Communication Coverage Improvement of Indoor SDM-VLC System Using NHS-OFDM with a Modified Imaging Receiver

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***Abstract*—This paper proposes two techniques to improve the communication coverage of an indoor space division multiplexing visible light communication (SDM-VLC) system. One technique is a non-Hermitian symmetry orthogonal frequency division multiplexing (NHS-OFDM) scheme which can be achieved by parallelly transmitting the real (Re) and imaginary (Im) parts of a complex-valued OFDM signal via a pair of white light-emitting diode (LED) lamps, and the other is a modified imaging receiver (ImR) which utilizes tilted photodetectors (PDs) to improve the performance of a conventional ImR. Analytical and simulation results show that the communication coverage of an indoor 2×2 SDM-VLC system can be substantially improved by using NHS-OFDM with a modified ImR, compared with the system using Hermitian symmetry based OFDM (HS-OFDM) with a conventional ImR.**

***Index Terms*—Visible light communication; space division multiplexing; coverage; imaging receiver; orthogonal frequency division multiplexing**

I. Introduction

Driven by the rapid development of solid-state lighting technology, white light-emitting diodes (LEDs) based visible light communication (VLC) has attracted tremendous attention in recent years [1]–[3]. VLC systems have many inherent advantages such as potentially large license-free bandwidth, high security and electromagnetic interference-free operation. However, the relatively small modulation bandwidth of white LEDs (typically less than tens of MHz) is one of the greatest limitations that hinder the further development of high-speed VLC systems [4]. So far, many techniques have been proposed to address this limitation, such as spectral-efficient modulation schemes including orthogonal frequency division multiplexing (OFDM) [5], [6] and multiple-input multiple-output (MIMO) transmission [7], [8].

In OFDM based VLC systems, intensity modulation/direct detection (IM/DD) is usually adopted and thus only real-valued signals can be successfully transmitted by LEDs [5]. Generally, the input data of inverse fast Fourier transform (IFFT) must have Hermitian symmetry to guarantee a real-valued output, which doubles the size of IFFT and increase the transceiver complexity. Hermitian symmetry based OFDM (HS-OFDM) is also known as DC biased optical OFDM (DCO-OFDM) [9]. Several approaches have been proposed to remove the Hermitian symmetry constraint, for example, transmitting the real (Re) and imaginary (Im) parts of a complex-valued OFDM signal via multiple consecutive symbols [10], [11] or via two chips of a RGB-LED [12], [13]. However, using multiple symbols to transmit one OFDM frame inevitably reduces the system capacity. Transmitting the Re and Im parts separately via two chips of a RGB-LED would increase the cost of indoor VLC systems since RGB-LEDs are much more expensive than the commonly used phosphor-based LEDs [1].

MIMO transmission is an intuitional and effective way to increase the capacity of VLC systems. Two types of receivers are generally used in indoor MIMO-VLC systems, including a non-imaging receiver (NImR) and an imaging receiver (ImR) [14]. Since an ImR can demultiplex the transmitted signals and successfully eliminate the inter-channel interference (ICI), ImR based MIMO-VLC systems can achieve high spatial diversity, which are also referred to as space division multiplexing (SDM) systems [14], [15]. Thus, the SDM-VLC systems are promising for future high-speed indoor wireless communications.

Besides the small modulation bandwidth of white LEDs, the communication coverage of an indoor VLC system is another limitation. Compared with its radio-frequency (RF) counterpart that has full coverage of an indoor environment, achieving the full coverage of an indoor VLC system remains to be an issue that has not yet been adequately investigated [16]. In order to improve the communication coverage of indoor VLC systems, optimization of the LED arrangement in the ceiling has been proposed so as to reduce the fluctuation of signal-to-noise ratio (SNR) and maximize the area spectral efficiency [17], [18].

In this paper, for the first time, we propose a non-Hermitian symmetry orthogonal frequency division multiplexing (NHS-OFDM) scheme together with a modified ImR to improve the communication coverage of indoor SDM-VLC systems. Through both theoretical analysis and Monte Carlo simulations, we show that the indoor SDM-VLC system using NHS-OFDM with a modified ImR can achieve a significant communication coverage improvement, compared with the system using HS-OFDM with a conventional ImR.

