Coded Index Modulation for Non-DC-Biased OFDM in Multiple LED Visible Light Communication

S. P. Alaka, T. Lakshmi Narasimhan[†], and A. Chockalingam
Department of ECE, Indian Institute of Science, Bangalore 560012
† Presently with National Instruments Private Limited, Bangalore 560029

***Abstract*—Use of multiple light emitting diodes (LED) is an attractive way to increase spectral efficiency in visible light communications (VLC). A non-DC-biased OFDM (NDC OFDM) scheme that uses two LEDs has been proposed in the literature recently. NDC OFDM has been shown to perform better than other OFDM schemes for VLC like DC-biased OFDM (DCO OFDM) and asymmetrically clipped OFDM (ACO OFDM) in multiple LEDs settings. In this paper, we propose an efficient multiple LED OFDM scheme for VLC which uses *coded index modulation*. The proposed scheme uses two transmitter blocks, each having a pair of LEDs. Within each block, NDC OFDM signaling is done. The selection of which block is activated in a signaling interval is decided by information bits (i.e., index bits). In order to improve the reliability of the index bits at the receiver (which is critical because of high channel correlation in multiple LEDs settings), we propose to use coding on the index bits alone. We call the proposed scheme as CI-NDC OFDM (coded index NDC OFDM) scheme. We present the performance results of CI-NDC OFDM scheme with the index bits coded by (i) LDPC and (ii) Walsh-Hadamard codes. Simulation results show that, for the same spectral efficiency, CI-NDC OFDM that uses coding on the index bits performs better than NDC OFDM.**

Keywords *– Multiple LED VLC, DC-biased OFDM, asymmetrically clipped OFDM, Flip OFDM, non-DC-biased OFDM, coded index modulation, LDPC.*

I. Introduction

Optical wireless communication, where information is conveyed through optical radiations in free space in outdoor and indoor environments, is emerging as a promising complementary technology to RF wireless communication. While communication using infrared wavelengths has been in existence for quite some time [1], more recent interest centers around indoor communication using visible light wavelengths [2],[3]. A major attraction in indoor visible light communication (VLC) is the potential to simultaneously provide both energy-efficient lighting as well as high-speed short-range communication using inexpensive high-luminance light-emitting diodes (LED). Several other advantages including no RF radiation hazard, abundant VLC spectrum at no cost, and very high data rates make VLC increasingly popular.

OFDM can be applied to VLC in context of intensity modulation and direct detection (IM/DD), where IM/DD is non-coherent and the transmit signal must be real and positive. This can be achieved by imposing Hermitian symmetry on the information symbols before the inverse fast Fourier transform (IFFT) operation. Several papers have investigated OFDM in VLC [4]-[6], which have shown that OFDM is attractive in VLC systems. A 3 Gbps single-LED VLC link based on OFDM has been reported in [7].

Several techniques that generate VLC compatible OFDM signals in the positive real domain have been proposed in the literature [8]-[14]. These techniques include DC-biased optical (DCO) OFDM [8], asymmetrically clipped optical (ACO) OFDM [9]-[11], flip OFDM [12],[13], and non-DC biased (NDC) OFDM [14]. In the above works, DCO OFDM, ACO OFDM, and flip OFDM are studied for single-LED systems. The NDC OFDM in [14] uses two LEDs. In [14], it has been that NDC OFDM performs better compared with DCO OFDM and ACO OFDM that use two LEDs.

Use of multiple LEDs is a natural and attractive means to achieve increased spectral efficiencies in VLC. Our study in this paper focuses on multiple LED OFDM techniques to VLC. Our new contribution is the proposal of a scheme which brings in the advantage of 'spatial indexing' to OFDM schemes for VLC. In particular, we propose a *'indexed NDC (I-NDC) OFDM'* scheme, where information bits are not only conveyed through the modulation symbols sent on the active LED, but also through the index of the active LED. This brings in the benefit of higher rate and better performance. Our simulation results show that, for the same spectral efficiency, the proposed I-NDC OFDM outperforms NDC OFDM in the low-to-moderate SNR regime. This is because, to achieve the same spectral efficiency, I-NDC OFDM can use a smaller-sized QAM. However, in the high-SNR regime, NDC OFDM performs better. We find that this is because of the high error rates witnessed by the index bits in I-NDC OFDM due to high channel correlation in multiple LED settings. In order to alleviate this problem and improve the reliability of the index bits at the receiver, we propose to use coding on the index bits alone. This proposed scheme is called *'coded I-NDC OFDM' (CI-NDC OFDM)* scheme. Our simulation results show that, for the same spectral efficiency, the proposed CI-NDC OFDM with coding on the index bits outperforms NDC OFDM.

