Location-Based Equalization for MIMO Indoor Visible Light Communication Systems

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***Abstract*—We propose a location-based equalization (LBE) scheme for indoor visible light communication (VLC) systems using multiple-input multiple-output (MIMO). By utilizing the location information of photo-detectors, LBE can effectively recover MIMO VLC signals with BER <10^{-3}.**

Keywords—Visible light communication, location-based equalization, multiple-input multiple-output

I. Introduction

Visible light communication (VLC) using light-emitting diodes (LEDs) is a promising candidate for indoor data transmission [1], [2]. Indoor VLC systems are typically equipped with multiple LEDs to provide sufficient and uniform illumination. This feature can be exploited to create VLC systems using multiple-input multiple-output (MIMO). As compared with the single-input single-output (SISO) counterpart, MIMO-based VLC can provide higher date rates, and therefore has become a hot research topic [3], [4]. In MIMO-based VLC systems, multiple LEDs are adopted to create multiple spatial channels to increase the capacity, and multiple photo-detectors (PDs) are adopted at the receiver to increase signal detection sensitivity. Since the transmitted signals are non-orthogonal, inter-channel crosstalk (ICC) will occur among these spatial channels [5]. To recover the transmitted data, the channel matrix needs to be estimated to combat the effect of such crosstalk [4]. It is common to employ training sequences for channel estimation. However, this will reduce the transmission efficiency and limit the system performance if the estimated channel state information is not accurate. This paper aims to develop a novel and simple equalization technique for the VLC channel based on MIMO.

Recently, the integration of communication and positioning has gained increasing interests in the field of both RF and VLC [6], [7]. VLC systems usually employ intensity modulation and direct detection (IM/DD), their channels are generally much simpler and more stable than the time-varying radio frequency (RF) channels. The channel characteristics of a VLC link are highly correlated with the relative positions of the LED transmitter and the mobile receiver [8]. Since it is quite easy for a VLC receiver to obtain its accurate indoor location, the location information of the VLC receiver has been utilized to predict channel characteristics, which can further help increase the spectral efficiency [9], compensate for the multi-path distortion [8], improve the spectrum sensing accuracy [10], and assist link alignment [11]. However, all these works have focused on VLC systems based on SISO, and relevant studies are quite few for MIMO.

In this paper, we design a location-based equalization (LBE) scheme for MIMO VLC systems. The concept of LBE has been proposed to equalize the multi-path channel distortion in the SISO VLC systems [8], [12]. In this work, we extend the LBE scheme in the MIMO scenario considering multiple LEDs and multiple PDs. By utilizing the location information of the PDs at the receiver, we first estimate the MIMO channel and then construct the location-based channel matrix to equalize and recover the signals received at the PDs without any training sequences, thereby potentially increasing system efficiency. Two implementation methods for LBE are designed and discussed. Numerical results show the effectiveness of the proposed LBE scheme.

The rest of this paper is organized as follows. In Section II, we introduce the principle of the LBE scheme in MIMO VLC systems. In Section III, we provide numerical results and discussions. Finally, Section IV concludes the paper.

II. Principle of the Proposed Scheme

We consider a MIMO VLC system with T LEDs at the transmitter and R PDs at the receiver. The system model is shown in Fig. 1. At the transmitter, the serial source bits are converted into several parallel data streams, then mapped and modulated, and finally emitted from multiple LEDs. After passing through the MIMO channel, the VLC signal arrives at the receiver. At the output of the jth PD, the received electrical signal can be expressed by:

$$y_j(t) = \sum_{i=1}^{T} \gamma(x_i(t) \odot h_{ji}(t)) + n(t) \ (j = 1, 2, \cdots R), \quad (1)$$

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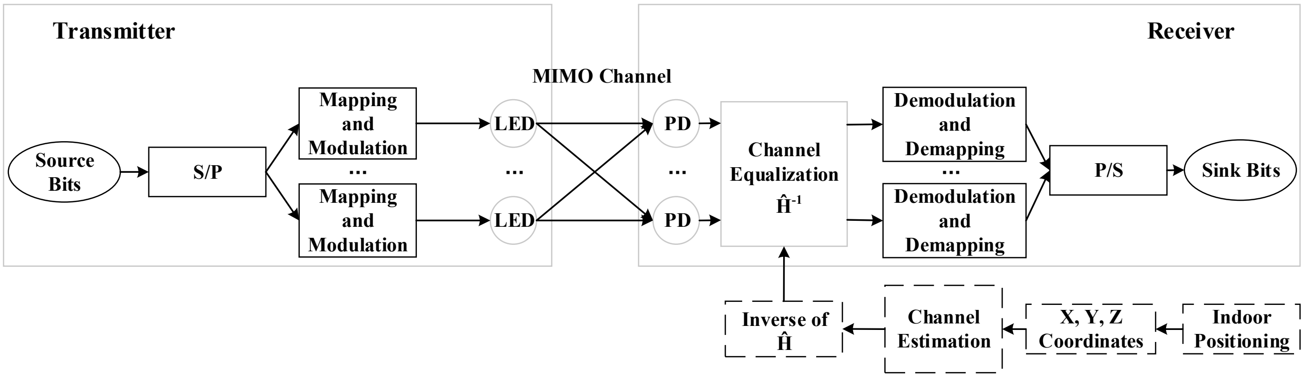