The rest of the paper is organized as follows. In Section II, we describe an indoor 2×2 SDM-VLC system using the proposed NHS-OFDM, in which both a conventional ImR and

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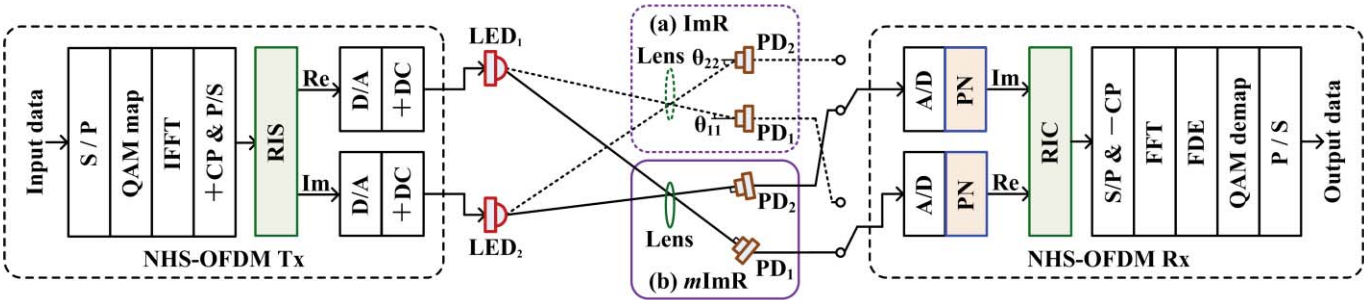

Fig. 1. Schematic diagram of an indoor 2×2 SDM-VLC system using NHS-OFDM with (a) a conventional ImR and (b) a modified ImR (*m*ImR).

a modified ImR are considered. Section III derives the analytical bit error rate (BER) expression of the proposed indoor SDM-VLC system using NHS-OFDM with a modified ImR. In Section IV, performance comparisons between two different modulation techniques and two different types of receivers are performed, in terms of BER and communication coverage. Finally, the conclusion is given in Section V.

II. Indoor SDM-VLC System Using NHS-OFDM with a Modified Imaging Receiver

Fig. 1 shows the schematic diagram of a NHS-OFDM based indoor 2×2 SDM-VLC system, where a conventional ImR or a modified ImR can be used as the receiver. The Re and Im parts of the complex-valued OFDM signal are separately transmitted by a pair of white LED lamps. After free-space propagation, a conventional ImR or a modified ImR is used to detect the optical signal. Both the conventional ImR and the modified ImR consist of an imaging lens and a detector array. After passing through the imaging lens, two signal spots can be observed on the detector array. The detector array normally comprises a lot of individual detectors (pixels), such that each received signal spot might cover multiple adjacent detectors. As discussed in [7], the line-of-sight (LOS) channel DC gain between an LED lamp and a detector can be individually calculated and an adequate threshold can be set to exclude the detectors which are not illuminated by the signal light. After that, an output electrical signal can be obtained through diversity combining [19]. In this work, for simplicity of calculation and without the loss of generality, we assume that the LED lamp is small enough such that each of the received signal spots falls entirely inside the corresponding detector.

A. Channel model

In typical indoor environments where white LEDs are used for illumination, optical detectors can receive both a LOS component and a diffuse component. Generally, the weakest LOS component is still at least 7 dB higher in electrical power than the strongest diffuse component [7], so we only consider the LOS component in the analysis. The LOS irradiance of an LED lamp can be modeled by a generalized Lambertian radiation pattern [2] and the LOS channel DC gain is given by

$$h = \begin{cases} \dfrac{(l+1)A}{2\pi d^2} \cos^l(\varphi)\, T_s(\theta) g(\theta) \cos(\theta)\ , 0 \le \theta \le \Theta_{1/2} \\ 0, \qquad\qquad\qquad\qquad\qquad\qquad\qquad \theta > \Theta_{1/2} \end{cases}, \quad (1)$$

where $l = -\ln 2/\ln(\cos \Psi_{1/2})$ is the order of Lambertian emission and $\Psi_{1/2}$ is the transmitter semi-angle at half power. A is the active area of the detector, d is the distance, φ is the angle of irradiance, θ is the angle of incidence, and $T_s(\theta)$ is the gain of an optical filter. $g(\theta)$ and $\Theta_{1/2}$ are the gain and the field of view (FOV) of the optical concentrator, respectively.