II. Non-DC biased OFDM for VLC

Non-DC biased (NDC) OFDM [14] exploits the spatial dimension to transmit the bipolar OFDM signal. That is, this scheme uses two LEDs to send the bipolar signals; positive and negative parts drive two different LEDs. Figure 1 shows the block diagram of NDC OFDM. $\left(\frac{N}{2}-1\right)\log_2 M$ incoming data bits are mapped to $\left(\frac{N}{2}-1\right)$ QAM symbols, where M is the QAM constellation size. The DC subcarrier (i.e., X_0) is set to zero. The $\left(\frac{N}{2}-1\right)$ QAM symbols are mapped to subcarriers 1 to $(\frac{N}{2}-1)$, i.e.,$\{X_1, X_2, \cdots, X_{\frac{N}{2}-1}\}$. Hermitian symmetry is applied to the remaining $\frac{N}{2}$ subcarriers, i.e.,

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complex conjugates of the symbols on the first $\frac{N}{2}$ subcarriers are mapped on the second half subcarriers in the reverse order, where the $\left(\frac{N}{2}+1\right)$th subcarrier is set to zero. That is, the input to the N-point IFFT is given by

$$[0,\ X_1,\ X_2,\cdots,\ X_{\frac{N}{2}-1},\ 0,\ X^*_{\frac{N}{2}-1},\cdots,\ X^*_2,\ X^*_1]^T.$$

This Hermitian symmetry ensures that the IFFT output will be real and bipolar. Let $x(n)$ be the bipolar IFFT output. This output is fed to a polarity separator, which separates the positive and negative parts of $x(n)$, i.e., $x(n) = x^+(n)+x^-(n)$, where $x^+(n)$ and $x^-(n)$ are defined as $x^+(n) = \begin{cases} x(n), & \text{if } x(n) \geq 0 \\ 0, & \text{if } x(n) < 0 \end{cases}$, $x^-(n) = \begin{cases} x(n), & \text{if } x(n) < 0 \\ 0, & \text{if } x(n) \geq 0. \end{cases}$ $x^+(n)$ drives the first LED, and $-x^-(n)$ (i.e., polarity inverted signal) drives the second LED. Therefore, at a given time, only one LED will be active, where the index of the active LED (i.e., LED1 and LED2) is decided by the sign of the OFDM signal. This scheme can be viewed as OFDM with spatial modulation (SM), where the LED to activate in a given channel use is chosen based on the sign.

Due to Hermitian symmetry, the number of independent QAM symbols transmitted per OFDM symbol is reduced from N to $\frac{N}{2}-1$. Thus, the achieved data rate of NDC OFDM is

$$\eta_{\text{ndc}} = \frac{N-2}{2N}\ \log_2 M \quad \text{bpcu}. \tag{1}$$

The unipolar OFDM signal is transmitted over the VLC MIMO channel $\mathbf{H}$, where $\mathbf{H}$ is a $N_r \times N_t$ channel matrix, N_t is the number of LEDs, and N_r is the number of PDs. Here, $N_t = N_r = 2$. The output of the PDs are fed to the ADCs. The digitized output of the ADCs, denoted by $\mathbf{y} = [y_1(n)\ \ y_2(n)]^T$, is fed as input to the SM detector. The SM detector, for example, can be zero forcing (ZF) detector. That is, the SM detector output, denoted by $y(n),\ n = 0, 1, \cdots, N-1$, is

$$|y(n)| \ = \ \max_{i=1,2}\ |z_i(n)|, \tag{2}$$

$$\text{sign}\{y(n)\} \ = \ \begin{cases} +\text{ve}, \ \text{if} \ \arg\max\limits_{i=1,2}\ |z_i(n)| = 1 \\ -\text{ve}, \ \text{if} \ \arg\max\limits_{i=1,2}\ |z_i(n)| = 2, \end{cases} \tag{3}$$

$$\begin{bmatrix} z_1(n) \\ z_2(n) \end{bmatrix} \ = \ \begin{bmatrix} \left(\mathbf{h}_1^T\mathbf{h}_1\right)^{-1}\mathbf{h}_1^T\ \mathbf{y} \\ \left(\mathbf{h}_2^T\mathbf{h}_2\right)^{-1}\mathbf{h}_2^T\ \mathbf{y} \end{bmatrix}, \tag{4}$$

and $\mathbf{h}_i$ is the ith column of channel matrix $\mathbf{H}, i = 1, 2$. The SM detector output $y(n)$ is then fed to the N-point FFT. From the N-point FFT output, the subcarriers 1 to $\left(\frac{N}{2}-1\right)$ are demodulated to get back the transmit data. It has been shown that NDC OFDM achieves better performance compared to other OFDM schemes in multiple LED settings [14].

III. Proposed CI-NDC OFDM for VLC

Motivated by the advantages of multiple LEDs and spatial indexing to achieve increased spectral efficiency, here we first propose a multiple LED OFDM scheme called 'indexed NDC OFDM (I-NDC OFDM)'. In this scheme, additional bits are conveyed through the index of the active LED. Then, realizing the need to protect the index bits better in this scheme, we propose to use coding on the index bits. This scheme is called 'coded index NDC OFDM (CI-NDC OFDM)'.

