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Visible-light communication multiple-input multiple-output technology for indoor lighting, communication, and positioning

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Abstract. Visible-light communication (VLC) is license free and electromagnetic-interference free; it thus can be deployed in radio-frequency forbidden areas. The light-emitting diode (LED) system providing simultaneously lighting, VLC, and positioning is highly desirable for providing real-time tracking, monitoring, and navigating with very little extra cost. We propose and demonstrate a multiple-input multiple-output (MIMO) VLC-positioning system using white-light LEDs. Our scheme is based on MIMO to provide both position and VLC. Experimental results show that the proposed MIMO VLC system can achieve a bit-error rate of 10^{-10}, while the positioning errors are within 1 cm. Numerical analyses are also performed, showing the positioning error can be measured within 1 cm. Further analysis of tilting angle of the receiver is also presented. [DOI: 10.1117/1.OE.54.12.120502]

Keywords: visible-light communication; positioning.

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1 Introduction

Due to continuous improvement of power efficiency and reduction in cost, white-light light-emitting diode (LED) is gradually replacing traditional lighting sources. In addition, visible-light communication (VLC) has attracted significant attention[1–4] as a promising candidate for providing optical wireless communication. VLC offers many advantages, such as high directionality and no electromagnetic interference (EMI) to equipment and machines, etc. Using LED as the transmitter (Tx) for VLC can simultaneously provide lighting and communication.

As VLC is license free and EMI free, it can be deployed in many indoor environments, even in radio-frequency (RF) forbidden areas, such as hospital operation theaters, electricity power plants, etc. In addition to simultaneously provide lighting and VLC, the LED system offering positioning function is highly desirable in real-time tracking, monitoring, and navigating. Potential applications of the VLC positioning include indoor navigation, device tracking, and controlling robot movement. For example, the receivers (Rx) in the trolleys of airports or department stores can detect the location information from nearby LEDs, and transmit the information using VLC or RF to the central computer, which contains a database of the identities of all the LEDs and the corresponding locations. Hence, the trolleys can be tracked and positioned.

In this work, we propose and demonstrate a multiple-input multiple-output (MIMO) VLC-positioning system using white-light LEDs. Although MIMO has been used in several VLC systems,[5] this work is the experimental demonstration using MIMO for positioning and communication. Chang et al.[6] also propose and demonstrate an MIMO VLC system, in which the MIMO technique is used to increase the aggregate data rate, while our scheme uses MIMO for simultaneously positioning and increasing data rate. In addition, the optical sources in Ref. 6 are red light lasers; hence, much higher data rate and transmission distance can be achieved. In our case, white-light LEDs are used; hence, the data rate and transmission distance are limited. Unlike the VLC-positioning system,[7] our scheme is based on MIMO to provide both position and VLC. Yasir et al.[8] also reported an interesting positioning; however, the orientation of the Rx is very important. Users need to measure the received powers from each transmitter (i.e., LED source) twice by varying the receiver orientations. Accelerometer in the Rx is required, and it will increase the system cost and complexity if a smart phone is not used. Here, in our proposed work, experimental results show that the proposed MIMO VLC system can achieve a bit-error rate (BER) of 10^{-10}, while the positioning errors are within 1 cm. Numerical analyses of the VLC-positioning systems are also performed, showing the positioning error within 1 cm. Further analysis of tilting angle of the Rx is also presented.

2 Proposed System and Experiment

The system design using MIMO and the channel model of the VLC system is first described. Assume there are t Txs and r Rxs in the VLC-lighting and -positioning system, the output optical signals emitted from these Txs are $X = [x_1, x_2, \dots, x_t]$, where each element of X is the data emitted from LED_1 to LED_t, respectively. Assume the received signals by these Rxs are $Y = [y_1, y_2, \dots, y_r]$, where each element of Y is the received data by Rx_1 to Rx_r, respectively. The relationship of X and Y can be described by

$$Y = H * X + n, \tag{1}$$

where H is the channel response described in Eq. (2) and n is the noise added to the channel

$$H = \begin{bmatrix} h_{11} & \cdots & h_{1t} \\ \vdots & \ddots & \vdots \\ h_{r1} & \cdots & h_{rt} \end{bmatrix}. \tag{2}$$

