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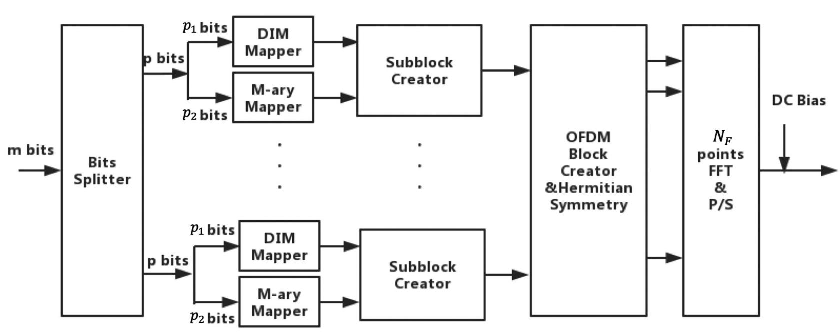

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OFDM With Differential Index Modulation for Visible Light Communication

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Abstract: In this paper, orthogonal frequency division multiplexing with differential index modulation (OFDM-DIM) is proposed for visible light communication. Compared with traditional OFDM with index modulation (OFDM-IM), the proposed scheme decreases the average number of used subcarriers when transmits the same amount of information bits, therefore higher spectral efficiency can be achieved. The simulation results present that OFDM-DIM can provide higher data transmission rate and lower bit error rate (BER) over additive white gaussian noise (AWGN) optical channel. Meanwhile, simulations over reference channels of short range optical wireless communication are implemented, where OFDM-DIM performances better than OFDM-IM when line-of-sight (LOS) components are dominant.

Index Terms: Differential index modulation, optical wireless communication, spectral efficiency.

1. Introduction

As the demands of high speed wireless communication grow rapidly and available bandwidth becomes scarce, visible light communication (VLC) technology brings a surge of interest on account of its unlimited modulation bandwidth [1]. To enhance the spectral efficiency of the communication system, orthogonal frequency division multiplexing (OFDM), as a kind of digital multi-carrier modulation, has been widely used in wireless communication. While in VLC systems, the transmitted signals must be real and positive due to intensity modulation and direct detection (IM/DD), thus modulation schemes for VLC, such as direct current biased optical OFDM (DCO-OFDM), are proposed [2].

Index modulation (IM) has attracted researchers' attention for years and is considered as a novel and competitive scheme for next-generation wireless communication. IM utilizes additional dimensions to convey information by using the on/off status of the transmission entities (antennas, subcarriers, time slots, etc.) over time domain, spatial domain or frequency domain. For instance, in spatial modulation schemes of visible light communication, indices of the activated light emitting diodes (LED) represent additional transmitted bits. Besides, OFDM with index modulation (OFDM-IM) divides all subcarriers into several subblocks, and activates only part of the subcarriers in each subblock [3]. Therefore, information can be transmitted not only by the activated subcarriers, but also by the indices of the activated subcarriers in each subblock. OFDM-IM can be regarded

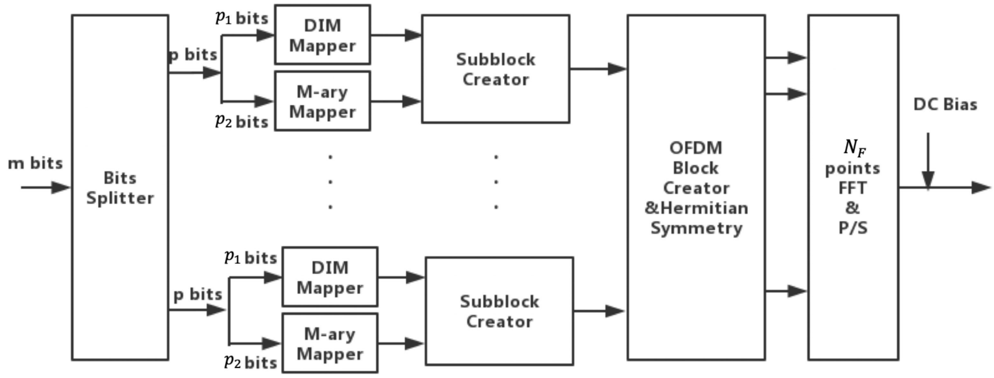

Fig. 1. OFDM-DIM transmitter structure.

as a combination of traditional OFDM and multiple pulse position modulation (MPPM) scheme in frequency domain, where more than one subcarrier (position) can be activated in each subblock and the number of activated subcarriers in one subblock is fixed [4].

