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Hybrid space-frequency domain pre-equalization for DC-biased optical orthogonal frequency division multiplexing based imaging multiple-input multiple-output visible light communication systems

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Abstract. We propose a hybrid space-frequency domain pre-equalization technique for indoor multiple-input multiple-output visible light communication (MIMO-VLC) systems using DC-biased optical orthogonal frequency division multiplexing with an imaging receiver. The proposed hybrid space-frequency domain pre-equalization is jointly performed in both space and frequency domains for the purpose of achieving comparable signal-to-noise ratio performances of different channels in an imaging MIMO-VLC system. It is shown by the simulation results that a four-channel imaging MIMO-VLC system with a raw data rate of 1.2 Gb/s using hybrid space-frequency domain pre-equalization achieves significantly improved bit error rate performance than the system using only frequency domain pre-equalization, resulting in up to 52.6% improvement in communication coverage area at a target BER of 10^{-3} . © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.56.3.036102](https://doi.org/10.1117/1.OE.56.3.036102)]

Keywords: visible light communication; multiple-input multiple-output; orthogonal frequency division multiplexing; pre-equalization; communication coverage.

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1 Introduction

The last several years have witnessed tremendous interest in white light-emitting diodes (LEDs)-enabled visible light communications (VLCs) due to many inherent advantages, such as license-free spectrum, cost-effective front-ends, high security, and immunity to electromagnetic interference.^{1,2} However, one major challenge for achieving a high capacity in VLC systems is the limited modulation bandwidth of LEDs, which is typically about a few megahertz.³ To extend the modulation bandwidth of LEDs, various pre-frequency domain equalization (pre-FDE) techniques have been reported, for example, hardware-circuit-based analog pre-FDE,³ digital-signal-processing-based digital pre-FDE,⁴ and adaptive digital pre-FDE.⁵ In addition, orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) transmission are two other promising techniques that have been widely investigated in VLC systems.^{6–8}

MIMO transmission is a very natural and effective way to improve the capacity of VLC systems as multiple LEDs are commonly deployed in the ceiling for illumination in practical indoor environments.⁸ Generally, two types of receivers can be used in MIMO-VLC systems: one is a nonimaging receiver (NImR) and the other is an imaging receiver (ImR). The capacity improvement of NImR-based MIMO-VLC systems is limited by significant interchannel interference (ICI),⁹ while an ImR can fully exploit the capacity of MIMO-VLC systems due to its ability to effectively decorrelate the multiplexed channels, resulting in negligible ICI.¹⁰

ImR-based MIMO is also referred to as space division multiplexing (SDM).¹⁰ We have recently proposed an imaging angle diversity receiver (ImADR) for SDM-VLC systems, which achieves a wider field-of-view (FOV) and higher gain than a conventional ImR.¹¹ To further improve the performance of MIMO-VLC systems, several techniques have been proposed in the literature. In Ref. 12, an imaging MIMO-VLC system was demonstrated in which a combination of digital pre-FDE and OFDM was used to achieve a total data rate of 1 Gb/s. In Ref. 13, the authors investigated a nonimaging MIMO-VLC system in which singular value decomposition-based precoding and adaptive-modulated OFDM were employed.

In this paper, for the first time, we propose a hybrid space-frequency domain pre-equalization technique for DC-biased optical OFDM (DCO-OFDM)-based imaging MIMO-VLC systems. We digitally perform pre-equalization in both space and frequency domains such that all the channels in an imaging MIMO-VLC system can achieve comparable signal-to-noise ratio (SNR) performances. Monte Carlo simulations are carried out to evaluate the performance of an indoor N -channel imaging MIMO-VLC system with $N = 1, 2, 3, 4$ using the proposed hybrid space-frequency domain pre-equalization technique.

Notation: $(\cdot)^T$ and $(\cdot)^{-1}$ denote the transpose and inverse operators, respectively. $\text{diag}(\cdot)$ stands for the diagonal matrix whose diagonal elements are the values given inside the round brackets. Nonboldface italic letters, lowercase boldface letters, and capital boldface letters represent scalars, vectors, and matrices, respectively.

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Fig. 1 Block diagram of a DCO-OFDM-based indoor imaging MIMO-VLC system using hybrid space-frequency domain pre-equalization. Insets: side views of (a) a conventional ImR and (b) an ImADR.

