A Novel Optical Index Modulation Aided DCO-OFDM Scheme for VLC Systems

Haodong Li[1], Jian Sun[1], Wensheng Zhang[1](✉), and Cheng-Xiang Wang[2]

[1] School of Engineering, School of Information Science and Engineering, Institute of Sensors, Signals and Systems, Shandong University, Jinan 250100, Shandong, People's Republic of China
392467887@qq.com, {sunjian,zhangwsh}@sdu.edu.cn

[2] Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
cheng-xiang.wang@hw.ac.uk

Abstract. In this paper, a novel optical index modulation (OIM) aided direct-current (DC) biased optical OFDM (OIM-DCO-OFDM) scheme for visible light communication (VLC) systems is proposed. Different with traditional index modulation schemes, the proposed OIM-DCO-OFDM scheme uses index bits to determine which subcarrier transmit original signals and which subcarrier transmit conjugate signals. The constellation of traditional phase-shift keying (PSK) and quadrature amplitude modulation (QAM) is symmetrical about the real axis. It means that we cannot distinguish the original signals and conjugate signals. In order to recover index bits at the receiver, we propose a unipolar pulse amplitude modulation (PAM) scheme for the modulation of constellation bits, and design a zero-forcing (ZF) based detector. Compared with dual-mode index modulation aided DCO-OFDM (DM-DCO-OFDM) scheme, the proposed scheme has 1 dB and 2 dB performance gain at the bit error rate (BER) level of 10^{-4} when the spectral efficiency is 1.21 bits/s/Hz and 2.18 bits/s/Hz, respectively. The proposed OIM-DCO-OFDM scheme can achieve 80% spectral efficiency improvement than the DM-DCO-OFDM scheme at the modulation order of $M = 4$.

Keywords: Visible light communication · Optical index modulation DC-biased optical OFDM · PAM

1 Introduction

VLC is a green communication technology without electromagnetic interference by using light-emitting diodes (LEDs) and photodiodes (PDs) to transmit and receive information. Moreover, VLC has many other advantages compared with radio frequency communication, such as wide bandwidth with no license application, energy efficiency and low deployment cost [1,2].

Orthogonal frequency division multiplexing (OFDM) has been widely used in radio frequency communication because it can combat the inter-symbol interference (ISI) effectively. OFDM has been used in VLC [3,4]. Since the signal only

C. Li and S. Mao (Eds.): WiCON 2017, LNICST 230, pp. 328–337, 2018.
https://doi.org/10.1007/978-3-319-90802-1_29

can be transmitted by the intensity of light and no phase can be transmitted simultaneously, conventional OFDM cannot be adopted in VLC. Many optical OFDM schemes have been proposed, such as DC-biased optical OFDM (DCO-OFDM) [5], asymmetrically clipped optical OFDM (ACO-OFDM) [6], unipolar OFDM (U-OFDM) [7] and Flip-OFDM [8]. All of the above schemes make use of Hermitian symmetry to create real signal before IFFT operation. Thus a half of carriers cannot transmit efficient signals, which leads to low spectral efficiency.

IM was recently studied for 5G wireless communication systems in [9]. Recently, optical OFDM-IM (O-OFDM-IM) scheme was proposed [10]. Compared with traditional optical OFDM schemes, O-OFDM-IM scheme transmits the information bits by the M-ary signal constellation and the indices of subcarriers. The subcarriers are divided into G groups. For each group, the subcarriers are activated by index bits to transmit constellation signals. It means that some subcarriers transmit nothing. The O-OFDM-IM scheme represents better performance compared with classical DCO-OFDM and ACO-OFDM. However, the O-OFDM-IM scheme has a low spectral efficiency since not all the subcarriers are used to transmit constellation signals.

Motivated by the O-OFDM-IM scheme, authors of [11] proposed a dual-mode index modulation aided DC-biased optical OFDM (DM-DCO-OFDM) scheme. Same as O-OFDM-IM, DM-DCO-OFDM divides the subcarriers into two parts according to different index bits, and this two parts of subcarriers transmit different constellation mapping signals. After index modulation, the OFDM block is created. By using Hermitian symmetry operation and adding DC-bias, complex signals can be translated to real and positive signals. Finally, the unipolar signals are transmitted by LEDs. Compared with DCO-OFDM scheme, the DM-DCO-OFDM scheme achieves higher spectral efficiency and improves BER performance significantly. DM-DCO-OFDM has higher spectral efficiency than O-OFDM-IM. The reasons are that all subcarriers are used to transmit constellation signals in DM-DCO-OFDM.

