Joint Detection of Visible Light Communication Signals Under Non-Orthogonal Multiple Access

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***Abstract*— We present a phase pre-distorted joint detection (JD) method to improve the system performance of uplink non-orthogonal multiple access (NOMA) in visible light communications. The optimal phase pre-distortion term was first computed based on the channel information of different users. We then pre-distort the users' transmit signals with the optimal phase term to improve the system performance. The proposed scheme outperforms the previously proposed successive interference cancellation-based NOMA with or without pre-distortion. Experimental results show that the phase pre-distorted JD method works well under the cases of low, medium, and high power ratios.**

***Index Terms*— Light-emitting diode, visible light communication (VLC), non-orthogonal multiple access (NOMA), multiuser detection (MUD), OFDM.**

I. Introduction

As a promising candidate of future wireless communication technologies, visible light communication (VLC) is arousing great interest in both wireless and optical research areas. The advantages of VLC include license-free, high confidentiality, and low-cost [1]. Similar to other wireless communication technologies, multiple access strategies are crucial for VLC to support multiple services to multiple users concurrently. Popular multiple access methods include time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA). They, however, suffer from the tradeoff of throughput versus fairness, especially in the scenario where the near-far effect exists [2]. Non-orthogonal multiple access (NOMA), a novel multiple access strategy, has drawn great attention recently. Unlike the conventional multiple access technologies, NOMA can strike a balance between throughput and fairness. It has recently found applications in wireless [3], VLC [4], and fiber-optical systems [5].

NOMA adopts multi-user detection technique, which is based on successive interference cancellation (SIC), conventionally. The receiver first detects one signal from the received composite signal, while treating the other signals present in the same composite signal as noise. Then, the detected signal is subtracted from the received composite signal so as to detect the other signals. Nevertheless, another multi-user detection method, which is based on joint detection (JD), can decode multiple signals jointly. It has been successfully applied into CDMA systems [6] and NOMA downlink [7]. However, as shown in [8], due to the possible mismatch of the signal phases in the case of multiple transmitters, JD may not work well in conventional uplink NOMA. To date, the application of JD in VLC systems is still yet to be explored.

In this letter, we propose a phase pre-distortion based JD scheme for uplink NOMA in a VLC system. Our scheme can effectively improve the system performance under different conditions of signal-to-noise ratios (SNRs) and relative power ratios (PRs) among multiple users.

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II. System Model

Consider an uplink VLC system, as shown in Fig. 1(a), it comprises two light-emitting diodes (LEDs), namely LED_1 and LED_2, as transmitters and a photodiode (PD) as the receiver. The PD lies within the overlapping area of the two LEDs' lighting footprints, hence receiving the signals from both LEDs. Suppose the PD is closer to LED_1 than to LED_2, thus receives a stronger signal S from LED_1 but a weaker signal W from LED_2. The signals S and W overlap with each other, forming a composite signal C. Without loss of generality, we assume that S and W are both 4QAM-OFDM modulated, that is, modulated with four constellation points $\left(\sqrt{2}/2\right)\{1+\mathrm{i}, -1+\mathrm{i}, -1-\mathrm{i}, 1-\mathrm{i}\}$. Considering one subcarrier retrieved at the PD after OFDM demodulation and matched filtering, the received signal is

$$y_c = h_s x_s + h_w x_w + n \tag{1}$$

where x_s and x_w are the modulated data of S and W from LED_1 and LED_2, respectively, h_s and h_w are the respective individual channel responses between the transmitting LEDs and the PD, and n is the complex additive white Gaussian noise (AWGN). Let

$$h_s/h_w = re^{j\varphi}, \quad r_{dB} = 20\log r \tag{2}$$

where r denotes the amplitude ratio of the channel coefficients of S over W, r_{dB} denotes the power ratio in dB, and $\varphi \in [0, 2\pi)$ denotes the relative phase difference between h_s and h_w . Such relative phase difference is random, depending on multiple factors, such as different transmission distances, different angles of arrival, and multiple paths.