Fig. 1. Block diagram of the proposed LBE scheme in the MIMO VLC system. S/P: serial to parallel; and P/S: parallel to serial.

where γ is the detector responsivity, $x_i(t)$ is the transmitted signal from the ith LED, $h_{ji}(t)$ is the channel impulse response (CIR) of the VLC channel between the ith LED and the jth PD, $\odot$ denotes convolution, $n(t)$ is the additive noise. Here for $h_{ji}(t)$, we consider both the line-of-sight (LOS) and the non-LOS (NLOS) channels. Based on Eq. (1), we use a compact matrix form to represent the received signal in the frequency domain:

$$\mathbf{Y}(f) = \gamma \mathbf{H}(f)\mathbf{X}(f) + \mathbf{N}(f). \tag{2}$$

Here, $\mathbf{Y}(f)=[Y_1(f), Y_2(f), \cdots Y_R(f)]^T$, and $Y_j(f)$ is the frequency domain transfer function (FDTF) of $y_j(t)$. $\mathbf{X}(f)$ represents the transmitted signal in the frequency domain, i.e., $\mathbf{X}(f)=[X_1(f), X_2(f), \cdots X_T(f)]^T$, where $X_i(f)$ is the FDTF of $x_i(t)$. $\mathbf{H}(f)$ is the channel matrix of the MIMO channel in the frequency domain:

$$\mathbf{H}(f) = \begin{bmatrix} H_{11}(f) & \cdots & H_{1T}(f) \\ \vdots & \ddots & \vdots \\ H_{R1}(f) & \cdots & H_{RT}(f) \end{bmatrix}, \tag{3}$$

where $H_{ji}(f)$ is the FDTF of $h_{ji}(t)$. Ideally, the inverse of $\mathbf{H}(f)$, can be used for channel equalization to estimate the original transmitted signal at the receiver. In this way, the ICC between different spatial channels of MIMO can be removed, and this procedure is given by:

$$\widehat{\mathbf{X}}(f) = \mathbf{Y}(f)\mathbf{H}^{-1}(f). \tag{4}$$

Therefore, the key of recovering MIMO signal is to estimate the channel matrix $\mathbf{H}(f)$ as accurate as possible. In conventional MIMO VLC systems, training sequences are employed to estimate each element of $\mathbf{H}(f)$. However, if the length of training sequences is too long, the transmission efficiency will be reduced; otherwise, the accuracy of channel estimation will be affected by noise, which degrades the link performance of VLC.

To find a simple and efficient way for channel estimation, we propose a location-based equalization (LBE) scheme for MIMO VLC. Because VLC systems are based on IM/DD, the channel characteristics of a VLC system are highly related to the relative positions between the transmitter and the receiver, precisely speaking, the location of the receiver because the transmitter is usually fixed in the ceiling. Therefore, by utilizing a priori knowledge of the location information of the receiver, e.g., the three-dimensional (3D) coordinates obtained by indoor positioning, we can perform channel estimation effectively and then equalize the VLC channel. We have proved the feasibility of the LBE scheme in the SISO VLC scenarios [8], [12]. In this work, we extend the concept of LBE to the MIMO VLC systems. Specifically, by utilizing the 3D coordinates of the multiple PDs mounted on the MIMO receiver, we can achieve a close estimation for the real channel matrix $\mathbf{H}(f)$. Then, by using the zero-forcing criterion, the inverse of the location-based matrix is generated to equalize and recover the received signals based on Eq. (4).

Considering different application scenarios, we propose two implementation methods for the proposed LBE scheme to obtain the estimation of $\mathbf{H}(f)$:

- Method 1: Ignore indoor reflections and only consider the influence from LOS channels:

$$\widehat{\mathbf{H}}(f) \approx \mathbf{H}_{LOS}(f) = \begin{bmatrix} H_{LOS,11} & \cdots & H_{LOS,1T} \\ \vdots & \ddots & \vdots \\ H_{LOS,R1} & \cdots & H_{LOS,RT} \end{bmatrix}, \tag{5}$$

  where $H_{LOS,ji}(f)$ represents the LOS component of $H(f)$.

- Method 2: Consider both LOS and NLOS channels:

$$\widehat{\mathbf{H}}(f) \approx \mathbf{H}_{LOS}(f) + \widehat{\mathbf{H}}_{NLOS}(f), \tag{6}$$

  where $\widehat{\mathbf{H}}_{NLOS}(f)$ is a channel matrix whose element is the FDTF of the NLOS component of $h_{ji}(t)$.