B. NHS-OFDM

The block diagrams of NHS-OFDM transmitter (Tx) and receiver (Rx) are illustrated in Fig. 1. In the NHS-OFDM Tx, the input serial data are first converted to parallel data via serial-to-parallel (S/P) conversion. Then, the parallel data are mapped to QAM symbols. After IFFT, a cyclic prefix (CP) is added and the resultant parallel signal is parallel-to-serial (P/S) converted. In order to generate LED compatible real-valued signals, a real-and-imaginary separator (RIS) is adopted to separate the Re and Im parts of the complex-valued OFDM signal. After digital-to-analog (D/A) conversion, two DC bias currents are added to generate two unipolar signals for intensity modulation to the LED lamps.

In the NHS-OFDM Rx, the received Re and Im signals are first analog-to-digital (A/D) converted. In a practical indoor environment, the transmission distances of the Re and Im parts could be different, thus the received Re and Im parts could have different electrical powers. In order to correctly reconstruct the transmitted complex-valued OFDM signal, the powers of the Re and Im parts should be balanced, which can be achieved by separately normalizing the received Re and Im parts via power normalization (PN). During the process of PN, the input data symbol is divided by its average power which is the square root of the summation of the digital signals within the same data symbol. After PN, the balanced Re and Im parts are combined together in a real-and-imaginary combiner (RIC) to recover the complex-valued OFDM signal. After S/P conversion, CP removal, FFT and frequency domain equalization (FDE), the resultant signal is QAM demapped and P/S converted to obtain the output data.

C. Modified imaging receiver

A conventional ImR can be modeled as a grid of detectors sharing a common imaging lens [14]. An optical filter can also be used to minimize the received background light [2]. In [20], a detector with a tilted receiving plane was proposed to improve the SNR distribution of a point-to-point indoor VLC system. The optimal tilting angle of the detector can be determined by using the Newton method. In [21], angle diversity detectors were proposed to improve the capacity of indoor non-imaging MIMO-VLC systems. In this work, we propose a modified ImR to improve the performance of indoor SDM-VLC systems by employing tilted PDs.

Fig. 1(a) shows a conventional ImR where an imaging lens is placed in front of two photodetectors (PDs). The receiving planes of the two PDs are not tilted and the two incident angles θ_{11} and θ_{22} are determined by the relative positions of the corresponding LED lamps and PDs. The channel matrix of an indoor 2×2 SDM-VLC system using a conventional ImR is a diagonal matrix which can be expressed by [14]

$$\mathbf{H}_{\text{ImR}} = \begin{bmatrix} h_{11} & 0 \\ 0 & h_{22} \end{bmatrix}, \tag{2}$$

where h_{ii} is the LOS channel DC gain between the i^{th} LED lamp and the i^{th} PD ($i = 1, 2$), as given in (1).

In the proposed modified ImR, as shown in Fig. 1(b), the two PDs are tilted such that the incident light of each PD is always perpendicular to its receiving plane. Therefore, the two incident angles are always 0°, indicating that the $\cos(\theta)$ term in (1) reaches its maximum value, i.e. unity, and thus the maximum LOS channel DC gains can be obtained. Given the two incident angles θ_{11} and θ_{22} in the conventional ImR, the maximum LOS channel DC gains achieved by the modified ImR can be obtained as $h'_{ii} = h_{ii}/\cos(\theta_{ii})$ with $i = 1, 2$ for the indoor 2×2 SDM-VLC system. As a result, the channel matrix of an indoor 2×2 SDM-VLC system using the modified ImR can be obtained as

$$\mathbf{H}_{m\text{ImR}} = \begin{bmatrix} h'_{11} & 0 \\ 0 & h'_{22} \end{bmatrix}. \tag{3}$$