III. Multiuser Detection Algorithms for NOMA

At the NOMA receiver, the received symbols from multiple users are detected and retrieved from the received composite overlapped signal. Appropriate techniques are necessary to distinguish and decode the symbols from each transmitter. This necessitates appropriate multi-user detection strategies, such as SIC and JD.

A. SIC-Based NOMA

In SIC-based NOMA, upon receiving the composite overlapped signal, the receiver detects and decodes the signal from multiple transmitters in the descending order of the signal strengths [2]. Specifically, in the given two-user case, the SIC process at the PD consists of two steps: (1) decode the strong signal S while treating the weak signal W as noise; (2) subtract S from C and decode for W. When the decision of S in step (1) is wrong, the decoding output in step (2) would be inevitably erroneous. The key issue in SIC-based NOMA is to decrease the bit-error-rate (BER) in step (1) of SIC. It has been demonstrated in [8] that the performance of SIC-based NOMA could be effectively improved by applying phase predistortion.

B. JD-Based NOMA

In JD-based NOMA, S and W are detected jointly in one step. In the two-user case, the JD algorithm can be expressed as,

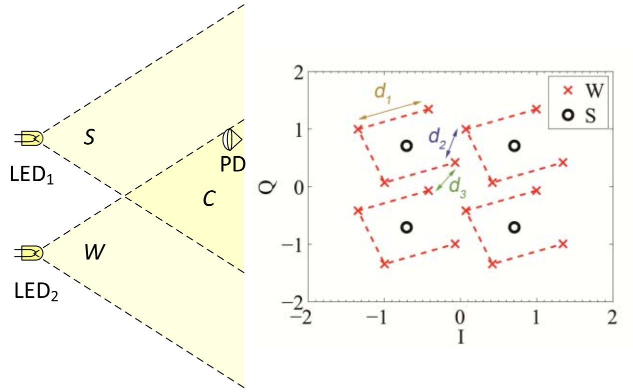
$$\begin{aligned}\left\{\hat{x}_s, \hat{x}_w\right\} &= \underset{\{x_s,x_w\}}{\arg\max}\,\mathrm{Prob}\left\{y_c \left| x_s, x_w\right.\right\} \\ &= \underset{\{x_s,x_w\}}{\arg\max}\,\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left\{-\frac{\left|y_c - h_s x_s - h_w x_w\right|^2}{2\sigma^2}\right\} \\ &= \underset{\{x_s,x_w\}}{\arg\min}\left|y_c - h_s x_s - h_w x_w\right|^2 \end{aligned} \tag{3}$$

where $\left\{\hat{x}_s, \hat{x}_w\right\}$ is the detected signal-pair output by the JD algorithm.

Unlike SIC, JD treats both S and W as useful information, thus is maximum-likelihood (ML) optimal. Considering the transmitted data symbols as well as the channel responses of S and W, the received symbol forms an irregular 16-QAM constellation. Fig. 1(b) illustrates an example. The detection of the signals S and W is to find the constellation point that is the closest to the received signal y_c. Therefore, the performance of JD is dominated by the distribution of the constellation points. In fact, the symbol error rate (SER) of the decision is bounded by [9],

$$\begin{aligned}\frac{1}{M}\sum_{\substack{1\le m\le M,\\ \exists m'\neq m:\left\|s_m - s_{m'}\right\| = d_{\min}}} Q\left(\frac{d_{\min}}{\sqrt{2N_0}}\right) \\ \le P_e \le (M-1)\,Q\left(\frac{d_{\min}}{\sqrt{2N_0}}\right)\end{aligned} \tag{4}$$

where M is the number of the constellation points of the composite overlapped signal ($M = 16$ here), N_0 is the



(a) (b)