Method 1 is much simpler because it requires only direct calculations for the CIR of the limited number of LOS links. This can easily be obtained from the coordinates of PDs and the LOS channel model. Method 2 can achieve a more accurate $\widehat{\mathbf{H}}(f)$ because it considers the NLOS channels, which may enhance the performance of the LBE scheme under strong reflections. However, to obtain the CIR of NLOS links means increased overhead for channel modeling, which can be optimized by using look-up tables [8].

III. Results And Discussions

In this section, we consider a 2×2 indoor MIMO VLC system model for proof-of-concept. To provide sufficient and uniform illumination, the VLC transmitter consists of four LEDs and we divide them into two groups (Group 1: LED1 and LED4; Group 2: LED2 and LED3). Each group transmits a dependent on-off-keying (OOK) data stream at a data rate of 100 Mb/s, respectively. Two PDs (PD1 and PD2) are mounted on the VLC receiver to receive the signal, both facing upwards. The LOS and the 1st indoor reflections are considered for channel modeling. Other key parameters are given in Table 1.

We first use the FDTF to evaluate the channel estimation

Table 1
CONFIGURATION PARAMETERS OF INDOOR MIMO VLC SYSTEM

Room size	5m×5m×3m
Location of LED1 (emit $x_1(t)$)	(1.5, 1.5, 3)
Location of LED2 (emit $x_2(t)$)	(1.5, 3.5, 3)
Location of LED3 (emit $x_2(t)$)	(3.5, 1.5, 3)
Location of LED4 (emit $x_1(t)$)	(3.5, 3.5, 3)
Height of receiving plane	0.85 m
Modulation index	0.2
Physical area of PDs	10^{-4} m^2
Refractive index	1.5
PDs' field of view	85 deg
Responsivity of PDs	0.35 A/W
Total data rate of MIMO system	200 Mb/s

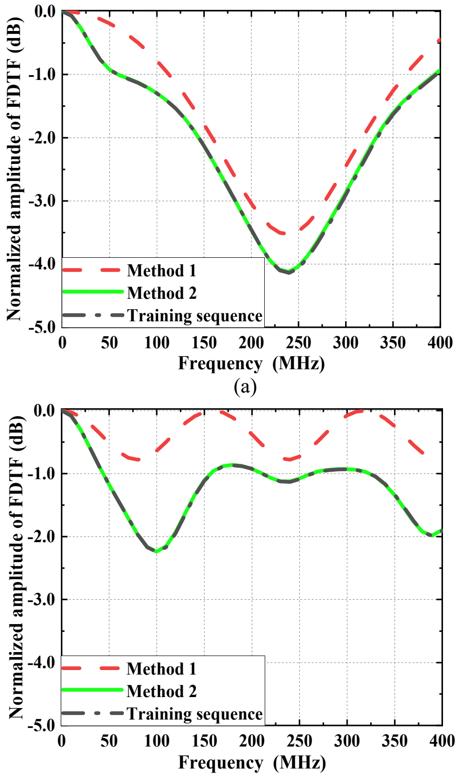


Fig. 2. Normalized amplitude of the channel FDTF when the receiver is fixed at: (a) center; (b)corner.

accuracy of different equalization schemes, including the conventional scheme using training sequences and the proposed LBE scheme. Fig. 2 shows the normalized amplitude of the FDTF for the estimated channel between LEDs in Group 1 and PD1. We consider the receiver is fixed at various test locations. For the center location, PD1 is located at (3.3, 2.55, 0.85) and PD2 is located at (3.3, 2.65, 0.85), while for the corner location, PD1 is located at (0.5, 0.5, 0.85) and PD2 is located at (0.5, 0.6, 0.85). The transmit optical power of each LED is 20 W. As shown in Fig. 2, at both locations, the FDTF curves obtained from the LBE scheme with Method 2 matches well with that from training sequences. This means that the LBE scheme considering both LOS and NLOS channels can achieve a very close estimation of the real channel. We also find that in Fig. 2(a), the FDTF curve of Method 1 is close to that of the conventional scheme. However, in Fig. 2(b), the distance between the FDTF curves of Method 1 and the conventional scheme becomes larger. This is because the NLOS components caused by indoor reflections are much weaker in the center than that in the corner. Therefore, it is possible to use Method 1 to equalize the MIMO channel around the center location.