In this paper, we propose a novel optical index modulation aided DC-biased optical OFDM scheme. In the OIM-DCO-OFDM scheme, the index bits are used to determine which subcarriers transmit original signals or their conjugate signals. Because the constellation of the conventional M-ary modulation schemes such as PSK and QAM, are symmetrical about the real axis. In other words, index bits are not recovered by distinguishing transmitted the original signals and their conjugate signals at the receiver. In order to detect index bit effectively, we employ unipolar PAM to map constellation bits. After PAM mapping operation, every two unipolar PAM signals constitute a complex signal. Only the real and unipolar signals can be transmitted in the VLC system, so we use Hermitian symmetry operation to get real signals. After adding DC-bias, the generated real and non-negative signals can be transmitted by LEDs. At the receiver, we design a low computational complexity detector which is called ZF based detector. After obtaining estimated signals by ZF estimator, the index bits can be recovered by judging the sign of the imaginary part of received signals, and constellation bits can be demodulated by unipolar PAM de-mapping. The simulation results confirm that the proposed scheme has significant BER performance gains compared with the DM-DCO-OFDM scheme at the same spectral efficiency. Under the condition of same modulation order, the proposed scheme has higher spectral efficiency improvement than DM-DCO-OFDM.

The rest of this paper is organized as follows. In Sect. 2, the system model of DM-DCO-OFDM is reviewed. The OIM-DCO-OFDM system model is presented in Sect. 3. The simulation results and spectral efficiency analysis are given in Sect. 4. Section 5 shows the conclusions.

2 Review of DM-DCO-OFDM

In DM-DCO-OFDM, N subcarriers are divided into G groups, each group contains n subcarriers and p_{DM} bits, $p_{DM} = p_1 + p_2$. p_1 bits are fed into index selector to determine index pattern and p_2 bits are modulated by two different constellations, M_{A}-ary A and M_{B}-ary B. For each group, k subcarriers out of n subcarriers are selected to transmit the constellation A signals, and other $n-k$ subcarriers transmit the constellation B signals. The transmitted bits in each group can be calculated by $p_{DM} = \lfloor \log_2 \left(C\left(n,k\right)\right) \rfloor + k\log_2(M_A) + (n-k)\log_2(M_B)$, where $\lfloor \rfloor$ is the floor function, $C\left(n,l\right)$ is the binomial coefficient. Noted that the symbol of constellation A and constellation B should be differentiated with each other. Otherwise, the index bits cannot be recovered at the receiver, which will lead to bad BER performance. After index modulation and constellation mapping, Hermitian symmetry operation is used to obtain real signals before IFFT operation. The Hermitian symmetry property can be represented by

$$\begin{cases} X_i = X_{N-i}^*, 0 < i < N/2 \\ X_0 = X_{N/2} = 0 \end{cases} \tag{1}$$

where $X_i \in \mathbf{X}$, $\mathbf{X} = [X_0, X_1, \ldots, X_{N-1}]$ is the frequency-domain complex signals after constellation mapping. Then IFFT and parallel-to-serial operation are employed to generate time-domain signal. Finally, a suitable DC-bias should be added on the time-domain signals to create unipolar signals, i.e., only the time-domain unipolar signals can be transmitted via LEDs. At the receiver side, the reverse operations are used to obtain transmitted frequency-domain signals. The maximum likelihood detector or the log-likelihood ratio detector can be selected to recover index bits and constellation bits.

