On the Performance of Adaptive MIMO-OFDM Indoor Visible Light Communications

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***Abstract*— In this letter, we propose an adaptive indoor multiple input and multiple output (MIMO) orthogonal frequency division multiplexing (OFDM) visible light communication (VLC) system using a receiver module with angular diversity. In order to improve the capacity of indoor MIMO-OFDM VLC systems, tilted receivers are utilized to increase channel diversity, thus reducing channel correlation. With the help of singular value decomposition-based technique, which decomposes the MIMO VLC channels into independent parallel sub-channels, adaptive resource allocation, namely, bit and power loading, is used for these sub-channels to further improve the proposed system's capacity. Based on a 4 × 4 indoor MIMO-OFDM VLC system, we investigate bit error rate (BER) performance of the proposed adaptive system with different polar angles in two typical indoor scenarios. Numerical simulation results show that with 50-MHz modulation bandwidth, average BER can be improved from 4.97×10^{-3} to 1.66×10^{-5} and from 1.90×10^{-3} to 1.59×10^{-6} for the two scenarios, respectively.**

***Index Terms*— Visible light communications, optical MIMO-OFDM, singular value decomposition, bit and power loading.**

I. Introduction

THE last few years have witnessed the wide adoption of light emitting diodes (LEDs) for illumination due to their advantages such as long lifetime, compact size and low power consumption [1], [2]. Compared to conventional fluorescent light sources, LED sources have much faster switching speed, making it possible to directly modulate data on LED, so that both illumination and data communications can be provided simultaneously. However, with current LED production technology, modulation bandwidth of LED is limited to several megahertz by the slow response of phosphorescent component of visible light [2]. Among the approaches reported in previous works [3]–[6], multiple input and multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) techniques have been proved to be feasible ways for VLC systems to boost capacity and improve reliability. However, intensity modulation and direct detection (IM/DD) VLC systems limit the direct application of MIMO and OFDM theory from wireless communications. Nevertheless, OFDM has been adopted in optical wireless (OW) systems by constraining subcarriers to have Hermitian symmetry [6]. For indoor VLC systems, commonly multiple LEDs are deployed for illumination, spatial diversity of LED transmitters can be utilized to achieve high data rate transmission by using MIMO technique. However, channel matrix of indoor MIMO VLC systems can be highly correlated as the signals received by closely spaced receivers are nearly identical [3], [4].

The performances of four conventional MIMO detection methods are compared in [7] based on a 4 × 4 MIMO indoor VLC system. Experimental comparison of different bit and power allocation algorithms for VLC system using DC-biased optical OFDM (DCO-OFDM) is presented in [8]. In [9], a Gigabit/s transmission is reported with the help of MIMO-OFDM in the VLC system. Besides, tilting technique, i.e., optimizing the orientation angle of receiver module, has been used in VLC system to improve system's performance. A single tilted receiver is proposed in [10] to improve SNR distribution as well as spectral efficiency of an indoor OFDM system. We have adopted titled receivers in a pre-coded multiuser VLC system to improve BER performances of user terminals [4]. In [5], the performance of tilting technique and link blocked technique is compared in an indoor VLC system. However, in these MIMO VLC systems, system performance is not optimized as fixed modulation format are used. Moreover, only line of sight (LOS) channel gains between LED sources and photodetectors are used as channel matrix coefficients. Also nonlinearity and limited bandwidth properties of LED are not taken into account. That leads to inaccurate estimation of channel state information (CSI), resulting in limited system performance.

In this letter, we propose an adaptive indoor MIMO-OFDM VLC system and the BER performance of the proposed system is investigated in details. The performance of indoor MIMO-OFDM VLC system is optimized by SVD-based adaptive loading, which is originally proposed in wireless communications [11]. However, such scheme have limitation in VLC systems due to the high correlation mentioned above. We proposed to utilize a receiver module with four receiver heads that are oriented to an optimized polar angle with different azimuthal angles, to achieve significant enhancement of channel diversity. LED nonlinearity, modulation bandwidth, and multiple reflections are taken into account for CSI estimation for the proposed system. We investigate two typical scenarios of receiver module location in indoor environments, and the results show that BER performance of the system can be significantly improved for both scenarios by using the proposed adaptive loading scheme with angular diversity receiver module.