III. ANALYTICAL BER EXPRESSION OF THE PROPOSED SYSTEM

In this section, we derive the analytical BER expression of the proposed indoor SDM-VLC system using NHS-OFDM and a modified ImR. For simplicity of analysis, a 2×2 set-up is considered without the loss of generality. Assuming that the two LED lamps transmit an identical average optical power P_{tx}, the transmitted optical signal vector $\mathbf{s} = [s_{\text{Re}}\ s_{\text{Im}}]^T$ can be represented by

$$\mathbf{s} = P_{\text{tx}}(\mathbf{1} + \mu\mathbf{x}), \tag{4}$$

where $\mathbf{x} = [x_{\text{Re}}\ x_{\text{Im}}]^T$ is the modulating signal vector. $x_{\text{Re}}(t)$ and $x_{\text{Im}}(t)$ are the normalized Re and Im parts of the transmitted complex-valued OFDM signal $x(t)$, respectively. Hence, the complex-valued OFDM signal is given by $x(t) = x_{\text{Re}}(t) + j \times x_{\text{Im}}(t)$. μ is the modulation index which is assumed to be the same for all the LED lamps. The modulation index of each LED lamp is defined as the ratio of the maximum current variation caused by the modulating signal to the LED bias current [22].

After free-space channel propagation, the optical signal is detected by two PDs which are assumed to have the same responsivity R. The DC components of the detected signals are first removed. Hence, the received electrical signal vector $\mathbf{y} = [y_{\text{Re}}\ y_{\text{Im}}]^T$ is given by

$$\mathbf{y} = RP_{\text{tx}}\mu\mathbf{H}\mathbf{x} + \mathbf{n}, \tag{5}$$

where $\mathbf{H}$ is the channel matrix of the 2×2 SDM-VLC system and $\mathbf{n} = [n_{\text{Re}}\ n_{\text{Im}}]^T$ is the additive noise vector. $\mathbf{H}$ is given by (2) when a conventional ImR is used and $\mathbf{H}$ becomes (3) when a modified ImR is used. $n_{\text{Re}}(t)$ and $n_{\text{Im}}(t)$ can be modeled as real-valued additive white Gaussian noises (AWGNs), which consist of both shot and thermal noises. The variances of the shot and thermal noises are given as follows [22]

$$\sigma^2_{\text{shot}} = 2q\left(RP_{\text{rx}} + I_{\text{bg}}I_2\right)B, \tag{6}$$

$$\sigma^2_{\text{thermal}} = 8\pi k T_{\text{K}} \eta A B^2 \left(\frac{I_2}{G} + \frac{2\pi\Gamma}{g_{\text{m}}}\eta A I_3 B\right), \tag{7}$$

where P_{rx} is the total received power, I_{bg} is the background current and B is the equivalent noise bandwidth. The other parameters shown in (6) and (7) can be found in [22].

In the 2×2 SDM-VLC system using the modified ImR, the channel matrix $\mathbf{H}$ is a diagonal matrix given by (3), so we can rewrite (5) as

$$y_{\text{Re}}(t) = RP_{\text{tx}}\mu h'_{11} x_{\text{Re}}(t) + n_{\text{Re}}(t), \tag{8}$$

$$y_{\text{Im}}(t) = RP_{\text{tx}}\mu h'_{22} x_{\text{Im}}(t) + n_{\text{Im}}(t). \tag{9}$$

In order to balance the powers of the received Re and Im parts, $y_{\text{Re}}(t)$ and $y_{\text{Im}}(t)$ are normalized in power. The obtained Re and Im parts after PN can be represented by

$$\tilde{y}_{\text{Re}}(t) = x_{\text{Re}}(t) + \frac{n_{\text{Re}}(t)}{RP_{\text{tx}}\mu h'_{11}}, \tag{10}$$

$$\tilde{y}_{\text{Im}}(t) = x_{\text{Im}}(t) + \frac{n_{\text{Im}}(t)}{RP_{\text{tx}}\mu h'_{22}}. \tag{11}$$