2 System Model

The block diagram of a DCO-OFDM-based indoor imaging MIMO-VLC system using hybrid space-frequency domain pre-equalization is shown in Fig. 1. The serial input data are first split into N streams (corresponding to N LED lamps) via serial-to-parallel (S/P) conversion, and the data in each stream are then mapped to quadrature amplitude modulation (QAM) symbols. Hermitian symmetry (HS) is then imposed to generate LED-compatible real-valued signals. By employing a measured electrical-optical-electrical (EOE) frequency response, pre-FDE is performed before the inverse fast Fourier transform (IFFT) in each stream. After that, a cyclic prefix (CP) is added, and the resultant parallel signal is parallel-to-serial (P/S) converted. By exploiting the estimated channel matrix, pre-space domain equalization (pre-SDE) is performed among all the streams to ensure that the received N signals have the same SNR. After inserting a training sequence (TS) and digital-to-analog (D/A) conversion, a DC bias is added in each stream to obtain a unipolar signal. The obtained N streams of unipolar signals are then used to drive N LED lamps, respectively. The radiated LED light is detected by an ImR or an ImADR at the receiver side. The analog signals are then converted to digital signals via analog-to-digital (A/D) conversion, and the channel matrix is estimated utilizing the TSs. After S/P conversion, CP removal, FFT, post-FDE, QAM demapping, and P/S conversion, the output data are obtained. The insets in Fig. 1 show the side views of a conventional ImR and an ImADR. As we can see the ImR has a two-dimensional circular photodetector (PD) array consisting of vertically oriented PDs, while the ImADR has a three-dimensional spherical-cap-shaped PD array consisting of angle diversity PDs.¹¹

Because the detailed procedures for performing digital pre-FDE have been well studied in the literature,^{4,5,14} we assume that pre-FDE has already been performed and only focus on the principle of pre-SDE in the following analysis. In an optical DCO-OFDM-based N -channel imaging MIMO-VLC system, the output optical power and the modulation index of each LED lamp are assumed to be P_{opt} and ξ , respectively. To perform pre-SDE, a power allocation matrix $\mathbf{A} = \text{diag}(a_1, a_2, \dots, a_N)$ is adopted to adjust the electrical powers of different modulating signals. Hence, the transmitted optical signal vector $\mathbf{s} = (s_1 s_2 \dots s_N)^T$ can be represented by

$$\mathbf{s} = P_{\text{opt}}(1 + \xi \mathbf{A} \mathbf{x}), \quad (1)$$

where $\mathbf{x} = (x_1 x_2 \dots x_N)^T$ is a vector of modulating signals and $x_i (i = 1, 2, \dots, N)$ is the normalized bipolar OFDM signal with variance $\sigma_{x_i}^2 = 1$. Due to the introduction of $\mathbf{A}$, the electrical powers of different modulating signals could be different. To maintain a constant average electrical power when performing pre-SDE, a power constraint is imposed on the diagonal elements of $\mathbf{A}$

$$\frac{1}{N} \sum_{i=1}^N a_i^2 = 1. \quad (2)$$

After free-space propagation, the LED light is detected by an ImR or an ImADR, and the received electrical signal vector $\mathbf{y} = (y_1 y_2 \dots y_N)^T$ is obtained by

$$\mathbf{y} = R P_{\text{opt}} \xi \mathbf{H} \mathbf{A} \mathbf{x} + \mathbf{n}, \quad (3)$$

where R is the responsivity of the PD, $\mathbf{H}$ is the channel matrix, and $\mathbf{n} = (n_1 n_2 \dots n_N)^T$ is the additive noise vector. In typical indoor environments, the detector can receive both line-of-sight (LOS) and diffuse components. It has been shown that the diffuse component is strongest when the receiver is located at the corners of the room, which is still at least 7-dB lower in electrical power than the weakest LOS component received. For this reason, only LOS components are considered in the analysis.⁸ The LOS irradiance of an LED lamp can be modeled by a generalized Lambertian radiation pattern, and the optical LOS channel gain between the t 'th LED lamp and the r 'th PD is calculated by^{1,15}

$$h_{rt} = \frac{(m+1)A_{PD}}{2\pi d_{rt}^2} \mu \eta \cos^m(\phi_{rt}) \cos(\theta_{rt}), \quad (4)$$

where $m = -\ln 2 / \ln(\cos \Psi_{1/2})$ is the order of Lambertian emission with $\Psi_{1/2}$ being the transmitter semiangle at half power, A_{PD} is the active area of the PD, d_{rt} is the distance between the t 'th LED lamp and the r 'th PD, μ and η are the gains of the optical filter and the optical lens, respectively, ϕ_{rt} is the emission angle, and θ_{rt} is the incident angle. Note that if θ_{rt} is outside the FOV of the detector, the optical gain h_{rt} becomes zero. When an ImADR is used, θ_{rt} becomes zero, and, hence, the channel gain is improved. As the ICI is negligible using ImR or ImADR,^{8,11} the channel matrix of an N -channel imaging MIMO-VLC system is expressed by