3 System Model of OIM-DCO-OFDM

Motivated by DM-DCO-OFDM, the proposed OIM-DCO-OFDM scheme also uses all of subcarriers to transmit signals, which can achieve higher spectral efficiency than O-OFDM-IM scheme. The block diagram of OIM-DCO-OFDM transceiver is given in Fig. 1 For each OFDM block, m bits and N carriers are divided into G groups, each group contains p bits and n subcarriers i.e., $m = pG$, $N = nG$. For each group, p bits are split into three parts, p_1, p_2 and

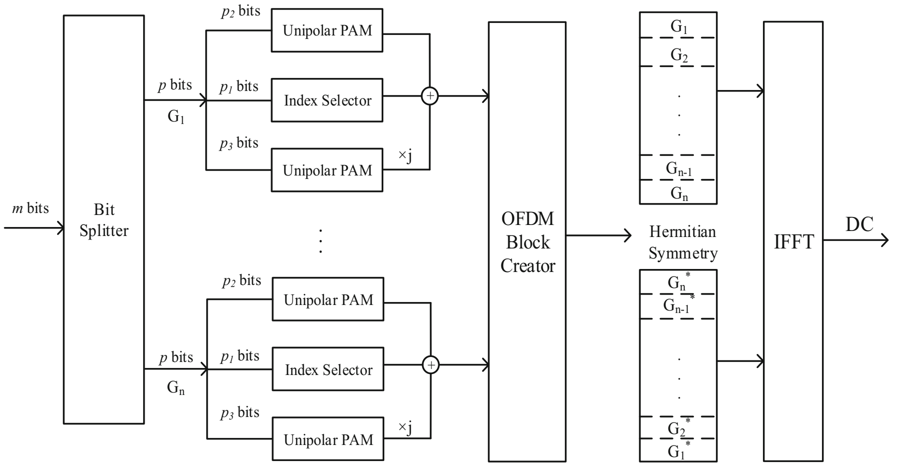

Fig. 1. The block diagram of the OIM-DCO-OFDM transmitter.

p_3, i.e., $p = p_1 + p_2 + p_3$. The index bits p_1 are fed into index selector to choose l subcarriers from n subcarriers, and these l subcarriers will transmit original signals while other $n - l$ subcarriers will transmit conjugate signals. Then p_1, p_2 and p_3 can be calculated by

$$p_1 = \lfloor \log_2 \left(C \left(n, l \right) \right) \rfloor \tag{2}$$

$$p_2 = p_3 = n\log_2 \left(M \right) \tag{3}$$

where M is the modulation order of unipolar PAM. The bits p entered into each group can be calculated by

$$p = \lfloor \log_2 \left(C \left(n, l \right) \right) \rfloor + 2n\log_2 \left(M \right). \tag{4}$$

Noted that the index bits cannot be detected successfully if use QAM or PSK to modulate constellation bits. Because conventional PSK and QAM constellation symbols are symmetrical about the real axis, it cannot distinguish original signals and its conjugate signals at the receiver, where we use the difference between original constellation signals and their conjugate signals to transmit index bits. In order to recover index bits, we use two unipolar PAM symbols to form a complex signal. p_2 and p_3 are modulated by unipolar M-ary PAM constellation. The unipolar PAM constellation symbols are denoted as $\mathbf{S} = [S_1, S_2, \ldots S_M]$. Every two unipolar PAM symbols form a complex signal, i.e., $X = S_\alpha + jS_\beta$, $S_\alpha, S_\beta \in \mathbf{S}$. The conjugate signal of X can be represented by $X^* = S_\alpha - jS_\beta$.

In OIM-DCO-OFDM scheme, the look-up table method is used to index selected procedure [12]. We illustrate the implementation by an example. The initial settings are assumed that $M = 2$, $\mathbf{S} = [1, 3]$, $n = 4$ and $l = 2$. Calculating Eq. (4), we can get $p = \lfloor \log_2 (C(4, 2)) \rfloor + 2 * 4 * \log_2 (2) = 10$ bits. The index bits p_1 can be obtained by Eq. (2) and we can get that $p_1 = 2$. The look-up table is illustrated in Table 1, and the first column of the table denotes the combination of binary bits. The second column is the indices pattern I generated according to the input index bits, where "1" denotes the subcarriers transmitting original signals X and "0" denotes the subcarriers transmitting conjugate signals X^*. The last column is the signal subblocks which generated by index modulation. For example, if input bits are "1011011001", the index pattern can be determined by Table 1. The index bits are "10", which indicates that the index pattern is "1,0,0,1" which means that the first and the fourth subcarrier transmit the original signals X, and the rest of subcarriers transmit conjugate signals X^*. The rest of bits are modulated by unipolar PAM and the generated complex signal subblock is $[3 + 3j, 1 - 3j, 3 - 1j, 1 + 3j]$.