Different from OFDM-IM, OFDM-DIM proposed in this paper preserves the concept of subblocks, but reduces the average number of the used subcarriers for each subblock. This scheme can be seen as combining OFDM with differential multiple pulse position modulation (DMPPM) scheme, where a new subblock begins immediately after all subcarriers carrying non-zero signals of the previous subblock [5]. Similarly, additional information can be transmitted by indices of the subcarriers selected in each subblock. However, the length of each subblock is different and is decided by the mapping relationship between information bits and indices of selected subcarriers. In OFDM-DIM, the non-activated subcarriers at the end of each subblock are removed, resulting in a decrease in the number of idle subcarriers. Therefore, compared with OFDM-IM, the proposed OFDM-DIM has a higher spectral efficiency.

In the previous studies, channels of short range visible light communication are usually modeled by additive white gaussian noise (AWGN) optical channel, where only LOS channel exists [6]. In this paper, the proposed OFDM-DIM scheme shows a better performance of bit error rate (BER) over AWGN optical channel. In our system, DCO-OFDM is utilized, since it is a common inplemmented visible light communication technique with the advantages of higher spectrum efficiency and low complexity among VLC modulation schemes [2]. To test the reliability of the proposed OFDM-DIM scheme, we also build simulations over channel models of IEEE 802.15.7r1 [7]. The simulated results present that OFDM-DIM performs better than traditional OFDM-IM when LOS channels effects are dominant.

The rest of this paper is organized as follows. The system model of the proposed OFDM-DIM is described in Section 2. In Section 3, performance analysis of spectral efficiency and BER are presented. Simulation results are shown in Section 4. Finally, conclusion is provided in Section 5.

2. OFDM-DIM System Model

We consider DCO-OFDM as the modulation scheme in this paper for its advantages of higher spectrum efficiency and low complexity among VLC modulation schemes. Suppose there are N_F points for Fast Fourier Transform (FFT), thus $N_F/2-1$ subcarriers are available to carry information. For the i_{th} OFDM block, m_i incoming bits are modulated by OFDM-DIM scheme. The transmitter structure of the proposed OFDM-DIM for visible light communication system is depicted in Fig. 1. The information bits are split into G groups, and bits of each group are carried within one subblock in frequency domain. Each group containing $p = p_1 + p_2$ bits, where p_1 is the number of information

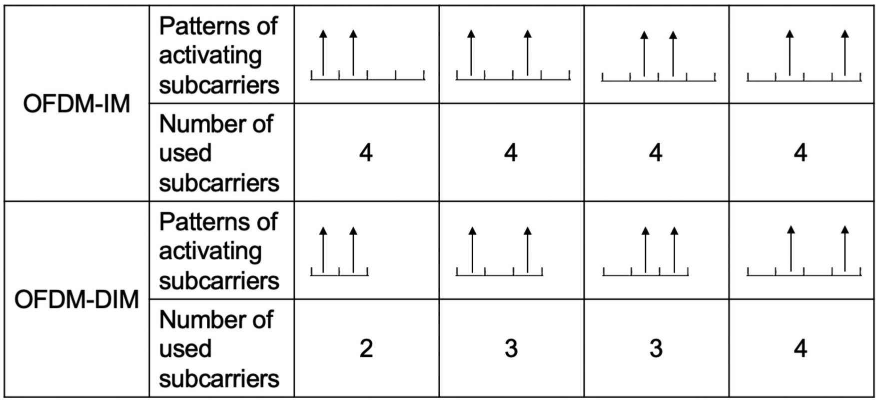

Fig. 2. An example of subcarriers selection in OFDM-IM scheme and OFDM-DIM scheme.