Fig. 1. (a) System model for the NOMA in visible light communications. LED: lighting emitted diode; PD: photo diode, S and W are the transmitted signals from LED$_1$ and LED$_2$, respectively; (b) an example of the three Euclidean distances at $r = 1.43$, where $d_1 = 1/r$; $d_2 = \left|1 - (1+j)/re^{j\varphi}\right|$; $d_3 = \left|1 - 1/re^{j\varphi}\right|$.

single-sided power spectrum density of the noise; d_{min} is the minimum Euclidean distance between any pair of constellation points, and can be expressed, based on the observations from Fig. 1(b), as,

$$\begin{aligned} d_{\min} &= \min\left\{\sqrt{2}\left|h_w\right|, \sqrt{2}\left|h_s - h_w\right|, \sqrt{2}\left|h_s - (1+j)\,h_w\right|\right\} \\ &= \min\left\{\frac{\sqrt{2}\left|h_s\right|}{r}, \sqrt{2}\left|h_s - \frac{h_s}{re^{j\varphi}}\right|, \sqrt{2}\left|h_s - (1+j)\,\frac{h_s}{re^{j\varphi}}\right|\right\} \\ &= \min\left\{\frac{1}{r}, \left|1 - \frac{1}{re^{j\varphi}}\right|, \left|1 - \frac{1+j}{re^{j\varphi}}\right|\right\}, \quad -\pi/4 < \varphi \le 0 \end{aligned} \tag{5}$$

where r is defined as the signal power ratio (PR) of S to W. As the constellation here is centro-symmetric, we only consider the range $\varphi \in (-\pi/4, 0]$. From Eq. (5), it is evident that both the upper and the lower bounds of SER largely depends on the value of d_{min}. A larger value of d_{min} leads to a smaller SER, thus better BER performance of NOMA.

We propose to maximize d_{min} by pre-distorting the phase of the signal W with a phase term, which corresponds to the relative phase difference φ in Eq. (5) and can be computed based on the channel response. To simplify the mathematical notation, we define a new metric function, as

$$\begin{aligned} \mathcal{M}_r(\varphi) &= \min\left\{d_1, d_2, d_3\right\} \\ d_1 = \frac{1}{r},\quad d_2 &= \left|1 - \frac{1+j}{re^{j\varphi}}\right|,\ d_3 = \left|1 - \frac{1}{re^{j\varphi}}\right| \end{aligned} \tag{6}$$

and the optimal phase term φ_{opt} can be determined by

$$\varphi_{opt} = \underset{\varphi}{\arg\max}\,\mathcal{M}_r(\varphi), \quad -\frac{\pi}{4} < \varphi \le 0 \tag{7}$$

In Eq. (6), the three Euclidean distances (d_1, d_2 and d_3) are constant, monotonically decreasing, and monotonically increasing, respectively. Hence, the solution of Eq. (7) can be divided into four cases, depending on the values of r.

(i) For the case of $r \ge 2.41$ (or $r_{dB} \ge 7.7$ dB), the following expression always holds.

$$\mathcal{M}_r(\varphi) = \frac{1}{r}, \varphi \in \left(0, \frac{\pi}{4}\right] \tag{8}$$

Thus, the value of d_{min} is determined by the value of r. Since r is constant within the range of φ, the BER performance cannot be improved by changing the phase difference between S and W. Hence, phase pre-distortion is ineffective. Fig. 2(a) shows the values of the three Euclidean distance terms when $r = 2.5$. As the minimum Euclidean distance is determined by the constant value $1/r$. Hence, phase pre-distortion does not work in this case.

