Indoor gigabit 2 × 2 imaging multiple-input–multiple-output visible light communication

Yuanquan Wang (王源泉) and Nan Chi (迟 楠)*

Key Laboratory for Information Science of Electromagnetic Waves (MoE), Department of Communication Science and Engineering, Fudan University, Shanghai 200433, China

**Corresponding author: nanchi@fudan.edu.cn*

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We propose and experimentally demonstrate a 2 × 2 imaging multiple-input–multiple-output (MIMO) Nyquist single carrier visible light communication (VLC) system based on spectral efficient 64/32-ary quadrature amplitude modulation, as well as pre- and post-equalizations. Two commercially available red–green–blue light-emitting diodes (LEDs) with 3 dB bandwidth of 10 MHz and two avalanche photodiodes with 3 dB bandwidth of 100 MHz are employed. Due to the limited experiment condition, three different colors/wavelengths are transmitted separately. The achieved data rates of red, green, and blue LED chips are 1.5 , 1.25, and 1.25 Gb/s, respectively. The resulting bit error ratios are below the 7% pre-forward error correction limit of 3.8×10^{-3} after 75 cm indoor transmission. To the best of our knowledge, this is the first experimental investigation of imaging MIMO system, and it is the highest data rate ever achieved in MIMO VLC system.

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Recently, visible light communication (VLC) is constantly gaining attention motivated by the dramatic development of light-emitting diode (LED) technologies and increasingly scarce spectrum resources[1–6]. Widespread used, high brightness, larger bandwidth compared with other typical radio frequency-based devices make it the most promising candidate for simultaneous illumination and communication, especially in some specific areas such as hospitals, aircrafts, and high security required environment. However, relatively low modulation bandwidth is the main technical limitation in VLC system. Many research efforts have been dedicated to overcome this challenge and increase the transmission data rates, such as digital signal processing[2–4], high-order modulation[5], and equalizations[6]. But most of these research studies are operated in single-input–single-output (SISO) systems, and there have been few reports in parallel transmissions which can offer a linear capacity gain with the number of channels in an ideal crosstalk-free system.

Multiple-input–multiple-output (MIMO) has been widely used in radio communication and multimode fiber communication[7]. In VLC, the availability of a large number of LEDs in a single room makes MIMO a promising candidate for achieving high data rates. Zeng *et al.*[8] compared non-imaging MIMO and imaging MIMO and Jivkova *et al.*[9] described the characteristic of a diffuse-transmission MIMO. Both aforementioned examples of parallel free-space transmission are all discussed via simulation. Azhar *et al.*[10] experimentally demonstrated a 4 × 9 non-imaging MIMO orthogonal frequency division multiplexing (OFDM) VLC system with the data rate of each LED at 250 Mb/s, but the MIMO processing algorithm is very complex due to the large number of receivers and non-imaging architecture. Moreover, the peak-to-average power ratio (PAPR) of OFDM signals is very high. In our previous work, we proposed a non-imaging MIMO system[11].

Here we propose and experimentally demonstrate a gigabit 2 × 2 imaging MIMO VLC system employing Nyquist single carrier (SC) modulation, which has the same spectral efficiency (SE) but low PAPR compared with OFDM. SE 64/32-ary quadrature amplitude modulation (64/32QAM), along with pre- and post-equalizations are adopted to increase the transmission data rate. We validate this MIMO scheme on three different colors in a single red–green–blue (RGB) LED. The achieved data rates of red, green, and blue colors are 1.5, 1.25, and 1.25 Gb/s, respectively. The measured bit error rates (BERs) for all wavelength channels and two receivers are below the 7% pre-forward error correction (pre-FEC) threshold of 3.8×10^{-3} after 75 cm free-air transmission. Due to the limited experiment condition, three different color channels can only be transmitted separately. By employing wavelength division multiplexing (WDM), the aggregated data rate of this system can be further enhanced.