After index modulation and unipolar M-ary PAM mapping, the generated complex signal in γ-th subblock can be represented by

$$\mathbf{X}_\gamma = [X_{\gamma-1}, X_\gamma, \ldots, X_{\gamma+n-1}]^{\mathrm{T}}. \tag{5}$$

Since in VLC system only real and unipolar signals can be transmitted, Hermitian symmetry is used to generate real-value signal aforementioned in Eq. (1), which means that half of subcarriers transmit no information bits. Hence the spectral efficiency of OIM-DCO-OFDM can be calculated by $\eta = \frac{pG}{2N}$ bits/s/Hz and the spectral efficiency of DM-DCO-OFDM also can be obtained by this equation. After Hermitian symmetry operation, the frequency-domain signals in an OFDM block can be represented as

$$\mathbf{X} = [0, X_1, X_2, \ldots, X_{N-1}, 0, X^*_{N-1}, \ldots, X^*_2, X^*_1]^{\mathrm{T}}. \tag{6}$$

The real-value time-domain signals are obtained by IFFT operation of $\mathbf{X}$ and can be denoted as

$$\mathbf{x} = [x_1, x_2, \ldots, x_{2N}]^T. \tag{7}$$

Before transmitting signals by LEDs, a suitable DC-bias U_{DC} is adopted to obtain real and unipolar signals by

$$U_{DC} = \mu \sqrt{E\{(x_i)^2\}} \tag{8}$$

where $x_i \in \mathbf{x}$, μ is a proportionality constant, and U_{DC} is defined as a bias of $10\log_{10}(\mu^2 + 1)$ [13].

Figure 2 is the scenario model. In order to simplify the model, we only consider the line-of-sight (LOS) component [14]. The optical channel can be modeled as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}_{\mathrm{A}} \tag{9}$$

Table 1. A Look-up Table for OIM-DCO-OFDM with $n = 4$ and $l = 2$.

Index bits	Indices pattern	Subblocks
[0, 0]	[1, 1, 0, 0]	$[X, X, X^*, X^*]$
[0, 1]	[0, 1, 0, 1]	$[X^*, X, X^*, X]$
[1, 0]	[1, 0, 0, 1]	$[X, X^*, X^*, X]$
[1, 1]	[0, 1, 1, 0]	$[X^*, X, X, X^*]$

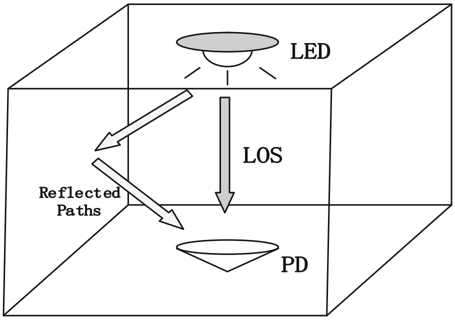

Fig. 2. The scenario model.

where $\mathbf{y} = [y_1, y_2, \dots y_{2N}]$ is a received signal vector, $\mathbf{H}$ is the optical channel gain, and $\mathbf{n}_\mathrm{A}$ denotes $2N \times 1$ real-valued additive white Gaussian noise (AWGN) vector.

At the receiver, in order to recover index bits and information bits, we design a ZF based detector. Firstly, the ZF estimator is used to yield an estimation of $\mathbf{x}$ which can be obtained as

$$\hat{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{y}. \tag{10}$$

Then, $\hat{\mathbf{x}}$ is fed into FFT operation and performs the inverse operation of Hermitian symmetry to obtain the frequency-domain estimated signal $\hat{\mathbf{X}}$. Secondly, the index pattern of ξ-th group can be determined by judging the sign of $\hat{\mathbf{X}}^\xi$ imaginary part, which can be represented by

$$I_i^\xi = \begin{cases} 1, \text{if } \mathrm{Imag}(\hat{X}_i^\xi) \geq 0 \\ 0, \text{if } \mathrm{Imag}(\hat{X}_i^\xi) < 0 \end{cases} \tag{11}$$

where $\mathrm{Imag}(\hat{X}_i^\xi)$ denotes the imaginary part of $\hat{X}_i^\xi$. Then, inputting index pattern into the look-up table, the index bits p_1 can be recovered. The constellation bits p_2 and p_3 can be recovered by putting the real part and imaginary part of $\hat{\mathbf{X}}$ into unipolar M-PAM demodulator respectively. We summarize the step of the designed ZF based detector in Algorithm 1. The computational complexity of ZF based detector is about the order of $O(3n)$ per group.