II. System Model

In this section, we consider an indoor MIMO-OFDM VLC system with the number of LED transmitter and receiver

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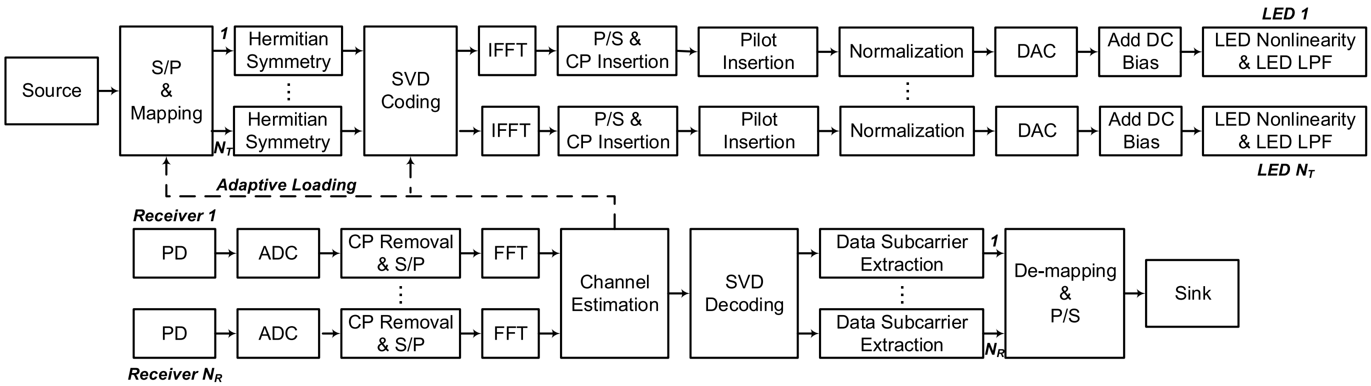

Fig. 1. Block diagram of the adaptive indoor MIMO-OFDM VLC system.

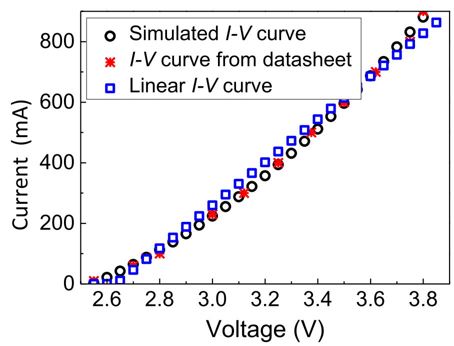

Fig. 2. *I-V* property of LED.

being $\mathrm{N_T}$ and $\mathrm{N_R}$, respectively. The system block diagram is shown in Fig. 1. The source bits are allocated adaptively according to CSI. After Hermitian symmetry, a linear transformation of the original signal is preformed, i.e., the mapped signal of each subcarrier is multiplied with the corresponding matrix obtained from SVD of channel matrix. Then, inverse fast Fourier transform (IFFT), parallel to serial (P/S) conversion, and cyclic prefix (CP) insertion are performed to obtain the time domain signal. After that, pilot symbols are added for the channel estimation at receivers. Before digital to analog conversion (DAC) and low pass filtering (LPF), the signal is normalized between -0.5 and $+0.5$ since the output signal of arbitrary signal generator (AWG) is limited within this range. The LPFs used are second-order Butterworth filters. After DAC, DC bias is added to drive LED. The 3-dB modulation bandwidth of LED is set as 10 MHz. Since nonlinearity of LED is an essential issue for optical OFDM due to its sensitivity to the resulting distortion, LED nonlinearity is considered in this letter.

The scheme proposed in [12] is used to model the nonlinearity of LED's I-V property. Fig. 2 shows that simulated I-V property fits well with the data obtained from the LED datasheet (OSRAM LUW W5AM). The linear I-V curve that is obtained by linear regression of the data in LED datasheet is also presented in Fig. 2.

Consider a MIMO-OFDM indoor VLC system with $\mathrm{N_T}$ LED transmitters, $\mathrm{N_R}$ receivers and K OFDM subcarriers. Let $X_i(k)$ denote the transmitted signal on the k-th subcarrier at the i-th LED transmitter, $Y_j(k)$ denote the received signal on the k-th subcarrier at the j-th receiver, and $N_j(k)$ denote the noise on the k-th subcarrier at the j-th receiver. Then, $Y_j(k)$ is given by

$$Y_j(k) = \sum_{i=1}^{Nt} H_{ji}(k) X_i(k) + N_j(k), \tag{1}$$

where $\mathrm{N}_j(k)$ represents the noise with zero mean and its variance is defined in [4] and [10]. $H_{ji}(k)$ is the frequency domain channel response from the i-th LED transmitter to the j-th receiver on k-th subcarrier. In this work, we use Monte Carlo method [13], which can evaluate non-LOS response efficiently, to model the channel characteristics of the proposed indoor MIMO-OFDM VLC system.