The architecture and principle of the imaging MIMO VLC system is shown in Fig. 1. In this demonstration, two commercial available RGB LEDs (Cree, red: 620 nm; green: 520 nm; blue: 470 nm) generating a luminous flux of about 6 lm used as the transmitters (TXs) and two avalanche photodiodes (APD) (Hamamatsu APD, 0.5 A/W sensitivity at 800 nm) used as the receivers (RXs) are adopted. The 3 dB bandwidths of the red LED chip and APD are 10 and 100 MHz, respectively. An imaging lens with the diameter of 76 mm and focus length of 100 mm is implemented

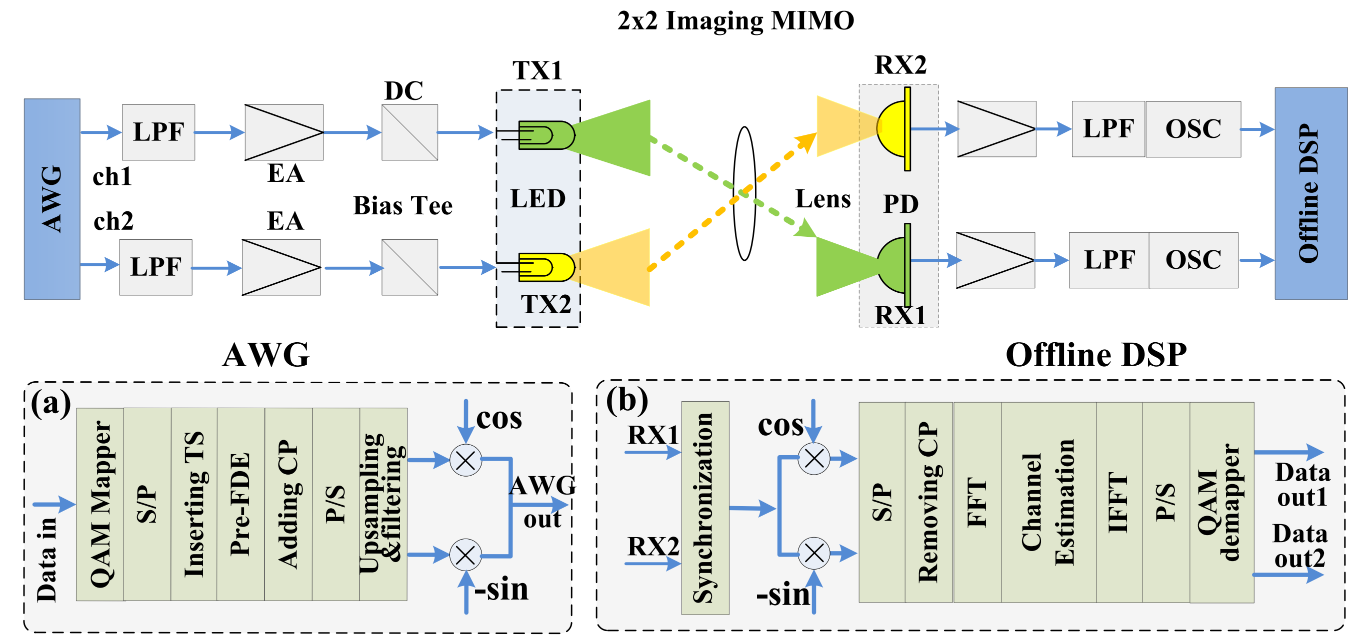

Fig. 1. Architecture of the imaging MIMO Nyquist SC-FDE VLC system. P/S, parallel to serial; LPF, low-pass filter; FFT, fast Fourier transform.

infront of RXs, to render each of LEDs precisely imaged onto the individual APD. The concept of Nyquist SC with frequency domain equalization (SC-FDE)[12] is very similar to that of OFDM with a difference that, in SC-FDE, the inverse fast Fourier transform (IFFT) block is moved from the transmitter to the receiver. The binary data would be mapped into 64/32QAM format and then the training sequences (TSs) are inserted into the signals. After making pre-equalization in frequency domain and up-sampling, cyclic prefix (CP) is added and low-pass filters are used to remove out-of-band radiation.