bits conveyed by indices of activated subcarriers, and p_2 represents the number of bits transmitted by M-ary constellations. The length of each subblock is not fixed and is decided by the mapping relationship between transmitted information bits and the indices of selected subcarriers. Each mapper in OFDM-DIM scheme has a corresponding counterpart in OFDM-IM scheme, and Fig. 2 illustrates an example. The mapper in OFDM-DIM can be attained by removing the continuous non-activated subcarriers at the end of the subblock in the corresponding OFDM-IM scheme. Thus, the average length of subblocks can be reduced and more bits can be transmitted by one OFDM block. Suppose the size of subblocks in OFDM-IM scheme is N, and the number of activated subcarriers in one subblock is K. In this case,

$$p_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor, \tag{1}$$

$$p_2 = K \log_2(M), \tag{2}$$

where $\binom{N}{K}$ stands for the number of a K-combination of a set with N elements, and $\lfloor\cdot\rfloor$ indicates rounding down operation. There are $n_l = 2^{p_1}$ different index patterns, where all the patterns are given by

$$\mathcal{I} = \left\{ \boldsymbol{I}_1, \boldsymbol{I}_2, \ldots, \boldsymbol{I}_{n_l} \right\}. \tag{3}$$

The length of each index pattern is defined as the set

$$\mathcal{L} = \left\{ l_1, l_2, \ldots, l_{n_l} \right\}. \tag{4}$$

With regard to each index pattern, there are $n_Q = 2^K$ distinctive signals, which can be represented by

$$\mathcal{S}_{I_i} = \left\{ \boldsymbol{S}_{I_i}^1, \boldsymbol{S}_{I_i}^2, \ldots, \boldsymbol{S}_{I_i}^{n_Q} \right\}. \tag{5}$$

The length of $\boldsymbol{S}_{I_i}^j\,(j \in \{1, 2, \ldots, n_Q\})$ vector is no more than N, and is determined by the DIM mapper. As shown in Table 1, an example of mapper in OFDM-DIM scheme and mapper in OFDM-IM scheme are compared, where $N = 4$ and $K = 2$. Thus, $p_1 = \lfloor \log_2 \binom{4}{2} \rfloor = 2$ and $p_2 = K \log_2(2) = 2$. Both schemes transmit 4 bits by one subblock when Binary Phase Shift Keying (BPSK) is used, where two of them are sent by indices and others are sent by BPSK. Since $p_1 = 2$ bits should be transmitted through indices of activated subcarriers in each subblock, $2^{p_1} = 4$ combinations of subcarrier-activation are required. Although there exists $\binom{N}{K} = 6$ available combinations, only 4 of them are needed to convey $p_1 = 2$ bits. In this example, 4 combinations (1100, 1010, 0110, 0101) are selected to achieve a higher spectrum efficiency. Other selective ways are allowed as well, and may result in different spectrum efficiency of the modulation scheme. By removing the last few

TABLE 1
Mapper in OFDM-IM and OFDM-DIM With $K = 2$ and $N = 4$

information bits	activated subcarriers in OFDM-IM	activated subcarriers in OFDM-DIM
$[0\ \ 0]$	$[1\ \ 1\ \ 0\ \ 0]$	$[1\ \ 1]$
$[0\ \ 1]$	$[1\ \ 0\ \ 1\ \ 0]$	$[1\ \ 0\ \ 1]$
$[1\ \ 0]$	$[0\ \ 1\ \ 1\ \ 0]$	$[0\ \ 1\ \ 1]$
$[1\ \ 1]$	$[0\ \ 1\ \ 0\ \ 1]$	$[0\ \ 1\ \ 0\ \ 1]$

