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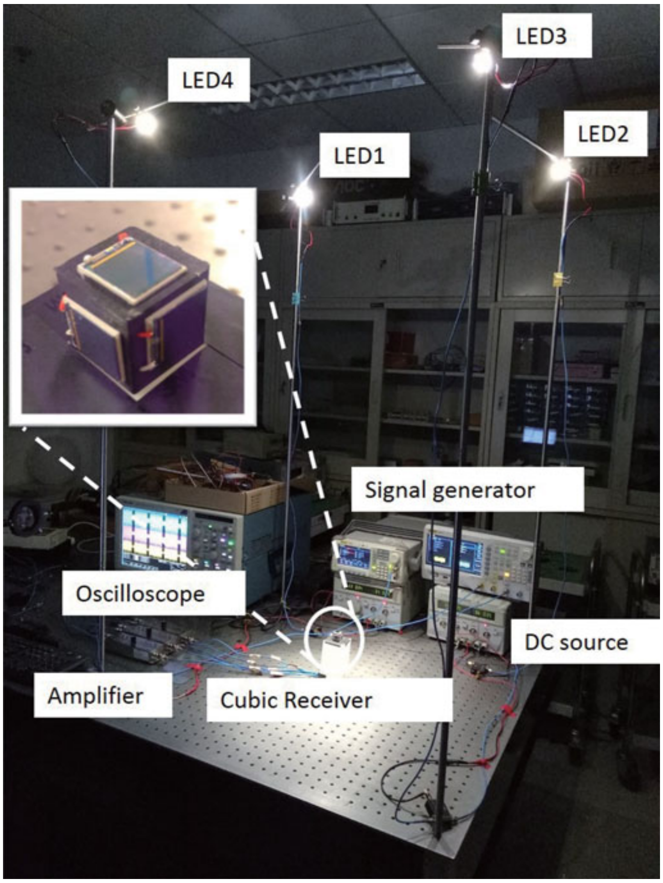

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Experimental Demonstration of a Cubic-Receiver-Based MIMO Visible Light Communication System

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Abstract: An experimental demonstration of a nonimaging multiple-input multiple-output (MIMO) visible light communication (VLC) system based on a cubic receiver is reported in this paper. The receiver is designed to have five photodetectors as a cubic structure to solve the problem of an ill-conditioned channel matrix. The experiment employs four independent white light-emitting diodes (LEDs) as transmitters. Each of them transmits a different bit stream with orthogonal frequency-division multiplexing (OFDM) modulation and a bit-and-power allocation algorithm. By measuring the highest achievable overall data rate in the typical illumination scene, the performance of the multiplexing gain of the system is demonstrated. The experimental results reveal that the highest spectral efficiency is about 14.5 bit/s/Hz, and the multiplexing gain is up to 2.134 times at the center point among four LEDs. Besides, the system can support user mobility in real time, since it does not require the receiver adjustment and alignment.

Index Terms: Visible light communication (VLC), cubic receiver, multiple-input-multiple-output (MIMO), orthogonal frequency division multiplexing (OFDM).

1. Introduction

With the rapid growth of the light emitting diode (LED) industry and the increasing demand for indoor wireless data transmission, visible light communication (VLC) has attracted much interest [1], [2] in recent years. Since multiple LEDs can provide uniform room illumination and transmit the parallel bit stream simultaneously, multiple-input-multiple-output visible light communication (MIMO-VLC) technology is considered as a natural candidate for indoor VLC system. Meanwhile, in order to make full use of the limited bandwidth of LED and further improve the data rate, orthogonal frequency-division multiplexing (OFDM) modulation can be adopted in the MIMO-VLC system [3].