Subsequently, the signals from arbitrary waveform generator (AWG) are first amplified by electrical amplifier (EA) (Minicircuits, 25-dB gain), combined with direct current (DC)-bias via bias tee, and then applied to these three different color chips. Passing through free-space transmission, lens, and APD, the signals are recorded by a commercial LeCroy high-speed digital oscilloscope (OCS) and sent for off-line processing. At the receiver, after synchronization, resampling, and removing CP, post-FDE is implemented via zero-forcing algorithms.

In order to measure the crosstalk between two transmission links, a time-multiplexed TS is adopted in this demonstration as shown in Fig. 2. It can be expressed as

$$\mathbf{T}_1 = \begin{pmatrix} \mathrm{TS}_1 \\ 0 \end{pmatrix} \qquad \mathbf{T}_2 = \begin{pmatrix} 0 \\ \mathrm{TS}_2 \end{pmatrix}, \tag{1}$$

where $\mathbf{T}_1$ and $\mathbf{T}_2$ represent the TS inserted in the first and second time slots, respectively; $\mathbf{TS}_1$ and $\mathbf{TS}_2$ denote the individual TS in one transmitter. Assume the received signals of RX1 and RX2 at first and second time slots be $Y_{1,1}$, $Y_{1,2}$, $Y_{2,1}$, and $Y_{2,2}$, respectively. The channel matrix $\mathbf{H}$ can be written as

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} Y_{1,1}/\mathrm{TS}_1 & Y_{1,2}/\mathrm{TS}_2 \\ Y_{2,1}/\mathrm{TS}_1 & Y_{2,2}/\mathrm{TS}_2 \end{pmatrix}, \tag{2}$$

where H_{12} and H_{21} denote the crosstalk, and H_{11} and H_{22} represent the signal gains. As each of LED is imaged onto the corresponding APD, the crosstalk can be neglected, and the channel matrix can be simplified and regarded as a diagonal matrix and can be expressed as

$$\mathbf{H} = \begin{pmatrix} H_{11} & 0 \\ 0 & H_{22} \end{pmatrix} = \begin{pmatrix} Y_{1,1}/\mathrm{TS}_1 & 0 \\ 0 & Y_{2,2}/\mathrm{TS}_2 \end{pmatrix}. \tag{3}$$

In this way, no MIMO de-multiplexing processor is needed at receiver.

The experimental setups are depicted in Fig. 1. The SC-FDE signals were generated by Tektronix arbitrary waveform generator (AWG) 7122C with the maximum sampling rates of 24 GS/s and bandwidths of 6 GHz,

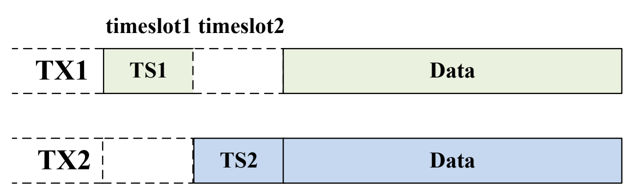

Fig. 2. Time-multiplexed TSs.

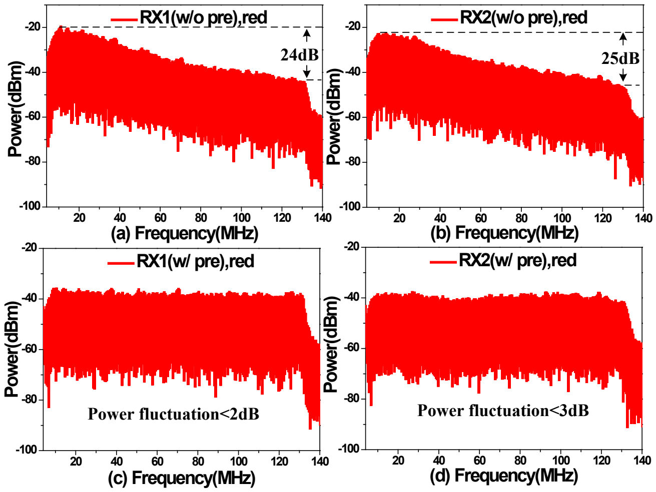

Fig. 3. Measured electric spectra of red LED chip at (a) RX1 and (b) RX2, w/o pre-equalization, (c) RX1 and (d) RX2, w/ pre-equalization.