Fig. 2 (a) Geometric setup of the N -channel imaging MIMO-VLC system and (b) measured EOE frequency response of a commercially available LED.

$$\mathbf{H} = \text{diag}(h_{11}, h_{22}, \dots, h_{NN}). \quad (5)$$

Moreover, n_i ($i = 1, 2, \dots, N$) can be modeled as real-valued zero-mean additive white Gaussian noises (AWGNs) with variance $\sigma_{n_i}^2$. The additive noises consist of both shot and thermal noises, and, hence, $\sigma_{n_i}^2 = \sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2$, where the variances of shot and thermal noises are given by^{10,16}

$$\sigma_{\text{shot}}^2 = 2q(RP_{\text{signal}} + I_{bg}I_2)B, \quad (6)$$

$$\sigma_{\text{thermal}}^2 = 8\pi kT_K \eta AB^2 \left(\frac{I_2}{G} + \frac{2\pi\Gamma}{g_m} \eta AI_3 B \right), \quad (7)$$

where P_{signal} is the received optical signal power, I_{bg} is the background current due to ambient light, and B is the equivalent noise bandwidth. The other parameters in Eqs. (6) and (7) can be found in Refs. 1 and 10.

To recover data from the received signals, MIMO demultiplexing is performed, and zero-forcing (ZF) using basic channel inversion is adopted due to its low complexity.⁹ After ZF-based MIMO demultiplexing, we have

$$\tilde{\mathbf{x}} = \mathbf{H}^{-1} \mathbf{y} = RP_{\text{opt}} \xi \mathbf{A} \mathbf{x} + \mathbf{H}^{-1} \mathbf{n}. \quad (8)$$

As per Eq. (8), the SNRs of four estimated electrical signals are calculated by

$$\text{SNR}'_i = \frac{(RP_{\text{opt}} \xi a_i h_{ii})^2}{\sigma_{n_i}^2} = a_i^2 \text{SNR}_i, \quad (9)$$

where $\text{SNR}_i = (RP_{\text{opt}} \xi h_{ii})^2 \sigma_{x_i}^2 / \sigma_{n_i}^2$, $i = 1, 2, \dots, N$. Since the purpose of performing pre-SDE is to guarantee that the received four signals have the same SNR, as per Eq. (9), the following requirement must be satisfied

$$a_1^2 \text{SNR}_1 = a_2^2 \text{SNR}_2 = \dots = a_N^2 \text{SNR}_N. \quad (10)$$

By solving Eqs. (2) and (10), the N diagonal elements of $\mathbf{A}$ can be obtained by

$$a_i = \sqrt{\frac{N}{\text{SNR}_i \sum_{i=1}^N \frac{1}{\text{SNR}_i}}}. \quad (11)$$

Therefore, pre-SDE can be successfully performed by substituting Eqs. (11) into (1). It can be seen that the diagonal elements of $\mathbf{A}$ are generated based on the SNR value of each channel in the MIMO-VLC system. Hence, the estimated SNR values should be transmitted back to the ceiling as the feedback information via the uplink channels. Generally, there are two types of uplink channels that can be used in indoor environments: one is Wi-Fi-based uplink channel that is available nearly everywhere but has a relative low data rate, and the other is infrared-based uplink that can support a much higher data rate but is not widely deployed currently.¹⁶ In typical indoor environments, the optical channel remains static for most of the time, while VLC users are normally located at fixed positions or moving with a relatively slow speed. Therefore, uplink delay should have negligible impact on the performance of pre-SDE.² It should also be noted that the electrical power of each channel should be adjustable to a certain extent so as to successfully perform pre-SDE, as generally required in precoded MIMO-VLC systems.^{17,18} Hence, pre-SDE can be considered as a precoding technique for MIMO-VLC systems.

