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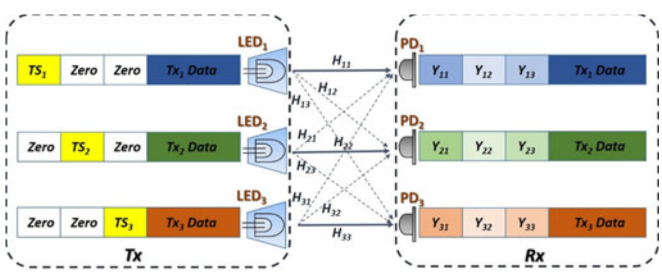

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High Speed Imaging 3 × 3 MIMO Phosphor White-Light LED Based Visible Light Communication System

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Abstract: The phosphor light-emitting diode (LED) has been widely used not only for indoor illumination but for the optical transmitter (Tx) as well in visible light communication (VLC). However, the transmission data rate is significantly limited by the modulation bandwidth of LED because of the low-speed response of phosphor. In order to enhance the data rate of the VLC system, we demonstrate a 3 × 3 imaging multiple-input multiple-output (MIMO) VLC system. Besides, the pre-equalizer circuit is used to extend the bandwidth of the LED Tx. Orthogonal frequency division multiplexing (OFDM) with bit-loading algorithm is used. By using the proposed scheme, the original 1 MHz bandwidth commercially available phosphor white light LED can achieve 1 Gbps data rate over 1-m free-space transmission distance.

Index Terms: Light-emitting diode (LED), multiple-input multiple-output (MIMO), visible light communication (VLC).

1. Introduction

Nowadays, the light-emitting diode (LED) has been widely used for illumination because of its advantages such as low cost, long lifetime, and conservation of energy. In addition, it has been used as the light source for the visible light communication (VLC) [1]. Unlike laser based VLC systems [2]–[5], the LED based VLC can combine the lighting and communication at the same time. As the primary function of the LED is for lighting; hence little extra cost and energy is needed to provide the communication purpose. Previously, we have demonstrated the white light LED based VLC can also provide high precision indoor positioning [6] and light encryption [7]. In the LED based VLC system, the data rate is limited by the low modulation bandwidth ($<$ 3 MHz) of phosphor white LED. Therefore, several methods have been proposed to increase the data rates. In [8], the use of an equalizer and blue-filter was reported to achieve a 100 Mbit/s non-return-to-zero (NRZ) over 0.1 m. Besides, advanced modulations, such as orthogonal frequency division multiplexing (OFDM) can provide a high spectrally efficiency, and [9] reported using OFDM, blue-filter and avalanche photodiode (APD) to achieve a 513 Mbit/s VLC over 0.3 m. To further increase

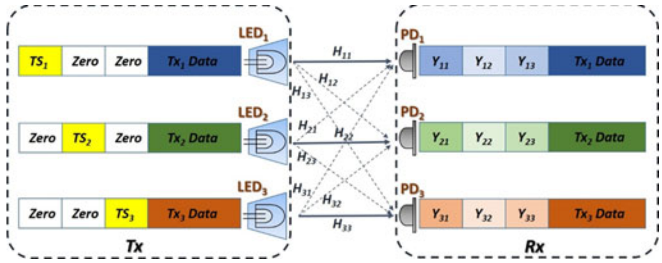

Fig. 1. Configuration of 3 × 3 MIMO VLC system. PD: photodiode.

the data rates, multiple-input multiple-output (MIMO) technique has been proposed and studied [10], [11]. In the non-imaging MIMO, separate focusing lens is required in front of each photodiode (PD). Non-imaging 4 × 4 MIMO VLC of 50 Mbit/s over 2 m was demonstrated [12]. The dedicated focusing lens for each PD made the size of VLC receiver (Rx) very big. In [13], use of an imaging 4 × 9 MIMO VLC of 1 Gbit/s over 1 m using an imaging lens, blue filter, and a 3 × 3 PD array is demonstrated; however, a complicated 3 × 3 PD array was required to achieve 1 Gbit/s. In [14], a 4 × 4 imaging MIMO achieving an aggregate data rate of 920 Mbit/s is reported; however, special μLEDs were required, and this system may not good for lighting. In [15], another imaging MIMO imaging Rx is reported; however, only simulations were provided.

In this work, we propose and demonstrate a high speed 3 × 3 imaging MIMO VLC system using commercial phosphorescent white LEDs and low-cost PIN PDs. Only one focusing lens is needed at the Rx, and therefore, the size of Rx can be more compact than non-imaging MIMO system. Besides, commercially available white LEDs are used; hence the proposed MIMO system can perform lighting and communication simultaneously. By combining the equalizer circuit and OFDM bit-loading, the total data rate of the system can achieve 1 Gbit/s over 1 m free space transmission.