The overall system response, including the multi-reflections VLC channel, low-pass filtering and LED nonlinearity, is estimated by least square (LS) scheme for MIMO-OFDM system with the help of pilot symbols. The estimated channel matrix of k-th subcarrier can be expressed as

$$\boldsymbol{H}(k) = \begin{bmatrix} H_{11}(k) & \ldots & H_{1N_T}(k) \\ \ldots & & \ldots \\ H_{N_R 1}(k) & \ldots & H_{N_R N_T}(k) \end{bmatrix}. \tag{2}$$

Based on the channel matrix, SVD is performed to obtain the precoding matrices for transmitter, i.e., $\boldsymbol{H} = \boldsymbol{UDV}^*$, where $(\cdot)^*$ denotes Hermitian transpose, $\boldsymbol{V}$ is an $\mathrm{N_T} \times \mathrm{N_T}$ unitary matrix that will be used in transmitter to pre-process transmitted signal and $\boldsymbol{U}$ is an $\mathrm{N_R} \times \mathrm{N_R}$ unitary matrix. $\boldsymbol{D}$ is an $\mathrm{N_R} \times \mathrm{N_T}$ diagonal matrix with nonnegative diagonal elements (singular values of matrix $\boldsymbol{H}$) λ_{mk}, where $m = 1, 2, \ldots$, M and $\mathrm{M} = min\,(\mathrm{N_T}, \mathrm{N_R})$. After precoding, the transmitted signal is given by $\boldsymbol{V} \cdot \boldsymbol{X}$, and the received signal (in frequency domain) is multiplied by $\boldsymbol{U}^*$ to yield

$$\boldsymbol{Y} = \boldsymbol{U}^* \cdot \{\boldsymbol{H} \cdot (\boldsymbol{V} \cdot \boldsymbol{X}) + \boldsymbol{N}\} = \boldsymbol{D} \cdot \boldsymbol{X} + \boldsymbol{U}^* \cdot \boldsymbol{N}. \tag{3}$$

Because $\boldsymbol{D}$ is a diagonal matrix, the indoor MIMO VLC channels are decomposed into M independent parallel sub-channels. Therefore, for the SVD-based indoor MIMO VLC system, the equivalent channel gain of M independent sub-channels is given by

$$G = [\lambda_{11}, \ldots, \lambda_{1K}; \lambda_{21}, \ldots, \lambda_{2K}; \ldots; \lambda_{M1}, \ldots, \lambda_{MK}]. \tag{4}$$

By utilizing the algorithm proposed in [14], we can adaptively allocate the bits and power to these independent sub-channels for the indoor MIMO-OFDM VLC system. Note that

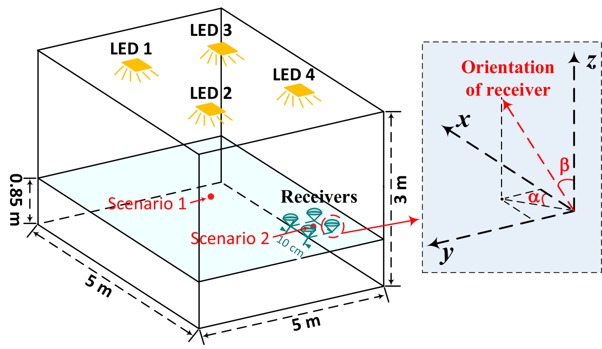

Fig. 3. The configuration of the indoor MIMO-OFDM VLC system. The inset shows the definition of azimuth and polar angles for the receiver orientation.

TABLE I
LOCATION OF LEDs AND RECEIVERS

Tx / Rx	Location (meter)
LED	(3.5,3.5,3); (1.5,3.5,3) (3.5,1.5,3); (1.5,1.5,3)
Receiver (Scenario 1 - center)	(2.55,2.55,0.85); (2.45,2.55,0.85) (2.55,2.45,0.85); (2.45,2.45,0.85)
Receiver (Scenario 2 - corner)	(0.5,0.5,0.85); (0.4,0.5,0.85) (0.5,0.4,0.85); (0.4,0.4,0.85)

the adaptive loading approach for MIMO system is not limited to specific OFDM schemes. In this letter, we utilize the DCO-OFDM scheme to investigate performances of the proposed system as the LED model requires DC bias and also DCO-OFDM can carry more data subcarriers.