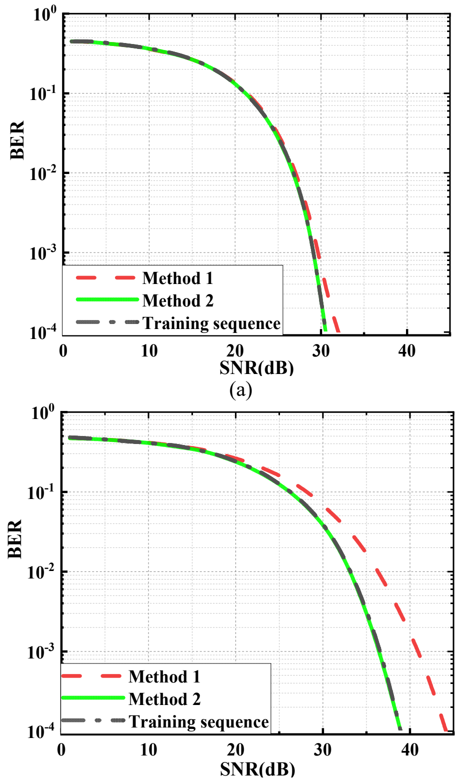
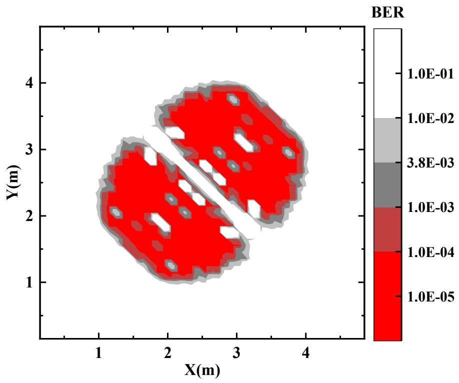


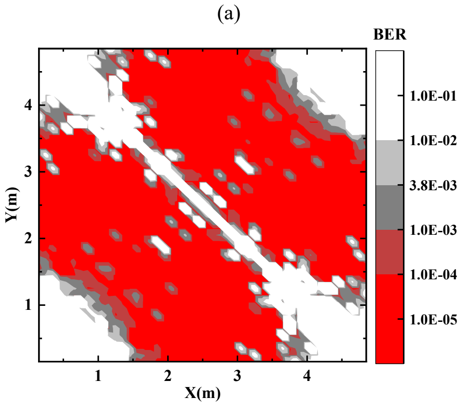
Fig. 3. Comparison of system BER performance when the receiver is located at: (a) center; (b)corner.

Next, in Figs. 3(a) and (b), we evaluate the BER performance of the LBE scheme under various signal-to-noise ratio (SNR) conditions when the receiver is fixed at the center and corner, respectively. In Fig. 3(a), we see that in the center, when the SNR is higher than 30 dB, the BER of all schemes are less than 10^{-3}, which means a reliable link transmission quality [13]. The BER of Method 2 is almost the same as the conventional scheme using training sequences, while Method 1 can also achieve a similar performance as the conventional scheme. However, in Fig. 3(b), to obtain a BER less than 10^{-3}, both Method 2 and the conventional scheme requires a SNR no less than 37 dB, while the SNR required by Method 1 is much higher, up to 41 dB. This is due to the strong NLOS components in the corner. Therefore, if we obtain a priori knowledge of both LOS and NLOS channels, LBE with Method 2 is a promising alternative to the conventional scheme at different locations.

Finally, we evaluate the BER performance of the LBE scheme when the receiver moves around the 5m×5m receiving plane. Figs. 4(a) and (b) show the BER distribution when the LBE with Methods 1 and 2 are adopted, respectively. Here, we use the midpoint of PD1 and PD2 to represent the location of the receiver. The distance between PD1 and PD2 is fixed at 0.1 m and the intersection angle between the direction pointing from PD1 towards PD2 and the positive X-axis is set at 45°. As shown in Fig. 4(a), when adopting the LBE scheme using Method 1, BER less than 3.8×10^{-3} can be achieved within around 24% areas of the receiving plane, and these areas are mainly distributed around the center of the room where NLOS components are weak. However, for the edge and near corner locations, due to stronger indoor reflections, the MIMO VLC signals cannot be recovered successfully by using Method 1, which can be



(a)



(b)

Fig. 4. BER distribution within the receiving plane when adopting LBE with: (a) Method 1; (b) Method 2.

improved by Method 2. As shown in Fig. 4(b), by adopting the LBE scheme with Method 2, BER less than 3.8×10^{-3} can be achieved within around 73% areas of the receiving plane. Also note that, in Figs. 4(a) and (b), when the receiver is located at a strip region in the diagonal line of the receiving plane, BER performance degrades inevitably due to the undesirable symmetry of the MIMO channel matrix.

IV. Conclusion

We proposed a LBE scheme for MIMO VLC systems. The location information of PDs at the receiver can efficiently be used for channel estimation and equalization. The LBE design based on only the LOS channel can achieve a reliable link quality within around 24% of the receiving plane, and this percentage can be improved to 73% when the LBE scheme considers both LOS and NLOS channels.

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