MIMO-VLC system is mainly generalized into two categories, i.e. the imaging MIMO system and the non-imaging MIMO system. Generally, due to the use of imaging equipment in the imaging MIMO system, the channel matrix is guaranteed to be with full-rank and the multiplexing gain can be extremely high. In [4], an experiment demonstration of the 4×9 imaging MIMO-VLC system with

Gb/s throughput is reported, where OFDM modulation is employed for each transmitting signals. In addition, a 1.25 Gb/s imaging MIMO-VLC system [5] is demonstrated using RGB LEDs and WDM modulation. However, in such systems, precise alignment is required to make each LED imaged onto a dedicated photo-detector (PD), resulting in a complicated system design and a narrow field of view (FOV). As for the non-imaging MIMO-VLC system, Burton *et al.* [6] experimentally demonstrate a 4×4 non-imaging MIMO-VLC transmission with a 50 Mb/s data rate, and in [7], Wang and Chi report a high-speed non-imaging MIMO-VLC experiment with a data rate as high as 500 Mb/s. Nevertheless, such systems always suffer from the ill-conditioned channel matrix resulting from the very similar channel gains from one LED to different PDs, and lead to a lower data rate while multiple PDs at the receiver are placed too closely. As a result, an optical receiver using PDs with different FOVs [8] was proposed to solve the problem. This can result in an invertible channel matrix. Furthermore, several angle diversity receivers [9], [10] are designed to achieve high-rank channel matrix. In [9], a really novel design of an angle diversity receiver for a MIMO-VLC system is proposed. However, all of them are demonstrated by simulation or simple verification experiment.

In this paper, a cubic receiver based non-imaging MIMO VLC system is proposed and the experimental demonstration is reported to verify the performance of multiplexing gain. The cubic receiver, which consists of five PDs designed as a cubic structure, is designed to solve the problem of the ill-conditioned channel matrix of non-imaging MIMO-VLC system. Due to the cubic receiver, the channel gains from one LED to different PDs become obviously distinguishable. As a result, it reduces the correlation between sub-channels and makes the channel matrix well-conditioned. The cubic receiver is a little similar to the angle diversity receiver [9] but not exactly the same. In our experiment, orthogonal frequency division multiplexing (OFDM) modulation is employed to improve the bandwidth efficiency, and bit-and-power allocation (BPA) algorithm and minimum mean square error (MMSE) de-multiplexing techniques are applied as well. Making use of four LEDs installed on the ceiling, the highest spectral efficiency of 14.5 bit/s/Hz can be achieved within 2 MHz modulation bandwidth. Compared with traditional VLC system based on individual LED, the largest multiplexing gain of the proposed MIMO-VLC system using four LEDs is almost 2.134 times. Besides, the cubic receiver can be used to measure the angle-of-arrivals (AOAs) of the light from LEDs conveniently, which can be used to achieve an indoor VLC positioning system, which we completed in [11].

2. System Description

In this section, the proposed non-imaging MIMO-VLC system model based on the cubic receiver is explained in details, and the theoretical analysis is also presented.

2.1 System Model

A typical schematic for the non-imaging MIMO-VLC system is described in Fig. 1. Four LEDs used for illumination and data transmission unit are installed on the ceiling. The serial bit stream is first converted into parallel and modulated into OFDM symbols, where the BPA strategy [12] and quadrature amplitude modulation (QAM) are adopted for each sub-carrier. Particularly, the independent signal streams are transmitted simultaneously by different LEDs with equal signal power [13]. The illumination intensity distribution of the LEDs is modeled by the Lambertian distribution. Multi-path effect and time delay of the optical signal are ignored in indoor VLC channels. As for the receiver, the cubic receiver detects and de-multiplexes five parallel signals by means of MMSE algorithm in the same time. Finally, the received bit stream can be obtained after demodulation and parallel-to-serial conversion.