III. System Setup and Simulation Results

A. System Setup

The proposed indoor MIMO-OFDM VLC system implemented in a typical 5 m × 5 m × 3 m room is shown in Fig. 3. Four LEDs are mounted on ceiling, and are 3 m away from floor. The distance from the floor to the receiving plane is 0.85 m. Four receiver are arranged as a 10 cm × 10 cm square on the receiving plane, and form a 4 × 4 MIMO VLC system together with the four LED transmitters. We assume two receiver distribution scenarios, as marked in Fig. 3, to investigate the system performance. The locations of LED transmitter and receivers in the two scenarios are given in Table I.

As mentioned in Section I, the key factor that limits the performance of indoor MIMO VLC system is the high correlation between closely spaced receivers. Therefore, tilted receivers are used in this letter to improve channel diversity. The main idea of tilted receiver is to optimize the incident angle and detection coverage of photodiodes. Assume $\hat{n}_R$ is the orientation vector of the tilted receiver, then $\hat{n}_R = [sin\beta \cdot cos\alpha, sin\beta \cdot cos\alpha, cos\beta]$, where β is the polar angle and α is the azimuthal angle on *x*-*y* plane, as shown in Fig. 3. In this letter, the values of azimuthal angle α of the four receiver heads are set as 45°, 135°, 225° and 315°, respectively. We then investigate the effects of different polar angle to the system performance, whereas the influence of azimuthal angle will be studied in the future.

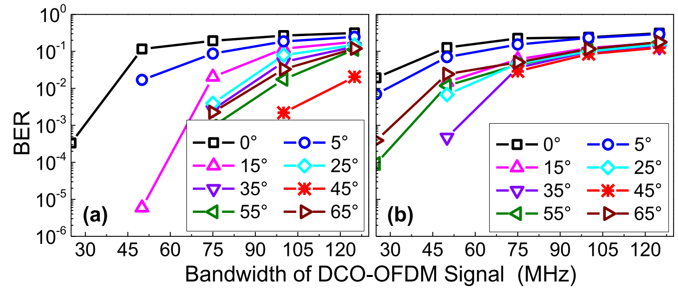

Fig. 4. Average BER performance with different polar angle: (a) Scenario 1; (b) Scenario 2.

B. Simulation Results

The parameter values in simulations are set as follows: the IFFT/FFT size is 256; the CP length is 8; the responsivity of photodetector is 0.53 A/W; LED bias voltage is set as 3.2 V; LED power is 10 W; the physical detection area of photodetector is 1 cm^2; the field of view (FOV) is 70° [4]; and the number of generated rays to simulate VLC channel is 100,000. We assume that each ray will experience five reflections in the simulation, and the reflection factors of walls, floor and ceiling are 0.83, 0.63 and 0.4, respectively [13].

Fig. 4 shows the comparison of average system BER with different polar angle. Here, adaptive modulation is not utilized yet, the data subcarriers of DCO-OFDM signal are modulated with BPSK and conventional ZF detection scheme is utilized to recover detected signal. Generally, the average BER of receivers in scenario 1 is superior to that in scenario 2, since higher received signal intensity can be obtained in scenario 1 and multipath effect induced by multiple reflections is less severe.

It is shown in Fig. 4 that system BER can be improved significantly when the polar angle is increased from 5° to 45°, with a 10° step size. However, BER performance will decrease when the polar angle is larger than 45°. This is because large polar angle will also reduce the LOS component of received signal. When the polar angle is too large, LOS component can be comparable or even smaller than the non-LOS component, which will conversely limit the system's performance. Note that the optimum polar angle may vary when the vertical distance between receiving plane and LED sources is changed.

Fig. 5 shows the signal constellations and corresponding BER performances of the recovered signal with optimum polar angle, i.e., 45° , in both scenarios. The bandwidth of DCO-OFDM signal is 50 MHz. As shown in Fig. 4, BER performance of scenario 1 outperforms that of scenario 2, therefore, in Fig. 5, we use 16QAM-OFDM and 8QAM-OFDM modulation format for the two scenarios, respectively. The average BER with 16QAM-OFDM in scenario 1 is 4.97×10^{-3}, while average BER with 8QAM-OFDM in scenario 2 is 1.90×10^{-3}. It is obvious that the BERs of the recovered signals from different transmitters are different.