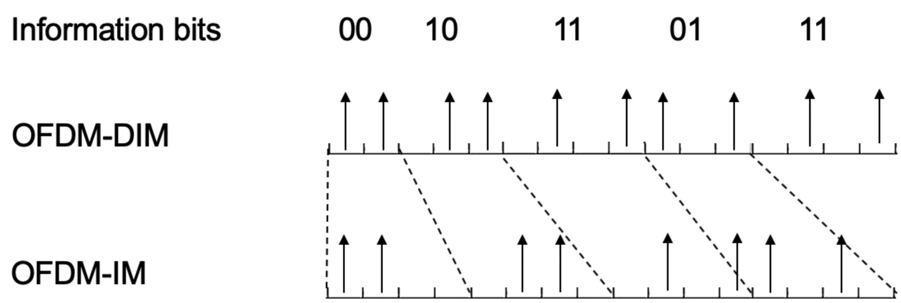

Fig. 3. An example of different subcarrier-selection strategies by using OFDM-DIM scheme and OFDM-DIM scheme.

non-activated subcarriers, the average size of subblocks in OFDM-DIM scheme is less than that in OFDM-IM scheme. Therefore, OFDM-DIM can transmit more subblocks and more information bits than OFDM-IM in one OFDM block. Fig. 3 shows an example of different subcarrier-selection strategies by using OFDM-DIM scheme and OFDM-IM scheme, respectively. In this example, we assume that there are 16 subcarriers in the system. For OFDM-IM scheme, information bits are carried by 4 subblocks, and each subblock can convey 4 bits (2 bits carried by indices of the activated subcarriers in one subblock, 2 bits carried by BPSK-modulation scheme). While for OFDM-DIM scheme, information bits are carried by 5 subblocks, and each subblock can convey 4 bits as well. Therefore, OFDM-DIM can convey more information bits than OFDM-IM by using the same number of subcarriers. And the advantage of OFDM-DIM is not limited in this single example. Based on law of large numbers, the probability of each combination is equal. Thus, the average length of subblocks is 3 in OFDM-DIM scheme. Compared with OFDM-IM, OFDM-DIM can convey more information bits when the same number of subcarriers are available.

Since DCO-OFDM is introduced in our system, $N_F/2 - 1$ subcarriers are available to transmit data. After Hermitian symmetry and Inverse Fast Fourier Transform (IFFT), adding DC bias, the resulting signals can be represented as $\boldsymbol{x}_t$. We assume that AWGN optical channel is introduced in the system, thus the received signal becomes

$$\boldsymbol{y}_t = \boldsymbol{x}_t * \boldsymbol{h}_t + \boldsymbol{n}_t, \tag{6}$$

where $\boldsymbol{h}_t$ represents channel impulses response and $\boldsymbol{n}_t$ is gaussian noise with distribution of $\mathcal{CN} \sim (0, N_0)$. De-modulation operations at the receiver are reversal of modulation operations, including FFT, DIM de-mapping and detection. After FFT and equalization operation, the complex signals in frequency domain for one OFDM block is given as $\boldsymbol{Y} = \{Y_1, Y_2, \ldots, Y_{N_F/2-1}\}$. Maximum likelihood (ML) based detector is used to figure out the activated subcarriers pattern. For the subblock starts from the m_{th} subcarrier, the retrieved information bits can be calculated by minimizing the distance between the transmitted symbols and the received symbols

$$\left\{ \boldsymbol{l}_i, \boldsymbol{S}^j_{\boldsymbol{l}_i} \right\} = \underset{l_i \in \mathcal{I}, \boldsymbol{S}^j_{l_i} \in \mathcal{S}_{l_i}}{\arg\min} \frac{1}{l_i} \sum_{l_i \in \mathcal{L}} \left| (Y_m, \ldots, Y_{m+l_i}) - \boldsymbol{S}^j_{\boldsymbol{l}_i} \right|^2. \tag{7}$$

Then, the corresponding information bits are retrieved according to the OFDM-DIM and BPSK mapper subblock by subblock. By doing the same de-modulation operations for all OFDM blocks, all data streams are derived.