Based on (10) and (11), the complex-valued OFDM signal can be recovered by combing $\tilde{y}_{\text{Re}}(t)$ and $\tilde{y}_{\text{Im}}(t)$ together in a RIC

$$\tilde{y}(t) = \tilde{y}_{\text{Re}}(t) + j \times \tilde{y}_{\text{Im}}(t) = x(t) + \frac{n(t)}{RP_{\text{tx}}\mu h'_{11} h'_{22}}, \tag{12}$$

where $n(t) = h'_{22} n_{\text{Re}}(t) + j \times h'_{11} n_{\text{Im}}(t)$ is the generated complex-valued additive noise. As per (12), the SNR of the recovered complex-valued OFDM signal in the 2×2 SDM-VLC system using a modified ImR can be calculated by

$$SNR = \frac{(RP_{\text{tx}}\mu h'_{11} h'_{22})^2 \sigma_x^2}{\sigma_n^2}, \tag{13}$$

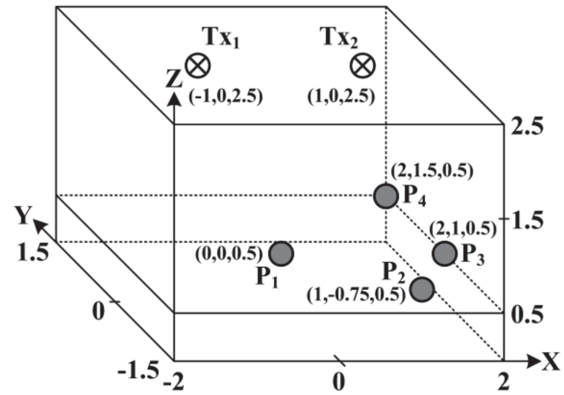

Fig. 2. Geometric set-up of the considered indoor 2 × 2 SDM-VLC system.

where σ_x^2 is the variance of the transmitted complex-valued OFDM signal and σ_n^2 is the variance of the generated complex-valued additive noise. For the 2×2 SDM-VLC system using a conventional ImR, the corresponding SNR can also be calculated by (13) except that h'_{11} and h'_{22} should be replaced by h_{11} and h_{22}, respectively. The BER expression of an OFDM signal using general $I\times J$ rectangular QAM mapping over an AWGN channel can be approximated by [23]

$$BER=\frac{2}{\log_2(I\times J)}\left(\frac{I-1}{I}+\frac{J-1}{J}\right)Q\left(\sqrt{\frac{6\times SNR}{I^2+J^2-2}}\right),\quad(14)$$

where $Q(\cdot)$ is the Q-function. Substituting (13) into (14) yields the analytical BER expression of the 2×2 SDM-VLC system using NHS-OFDM with a modified ImR.

IV. Performance Evaluation and Comparisons

Based on the analytical BER expression derived in Section III, we examine the performance of an indoor 2×2 SDM-VLC system using NHS-OFDM with a modified ImR. Monte Carlo simulations are performed to verify the validity of the analytical derivation. We compare the performance of the indoor 2×2 SDM-VLC system using NHS-OFDM with a modified ImR with the system using HS-OFDM with a conventional ImR, in terms of BER and communication coverage. It should be noted that, even though a simple 2×2 SDM-VLC setup is examined in detail, the following obtained results are applicable to general indoor SDM-VLC systems.

A. BER

Fig. 2 shows the geometric set-up of the considered indoor 2×2 SDM-VLC system in a typical $4\text{m}\times 3\text{m}\times 2.5\text{m}$ room. The detailed parameters of the set-up in Fig. 2 are given in Table I. The coordinates of the floor center are set to $(0,0,0)$ and the units of all the coordinates are meters. The two LED lamps are located at $(-1,0,2.5)$ and $(1,0,2.5)$ in the ceiling, respectively. The receiving plane is 0.5 m above the floor and four receiver positions P_1, P_2, P_3 and P_4 in the receiving plane are considered for BER performance evaluation, as shown in Fig. 2. In the analysis, the modulation index is set to 0.2 and the responsivity of the PD is set to 1 A/W. The transmitter semi-angle at half power and the FOV of the concentrator are $60°$ and $120°$, respectively. The active area of the PD is set to 1 cm^2 and the distance between two PDs is assumed to be 1 cm. The other parameters of the considered SDM-VLC system can be found in [22]. For both NHS-OFDM and HS-OFDM, the IFFT size is set to 128. Using a bandwidth of 50 MHz and 64QAM (8×8 rectangular QAM) mapping, the achievable data rate of the considered 2×2 SDM-VLC system using either NHS-OFDM or HS-OFDM is 300 Mb/s.