To further optimize BER performance, SVD-based bit loading and power loading are used. Note that the total bits are the same with that in Fig. 5. Data bits are allocated to the transmitters and subcarriers adaptively according to the equivalent channel gain. The bit and power allocation results of both scenarios are shown in Fig. 6.

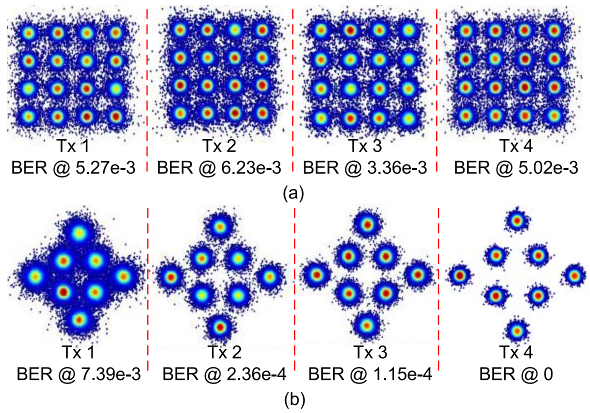

Fig. 5. Recovered signal constellations: (a) 16QAM-OFDM for scenario 1, (b) 8QAM-OFDM for scenario 2.

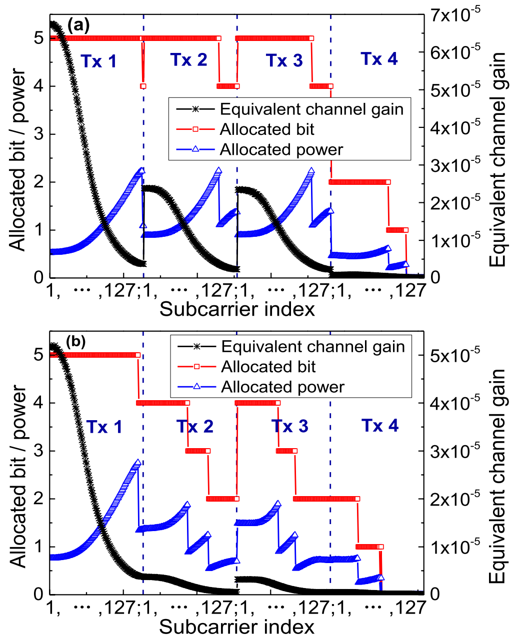

Fig. 6. Bit and power allocation results: (a) Scenario 1, (b) Scenario 2.

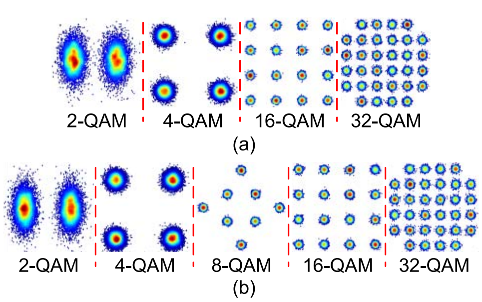

Fig. 7. Recovered signal constellations with bit and power loading: (a) Scenario 1, (b) Scenario 2.

The signal constellations of recovered signal with adaptive modulation is shown in Fig. 7. Results show that the quality of recovered signal can be improved significantly by bit and power loading scheme. As shown in Table II, the average BER can be improved from 4.97×10^{-3} to 1.66×10^{-5} (Scenario 1) and from 1.90×10^{-3} to 1.59×10^{-6} (Scenario 2), respectively.

TABLE II

BER Comparison of the System With and Without Adaptive Loading

	w/o the proposed scheme	w/ the proposed scheme
Scenario 1 (16QAM-OFDM)	4.97×10^{-3}	1.66×10^{-5}
Scenario 2 (8QAM-OFDM)	1.90×10^{-3}	1.59×10^{-6}

IV. Conclusion

An adaptive indoor MIMO-OFDM VLC system is proposed in this letter. We show that using a receiver module with angular diversity is effective to improve the BER of the proposed VLC system. By using SVD-based technique, the MIMO VLC channel is decomposed into independent parallel sub-channels so as to optimize the allocation of bit and power. Simulation results show that with the help of adaptive resource allocation, BER can be improved from $\sim10^{-3}$ to $\sim10^{-6}$ for both center and off-center of indoor coverage.

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