2.2 Theoretical Analysis

Consider an indoor MIMO-VLC system with N white LEDs used for transmission on the ceiling. The transmitted signal $\mathbf{x}$ and the received signal $\mathbf{y}$ can be modeled as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

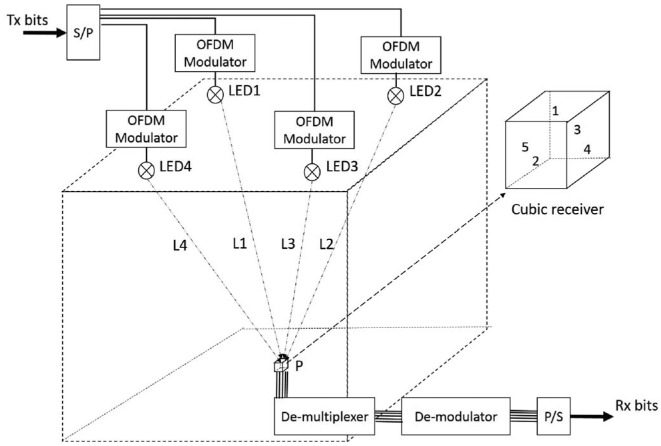

Fig. 1. Non-imaging MIMO-VLC system model.

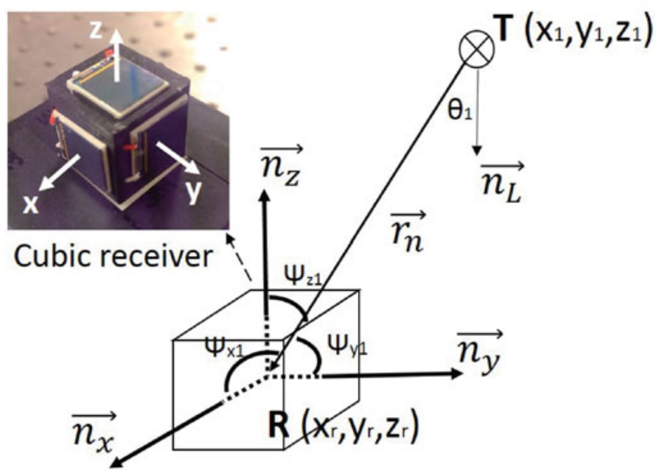

Fig. 2. Geometric model for the cubic receiver.

where **H** denotes the channel matrix, and **n** is the AWGN vector with zero mean and variance of σ^2.

The geometric model of the cubic receiver is shown in Fig. 2. Take LED 1 for example. $\mathbf{T}(x_1, y_1, z_1)$ and $\mathbf{R}(x_r, y_r, z_r)$ represent the 3-D coordinates of the LED and receiver, respectively. The unit normal vector of the pointing of the LED is denoted as $\mathbf{n}_L$, and the unit normal vectors of the PDs in the cubic receiver are $\mathbf{n}_x$, $\mathbf{n}_y$, $\mathbf{n}_z$. θ_1 is the radiation angle of the LED, and ψ_{x1}, ψ_{y1}, ψ_{z1} are the incidence angles corresponding to the LED and the cubic receiver. $\mathbf{r}_n$ is the vector from the LED to the receiver and $\|\mathbf{r}_n\| = d_1$. Therefore, the channel matrix element $h_{m,n}$ which indicates the channel gain from the n-th LED to the m-th PD can be expressed as [14]

$$h_{m,n} = \begin{cases} \dfrac{A_0 \frac{(\rho+1)}{2\pi} \langle r_n, n_L \rangle^{\rho} \langle -r_n, n_m \rangle}{{d_n}^{\rho+3}}, & \langle r_n, n_m \rangle \leq 0 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where ρ is the order of the Lambertian distribution, and A_0 is the area of each PD. Particularly, there are only five PDs in the cubic receiver, and therefore, m ranges from 1 to 5. Note that the incident light of one LED can be detected by at most three PDs simultaneously due to the cubic structure. In this way, the vector of channel gain $(h_{1,n}, h_{2,n}, h_{3,n}, h_{4,n}, h_{5,n})^T$ for one LED has at most