2. Operation Principle of 3 × 3 MIMO VLC System

Fig. 1 shows the configuration of 3 × 3 MIMO VLC system. Here, LEDs are used as transmitters (Txs) and the transmitted signal will be received by PDs. However, each PD will not only receive the light signal from one transmitter but the interference light from other channels as well. In addition, these interferences will distort the target signal so that the performance of that channel will deteriorate. Such multi-channel communication system can be expressed as a MIMO model

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \tag{1}$$

where $[Y_1\, Y_2\, Y_3]^T$ and $[X_1\, X_2\, X_3]^T$ represent received signal and original signal, respectively. $[N_1\, N_2\, N_3]^T$ is the noise of the system. The coefficients in the matrix H is the channel response for each path of the transmission. In order to obtain the channel coefficients, the time-multiplexing training sequences (TS) are added in front of the transmit data that can be expressed as

$$T_1 = \begin{bmatrix} TS_1 \\ 0 \\ 0 \end{bmatrix}, \quad T_2 = \begin{bmatrix} 0 \\ TS_2 \\ 0 \end{bmatrix}, \text{ and } T_3 = \begin{bmatrix} 0 \\ 0 \\ TS_3 \end{bmatrix}. \tag{2}$$

After the free space transmission, the originally zero parts in the training sequence become not zeros anymore; that is, the interferences from other channels and system noise will be included in the training sequence of the received signal. By dividing the received training data with the original ones, the channel response of each path can be calculated. Then, the channel matrix can be

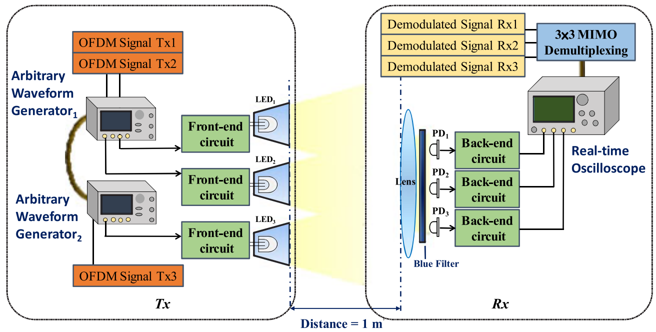

Fig. 2. Experiment setup of 3 × 3 MIMO-OFDM VLC.

estimated:

$$\mathrm{H} = \begin{bmatrix} Y_{11}/TS_1 & Y_{12}/TS_2 & Y_{13}/TS_3 \\ Y_{21}/TS_1 & Y_{22}/TS_2 & Y_{23}/TS_3 \\ Y_{31}/TS_1 & Y_{32}/TS_2 & Y_{33}/TS_3 \end{bmatrix} \quad (3)$$

where Y_{ij} denotes the received training sequence of j^{th} symbol of Rx_i. Once the channel matrix is obtained, the original data $[X_1\, X_2\, X_3]^T$ can be recovered by multiplied the inverse matrix H^{-1} to the left of the received signal to eliminate the interference from other channels, that is

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix}^{-1} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix}. \quad (4)$$

In this work, the MIMO training sequence is based on time-multiplexing in order to simplify the calculation of channel matrix H. As illustrated in the Tx side of Fig. 1, each training sequence of VLC signal consists of three durations, and only one duration carries the training data. For example, in the first time duration of training sequence at the Tx side, only LED_1 sends TS_1, and the signals sent from LED_2 and LED_3 at that time duration are zeros. Therefore, at the Rx side, Y_{11} will be the correct information; and Y_{21} and Y_{31} will be the interference from LED_1 to PD_2 and PD_3. Hence, the channel response from LED_1 to each PD can be simplified to the received training data divided by TS_1 as shown in the first column of channel matrix H presented in (3). Similarly, the values of the other two columns of H can be calculated in the same way. As a result, the calculation of channel matrix H can be simplified by using the time-multiplexing scheme (i.e., one channel sending training data, and the other channels sending zeros) when compared with the other scheme.

3. Experimental Demonstration

Fig. 2 presents the experiment setup of the 3 x 3 MIMO VLC system. First, three independent OFDM signals are created using offline MATLAB program with the parameters: fast Fourier transform (FFT) size of 256, cyclic prefix (CP) of 3.03%, and the subcarrier number of 30. Here, the bit-loading technique is used in order to enhance the spectral efficiency; and the modulation order (using different quadrature-amplitude-modulation, QAM) is from 2 to 7 depending on the signal-to-noise ratio (SNR) of each subcarrier. In the experiment, the 3 independent electrical OFDM signals are generated by two arbitrary waveform generators (Tektronix, AWG7122B and AWG7082C) with sampling rate of 625 MSample/s. Here, two arbitrary waveform generators are used since each arbitrary waveform generator only has two ports and these two arbitrary waveform generators are synchronized. Then, they are applied to our developed front-end circuits, which contain pre-equalizers, electrical amplifiers and bias-tees for directly modulating the white LEDs with the distance of 12 cm between each LED as shown in Fig. 2. Three lenses are used to focus the light. The LED is from Cree® (XR-E).