(ii) For the case of $2 \le r < 2.41$ (or 6.0 dB $\le r_{dB} < 7.7$ dB), the following expression holds.

$$\mathcal{M}_r(\varphi) = \begin{cases} \dfrac{1}{r}, & \varphi \in \left(0, \dfrac{\pi}{4} - \arccos\left(\frac{r^2+1}{2\sqrt{2}r}\right)\right] \\ \left|1 - \dfrac{1+j}{re^{j\varphi}}\right|, & \varphi \in \left(\dfrac{\pi}{4} - \arccos\left(\dfrac{r^2+1}{2\sqrt{2}r}\right), \dfrac{\pi}{4}\right] \end{cases} \tag{9}$$

Considering the monotonicities of the three functions, the value of d_{min} is maximized at $\varphi \in [\arccos\left(\frac{1+r^2}{2\sqrt{2}r}\right) - \frac{\pi}{4}, 0]$. Thus, the optimal pre-distorted phase is within a range rather than a single value. Fig. 2(b) shows the values of the three Euclidean distance terms when $r = 2.2$. Obviously, the SER can be minimized by pre-distorting the relative phase difference to this region.

(iii) For the case of $1.93 \le r < 2.0$ (or 5.7 dB $\le r_{dB} < 6.0$ dB), the following expression holds.

$$\mathcal{M}_r(\varphi) = \begin{cases} \left|1 - \dfrac{1}{re^{j\varphi}}\right|, & \varphi \in \left(0, \arccos(\dfrac{r}{2})\right] \\ \dfrac{1}{r}, & \varphi \in \left(\arccos(\dfrac{r}{2}), \dfrac{\pi}{4} - \arccos\left(\dfrac{r^2+1}{2\sqrt{2}r}\right)\right] \\ \left|1 - \dfrac{1+j}{re^{j\varphi}}\right|, & \varphi \in \left(\dfrac{\pi}{4} - \arccos\left(\dfrac{r^2+1}{2\sqrt{2}r}\right), \dfrac{\pi}{4}\right] \end{cases} \tag{10}$$

Similar to the previous case, the value of d_{min} is also maximized in a range of φ, that is,$\arccos\left(\frac{r}{2}\right) < \varphi \le \arccos\left(\frac{\sqrt{2}}{2}r - \frac{1}{2}\right)$. Therefore, the phase pre-distortion is effective. Fig. 2(c) shows the values of the three Euclidean distance terms when $r = 1.98$. The minimum Euclidean distance can be maximized by pre-distorting φ to $\arccos\left(\frac{r}{2}\right) < \varphi \le \arccos\left(\frac{\sqrt{2}}{2}r - \frac{1}{2}\right)$.

(iv) For the case of $1.0 \le r < 1.93$ (or 0 dB $\le r_{dB} < 5.7$ dB), the following expression holds.

$$\mathcal{M}_r(\varphi) = \begin{cases} \left|1 - \dfrac{1}{re^{j\varphi}}\right|, & \varphi \in \left(0, \arcsin(\dfrac{1}{2r})\right] \\ \left|1 - \dfrac{1+j}{re^{j\varphi}}\right|, & \varphi \in \left(\arcsin(\dfrac{1}{2r}), \frac{\pi}{4}\right] \end{cases} \tag{11}$$

Therefore, the value of d_{min} reaches its maximum value at $\varphi = \arcsin\left(\frac{1}{2r}\right)$. Fig. 2(d) shows the values of the three Euclidean distance terms when $r = 1.43$. Apparently, it is beneficial to pre-distort the relative phase difference to the optimal point $\varphi = \arcsin\left(\frac{1}{2r}\right)$, which is the intersection point of the blue line and magenta line (in Fig. 2(d)), for better system performance.