3. Performance Analysis of OFDM-DIM

3.1 Spectral Efficiency

The spectral efficiency of the proposed OFDM-DIM scheme for DCO-OFDM based visible light communication system can be formulated as [4]

$$\eta_{DCO-OFDM-DIM} = \frac{G \cdot \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + log_2(M) \cdot K \right)}{N_F/2 - 1}, \tag{8}$$

where G represents the number of subblocks in one OFDM block. As subblock size is variable in OFDM-DIM scheme, the number of subblocks in a specific OFDM block depends on the transmitted bits. However, we can estimate G by formula

$$G \approx \frac{N_F/2 - 1}{\bar{l}}, \tag{9}$$

where N_F represents the number of FFT size, and $\bar{l}$ represents the average length of subblocks. For example, if $N = 4$, $K = 2$ and $N_F = 128$ are set for both OFDM-IM and OFDM-DIM, and the corresponding mapper of OFDM-DIM is shown in Table 1, then $\bar{l} = 3$ based on law of large numbers and equal probability principle. According to formula (8), when BPSK is used, spectral efficiency of OFDM-DIM equals to $\eta_{OFDM-DIM} \approx 1.313$, while that of OFDM-IM scheme for DCO-OFDM based visible light communication system equals to $\eta_{DCO-OFDM-IM} \approx 0.984$. As can be seen, OFDM-DIM sheme reduces the average length of subblocks and enhances the spectral efficiency of VLC system.

3.2 Bit Error Probability

In OFDM-DIM scheme, information bits are transmitted through indices of activated subcarriers and the carried OFDM symbols. The received OFDM symbols in frequency domain within one subblock can be expressed as

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{h} + \boldsymbol{w}. \tag{10}$$

Suppose the length of the subblock is l, $\boldsymbol{X}$ is a $l \times l$ diagonal matrix whose diagonal elements are defined as $[x(1), \ldots, x(l)]^T$, $\boldsymbol{h} = [h(1), \ldots, h(l)]^T$, $\boldsymbol{y} = [y(1), \ldots, y(l)]^T$, and $\boldsymbol{w} = [w(1), \ldots, w(l)]^T$ is gaussian noise with distribution of $\mathcal{CN} \sim (0, N_0)$. The channel frequency response $\boldsymbol{h}$ can be described by its mean and covariance matrix

$$\boldsymbol{K_n} = \boldsymbol{E}\{\boldsymbol{h}\boldsymbol{h}^{\boldsymbol{H}}\}, \tag{11}$$

where $rank(\boldsymbol{K_n}) < l$. The corresponding received symbols can be defined by $\hat{\boldsymbol{X}}$, and the ML detector can make errors on both indices and OFDM constellations. The conditioned pairwise error probability (CPEP) is given by [8]

$$P(\boldsymbol{X} \rightarrow \hat{\boldsymbol{X}} | \boldsymbol{h}) = Q\left(\frac{\|(\boldsymbol{X} - \hat{\boldsymbol{X}})\boldsymbol{h}\|_F}{\sqrt{N_0/2}} \right), \tag{12}$$

where $Q(\cdot)$ is the Gaussian Q-function, $\|\cdot\|_F$ denotes the F-norm. Defining matrix A as

$$\boldsymbol{A} = (\boldsymbol{X} - \hat{\boldsymbol{X}})^H(\boldsymbol{X} - \hat{\boldsymbol{X}}), \tag{13}$$

then the CPEP can be expressed as

$$P(\boldsymbol{X} \rightarrow \hat{\boldsymbol{X}}|\boldsymbol{h}) = Q(\sqrt{\frac{\boldsymbol{h}^H\boldsymbol{A}\boldsymbol{h}}{2N_0}}). \tag{14}$$