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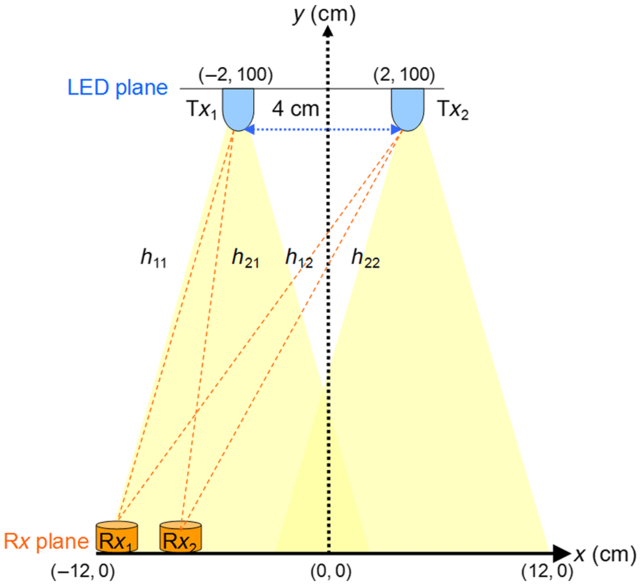

Fig. 1 Proposed 2×2 MIMO system supporting simultaneously visible-light communication (VLC), positioning, and lighting.

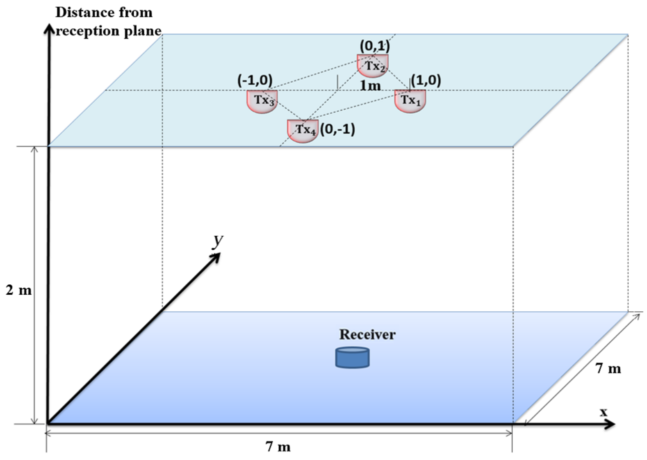

Fig. 3 Setup of a room for the proposed VLC-positioning system.

The channel response is different for different Rx positions. The matrix H can be used to locate the position of the Rx; hence, the position of the Rx can be obtained. For instance, the element h_{rt} in H represents the optical power emitted from the t'th Tx and received by the r'th Rx.

Figure 1 shows the proposed experiment of a 2×2 MIMO system. As the direct modulation response of the white-light LED is ~1 MHz, without using optical blue filter and advanced equalization circuit, we can only overmodulate each LED to 5 Mbit/s using pseudorandom binary sequence nonreturn-to-zero (NRZ) data, and the transmission distance is 1 m. Higher data rates and longer transmission distances can be expected using equalization in both Tx and Rx. Here, $X = [x_1, x_2]$ are applied to the two while-light LEDs, respectively. Lenses are used in front of the LEDs. The white LEDs used in this demonstration have the modulation bandwidth of ~1 MHz. Using different equalization techniques[9] and spectral efficient modulation format,[10] the data rate of VLC can be enhanced, and MIMO can also be applied to further increase the data rate.

3 Results and Discussion

The VLC system performances received by Rx_1 and Rx_2 in terms of BER are shown in Figs. 2(a) and 2(b), respectively. BER of $<10^{-10}$ can be achieved around the center position. As the LED transmission is quite directional, the BERs degrade quickly at both ends of the Rx plane due to low illumination. The slightly performance difference between Figs. 2(a) and 2(b) is due to different modulation responses of the two LEDs. The overall data rate of the proposed system is $\sim 2 \times 5$ Mbit/s. In our proposed scheme, the positioning information can be achieved based on the channel