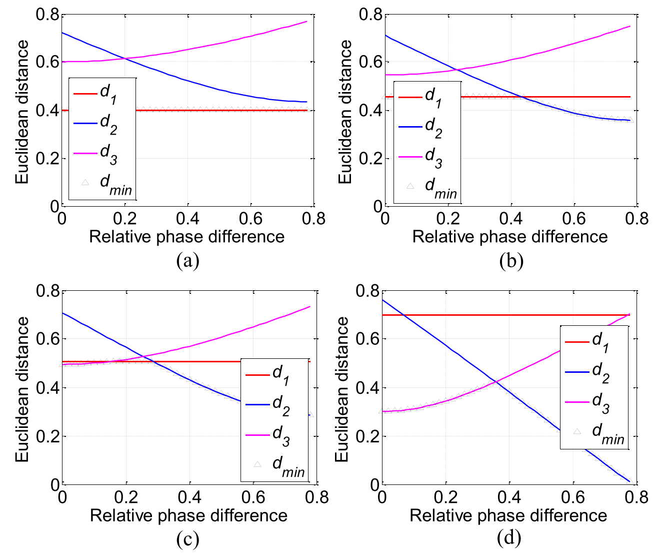


Fig. 2. Comparison of the three Euclidean distance terms in three cases: (a) $r = 2.5$; (b) $r = 2.2$; (c) $r = 1.98$; (d) $r = 1.43$.

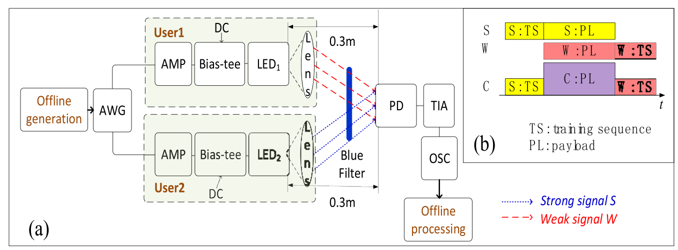


Fig. 3. (a) Experimental setup; (b) signal frame structure.

IV. Experimental Validation

Figure 3(a) shows the experimental setup. For conventional NOMA, the transmitted data was offline generated and sent to an arbitrary waveform generator (AWG). Each output of AWG was individually amplified by an amplifier (AMP) and biased by a bias-tee before driving a LED (OSRAM LUW W5AM). Two lenses were mounted after the LEDs to direct the light to the same PD (HAMAMATSU S10784) after a blue filter. The distances between the LEDs and the PD were both fixed at 0.3 m. The receiving powers and the power ratios r_{dB} were tuned by changing the LED driving signals. The received signal was then amplified by a trans-impedance amplifier (TIA), sampled by a digital storage oscilloscope (DSC) and offline processed using MATLAB. The fast Fourier transform (FFT) size of OFDM was 256 and the cyclic prefix (CP) length was 32. Due to the DC block property of the bias-tees, the two subcarriers next to the DC term were set to null. Therefore, the effective number of subcarriers in each symbol was 124 out of 256. Each frame consisted of 10 OFDM training symbols (TS) and 240 payload symbols. As shown in Fig. 3(b), we deliberately designed the frames of S and W to make their TS non-overlapped. The sampling rates of AWG