$Q(x)$ can be approximated by [9]

$$Q(x) \approx \frac{1}{12}e^{-x^2/2} + \frac{1}{4}e^{-2x^2/3}. \tag{15}$$

Therefore, the unconditional pairwise error probability (UPEP) is given as

$$P(\boldsymbol{X} \rightarrow \hat{\boldsymbol{X}}) \approx \boldsymbol{E}_h\left\{\frac{1}{12}e^{-\frac{h^HAh}{4N_0}} + \frac{1}{4}e^{-\frac{h^HAh}{3N_0}}\right\}. \tag{16}$$

According to [3], the expectation can be calculated by spectral theorem, then the UPEP can be calculated as

$$P(\boldsymbol{X} \rightarrow \hat{\boldsymbol{X}}) \approx \frac{1}{12\mathbf{det}\left(\boldsymbol{I}_n + \frac{1}{4N_0}\boldsymbol{K}_n\boldsymbol{A}\right)} + \frac{1}{4\mathbf{det}\left(\boldsymbol{I}_n + \frac{1}{3N_0}\boldsymbol{K}_n\boldsymbol{A}\right)}. \tag{17}$$

The average bit error probability is given by

$$P_b \approx \frac{1}{pn_X}\sum_{X}\sum_{\hat{X}} P\left(\boldsymbol{X} \rightarrow \hat{\boldsymbol{X}}\right) e\left(\boldsymbol{X}, \hat{\boldsymbol{X}}\right), \tag{18}$$

where p represents the number of transmitted bits within one subblock, n_X is the possible realizations of $\boldsymbol{X}$, and $e(\boldsymbol{X}, \hat{\boldsymbol{X}})$ denotes the number of bit errors introduced by the corresponding pairwise error event.

4. Simulation Results

In this Section, BER performances of OFDM-DIM system over different channels are simulated and compared with OFDM-IM system. In the simulations, $N_F = 128$, mapping principles of OFDM-IM and OFDM-DIM are shown in Table 1, and BPSK is used in the systems. The demodulation process contains two steps:

1) Figure out the beginning of all subblocks and the indices of the activated subcarriers.
2) Apply BPSK-demodulation of the activated subcarriers.

As the performance of OFDM-DIM highly depends on the results of subblock-recognition, we add parity symbols to alleviate error propagation. Simulation results over AWGN channel are presented in Fig. 4. When E_b/N_0 is low ($E_b/N_0 < 4$ dB), the error probability of recognizing parity symbols increases, thus the BER performance of the system becomes worse. And this may lead to the simulation results that OFDM-DIM does not outperform OFDM-IM with low E_b/N_0. However, the simulation results show that OFDM-DIM has a better BER performance than conventional OFDM-IM when $E_b/N_0 > 4$ dB. In addition, the spectral efficiency of OFDM-IM system is 0.984 and that of OFDM-DIM is 1.313. Therefore, the results indicates that the proposed OFDM-DIM provides a higer spectral efficiency and lower BER than OFDM-IM over AWGN optical channel.

The IEEE has established the the standardarlization of short rangle optical wireless communication, and reference channel models are developed. Therefore, we also implement simulations over part of these reference VLC channel models and compare the performance of the proposed OFDM-DIM scheme and traditional OFDM-IM scheme. Four scenarios of indoor VLC are discussed and the corresponding channel impulses responses (CIRs) are provided [7], [10]. In this paper, we implement simulations over the reference channels of work place, office room with secondary light and living room scenarios. Fig. 5 depicts the simulation results over channels of Scenario 1

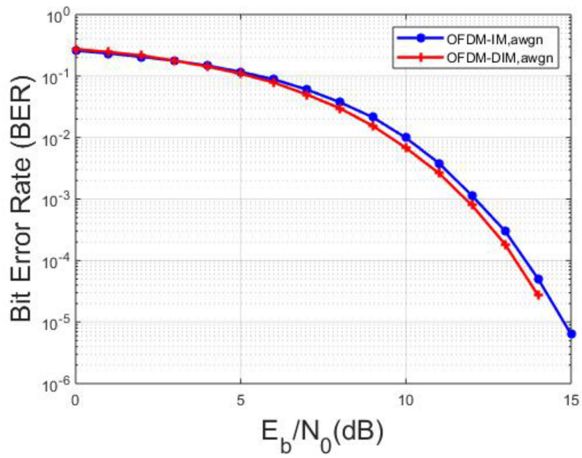

Fig. 4. BER vs. E_b/N_0 over AWGN optical channel model.