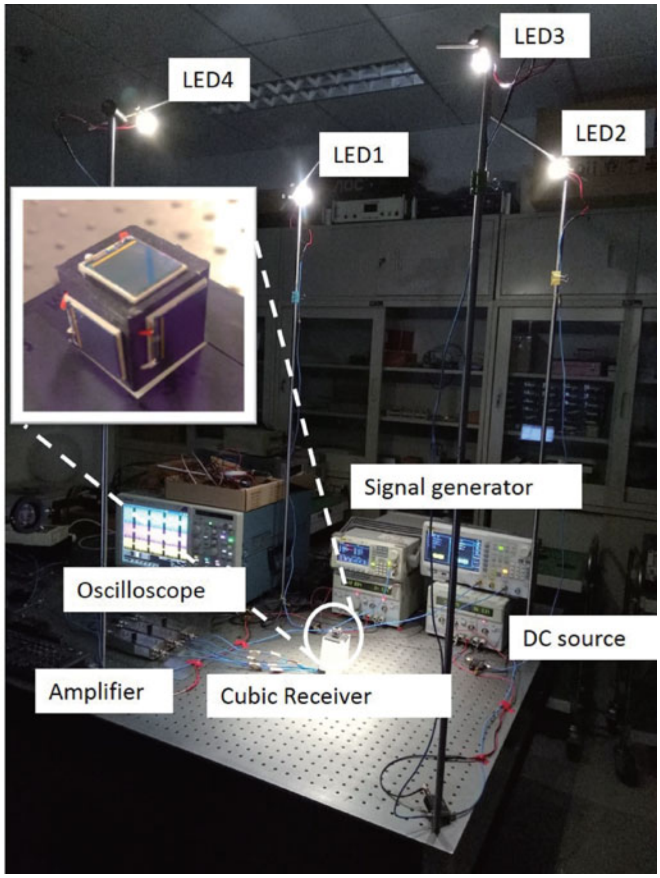

Fig. 3. Experiment setup.

three non-zero elements, which depends on the direction of $\mathbf{r}_n$. Thus it is obvious to see that the correlation between sub-channels is reduced and the channel matrix becomes well-conditioned.

In the receiver, the simplest method to estimate the parallel transmitted bit stream would be to pseudo-invert $\mathbf{H}$ and multiply it with the received signal $\mathbf{y}$. However, the pseudo inversion of $\mathbf{H}$ will lead to noise amplification, therefore MMSE algorithm is used to replace the pseudo invert $\mathbf{H}$ with a regularized inversion of $\mathbf{H}$ [6], which can be expressed by

$$\mathbf{G}y = \mathbf{GH}x + \mathbf{G}n = x_{est} + n'$$
$$\mathbf{G} = (\mathbf{H}^T\mathbf{H} + \sigma^2\mathbf{I})^{-1}\mathbf{H}^T; \quad (3)$$

where σ^2 is the Rx noise power variance, and $\mathbf{I}$ is an identity matrix. Finally, the received bit stream x_{est} can be estimated by the cubic receiver.

3. Experiment Setup

The experimental platform is designed to demonstrate and evaluate the proposed cubic receiver based MIMO-VLC system and verify its performance of multiplexing gain. There are two periods in the experiment. The first one measures the bit-error-ratio (BER) curves and the second one presents the distribution of overall data rate.

Firstly, the experimental setup shown in Fig. 3 consists of four independent white LEDs with collector lens as transmitters. Each of them has the maximum optical power of 1 W, the height of LEDs is set to 100 cm, and the spacing of adjacent LEDs is 70 cm. The different OFDM signals