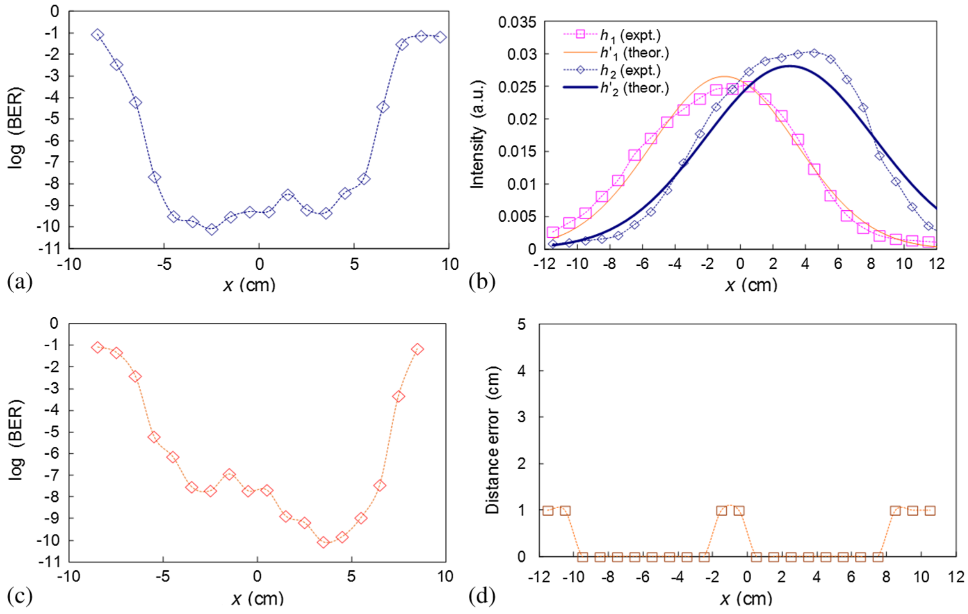

Fig. 2 Measured bit-error-rate at different positions by (a) Rx_1 and (b) Rx_2; (c) experimental and theoretical channel values h at difference x positions; (d) measured distance error of the proposed positioning system.

response H obtained in MIMO experiment and the Lambertian radiation pattern. The experimental value of $h_t(x)$ can be obtained using the MIMO algorithm as shown in Eqs. (1) and (2), while the theoretical value of $h_t'(x)$ can be obtained by Lambertian radiation pattern[11] as described in

$$h_t'(x) = \frac{(m+1)A\cos^m(\theta)\cos(\phi)}{2\pi d^2}, \tag{3}$$

where m is the order of Lambertian emission defined by the LED semiangle at half-power $\phi_{1/2}$, which is $m = \ln(1/2)/\ln[\cos(\phi_{1/2})]$; A is the Rx detection area; d is the distance