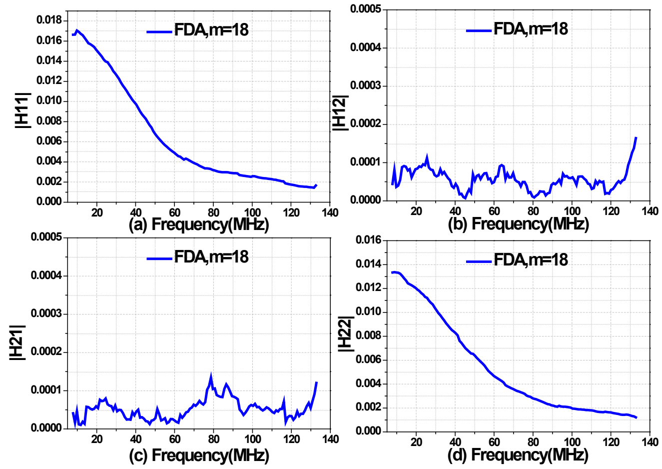

Fig. 5. Amplitude frequency responses of (a) H_{11}, (b) H_{12}, (c) H_{21}, and (d) H_{22}.

and detected by a commercial high-speed real-time OCS. The fast Fourier transform (FFT) size was 128, and the CP length was set at 1/16 of FFT size. The up-sampling factor was 10, and the sample rates of AWG and OSC were set to 1.25 and 2.5 GS/s, respectively. A square function with roll factor of 0 was used as the filter at the TX and RX. Thus, the valid occupied bandwidth of signals was 125 MHz ranging from 7.8125 to 132.8125 MHz. The voltages of bias tee and amplitudes of signals were finely adjusted to render the whole system work at the quasi-linear region of LED.

As the channel response of LED was fast attenuated due to the increase in frequency, pre-equalization was needed to improve the overall bandwidth. Figure 3 shows the measured electrical spectra of red LEDs before and after pre-equalization. Without pre-equalization, the power fluctuations of 132.8125 MHz were 24 and 25 dB smaller than those of 7.8125 MHz of RX1 and RX2, respectively. After pre-equalization, the power fluctuations of two receivers were lower than 1 dB. Then, the BER performances with and without pre-equalization were compared. The BER performances versus different transmission distances are illustrated in Fig. 4. By adopting pre-equalization, the BER performances of RX1 and RX2 can be enhanced by 9.4 and 7.5 dB at a distance of 70 cm, respectively. And the BERs of two receivers can be lower than 7% pre-FEC threshold of 3.8×10^{-3} after 75 cm free-space transmission.

The crosstalk of imaging MIMO is measured and analyzed based on the aforementioned time-multiplexed TSs. The amplitudes of channel elements at frequency domain are depicted in Fig. 5. It should be noted that in this measurement, frequency domain averaging proposed in Refs. [13, 14] was adopted. The index “m” listed in Fig. 5 represents the averaging window size, which should be optimized. From Fig. 5, the values of H_{12} and H_{21} can be regarded as the additive white Gaussian noise (AWGN), which is about 100 times smaller than H_{11} and H_{22} at low-frequency component. So we conclude that the crosstalk is very limited as we analyze above.

The BER performances of RX2 in the case of MIMO and SISO are depicted in Fig. 6. In SISO link, only TX2 works, whereas in MIMO link, TX1 and TX2 work at

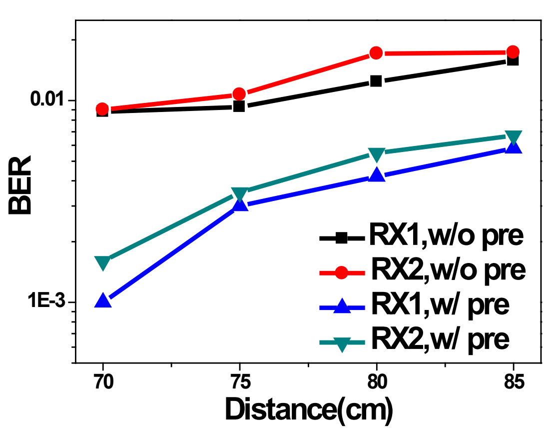

Fig. 4. Measured BER performance versus different transmission distances of two receivers in the case of with and without pre-equalization of red LED chips.