Algorithm 1. ZF based detector for OIM-DCO-OFDM.

Input: Received signals $\mathbf{y}$, number of groups G, number of subcarriers in each group n, number of subcarriers modulated by original signals l.
Operation: Calculating the frequency-domain estimated signals $\mathbf{X}$ by Eq. (10), FFT and removing Hermitian symmetry operation.
Recovering index bits:
for $\xi = 1;\ \xi \le G;\ \xi + +$ **do**
    for $i = 1;\ i \le n;\ i + +$ **do**
        if $\mathrm{Imag}(X_i^{\xi}) \ge 0$ **then**
            $I_i^{\xi} = 1$
        else
            $I_i^{\xi} = 0$
        end
    end
    Input index pattern $\mathbf{I}_i^{\xi}$ to look-up table, index bit p_1 can be obtained.
end
Recovering constellation bits:
for $\xi = 1;\ \xi \le G;\ \xi + +$ **do**
    for $i = 1;\ i \le n;\ i + +$ **do**
        p_2 = demodulate the real part of X_i^{ξ}
        p_3 = demodulate the imaginary part of X_i^{ξ}
    end
end

4 Simulation Results and Analysis

In this section, the performance of the proposed OIM-DCO-OFDM scheme is validated. The simulation results are compared with the DM-DCO-OFDM scheme results under optical AWGN channel. The simulation parameter settings are same as [11]. The number of carriers is $N = 128$, and efficient carriers are split into $G = 31$ groups which contains $n = 4$ subcarriers. For each group, $l = 2$ subcarriers are selected to transmit original symbols, and the rest of subcarriers transmit conjugate originals. The size of IFFT is 256. The proportionality constant $\mu = 1.05$. The signal-to-noise ratio (SNR) is defined as E_b/N_0 in the OIM-DCO-OFDM scheme.

Figure 3 presents the BER performance comparison between OIM-DCO-OFDM and DM-DCO-OFDM in same spectral efficiency of 1.21 bits/s/Hz and 2.18 bits/s/Hz. When the spectral efficiency is 1.21 bits/s/Hz, the proposed scheme uses unipolar 2-PAM to modulate constellation bits, and the set of unipolar 2-PAM constellation can be represented by $\mathbf{S} = [1, 3]$. As for DM-DCO-OFDM scheme, the two distinguished QPSK constellation sets $\mathbf{S}_\mathrm{A}$ and $\mathbf{S}_\mathrm{B}$ are $[1+\mathrm{j}, -1+\mathrm{j}, -1-1\mathrm{j}, 1-\mathrm{j}]$ and $\left[1+\sqrt{3}, (1+\sqrt{3})\mathrm{j}, -1-\sqrt{3}, -(1+\sqrt{3})\mathrm{j}\right]$ [15]. The spectral efficiency is 2.18 bits/s/Hz, and the unipolar 4-PAM constellation set can be represented by $\mathbf{S} = [1, 3, 5, 7]$. For DM-DCO-OFDM scheme, the two distributed 16-QAM constellation sets $\mathbf{S}_\mathrm{A}$ and $\mathbf{S}_\mathrm{B}$ are $[3+3\mathrm{j}, 1+3\mathrm{j}, -1+3\mathrm{j}, -3+$

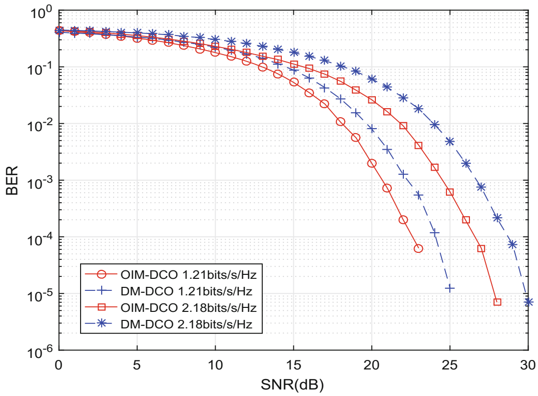

Fig. 3. Performance comparison of OIM-DCO-OFDM and DM-DCO-OFDM schemes under AWGN channels with the spectral efficiency of 1.21 bits/s/Hz and 2.18 bits/s/Hz.