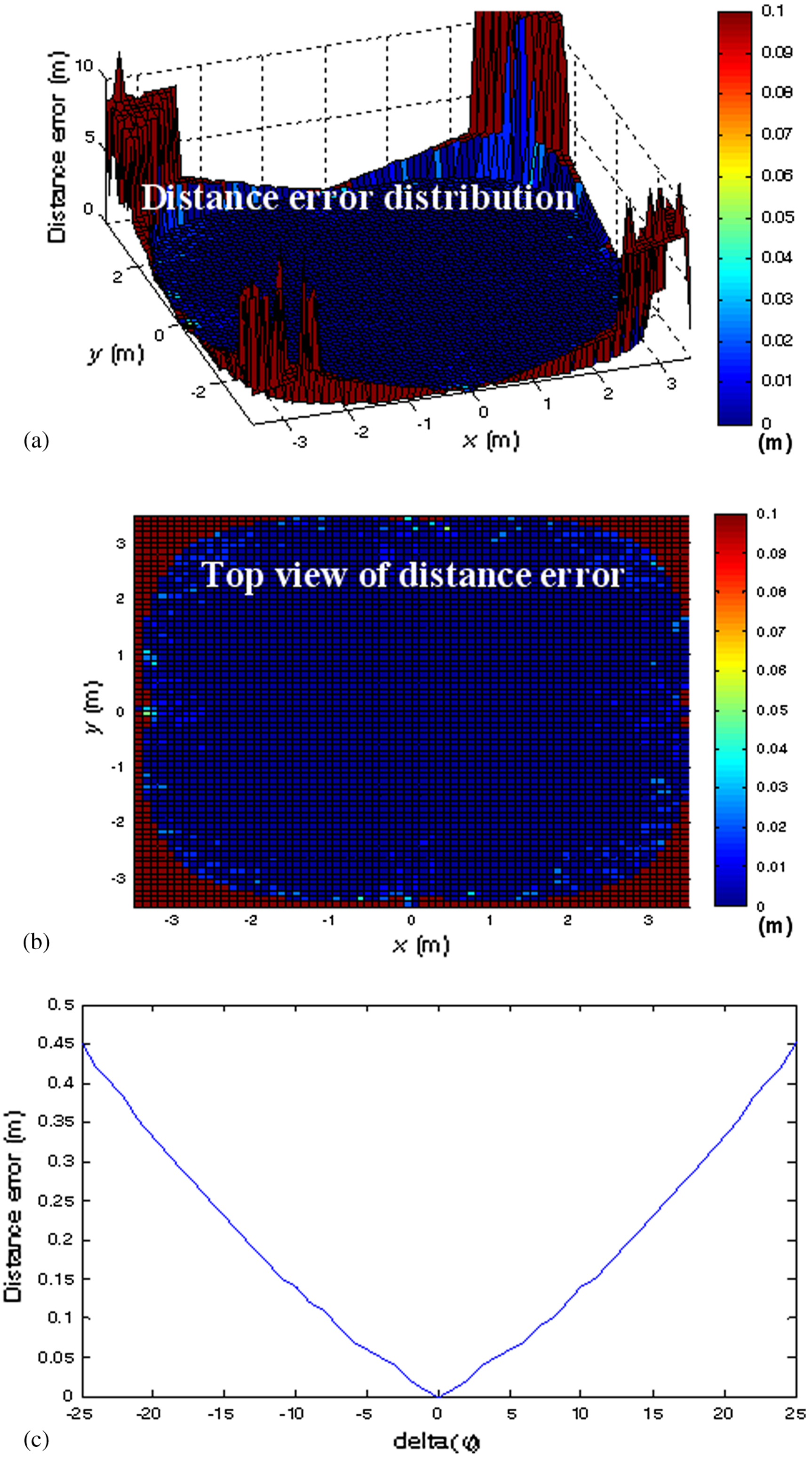

Fig. 4 Distance error of the proposed positioning system at (a) three-dimensional view and (b) top view. (c) Positioning error when the Rx is tilted.

between LED and Rx; θ and ϕ are the angle of incidence of Tx and Rx, respectively. In this experiment, $A = 4\ \text{cm}^2$ and no rotation of Tx and Rx is used; hence, $\theta = \phi$.

Figure 2(c) shows the experimental and theoretical channel values h at different position x. h_1 and h_2 are the actual channel values obtained in MIMO experiment, while h_1' and h_2' are the theoretical channel values obtained in the Lambertian radiation pattern, which act as the reference for the positioning system. For instance, if the Rx is at position x_r, two specific values $h_1(x_r)$ and $h_2(x_r)$ can be obtained. Then, these two values are used to minus the theoretical channel values at different position x, i.e., $h_1(x_r)$ minus each $h_1'(x)$ at all position x; and $h_2(x_r)$ minus each $h_2'(x)$ at all position x. Then, a minimum value can be obtained, which represents the smallest channel value difference. Hence, the corresponding x (the location of Rx) can be obtained. The above operation can be implemented in computer program by

$$x = \text{argmin}[|h_1(x_r) - h_1'(x)| + |h_2(x_r) - h_2'(x)|]. \tag{4}$$

Finally, we evaluate the accuracy of our proposed VLC MIMO positioning scheme by comparing the results obtained in Eq. (4) with the actual position. Figure 2(d) shows the experimental distance error of our proposed scheme. The distance error is within 1 cm.

Then, we numerically evaluate the proposed scheme to a two-dimensional (2-D) room as shown in Fig. 3. The room size is $7\ \text{m} \times 7\ \text{m} \times 2\ \text{m}$. In order to provide higher coverage of the room, the simulation parameters are different from the one-dimensional (1-D) case. The LED semiangle at half-power $\phi_{1/2}$ is 70 deg; the field of view (FOV) of the Rx is 60 deg with detection area of $1\ \text{cm}^2$. The LED arrangement is shown in Fig. 3, and they are emitting 4×5 Mb/s NRZ data. Figures 4(a) and 4(b) show the distance error distribution in 3-D and in top view, respectively. We can achieve the positioning distance error within 1 cm in over 90% of the room. Higher positioning errors are observed at the corners of the room due to lower illuminance (i.e., lower signal-to-noise). It is worth mentioning that the higher positioning errors at the corners can be reduced by adding more LED for MIMO inside the room. As we know that it is not very user-friendly if the Rx should be positioned a horizontal position, here, we also study the case when the Rx is tilted, and this will introduce positioning error, as shown in Fig. 4(c). When the tilting angle is within ± 5°C, an additional positing error of 5 cm can be observed. When the tilting angle is larger than half of the FOV, no optical signal can be received.

4 Conclusion

We proposed and demonstrated an MIMO VLC-positioning system using white-light LEDs. Unlike other schemes in the literature, our scheme was based on MIMO to provide both position and VLC. Experimental results showed that the proposed MIMO VLC system can achieve a BER of 10^{-10}, while the positioning errors were within 1 cm. Numerical analyses of the VLC-positioning systems were also performed, showing the positioning error within 1 cm. Further analysis of the tilting angle of the Rx was also presented.

Acknowledgments

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