# Optical OFDM with Index Modulation for Visible Light Communications

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***Abstract*—In this paper, we propose optical orthogonal frequency division multiplexing with index modulation (O-OFDM-IM) for visible light communications (VLC) systems employing light emitting diodes (LEDs) and photodetectors (PDs). The proposed scheme uses the indices of the active subcarriers of an optical OFDM system to transmit additional information bits. In the proposed scheme, the bipolar signals are asymmetrically clipped or DC biased and a log-likelihood ratio (LLR) calculation based detector is used to determine the indices of the active subcarriers. Our computer simulations show that the O-OFDM-IM achieves better error peformance compared to classical optical OFDM schemes.**

## I. INTRODUCTION

The increasing demand for higher data rates and network capacity from next generation wireless communications systems lead the researchers to investigate the new parts of the frequency spectrum as an alternative to radio frequency (RF) bands for high-speed transmission of the digital data. One of the main reasons for this evolution is the bottleneck in which RF based wireless communications has arrived [1]. Highly dense nature of the current RF spectrum and the interference caused by frequency reusing make the search for alternatives to RF communications inevitable. Visible light communications (VLC) is a promising new technology for next generation wireless communications systems due to its advantages over radio frequency (RF) based systems such as the operation in unregulated and very wide spectrum, no licensing requirements, low cost operation and less interference to RF sensitive devices. More importantly, since the VLC systems combine lighting and communications, the available lightning infrastructure can be used in VLC systems and there are no health concerns related to visible light once the eye safety is ensured. Therefore, VLC appears as a green technology for future wireless standards.

Light emitting diodes (LEDs) can be effectively used in indoor environments for both illumination and communications purposes. Therefore, a VLC system can be easily implemented with LEDs and photodiodes (PDs) by using intensity modulation and direct detection (IM/DD). The major difference between RF based and VL communications systems is the nature of the transmitted signals. In RF based systems, transmitted signals can be complex and bipolar; however, for IM/DD based VLC systems they must be real and positive since the intensity of the LEDs are modulated. Therefore, only real modulation formats such as on-off keying (OOK) and pulse amplitude modulation (PAM) are directly suitable for VLC systems. On the other hand, due to the intersymbol interference caused by increasing transmission rates, the use of more robust technqiues such as orthogonal frequency division multiplexing (OFDM) [2] becomes a necessity. However, the complex form of OFDM signals has been the major design challenge for VLC-OFDM systems and different approaches have been adopted to modify the classical OFDM for VLC systems. In these modified systems, Hermitian symmetry is applied in the frequency domain to obtain real OFDM signals after inverse fast Fourier transform (IFFT) operation. To make the resulting signal positive, either a DC bias can be added on it as in the DC biased optical OFDM (DCO-OFDM) scheme or the signal can be clipped at zero level and only positive-valued signals are transmitted as in the asymmetrically clipped optical OFDM (ACO-OFDM) scheme, where both techniques have their advantages and disadvantages [3]. In order to solve the DC biasing problem of DCO-OFDM and to achieve higher spectral efficiency than ACO-OFDM, a unipolar OFDM scheme (U-OFDM) is proposed [4]. The U-OFDM scheme and the Flip-OFDM scheme proposed in [5] transform the real and bipolar OFDM signals into unipolar form for the transmission through optical wireless links.

OFDM with index modulation (OFDM-IM) is a novel OFDM scheme which transmits the information not only by the $M$-ary signal constellations, but also by the indices of the subcarriers, which are activated according to the corresponding information bits [6]. Compared to the classical OFDM, OFDM-IM provides an interesting trade-off between performance and spectral efficiency by the adjustment of the number of active subcarriers in the system. Therefore, the employment of OFDM-IM for VLC systems appears as an interesting and promising design problem.