$3j, -3+j, -1+j, 1+j, 3+j, 3-j, 1-j, -1-j, -3-j, -3-3j, -1-3j, 1-3j, 3-3j]$ and $[5+j, 5+3j, 3+5j, 1+5j, -1+5j, -3+5j, -5+3j, -5+j, -5-j, -5-3j, -3-5j, -1-5j, 1-5j, 3-5j, 5-3j, 5-j]$ [15]. We can observe from Fig. 3 that the proposed OIM-DCO-OFDM scheme has 1 dB and 2 dB performance gain over DM-DCO-OFDM scheme at the BER level of 10^{-4} when the spectral efficiency is 1.21 bits/s/Hz and 2.18 bits/s/Hz, respectively. The wrong recovered index bits have no impact on constellation bits recover at low SNR level. The index bits and constellation bits can be recovered successfully by the ideal ZF estimator at high SNR level. Other reason is the proposed scheme has low order constellation at same spectral efficiency with DM-DCO-OFDM, which is more robust to the noise. Therefore, the proposed scheme achieves better BER performance gains than DM-DCO-OFDM scheme.

Then, we focus on comparing the spectral efficiency between OIM-DCO-OFDM and DM-DCO-OFDM scheme. We assume both of two schemes have same system parameters and adopt the same subcarrier parameter settings. In the DM-DCO-OFDM scheme, the different signal constellations have same modulation order. As description in Sect. 3, the spectral efficiency can be obtained. Noted that the length of CP is not considered in spectral efficiency. In Fig. 4, the spectral efficiency between OIM-DCO-OFDM and DM-DCO-OFDM scheme are compared. At same modulation order, OIM-DCO-OFDM has higher spectral efficiency than DM-DCO-OFDM scheme. For example, the spectral efficiency of the proposed scheme is $\eta_{\mathrm{OIM}} = 2.18\,\mathrm{bits/s/Hz}$ at the modulation order $M = 4$, while the spectral efficiency of DM-DCO-OFDM is $\eta_{\mathrm{DM}} = 1.21\,\mathrm{bits/s/Hz}$. The proposed scheme has 80% spectral efficiency improvement than DM-DCO-OFDM. Because the signals transmitted by each subcarrier in OIM-DCO-OFDM, are constituted by two unipolar M-ary PAM symbols, but DM-DCO-OFDM only transmit one M-ary QAM symbol. It means that proposed scheme can transmit twice information bits on per subcarriers than DM-DCO-OFDM scheme.

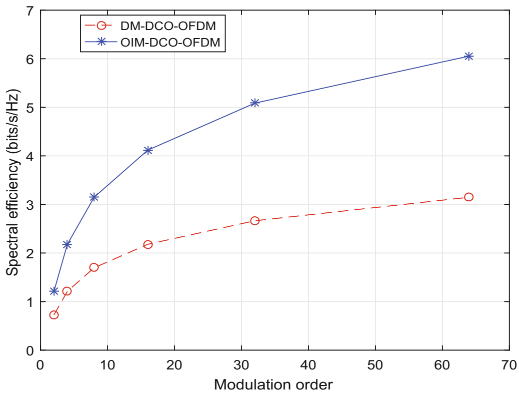

Fig. 4. Spectral efficiency comparison between OIM-DCO-OFDM and DM-DCO-OFDM schemes.