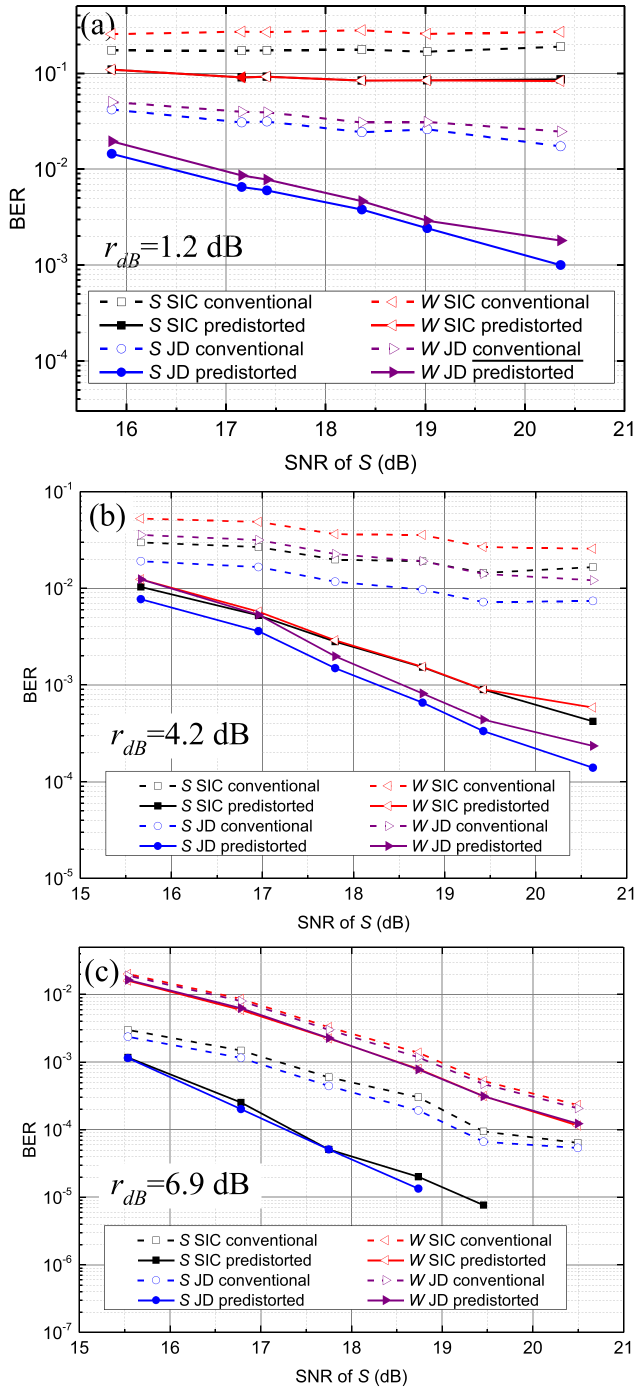


Fig. 4. Bit error rate (BER) versus the SNR of the strong signal at signal power ratios of (a) $r_{dB} = 1.2$ dB, (b) $r_{dB} = 4.2$ dB, (c) $r_{dB} = 6.9$ dB.

and DSC were 100 MS/s and 250 MS/s, respectively. On the other hand, the proposed JD-based phase pre-distorted NOMA, similar to its SIC counterpart reported in [8], comprised two steps. In the first step, a training sequence was offline generated and transmitted, as in the conventional NOMA. Upon receiving the composite overlapped signal, the PD estimated the channel state information (CSI) using the TS and fed the CSI back to the transmitters. In the second step, the transmitters pre-distorted the phase of the payload symbols based on the obtained CSI before transmitting the signals.

Fig. 4 shows the measured BER performances of both the strong signal (S) and the weak signal (W) using our proposed JD method and the conventional SIC methods with or without phase pre-distortion. From the results, the method of JD with phase pre-distortion achieved the best BER performance, and outperformed the others under all three cases of signal power ratios. The performance improvement was the most significant when the power ratio was low. In the case of low signal power ratio, such as $r_{dB} = 1.2$ dB as shown in Fig. 4(a), the performance of SIC showed error floors for both S and W at BER of about 10^{-1}, while JD was not bounded by any error floor. In the case of medium signal power ratio, such as $r_{dB} = 4.2$ dB as in Fig. 4(b), the performances of JD for both users were about 1-dB better than that of SIC at BER of 10^{-3}. In the case of high signal power ratio such as $r_{dB} = 6.9$ dB as shown in Fig. 4(c), the performance of JD was only slightly better than that of SIC. Thus, SIC required a higher signal power ratio to obtain good performance, while JD alleviated the signal power ratio requirement. Hence, our proposed phase pre-distorted joint detection based NOMA shows the best performance over other schemes, especially when the signal power ratio is low.

V. SUMMARY

We have proposed a phase pre-distorted joint detection method for uplink non-orthogonal multiple access (NOMA) in visible light communication systems. It achieves superior BER performance, compared to other previously reported schemes, such as SIC-based ones. Experimental results show that it works well under different power ratios of the signals from multiple users. In particular, when the signal power ratio is low, the proposed scheme eliminates the error floor that exists for the case of SIC-based NOMA.

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