In this paper, we propose optical OFDM-IM (O-OFDM-IM) as an alternative to the classical optical OFDM schemes. The proposed scheme uses the indices of the active subcarriers of an optical OFDM system to transmit additional information bits. The transceiver structure of the proposed scheme, which is based on asymmetrical clipping (AC) or DC biasing, is formulated and its error performance is evaluated via Monte Carlo simulations for realistic VLC channels. Our computer

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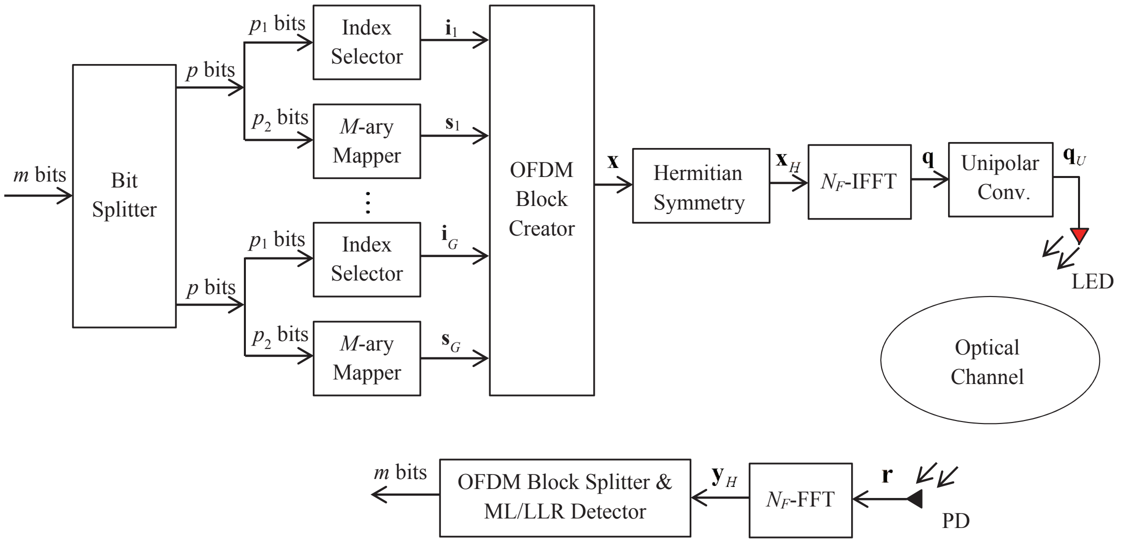


Fig. 1. Block Diagram of the O-OFDM-IM Transceiver

simulations indicate that O-OFDM-IM can be considered as an alternative to classical optical OFDM systems.

The rest of the paper is organized as follows. In Section II, the system model of O-OFDM-IM is given. Receiver structure of the O-OFDM-IM scheme is presented in Section III. Simulation results are provided in Section IV. Finally, conclusions are given in Section V.

*Notation*: Bold, lowercase and capital letters are used for column vectors and matrices, respectively. $(\cdot)^*$, $(\cdot)^T$ and $(\cdot)^H$ denote conjugation, transposition and conjugate transposition, respectively. $E\{\cdot\}$ stands for expectation. $C(N,K)$ stands for the binomial coefficient and $\lfloor\cdot\rfloor$ is the floor function. $\mathcal{S}$ denote $M$-ary signal constellations. $\mathbb{C}$ and $\mathbb{R}$ denotes the ring of complex and real numbers, respectively.

## II. SYSTEM MODEL OF OFDM-IM FOR VLC SYSTEMS

The block diagram of the O-OFDM-IM transceiver is given Fig. 1. As seen from Fig. 1, for the transmission of each OFDM block, a total of $m$ information bits enter the transmitter of the O-OFDM-IM scheme. These bits are split into $G$ groups each containing $p = p_1 + p_2$ bits, which are used to form OFDM subblocks of length

$$N = \begin{cases} (N_F/4)/G & \text{for AC} \\ (N_F/2-1)/G & \text{for DC biasing} \end{cases} \tag{1}$$

where $N_F$ is the size of the fast Fourier transform (FFT) and due to Hermitian symmetry requirement of optical OFDM, only $N_F/4$ and $N_F/2-1$ subcarriers are available for index selection and $M$-ary symbol transmission for AC and DC biasing, respectively. For each subblock $g$ $(g = 1, 2, \ldots, G)$, $K$ out of $N$ available subcarriers are activated by the index selector according to the corresponding