TABLE I
Set-Up Parameters

Parameter	Value
Room size (length × width × height)	4 m × 3 m × 2.5 m
Locations of two LEDs	(-1, 0, 2.5), (1, 0, 2.5)
Height of receiver plane	0.5 m
Transmitter semi-angle at half power	60°
Modulation index	0.2
FOV of concentrator	120°
Active area of PD	1 cm^2
Responsivity of PD	1 A/W
Data rate	300 Mb/s

Fig. 3 shows the detailed BER performance comparison of the considered indoor 2×2 SDM-VLC system using two different modulation techniques and two different types of receivers for four receiver positions in the receiving plane. The markers in Fig. 3 show the simulation results, while the lines give the analytical results. As can be seen, the simulation results agree very well with the analytical results, thus validating the theoretical analysis in Section III. When the receiver is located at P_1 $(0,0,0.5)$ which is the center of the receiving plane, as shown in Fig. 3(a), the conventional ImR based NHS-OFDM and HS-OFDM have the same BER performance and they both require a transmitted optical power per LED lamp of 3.3 W to achieve a BER of 10^{-3}. Moreover, the modified ImR based NHS-OFDM and HS-OFDM also achieve the same BER performance and the required transmitted optical power of each LED lamp to achieve $\text{BER}=10^{-3}$ is 2.9 W, indicating an optical power reduction of 0.4 W by replacing the conventional ImR with the modified ImR at the center of the receiving plane. When the receiver is moved away from the center to P_2 $(1,-0.75,0.5)$, P_3 $(2,1,0.5)$ and P_4 $(2,1.5,0.5)$, as shown in Figs. 3(b), (c) and (d), NHS-OFDM outperforms HS-OFDM employing either a conventional ImR or a modified ImR. Furthermore, for both NHS-OFDM and HS-OFDM, the modified ImR based system achieves much better BER performance than the conventional ImR based system for all four receiver positions. It can be clearly seen that the best BER performance is achieved by using NHS-OFDM with a modified ImR. More specifically, when the receiver is located at P_4 $(2,1.5,0.5)$, i.e. the corner of