It is phosphor-based and with color temperature of 5500 K. The driving voltage is 3.3 V. The front-end circuit consists of a pre-equalizer integrated with an electrical amplifier (Texas Instruments, OPA2677) and a bias-tee. The circuit layout and the detail parameters of the pre-equalizer circuit, such as the resistance and capacitance values can be found in [16]. In the experiment, each LED requires a DC bias voltage to turn-on, and the electrical OFDM data is applied together with the DC bias via a bias-tee circuit built inside the Tx. The DC bias voltage applied to the Tx is constant. As the OFDM is modulated at MHz range, during the experiment, we do not notice any flicking in illumination. Therefore, the modulation used here is the DC biased optical OFDM (DCO-OFDM).

In the beginning, the modulation levels of all OFDM subcarriers are set to 16-QAM, and then after the VLC MIMO experiment, the SNR of each subcarrier is measured. According to the measured SNR values, the modulation level of each subcarrier can be updated based on the bit-loading algorithm described in [9], so that the data rate of the system can be increased while satisfying the forward error correction (FEC) BER requirement. In the bit-loading, the subcarrier with higher SNR can carry higher modulation level (such as 64-QAM or 128-QAM). Finally, the new OFDM signal after bit-loading is updated in the arbitrary waveform generator, which is used to drive the LED system again.

After 1 m free space transmission, the three independent VLC signals are received with three PDs respectively. Instead of using three lens in front of each PD (known as non-imaging MIMO), we demonstrate imaging MIMO that only one lens is needed to focus three lights. Since the lens at Rx is used to focus the lights, the PDs can be closer to each other and thus the size of Rx will be more compact than non-imaging MIMO system. A blue filter can be included to attenuate the optical signal to avoid the PD saturation and to extend the analog bandwidth. Here, the Rx consists of PIN PDs (Hamamatsu, S10784) and trans-impedance amplifiers (TIA, Texas Instruments, OPA657). The PIN PD has the photosensitive area size of 7 mm^2, optical-to-electrical response bandwidth of 250 MHz, responsivity of 0.45 A/W, and dark current of 0.01 nA @ reverse bias voltage of 2.5 V. It has the spectral response range of 340 to 1040 nm. Afterwards, a real-time oscilloscope (Tektronix, CSA7404) with sampling rate of 1.25 GSample/s is utilized to receive the electrical signals from PDs for offline signal processing. First, the 3 × 3 MIMO demultiplexing as described in Section II is used to eliminate the interference of the signals from other channels. Then the recovered signals are demodulated and analyzed respectively. SNR and bit error rate (BER) measurement of each channel are performed in this paper. During the experiment, we do notice no flickering in illumination.

4. Results and Discussion

Before setting up the MIMO VLC system, the modulation bandwidth of Tx has been measured. Generally, the modulation bandwidth of LED is quite narrow and the whole system data rate will be limited. By using an electrical front-end Tx circuit which consists of a pre-equalizer integrated with an amplifier and a bias-tee, the modulation bandwidth of the system can be broadened widely. The detail implementation of the Tx circuit can be found in [14]. By adjusting the resistance and capacitance in order to match with the impedance of the LED, the available modulation bandwidth of the Tx can be extended as shown in Fig. 3. In this measurement, an electrical signal generator drives the VLC system with frequencies sweeping from 0 to 120 MHz, and the measured response by spectrum analyzer is illustrated in Fig. 3.

In the experiment, the OFDM signal consists of 30 OFDM subcarriers, and each is modulated in QAM format. Fig. 4(a) compares the measured SNRs of different OFDM-QAM subcarriers, and it also compares the SNRs of the received signals after MIMO demultiplexing. It can be observed that SNR drops dramatically at high frequencies. The low SNR is mainly caused by the limited modulation bandwidth of our VLC system and deficient optical power after 1 m transmission distance. Here, the SNR of Rx3 received signal is lower than other channels. The reason may be the imperfect match of impedance of LED so that the performance of the received signal will be a little worse. The corresponding modulation order of each subcarrier is shown in Fig. 4(b). The data rates of each channel are 258.79, 393.07, and 351.56 Mbit/s, respectively. The total data rate of