3 Simulation Setup and Results

In this section, we conduct simulation studies of an indoor N -channel imaging MIMO-VLC system in a typical room environment. To show the performance dependence on N , four different N values are considered, i.e., $N = 1, 2, 3, 4$. For $N = 1$, the system becomes an SISO system. The geometric setup of the system is shown in Fig. 2(a), where the coordinates of the lower-left corner are set to (0,0,0) and the unit is meter. The locations of the LED lamps in the ceiling corresponding to $N = 1, 2, 3, 4$ are given in Table 1.

Table 1 LED locations.

$N = 1$	$N = 2$	$N = 3$	$N = 4$
(2.5, 2.5, 3)	(1.5, 2.5, 3) (3.5, 2.5, 3)	(1.5, 1.5, 3) (3.5, 1.5, 3) (2.5, 3.5, 3)	(1.5, 1.5, 3) (3.5, 1.5, 3) (1.5, 3.5, 3) (3.5, 3.5, 3)

Table 2 Simulation parameters.

Room dimension (width, length, height)	5 m × 5 m × 3 m
Height of the receiving plane	0.85 m
Semi-angle at half power of LED ($\Psi_{1/2}$)	60 deg
Output optical power of LED (P_{opt})	10 W
Modulation index (ξ)	0.3
Gain of optical filter (μ)	1
Gain of optical lens (η)	1
FOV of detector	150 deg
Active area of PD (A_{PD})	19.6 mm ²
Responsivity of PD (R)	0.53 A/W
Background current (I_{bg})	190 μ A
Bandwidth (B)	50 MHz
QAM constellation order	64

Table 2 lists the key simulation parameters. As shown in Fig. 2(a), the room has a dimension of 5 m × 5 m × 3 m and the height of the receiving plane is 0.85 m. The semiangle at half power of LED is 60 deg, and each LED lamp has an output optical power of 10 W. The modulation index is set to 0.3. Both the optical filter and the optical lens are assumed to have a gain of 1. The active area and responsivity of the PD are 19.6 mm² and 0.53 A/W, respectively. The background current due to ambient light is 190 μ A. In each channel of the MIMO-VLC system, a DCO-OFDM signal is transmitted, using 64QAM mapping with an IFFT/FFT size of 256. The first subcarrier is unmodulated, which is corresponding to the DC component.⁵ To spectrally separate the baseband signal from the high-frequency products generated by the digital-to-analog converters, the subcarriers in the high-frequency part are left unmodulated for oversampling.^{6,7} In this simulation investigation, the 66th to 128th subcarriers in the high-frequency part are left unmodulated and HS is imposed. Therefore, 64 (2nd to 65th) subcarriers are used for data transmission. The sampling rate of each channel is set to 200 MSa/s, and hence, the raw data rate of each channel is given by $200 \times (64/256) \times \log_2 64 = 300$ (Mb/s).⁷ For the N -channel 64QAM DCO-OFDM-based MIMO-VLC system, the raw data rate of the system is then calculated by $N \times 300$ (Mb/s).¹² When $N = 4$, the raw data rate of

Fig. 3 SNR performance using an ImADR at corner (0, 0, 0.85) of the receiving plane for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, and (d) $N = 4$. Insets in (a) show the corresponding received OFDM spectra.

Fig. 4 BER performance along X direction with $Y = 1.5$ m for (a) $N = 1$, (b) $N = 2$, (c) $N = 3$, and (d) $N = 4$.

the system is 1.2 Gb/s. In practical systems, various training overheads, such as CP for mitigating multipath-induced intersymbol interference, TS for time synchronization, and forward error correction (FEC) coding, are usually added in the transmission.⁶ As per Refs. 5, 7, and 19, assuming that the typical CP, TS, and FEC overheads are 6.25%, 6%, and 7%, respectively, the net data rate of the four-channel 64QAM DCO-OFDM-based MIMO-VLC system is given by $4 \times 300 \times (1 - 6.25\%) \times (1 - 6\%) \times (1 - 7\%) \approx 983.6$ (Mb/s). The measured EOE frequency response of a commercially available LED (Luxeon Star) with 50-MHz modulation bandwidth is given in Fig. 2(b).