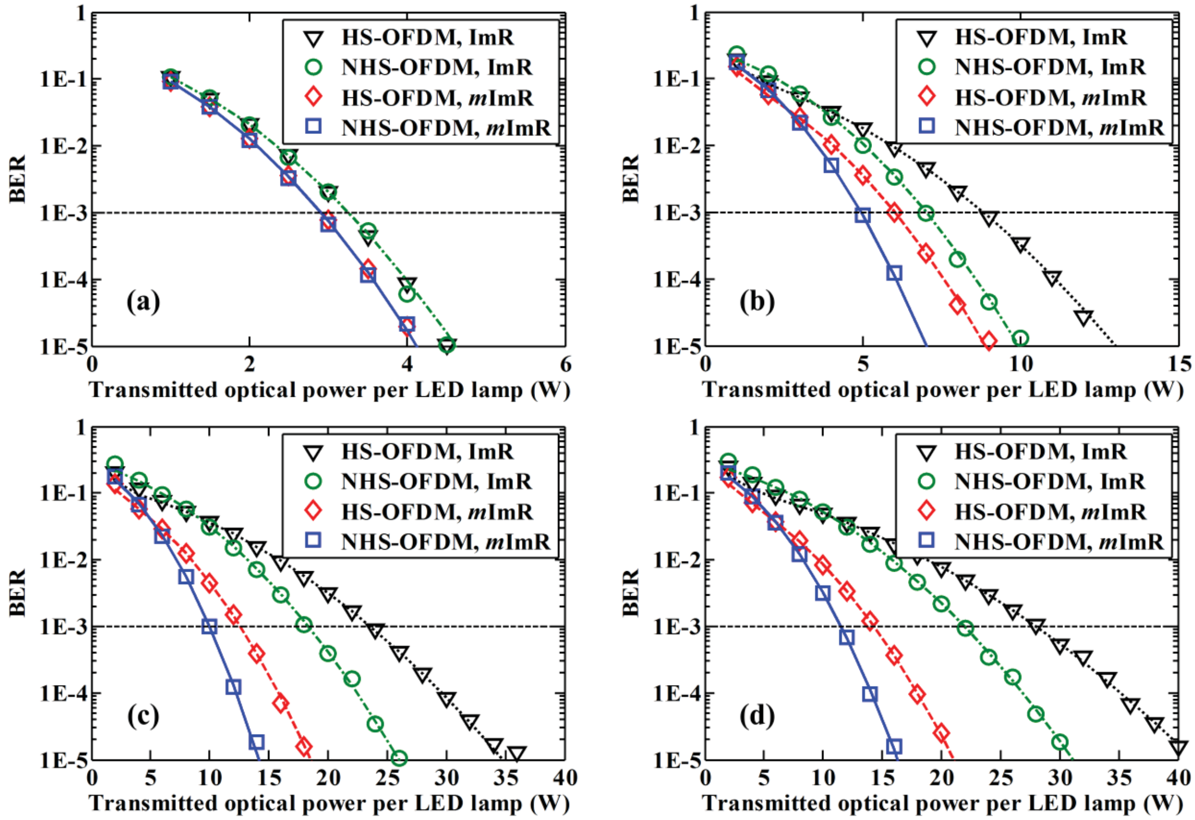

Fig. 3. BER performance comparison of HS-OFDM with a conventional ImR, NHS-OFDM with a conventional ImR, HS-OFDM with a modified ImR (*m*ImR) and NHS-OFDM with a *m*ImR in the 2×2 SDM-VLC system for four receiver positions: (a) P_1 (0, 0, 0.5), (b) P_2 (1, -0.75, 0.5), (c) P_3 (2, 1, 0.5) and (d) P_4 (2, 1.5, 0.5). Markers show the simulation results and lines give the corresponding analytical results.

the receiving plane, the required transmitted optical power per LED lamp for the modified ImR based NHS-OFDM to achieve a BER of 10^{-3} is 11.4 W. Compared with the conventional ImR based HS-OFDM and NHS-OFDM, and the modified ImR based HS-OFDM, the modified ImR based NHS-OFDM achieves transmitted optical power reductions of 58.99%, 48.18% and 20.28%, respectively. Therefore, indoor 2×2 SDM-VLC system using NHS-OFDM with a modified ImR achieves significantly improved BER performance than the system using HS-OFDM with a conventional ImR.

B. Communication coverage

Fig. 4 compares the communication coverage of the indoor 2×2 SDM-VLC system using two different modulation techniques and two different types of receivers for a target BER of 10^{-3} around the receiving plane. For a transmitted optical power per LED lamp of 6 W, the communication coverage of the indoor 2×2 SDM-VLC system using the conventional ImR based HS-OFDM is the smallest as covered by the black dotted line shown in Fig. 4(a). By replacing HS-OFDM with NHS-OFDM, the communication coverage of the indoor 2×2 SDM-VLC system using a conventional ImR is slightly increased along the X direction while coverage along the Y direction remains the same, as shown by the green dot-dash line in Fig. 4(a). However, when a modified ImR is employed in the indoor 2×2 SDM-VLC system, the communication coverage is significantly increased along both the X and Y directions, for both HS-OFDM and NHS-OFDM. Moreover, when the transmitted optical power per LED lamp is increased to 8 W, as shown in Fig. 4(b), the communication coverage of the indoor 2×2 SDM-VLC system is further greatly improved along both the X direction and the Y direction around the receiving plane.