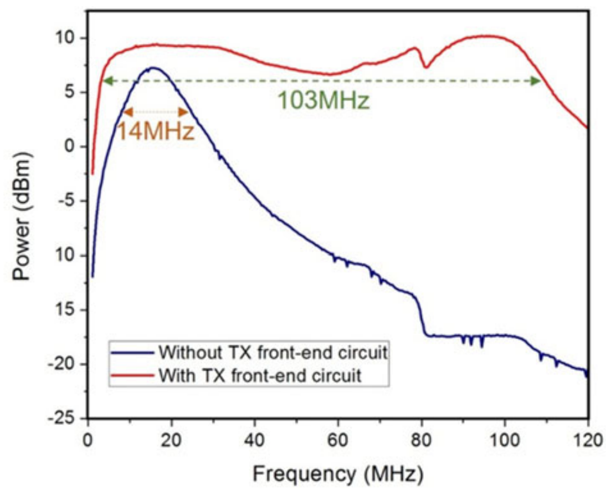

Fig. 3. Measured Tx modulation bandwidth without and with the front-end circuit.

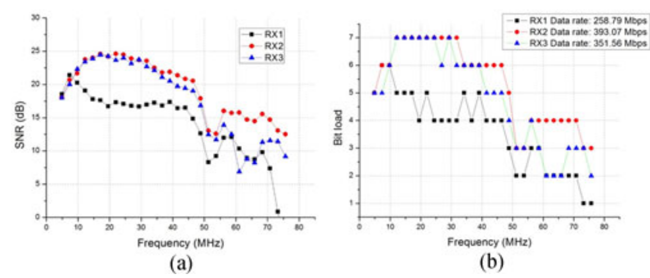

Fig. 4. (a) Measured SNR of each VLC channel after MIMO demultiplexing and demodulated. (b) Corresponding bit-loading can be achieved in the bandwidth.

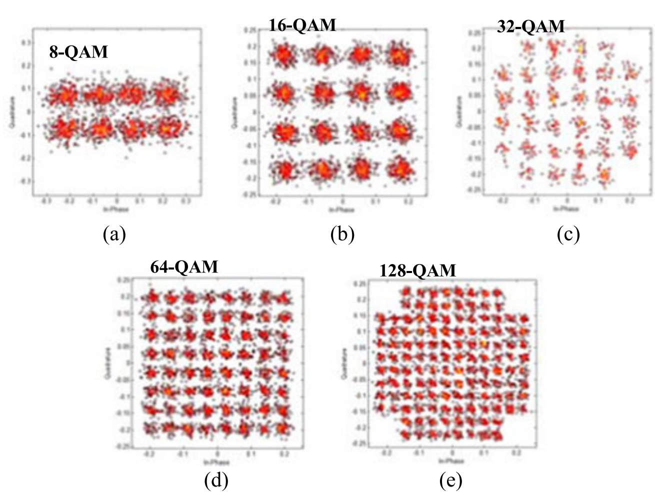

Fig. 5. Experimental constellation diagrams of received signal at Rx2, showing the constellation diagrams of the subcarriers with modulation order of 3 (8-QAM) to 7 (128-QAM).

the received signal in the MIMO OFDM VLC system can achieve 1 Gbit/s. By using the equations described in [17], the BER of each OFDM subcarrier can be obtained based on the measured SNR. Finally, the average BER of the three VLC MIMO channels can be calculated. The BERs of each Rx are 2.4×10^{-3}, 3.6×10^{-3} and 2.5×10^{-3}, respectively. All of them satisfy the 7% forward error correction (FEC) threshold of BER $= 3.8 \times 10^{-3}$. In addition, Fig. 5(a)–(e) shows the experimental constellation diagrams of received signal at Rx2, showing the constellation diagrams of the subcarriers with modulation order of 3 (8-QAM) to 7 (128-QAM).

5. Conclusions

VLC can be a potential candidate for the next generation wireless communications, and simultaneously providing indoor lighting. The phosphor white-light LED has the advantages of low-cost, long lifetime and conserving energy. However, the narrow modulation bandwidth of phosphor LED is a big issue for future high speed communication. In order to enhance the data rate of the VLC system, in this work, we demonstrated a 3 × 3 imaging MIMO VLC system. Besides, pre-equalizer circuit was used to extend the bandwidth of the LED Tx from 14 MHz to 103 MHz. OFDM with bit-loading algorithm was used to further improve the spectral efficiency. By using the proposed scheme, the original about 1 MHz bandwidth commercially available phosphor white light LED can achieve 1 Gbit/s data rate over 1-m free-space transmission distance, satisfying the 7% FEC threshold of BER $= 3.8 \times 10^{-3}$. The SNR and bit-load of the OFDM signal were also studied.

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