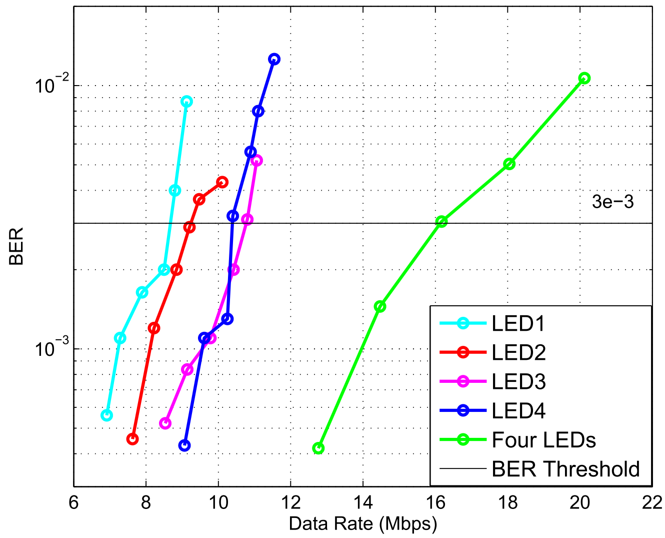

Fig. 4. Curves of BER at the center point of four LEDs.

with equal power generated from signal generator and direct current (DC) are loaded into LEDs through a bias-Tee module. At the receiver, each PD (Thorlabs, FDS1010) at the cubic receiver has a 10×10 mm^2 active area with a 0.725 A/W effective responsivity. The received signals are amplified through transimpedance amplifiers and recorded on a real time oscilloscope. Then they are processed offline. We measure the BER curves when the cubic receiver is placed at the center point among four LEDs. The achievable overall data rate of the cubic receiver is tested while four independent signal light are transmitted simultaneously. For comparison, the achievable data rates of single LED/PD pair (link) are tested as well.

In the second period, to measure the distribution of the data rate, because the LED drive current limits the light power of LEDs and the whole test area should meet the requirement of the illumination intensity, 100 lx $\sim$ 500 lx, the collector lens can't be used and the height of LEDs should be changed to 30cm. The spacing of adjacent LEDs is changed to 40 cm, too. The grid for test area is set to 40×40 cm^2, which is divided into 10×10 cm^2 squares. In the same way, at each tested point, we measure the achievable data rate of four LEDs as well as an individual LED for comparison.

4. Experimental Result and Discussion

To begin with, the bit stream of different data rates is transmitted from LEDs, and the BER curves are measured with the comparison of BER threshold (3×10^{-3}). In the first period, the experimental result at the center point of four LEDs is shown in Fig. 4. The green line indicates the curve of BER for overall data rate of four LEDs, which shows the highest achievable overall data rate is 16 Mbps with 2 MHz bandwidth(QAM order ranges from BPSK to 256QAM for different sub-carriers according to BPA algorithm). In contrast, the curves of BER for individual LED are measured, including LED1, LED2, LED3, LED4 (light blue line, red line, pink line and blue line in Fig. 4, respectively). The achievable data rates of them are different from each other because there is some deviation for the installment of LEDs and the receiver. It is found that if without the cubic receiver, the highest data rate falls to about 11 Mbps (LED4). Conveniently, we can defined the formulas to calculate the multiplexing gain as follows:

$$\text{Multiplexing gain} = \frac{\text{The overall data rate of four LEDs}}{\text{The highest data rate of single LED}}. \tag{4}$$