$$p_1 = \lfloor \log_2 (C(N,K)) \rfloor \tag{2}$$

bits, while the remaining $N-K$ subcarriers are inactive. For each subblock $g$, the selected active subcarrier indices are given by $\mathbf{i}_g = \left[i_1\ i_2 \cdots i_K\right]^T$, $g = 1, 2, \ldots, G$, where $i_k \in \{1, 2, \ldots, N\}$ for $k = 1, 2, \ldots, K$. This subcarrier index selection procedure can be performed either using a look-up table for smaller $N$ and $K$ values or using a one-to-one mapper based on combinatorial method, which maps natural numbers to $K$-combinations [6]. In Table I, an index selection example is provided for the look-up table method. As seen from Table I, for $N = 4$ and $K = 2$, the incoming $p_1 = 2$ bits can be used to select the indices of the two active subcarriers out of four available subcarriers according to a reference look-up table of size $R = 2^{p_1} = 4$. Since $C(4,2) = 6$, two out of six combinations are not considered in Table I. However, by the increasing number of information bits transmitted by the indices of the active subcarriers of the OFDM block, the use of a look-up table becomes infeasible; therefore, an effective technique based on combinatorial number theory is used to map the information bits to the subcarrier indices. A combinatorial method based index selection procedure can be performed for $N = 8$ and $K = 4$ as shown in Table II. As seen from Table II, a group of $p_1 = 6$ bits are converted from binary to decimal first, then this decimal number is given to the combinatorial algorithm to obtain the corresponding four $(K = 4)$ active indices [6], [7].

TABLE I
A LOOK-UP TABLE EXAMPLE FOR $N = 4, K = 2$ AND $p_1 = 2$

| $p_1$-*bits* | *Indices* $(\mathbf{i}_g^T)$ |
|---|---|
| [0 0] | [1 3] |
| [0 1] | [2 4] |
| [1 0] | [1 4] |
| [1 1] | [2 3] |

For each subblock, the remaining $p_2 = K(\log_2(M))$ bits of

TABLE II
AN INDEX SELECTION EXAMPLE FOR $N = 8, K = 4$ AND $p_1 = 6$

| $p_1$-*bits* | *Bin2Dec* | *Indices* ($\mathbf{i}_\beta^T$) |
|---|---|---|
| $[0\,0\,0\,0\,0\,0]$ | 0 | $[1\ 2\ 3\ 4]$ |
| $[0\,0\,0\,0\,0\,1]$ | 1 | $[1\ 2\ 3\ 5]$ |
| $[0\,0\,0\,0\,1\,0]$ | 2 | $[1\ 2\ 4\ 5]$ |
| $[0\,0\,0\,0\,1\,1]$ | 3 | $[1\ 3\ 4\ 5]$ |
| $\vdots$ | $\vdots$ | $\vdots$ |
| $[0\,1\,1\,1\,1\,1]$ | 31 | $[1\ 5\ 6\ 7]$ |
| $[1\,0\,0\,0\,0\,0]$ | 32 | $[2\ 5\ 6\ 7]$ |
| $\vdots$ | $\vdots$ | $\vdots$ |
| $[1\,1\,1\,1\,1\,0]$ | 62 | $[2\ 5\ 7\ 8]$ |
| $[1\,1\,1\,1\,1\,1]$ | 63 | $[3\ 5\ 7\ 8]$ |

the $p$-bit input bit sequence are mapped onto the $M$-ary signal constellation in order to determine the data symbols that are transmitted over the active subcarriers. For each subblock $g$, at the output of the $M$-ary mapper, $K$ complex data symbols are obtained as $\mathbf{s}_g = \left[s_1\ s_2\ \cdots\ s_K\right]^T$, where $s_k \in \mathcal{S}$ for $k = 1, 2, \ldots, K$. We assume that $E\{\mathbf{s}_g^H \mathbf{s}_g\} = K$, i.e., the signal constellation is normalized to have unit average power. Due to the fact that we do not use all of the available subcarriers, we compensate for the loss in the total number of transmitted bits by transmitting additional bits in the spatial domain of the OFDM block.

