phi+\frac{n\pi}{2}-\frac{\pi}{4}\right)}{\sqrt{N_0/2}}\right)\right)$$

where $Q(\cdot)$ is the Q-function of the standard normal distribution. Because the overlapped constellation is also rotational symmetry, we only consider $-\pi/4<\phi\le 0$. The optimal phase difference $\hat{\phi}$ is obtained by

$$\hat{\phi} = \arg\min_{\phi} P_{e1}, \quad \phi\in(-\pi/4, 0].$$

Using numerical analysis, we plot the value of P_{e1} in Fig. 1(b) with respect to the phase difference ϕ. Our numerical analysis shows that the optimal phase difference is $\phi = 0$. Consequently, the SER can be reduced by pre-distorting the transmitted signals to the optimal phase difference. We calculate the numerical results of P_{1e} in the conventional method and the proposed pre-distortion method, which are shown in Fig. 1(c). It can be concluded that our phase pre-distortion method improved the SER performances for different power ratios compared with conventional NOMA.

3. Experiments

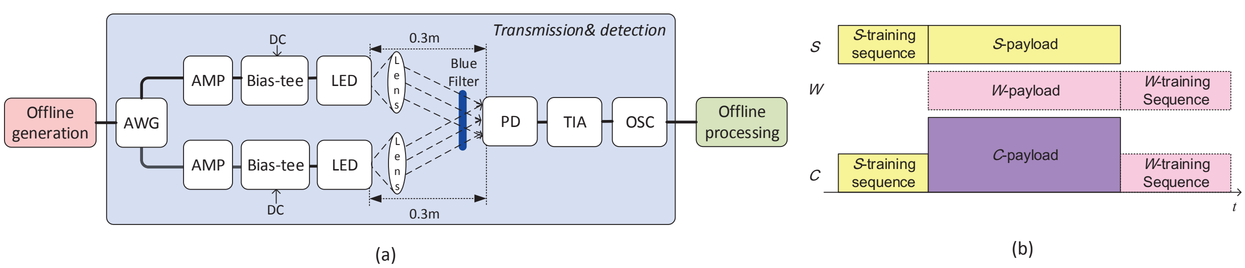

Fig. 2 (a) Experimental setup, (b) frame structure

We evaluate the proposed phase pre-distortion method using extensive VLC experiments in this section. Fig.2(a) shows the experimental setup. In conventional NOMA, the transmitted data was offline generated and sent to an arbitrary waveform generator (AWG). The two outputs of AWG were individually amplified by an amplifier (AMP), biased by a bias-tee, before being fed to a LED (OSRAM LUW W5AM). Two lenses were mounted after the LEDs to focus the light onto a common photodiode (HAMAMATU S10784) after a blue filter. The distances between the LEDs and the PD were both fixed at 0.3m. The receiving powers and power ratios were varied by adjusting the amplitudes of the LED driving signals. The received signal was then amplified by a transimpedance amplifier (TIA), sampled by the real time oscilloscope (OSC) and offline processed. In the offline data generation and processing, the FFT size was 256, with a cyclic prefix (CP) of 32. The two subcarriers near DC was nullified, due to the DC block property of bias-tees. Therefore, the effective subcarrier number in each symbol was 124/256. In each OFDM frame, 10 OFDM training symbols (TS) were accompanied by 240 payload symbols. As shown in Fig. 2(b), frame design of *S* and *W* made the TS not collided while the payloads of *S* and *W* composed the payload of *C*. The sample rates of

AWG and OSC were 100MS/s and 250MS/s, respectively. The net data rate was 86 Mbps for each of *S* and *W*. As the channel response of VLC drastically dropped in high frequency region and caused the non-uniform signal-to-noise ratio (SNR) on different subcarriers, the transmitted signal was digitally filtered to equalize the SNR to assure reliable and uniform SNR values in the experiments.

In phase pre-distorted NOMA, the experimental process comprised two phases. In the first phase, a training sequence was offline generated and transmitted over the whole system in the same process, as in conventional NOMA. The offline processing after the detection recovered the channel state information (CSI) before being fed to the transmitter side. In the second phase, the payload was generated with pre-distortion on the basis of the CSI from the first step. The payload then went through the conventional process.

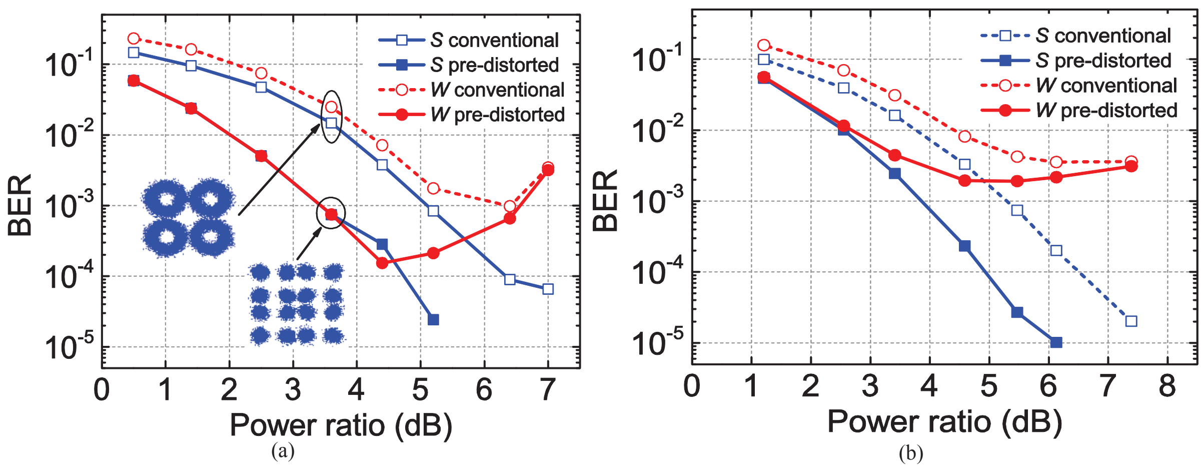

Fig. 3 Experimental results: (a) strong signal SNR=18.5 dB, (b) weak signal SNR=13 dB

Fig. 3 shows the experimental results. In Fig. 3(a), the SNR of *S* is fixed at 18.5 dB, while the power ratio between *S* and *W* varies. It could be observed that the proposed scheme generally showed a considerable improvement over the conventional NOMA. When the power ratio grew too large, the performance of *W* got deteriorated. This was mainly attributed to the degrading signal and the SNR of *W*. Specifically, in the proposed scheme, the minimum power ratios required for *S* and *W* to reach a bit-error-rate (BER) of 3.8×10^{-3} were 1.7 dB and 2.1 dB less than those in conventional NOMA. The inset in Fig 3.(a) shows the effect of pre-distortion on the composite constellation. Fig. 3(b) shows the BER results under different power ratios, while the SNR of *W* was kept at 13 dB. Again, the proposed scheme outperformed the conventional one. Similarly, a too-large power ratio value suppressed the decreasing trend of the BER of *W*. This should be mainly attributed to the nonlinear interference of the LED transmitting *S*. Nevertheless, in the cases of moderate power ratios, the proposed scheme showed good improvements.

4. Summary

We have proposed an effective phase pre-distortion scheme for NOMA in VLC. Theoretical and experimental studies have been conducted to study the performance of the proposed scheme. It was shown that the proposed scheme could relieve the stringent power ratio requirement on the multiple users, as in conventional NOMA. In the cases of moderate power ratios, the proposed scheme decreased the error rates and improved the system performance. This work was partially supported by a research grant from Hong Kong Research Grants Council (Project No. 14200614).

5. References

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