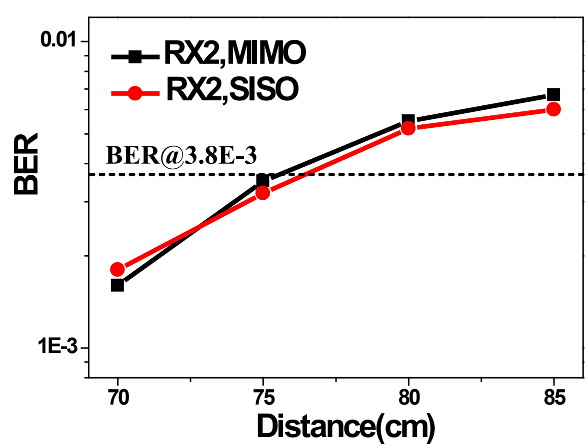

Fig. 6. Measured BER performance versus distance of RX2 in the case of MIMO and SISO links of red LED chip.

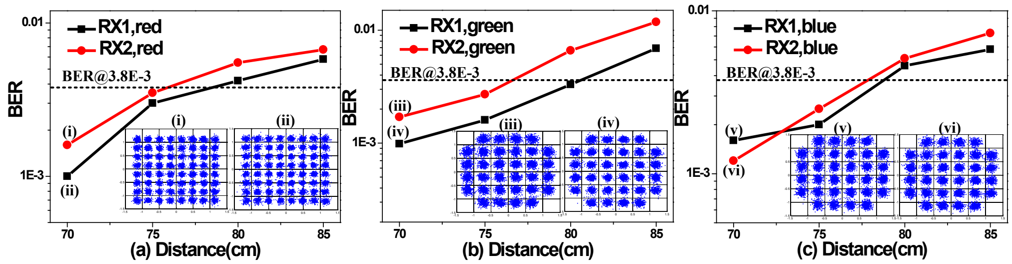

Fig. 7. Measured BER performance versus distance of (a) red color LED, (b) green color LED, and (c) blue color LED.

the same time. But we find that RX2 has almost same performance under these two conditions, which means that the degradation induced by the crosstalk is very small, and the crosstalk can be neglected in the signal processing procedure.

Lastly, the pre-equalized Nyquist SC-FDE signals with bandwidth of 125 MHz were modulated on three different color LED chips. The data rates of red, green, and blue chip obtained were 1.5, 1.25, and 1.25 Gb/s with the modulation formats of 64QAM, 32QAM, and 32QAM, respectively. As the peak responsibility of APD was located at the near-infrared region, the red link outperformed the blue and green links. The BER performances versus different transmission distances ranging from 70 to 85 cm varying in a step of 5 cm was measured and are depicted in Figs. 7(a)–(c), respectively. Both BER performance of two receivers are under the pre-FEC limit of 3.8×10^{-3} after 75 cm indoor delivery.

In conclusion, we experimentally demonstrate an imaging 2 × 2 MIMO Nyquist SC-FDE VLC system based on 64/32QAM. Unlike the non-imaging MIMO system, which needs complex de-multiplexing processing, the processing at the receivers of this scheme is very simple. Red, green, and blue LED chips are transmitted separately with the data rates of 1.5, 1.25, and 1.25 Gb/s, respectively, enabled by pre-FDE and post-FDE. The resulting BERs are below the 7% pre-FEC limit of 3.8×10^{-3} after 75 cm indoor transmission. To the best of our knowledge, this is the first experimental demonstration of imaging MIMO in VLC system and the capacity of this system can be further improved by a larger bandwidth APD and WDM.

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