In case of DC biasing, the OFDM block creator creates all of the subblocks by considering $\mathbf{i}_g$ and $\mathbf{c}_g$ for all $g$ before forming the main OFDM-IM block $\mathbf{x} \in \mathbb{C}^{(N_F/2-1)\times 1}$ which is given as

$$\mathbf{x} = \left[\mathbf{x}_1^T\ \mathbf{x}_2^T\ \cdots\ \mathbf{x}_G^T\right]^T. \tag{3}$$

After the formation of the main OFDM-IM block $\mathbf{x} = \left[x(1)\ x(2)\ \cdots\ x(N_F/2-1)\right]^T$ by the concatenation of $G$ subblocks, Hermitian symmetry is applied in order to make the resulting time-domain OFDM signals real as follows:

$$\mathbf{x}_H = \left[0\ x(1)\ \cdots\ x(N_F/2-1)\ 0\ x^*(N_F/2-1)\ \cdots\ x^*(1)\right]^T \tag{4}$$

where $\mathbf{x}_H = \left[x_H(1)\ x_H(2)\ \cdots\ x_H(N_F)\right]^T \in \mathbb{C}^{N_F\times 1}$ is the extended OFDM-IM block with Hermitian symmetry.

On the other hand, for AC, after the formation of the main OFDM-IM block $\mathbf{x} = \left[x(1)\ x(2)\ \cdots\ x(N_F/4)\right]^T$ by the concatenation of $G$ subblocks, Hermitian symmetry is applied after putting zeros to even subcarriers as

$$\mathbf{x}_H = \left[0\ x(1)\ 0\ x(2)\ \cdots\ x(\tfrac{N_F}{4})\ 0\ x^*(\tfrac{N_F}{4})\ \cdots\ x^*(2)\ 0\ x^*(1)\right]^T \tag{5}$$

which is required for clipping at zero without data loss.

After applying Hermitian symmetry, the resulting extended OFDM block is processed by the $N_F$-IFFT operator to obtain

$$\mathbf{q} = \left[q(1)\ q(2)\ \cdots\ q(N_F)\right]^T \in \mathbb{R}^{N_F\times 1}. \tag{6}$$

TABLE III
CHANNEL PARAMETERS

| | |
|---|---|
| Room Dimensions | $5 \times 5 \times 3\ (m^3)$ |
| Transmitter Position | $(0, 0, 3)$ |
| Receiver Position | $(1.7, 1.9, 0.7)$ |
| Reflectivity | Walls: 0.8, Ceiling: 0.8, Floor: 0.3 |

We assume that IFFT operation satisfies the $E\left\{\mathbf{q}^T\mathbf{q}\right\} = N_F$ normalization. After $N_F$-IFFT operation, the resulting time-domain OFDM signals in $\mathbf{q}$ are real but bipolar; therefore these signals are still unsuitable for transmission through optical links. At this point, bipolar-unipolar conversion is applied according to AC or DC biasing techniques. For AC, the negative samples in $\mathbf{q}$ are clipped at zero without data loss and the unipolar signal $\mathbf{q}_U$ is obtained. On the other hand, for DC biasing, a suitable DC bias value $B_{DC}$ is added to $\mathbf{q}$ and any remaining negative values are clipped resulting in the unipolar signal $\mathbf{q}_U$. The DC bias level is adjusted according to

$$B_{DC} = \mu\sqrt{E\left\{q(n_f)^2\right\}} \tag{7}$$

where $q(n_f) \in \mathbf{q}$, $\mu$ is a constant and $B_{DC}$ is defined as a bias of $10\log_{10}(\mu^2+1)$ dB [3].

After the bipolar-unipolar conversion, the resulting real and positive signals in $\mathbf{q}_U$ can be transmitted from the $L$-tap VLC channel $\mathbf{h} = \left[h(1)\ h(2)\ \cdots\ h(L)\right]^T$, whose impulse response is given in Fig. 2 (a), where $L = 81$. The channel impulse response shown in Fig. 2(a) is obtained using Zemax® software for the configuration shown in Fig. 2(b), where the corresponding channel parameters are shown in Table III.

After the addition of cyclic prefix with length $C_p$ to $\mathbf{q}_U$ and digital-to-analog conversion, the resulting signals in $\tilde{\mathbf{q}}_U$ are transmitted over the VLC channel. The received signals are converted to the electrical domain by the PD and after analog-to-digital conversion, the following signals, which contain the amplified/attenuated signals, inter-symbol interference and additive white Gaussian noise (AWGN) samples, are obtained:

$$\mathbf{r} = \tilde{\mathbf{q}}_U * \mathbf{h} + \mathbf{w} \tag{8}$$

where $*$ denotes linear convolution, $\mathbf{w}$ is the vector of noise samples with variance $\sigma_w^2$.