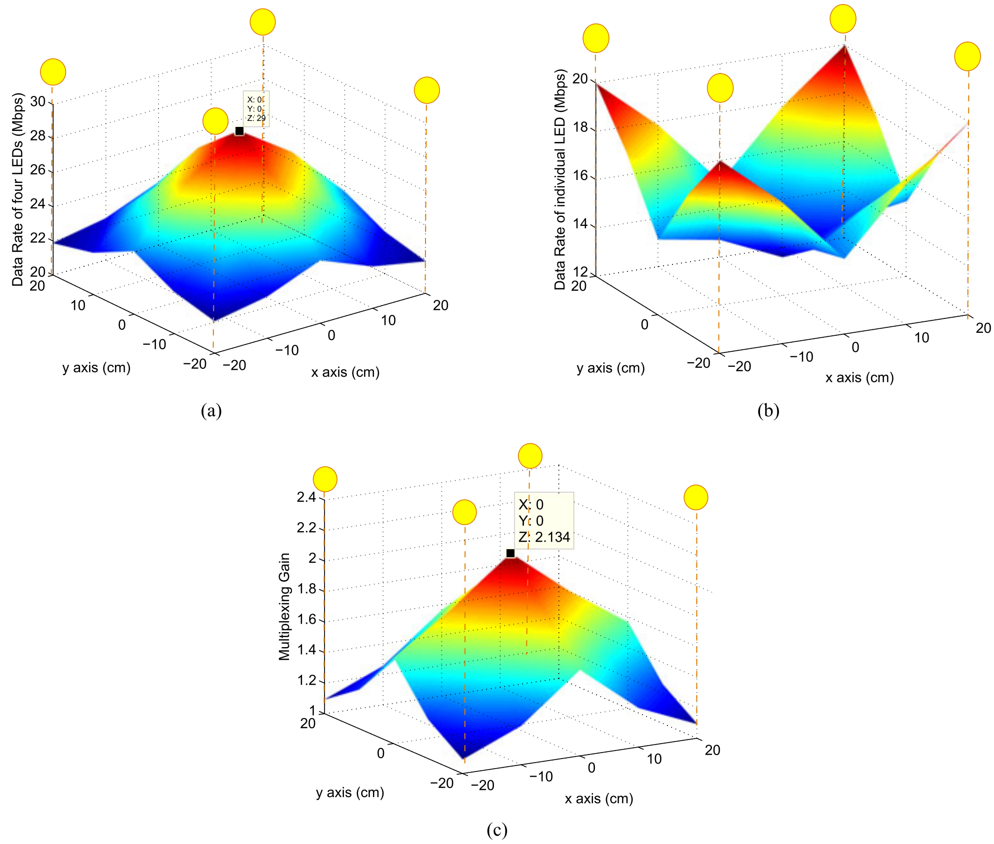

Fig. 5. Experimental result of second period. (a) Distribution of the data rate for four LEDs. (b) Distribution of the data rate for individual LED. (c) Distribution of multiplexing gain.

Therefore, the multiplexing gain is about 1.45 in the first period of experiment. The value of multiplexing gain depends on the signal noise ratio(SNR) of each signal light, which is affected by the fluctuation interference and amplifier noise in the receiver.

In the second period, after reducing the height of LEDs, the distributions of the data rate and the multiplexing gain in the whole area are tested. Fig. 5(a) reveals that the highest achievable data rate of four LEDs is 29 MHz at the center point, which also means the spectral efficiency of 14.5 bit/s/Hz can be achieved within 2 MHz bandwidth. The data rate decreases along x-axis and y-axis. This is because the asymmetry of transmission distances for four signal lights results in the such different SNRs of them, which seriously affects the de-multiplexing of signal lights. For comparison, the distribution of the data rate for individual LED is tested, as Fig. 5(b) shows. So far, we can calculate the multiplexing gain in the whole area, which is shown in Fig. 5(c). It indicates that the system can get highest multiplexing gain at the center point. Compared with the first experiment, due to the lower height of LEDs, the SNRs of signal light are higher, which leads to the higher multiplexing gain of 2.134. In addition, when the receiver is underneath individual LED, the multiplexing gain drops to nearly 1. It shows that under the condition, the multiplexing scheme can not effectively improve the data rate than traditional single-LED scheme even though the system complexity is still higher. Therefore, an optimal switching strategy for transmitters exists.

5. Conclusion

In this paper, the experimental demonstration of a non-imaging MIMO-VLC system using cubic receiver is proposed and reported. The cubic receiver consists of five PDs designed as a cubic structure to reduce the correlation between sub-channels for better reception. In the experiment, OFDM modulation and BPA algorithm are adopted to make full use of the limited bandwidth. The performance of the highest achievable overall data rate and the multiplexing gain are measured. The results reveal that the spectral efficiency of 14.5 bit/s/Hz can be achieved within 2 MHz bandwidth, and the maximum multiplexing gain is 2.134. Consequently, the proposed system is proved to be a promising scheme for indoor MIMO-VLC scenario. In the future, a better switching strategy for the MIMO-VLC system can be discussed, and we can further improve the overall capacity of data transmission.

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