5 Conclusions

In this paper, a novel OIM-DCO-OFDM scheme has been proposed. Same as the DM-DCO-OFDM scheme, the proposed OIM-DCO-OFDM scheme have used all subcarriers to transmit constellation signals. But the index bits in the proposed scheme are used to select which subcarrier to transmit the original signals or their conjugate signals. Since conventional PSK and QAM constellation schemes are symmetry about the real axis, they cannot be used in the proposed scheme. In order to recover index bits at the receiver, we have used two unipolar PAM symbols to constitute a complex signal. Generated complex signals and their conjugate signals can easily be distinguished by the sign of the imaginary part of signals. After index selection and constellation mapping, Hermitian symmetry operation and DC-bias have been adopted to translate bipolar complex signals to unipolar real signals. Then, the generated unipolar real signals can be transmitted by the LEDs. At the receiver, a ZF based detector has been designed for demodulation of index bits and constellation bits. It has been demonstrated via simulations that the proposed OIM-DCO-OFDM scheme has a performance gain compared with the conventional DM-DCO-OFDM scheme at the same spectral efficiency of 1.21 bits/s/Hz and 2.18 bits/s/Hz under AWGN channels. Moreover, we have analyzed the system spectral efficiency of the proposed scheme and DM-DCO-OFDM scheme. The proposed scheme can achieve 80% more spectral efficiency gain than the DM-DCO-OFDM scheme when the modulation order equals to four. In the future, we will investigate the upper bound of the BER of the proposed scheme as well as analyze the performance of OIM-DCO-OFDM under actual communication environments.

Acknowledgement. The authors gratefully acknowledge the support from Natural Science Foundation of China (No. 61371110), Fundamental Research Funds of Shandong University (No. 2017JC029), Key R&D Program of Shandong Province

(No. 2016GGX101014), Shandong Provincial Natural Science Foundation (No. ZR2017MF012), Science and Technology Project of Guangzhou (No. 201704030105), EPSRC TOUCAN project (Grant No. EP/L020009/1), and EU H2020 RISE TESTBED project (Grant No. 734325).

References

1. Karunatilaka, D., Zafar, F., Kalavally, V., Parthiban, R.: LED based indoor visible light communications: state of the art. IEEE Commun. Surv. Tutor. **17**(3), 1649–1678 (2015)
2. Cailean, A., Dimian, M.: Current challenges for visible light communications usage in vehicle applications: a survey. IEEE Commun. Surv. Tutor. **PP**(99), 1 (2017)
3. Afgani, M., Haas, H., Elgala, H., Knipp, D.: Visible light communication using OFDM. In: International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, Barcelona, pp. 129–134 (2006)
4. Zhang, G., De, M., Leenheer, A., Morea, B.M.: A survey on OFDM-based elastic core optical networking. IEEE Commun. Surv. Tutor. **15**(1), 65–87 (2013)
5. Carruthers, J., Kahn, J.: Multiple-subcarrier modulation for nondirected wireless infrared communication. IEEE J. Sel. Areas Commun. **14**(3), 538–546 (1996)
6. Armstrong, J., Lowery, A.J.: Power efficient optical OFDM. Electron. Lett. **42**(6), 370–372 (2006)
7. Tsonev, D., Sinanovic, S., Haas, H.: Novel unipolar orthogonal frequency division multiplexing (U-OFDM) for optical wireless. In: Vehicular Technology Conference, pp. 1–5. IEEE, Yokohama (2012)
8. Fernando, N., Hong, Y., Viterbo, E.: Flip-OFDM for unipolar communication systems. IEEE Trans. Commun. **60**(12), 3726–3733 (2012)
9. Patcharamaneepakorn, P., Wang, C.-X., Fu, Y., Aggoune, H., Alwakeel, M.M., Tao, X., Ge, X.: Quadrature space-frequency index modulation for 5G wireless communication systems. IEEE Trans. Commun. (accepted for publication)
10. Basar, E., Panayirci, E.: Optical OFDM with index modulation for visible light communications. In: International Workshop on Optical Wireless Communications, pp. 11–15. IEEE, Istanbul (2015)
11. Mao, T., Jiang, R., Bai, R.: Optical dual-mode index modulation aided OFDM for visible light communications. Optics Commun. **391**, 37–41 (2017)
12. Basar, E., Aygolu, U., Panayirci, E., Poor, H.V.: Orthogonal frequency division multiplexing with index modulation. IEEE Trans. Sig. Proc. **61**(22), 5536–5549 (2013)
13. Dissanayake, S.D., Armstrong, J.: Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems. J. Lightw. Technol. **31**(7), 1063–1072 (2013)
14. Kahn, J.M., Barry, J.R.: Wireless infrared communications. Proc. IEEE **85**(2), 265–298 (1997)
15. Mao, T., Wang, Z., Wang, Q., Chen, S., Hanzo, L.: Dual-mode index modulation aided OFDM. IEEE Access **5**, 50–60 (2016)