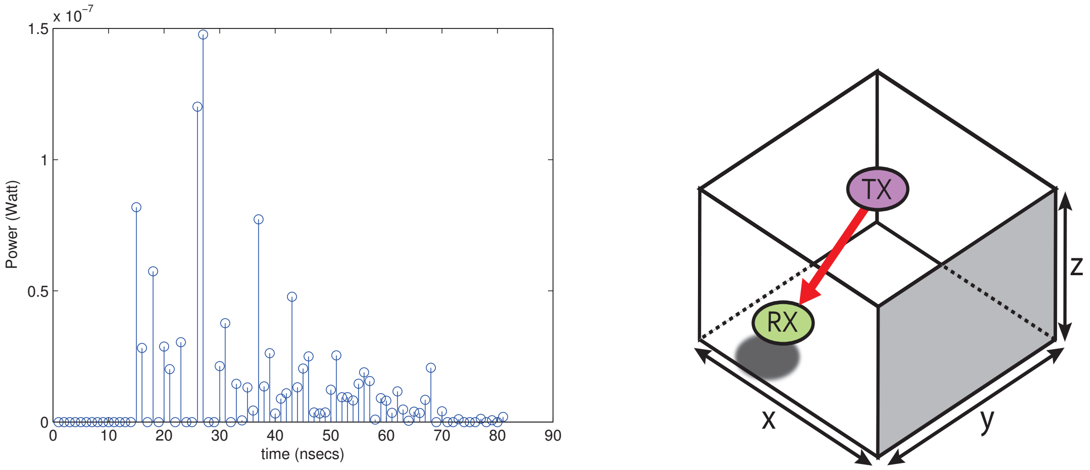
The signal-to-noise ratio (SNR) is defined for O-OFDM-IM scheme as

$$\rho = E_b/\sigma_w^2 \tag{9}$$

where $E_b$ is the average received electrical energy per bit which is calculated as

$$E_b = \frac{(N_F + C_p)P_e H_0}{m} \tag{10}$$

where $H_0$ is the mean power of optical channel determined as $E\left\{h(l)^2\right\} \approx 8 \times 10^{-16}$, $h(l) \in \mathbf{h}$, $P_e$ is the electrical power of O-OFDM-IM, which is equal to 0.5 and $\left((1+B_{DC})^2(1-Q(B_{DC})) + (\frac{B_{DC}}{\sqrt{2\pi}})e^{\frac{-B_{DC}^2}{2}}\right)$ for AC and DC biasing, respectively. On the other hand, the number of



(a) (b)

Fig. 2. VLC channel impulse response and the simulation setup

transmitted bits per OFDM frame is obtained for AC and DC biasing respectively as follows

$$m = \frac{N_F}{4N}\Big(\lfloor \log_2 (C(N,K))\rfloor + K\log_2(M)\Big)$$
$$m = \frac{N_F/2-1}{N}\Big(\lfloor \log_2 (C(N,K))\rfloor + K\log_2(M)\Big). \quad (11)$$

Finally, the spectral efficiency of the O-OFDM-IM scheme is calculated as

$$\eta = \frac{m}{N_F + C_p} \quad [bits/s/Hz]. \quad (12)$$

## III. Detection of O-OFDM-IM

Assuming $L = C_p$, after the removal of CP, and FFT operation, OFDM transforms the circular convolution to the multiplication and simplifies the task of the receiver as

$$y_H(n_f) = x_H(n_f)h_F(n_f) + w(n_f) \quad (13)$$

for $n_f = 2, 4, \ldots, N_F/2$ for AC, and $n_f = 2, 3, \ldots, N_F/2$ for DC biasing, where $h_F(n_f) \in \mathbf{h}_F$ is the frequency response of the VLC channel, and $w(n_f)$ is the noise sample in the frequency domain with variance $\sigma^2_{w,f}$.