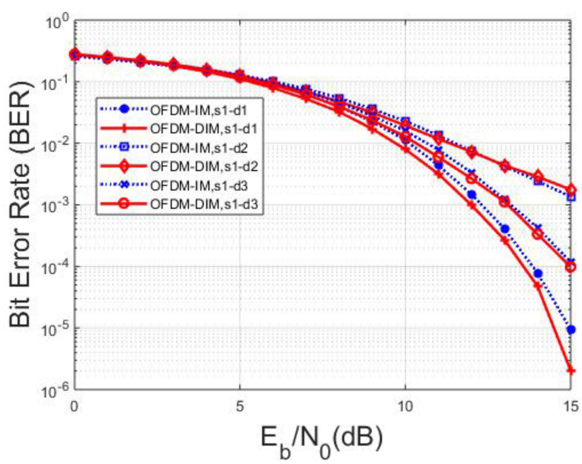

Fig. 5. BER vs. E_b/N_0 over reference VLC channel models of Scenario 1.

(workplace). There are twenty four different locations of receivers in Scenario 1, and we do simulations over all the channels. The channel impulse response of each channel will affect the BER performance of both OFDM-DIM and OFDM-IM scheme. According to the simulation results, we choose three typical channels (PD locations at d1, d2 and d3) in Scenario 1 to be displayed in Fig. 5, as the BER performance results of these situations can represent others. The specific locations are shown in Reference [10]. As can be seen, OFDM-DIM scheme is better than OFDM-IM in terms of BER performance, while the spectral efficiency of OFDM-DIM is also higher. However, when multi-path components become more obvious, such as situation when the detector is at d2 point, the performance of the proposed OFDM-DIM scheme deteriorates. For Scenario 2, the simulation results demonstrated in Fig. 6 illustrate that OFDM-DIM scheme provides lower BER over all reference channel models in office room with secondary light.

By compressing the average size of subblocks, the proposed OFDM-DIM scheme enables more information bits to be transmitted using the same bandwidth. Thus, the energy needed for each bit becomes less, leading to a lower bit error rate. But when multi-path components impact significantly, OFDM-DIM performances worse since it is more vulnerable to inter-symbol inteference. Solutions to the problem can be discovered in further research.

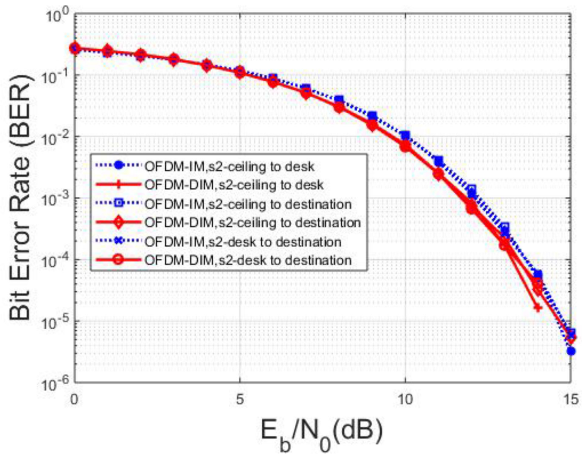

Fig. 6. BER vs. E_b/N_0 over reference VLC channel models of Scenario 2.

5. Conclusion

In this paper, a modulation scheme called OFDM-DIM is proposed and tested by simulations over AWGN optical channel and reference VLC channel models. OFDM-DIM scheme decreasess the average length of subblocks, thus enhances the spectral efficiency of the system. This paper illustrates simulations of OFDM-DIM and OFDM-IM scheme over VLC channels. The results show that the proposed OFDM-DIM scheme performances better than conventional OFDM-IM scheme in terms of BER when LOS components are dominant.

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