Figure 3 shows the SNR performance of the N -channel imaging MIMO-VLC system using an ImADR at corner (0,0,0.85) of the receiving plane. For $N = 1$, as shown in Fig. 3(a), the SNR decreases significantly with the increase of frequency when pre-FDE is not performed, and an SNR degradation of about 20 dB is observed. After performing

pre-FDE, the SNR profile is substantially flattened over 50-MHz bandwidth. The two insets in Fig. 3(a) show the received OFDM spectra without and with pre-FDE, respectively. For $N = 2$, the SNR performances of two different channels are uneven due to different spatial locations of the LED transmitters. As can be seen in Fig. 3(b), the SNR of channel 1 is ~ 8 dB higher than that of channel 2. Hence, the BER performances of different channels are quite different, which leads to a significant degradation in the overall BER performance of the system. However, by performing pre-SDE in the space domain after pre-FDE, both channels have nearly the same SNR performances; hence, the overall BER performance of the system can be greatly improved. Similarly, nearly the same SNR performance can be achieved by all the channels with both pre-FDE and pre-SDE for $N = 3$ and 4, as can be seen from Figs. 3(c) and 3(d), respectively.

Next, we investigate the BER performance of the N -channel imaging MIMO-VLC system. Figures 4(a)–4(d)

Fig. 5 Communication coverage area comparison at a target BER of 10^{-3} for (a) $N = 2$, (b) $N = 3$, and (c) $N = 4$. The black "+" indicates the position of an LED.

show the BER performance along the X direction with $Y = 1.5$ m for $N = 1, 2, 3$, and 4 , respectively. For $N = 1$, the BER is always above 10^{-3} without pre-FDE and the BER is significantly reduced when pre-FDE is performed. For $N = 2, 3$, and 4 , it is shown that the BER performance is significantly improved when the hybrid space-frequency domain pre-equalization technique is used, i.e., both pre-FDE and pre-SDE are performed, using either an ImR or an ImADR. Moreover, the system using an ImADR achieves much better BER performance than that using an ImR due to the high optical gain of ImADR. It can be further observed that the BER performance is gradually decreased with the increase of N . This is because a larger N value indicates more channels in the MIMO-VLC system and, hence, a higher overall capacity. The insets in Figs. 4(a)–4(c) show the corresponding constellation diagrams.

Finally, we evaluate the communication coverage of the N -channel imaging MIMO-VLC system at a target BER of 10^{-3} with $N = 2, 3$, and 4 . For $N = 2$ with an ImR, as shown in Fig. 5(a), the coverage contour with only pre-FDE is plotted by the blue dotted line, while the coverage contour with both pre-FDE and pre-SDE is given by the blue solid line. As can be seen, the coverage is increased along the X direction when pre-SDE is further performed, while the coverage

along the Y direction remains the same. This is because the SNRs of two channels in the system are always the same when $X = 2.5$ m due to the geometric symmetry of the two LEDs in the ceiling. However, the geometric symmetry no longer exists when $N = 3$ and 4 . As can be seen from Figs. 5(b) and 5(c), the coverage is always increased when pre-SDE is performed after pre-FDE. For $N = 4$, the coverage contours can be approximated as circles and the coverage areas can be estimated by the areas of the circles. It is found that the smallest coverage is obtained using only pre-FDE with an ImR, while the largest coverage is achieved using both pre-FDE and pre-SDE with an ImADR. For the system using an ImADR, the diameters of the coverage contours employing only pre-FDE and employing both pre-FDE and pre-SDE are 3.4 and 4.2 m, respectively. Therefore, a coverage area improvement of about 52.6% is achieved when the proposed hybrid space-frequency domain pre-equalization technique is employed.

4 Conclusion

In this paper, we proposed a hybrid space-frequency domain pre-equalization technique for DCO-OFDM-based imaging MIMO-VLC systems. The hybrid space-frequency domain pre-equalization includes both digital pre-FDE and pre-

SDE, which is performed in the transmitter side. Our simulation results showed that the BER performance of an imaging MIMO-VLC system can be significantly improved when both pre-FDE and pre-SDE are performed. At a target BER of 10^{-3} , a four-channel imaging MIMO-VLC system with a raw data rate of 1.2 Gb/s using the proposed hybrid space-frequency domain pre-equalization achieves a communication coverage area improvement of about 52.6% compared with the system using only pre-FDE. In addition, it should be noted that the proposed hybrid space-frequency domain pre-equalization technique is applicable to general indoor MIMO-VLC systems using either NImR or ImR.

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