The receiver's task is to detect the indices of the active subcarriers and the corresponding information symbols by processing $y_H(n_f)$. Unlike the classical OFDM, a simple maximum likelihood (ML) decision on $x_H(n_f)$ is not possible considering $y_H(n_f)$ only in our scheme, due to the spatial information carried by the O-OFDM-IM subblocks.

In order to determine the indices of the active subcarriers, the LLR detector of the O-OFDM-IM scheme calculates the logarithm of the ratio of a posteriori probabilities of the frequency domain symbols by considering that their values can be either zero or non-zero. This ratio, which is calculated as follows, gives valuable information on the active status of the corresponding index

$$\lambda(n_f) = \ln \frac{\sum_{m=1}^{M} P(x_H(n_f) = s_m \,|\, y_H(n_f))}{P(x_H(n_f) = 0 \,|\, y_H(n_f))} \quad (14)$$

where $s_m \in \mathcal{S}$, and $n_f = 2, 4, \ldots, N_F/2$ for AC, and $n_f = 2, 3, \ldots, N_F/2$ for DC biasing. As seen from (14), the LLR detector only considers $N_F/4$ and $N_F/2-1$ elements of $\mathbf{y}_H$ for AC and DC biasing, respectively, due to the Hermitian symmetry. Using Bayes formula in (14) and dropping the constant terms we obtain

$$\lambda(n_f) = \ln \frac{\sum_{m=1}^{M} P(y_H(n_f) \,|\, x_H(n_f) = s_m)}{P(y_H(n_f) \,|\, x_H(n_f) = 0)}. \quad (15)$$

Since $y_H(n_f)$ is Gaussian distributed conditioned on $x_H(n_f)$, the corresponding LLR values can be calculated as

$$\lambda(n_f) = \frac{|y_H(n_f)|^2}{\sigma^2_{w,f}} + \ln\left(\sum_{m=1}^{M} \exp\left(-\frac{|y_H(n_f) - s_m h_F(n_F)|^2}{\sigma^2_{w,f}}\right)\right). \quad (16)$$

In order to prevent numerical overflow in (16), we use the identity $\ln(e^{a_1} + e^{a_2} + \cdots + e^{a_M}) = f_{max}(f_{max}(\ldots f_{max}(f_{max}(a_1, a_2), a_3), \ldots), a_M)$, where

$$f_{max}(a,b) = \ln(e^{a_1} + e^{a_2}) = \max(a_1, a_2) + \ln\left(1 + e^{-|a_1 - a_2|}\right). \quad (17)$$

After the calculation of the $N_F/4$ or $N_F/2-1$ LLR values for AC or DC biasing, respectively, for each subblock, the receiver decides on $K$ active indices out of $N$ available subcarriers which have maximum LLR values. The active indices is applied to the index demapper to recover the index selecting $p_1$ bits for each subblock. The corresponding $p_2$ bits which were mapped onto $M$-ary signal constellation can be recovered easily once the active subcarriers are determined. Interested readers are referred to [6] for more information on index mapping/demapping operations.

## IV. SIMULATION RESULTS

In this section, we provide computer simulation results for the proposed O-OFDM-IM scheme and the classical ACO-OFDM and DCO-OFDM schemes. The bit error rate (BER) performance of these systems is evaluated for the realistic VLC channel whose impulse response is shown in Fig. 2(a).

In Fig. 3, we evaluate the BER performance of the proposed scheme for AC and DC biasing: namely, ACO-OFDM-IM and DCO-OFDM-IM with LLR detection. In order to achieve the same spectral efficiency of $0.3$ bits/s/Hz, the following system parameters are assumed for ACO-OFDM-IM and DCO-OFDM-IM, respectively: $M = 4, N = 4, K = 3$ and $M = 4, N = 9, K = 2$. The DC bias is set to $4$ dB. At the same spectral efficiency, the BER performances of the classical ACO-OFDM and DCO-OFDM schemes are also shown in Fig. 3. As seen from Fig. 3, the proposed O-OFDM-IM can provide better BER performance than the reference O-OFDM scheme either using AC and DC biasing techniques. The better BER performance of the proposed scheme can be explained by the information bits transmitted by the active subcarrier indices. It is interesting to note that for the considered spectral efficiency, AC provides better BER performance for O-OFDM while DC biasing outperforms AC for O-OFDM-IM.