As a result, the most easy and direct way to improve the communication coverage of an indoor SDM-VLC system is to increase the transmitted optical power of each LED lamp. However, when the transmitted optical power of each LED lamp is fixed for the indoor SDM-VLC system which is quite common in most of the practical indoor environments, the communication coverage of the indoor SDM-VLC system can still be substantially improved by employing the proposed NHS-OFDM scheme together with a modified ImR.

V. Conclusion

We have proposed two novel techniques to substantially improve the communication coverage of indoor SDM-VLC systems, including a NHS-OFDM scheme and a modified ImR. The performance of an indoor 2×2 SDM-VLC system using NHS-OFDM with a modified ImR has been investigated through both theoretical analysis and Monte Carlo simulations. The obtained analytical and simulation results show that, compared with the indoor 2×2 SDM-VLC system using HS-OFDM with a conventional ImR, a significant communication coverage improvement (for a target BER of 10^{-3}) can be achieved by using the NHS-OFDM scheme

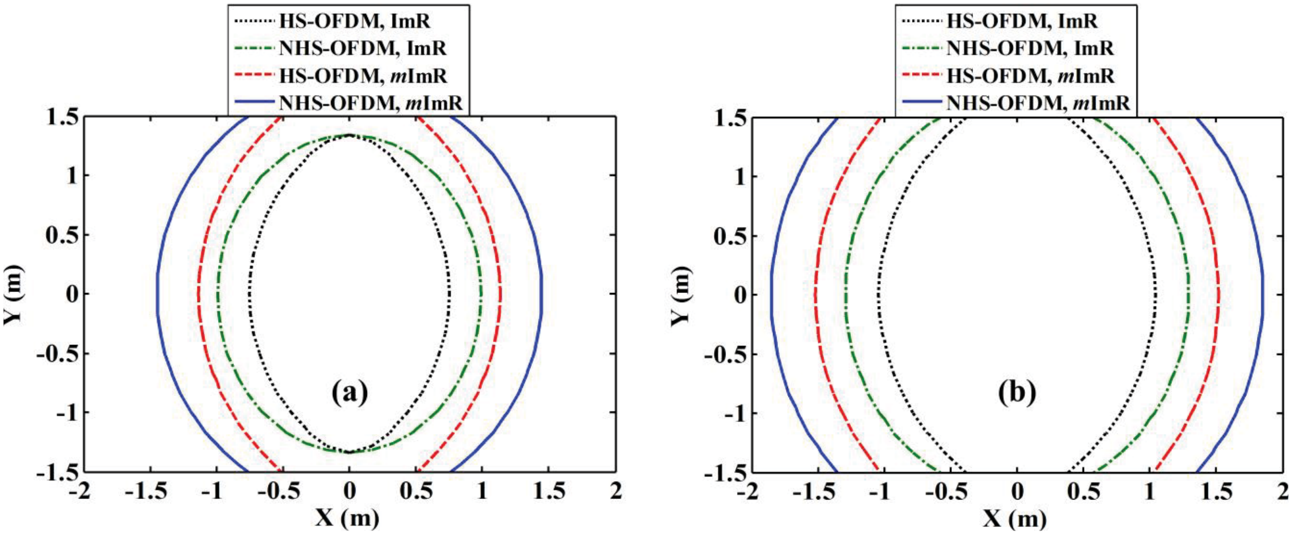

Fig. 4. Communication coverage comparison of HS-OFDM with a conventional ImR, NHS-OFDM with a conventional ImR, HS-OFDM with a modified ImR (*m*ImR) and NHS-OFDM with a *m*ImR for a target BER of 10^{-3} with a transmitted optical power per LED lamp of (a) 6 W and (b) 8 W.

together with a modified ImR. In conclusion, the NHS-OFDM scheme and the modified ImR are two promising techniques that can effectively improve the communication coverage of future indoor SDM-VLC systems.

In this paper, the concept of a modified ImR is proposed for the first time, which has been applied in an indoor 2×2 SDM-VLC system to improve its communication coverage together with the NHS-OFDM scheme. Our future work will focus on the structure design and the practical implementation of such a modified ImR for future indoor SDM-VLC systems.

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