In Fig. 4, the BER performances of the proposed O-OFDM-IM scheme and the classical O-OFDM scheme are compared, where both schemes achieves a spectral efficiency of $0.6$ bits/s/Hz. For this spectral efficiency, ACO-OFDM-IM uses $M = 16, N = 8, K = 7$, while DCO-OFDM-IM uses $M = 4, N = 9, K = 6$. As seen Fig. 4, the proposed O-OFDM-IM scheme outperforms the O-OFDM scheme for mid-to-high SNR values. It should be noted that DC biasing provides better performance than AC at moderate BER values for the proposed O-OFDM-IM due to its higher transmission rate; however, it tends to error floor for high SNR values when using a lower DC bias value. Since the increase of the DC bias reduces the power efficiency, the selection of AC or DC biasing methods for O-OFDM-IM should be carefully made according to the specific system configuration and target BER value.

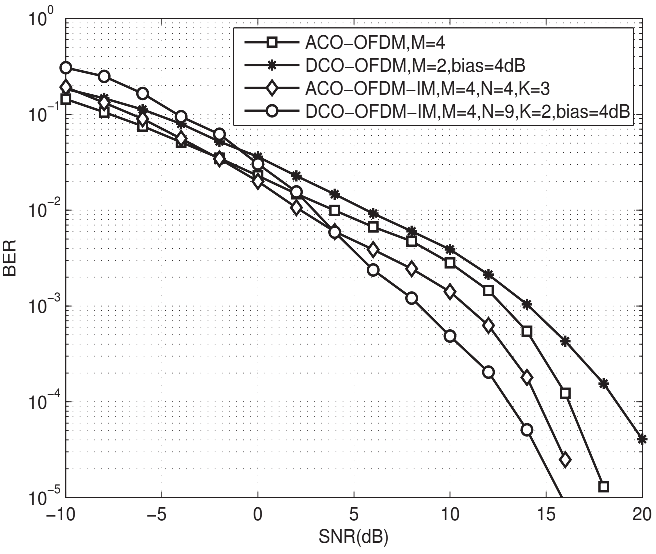


Fig. 3. Performance comparison of O-OFDM-IM and O-OFDM schemes for $0.3$ bits/s/Hz, $N_F = 128$ and realistic VLC channel $(L = 81)$

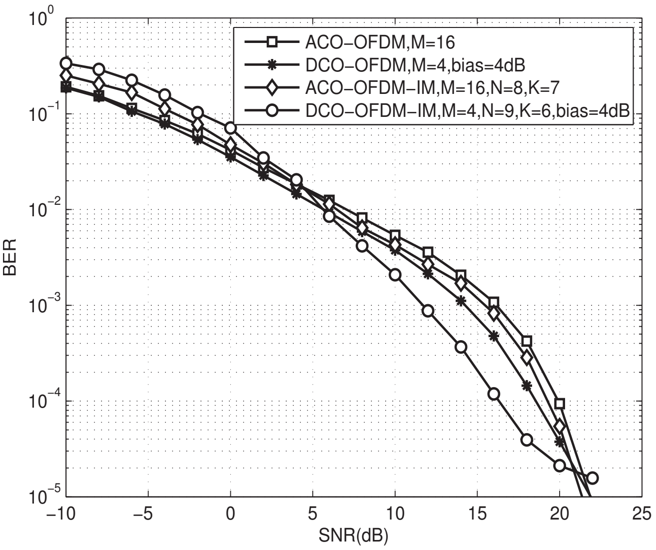


Fig. 4. Performance comparison of O-OFDM-IM and O-OFDM schemes for $0.6$ bits/s/Hz, $N_F = 128$ and realistic VLC channel $(L = 81)$

## V. CONCLUSIONS

In this study, we have proposed a novel optical OFDM scheme called O-OFDM-IM for VLC systems. The proposed scheme can provide an interesting tradeoff between the spectral efficiency and BER performance by adjusting the number of active subcarriers of an optical OFDM scheme using index modulation. It is shown via computer simulations that O-OFDM-IM can be considered as an alternative to classical optical OFDM for VLC systems.

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