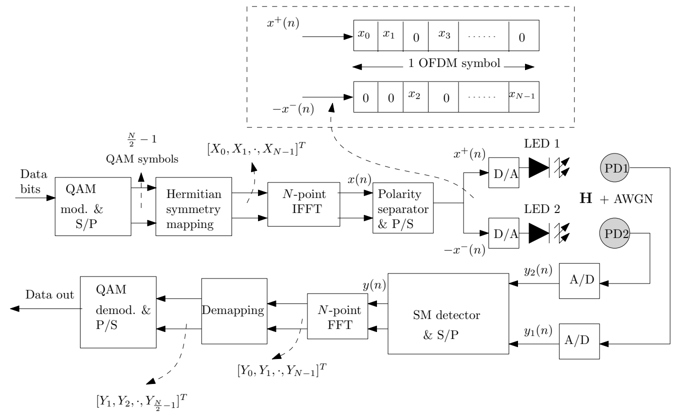

Fig. 1. Non-DC biased OFDM.

A. Proposed I-NDC OFDM

The block diagram of the proposed I-NDC OFDM transmitter is illustrated in Fig. 2. I-NDC OFDM is an N-subcarrier OFDM system with N_p pairs of LEDs and N_r photo detectors, where the total number of LEDs $N_t = 2N_p$. We consider $N_p = 2$, i.e., there are 2 pairs of LEDs. In Fig. 2, the $\{LED1, LED2\}$ pair forms BLOCK 1 and the $\{LED3, LED4\}$ pair forms BLOCK 2. In each channel use, only one LED in either BLOCK 1 or BLOCK 2 will be activated. The choice of which BLOCK has to be activated in a given channel use is made based on indexing. In a general setting, m index bits can select one BLOCK among 2^m BLOCKs. In the considered system, $m = 1$ and $N_p = 2$. Therefore, the BLOCK selection is done using one index bit per channel use. The LED pair in the selected BLOCK will be driven as per the NDC OFDM scheme in Sec. II.

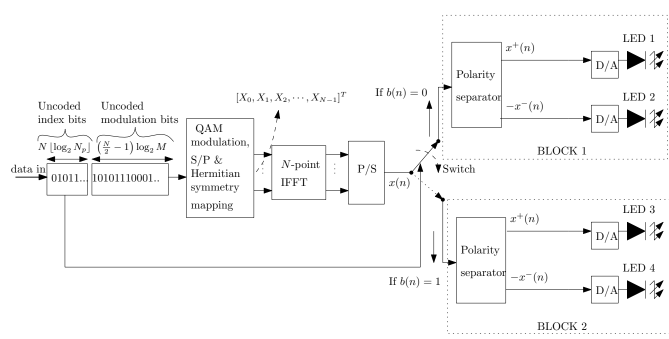

Fig. 2. Proposed I-NDC OFDM transmitter.

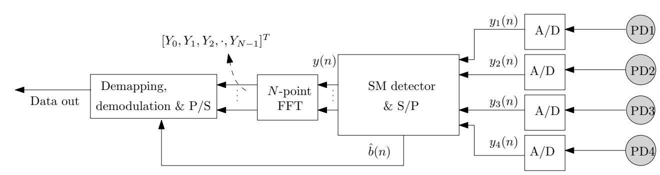

Fig. 3. Proposed I-NDC OFDM receiver.

I-NDC OFDM Transmitter: As in NDC OFDM, in I-NDC OFDM also, $\left(\frac{N}{2}-1\right)\log_2 M$ incoming data bits are first mapped to $\left(\frac{N}{2}-1\right)$ QAM symbols, and the input to the N-point IFFT is given by

$$[0,\ X_1,\ X_2,\cdots,\ X_{\frac{N}{2}-1},\ 0,\ X^*_{\frac{N}{2}-1},\cdots,\ X^*_2,\ X^*_1]^T.$$

This ensures real and bipolar IFFT output. Let $x(n),\ n = 0,1,\cdots,N-1$, be the IFFT output. For large N, (e.g., $N \geq 64$), $x(n)$ can be approximated as i.i.d. real Gaussian with zero mean and variance σ_x^2. Therefore, $|x(n)|$ has an approximately half-normal distribution with mean $\frac{\sigma_x}{\sqrt{2\pi}}$ and variance $\frac{\sigma_x^2(\pi-2)}{2\pi}$ [9]. The IFFT output sequence $x(n)$ is input to a BLOCK selector switch. For each $n,\ n = 0,1,\cdots,N-1$, the switch decides the BLOCK to which $x(n)$ has to be sent. This BLOCK selection in a given channel use is done using index bits. Let $b(n)$ denote the index bit for the nth channel use, $n = 0,1,\cdots,N-1$. The BLOCK selector switch performs the following operation:

$$\begin{aligned} \text{if } b(n) &= 0, \quad x(n) \text{ goes to BLOCK1} \\ \text{if } b(n) &= 1, \quad x(n) \text{ goes to BLOCK2.} \end{aligned}$$

In the selected BLOCK, the polarity separator separates positive and negative parts of $x(n)$; $x(n)$ can be written as

$$x(n) = x^+(n) + x^-(n),$$

$$x^+(n) = \begin{cases} x(n), & \text{if } x(n) \geq 0 \\ 0, & \text{if } x(n) < 0, \end{cases} \quad x^-(n) = \begin{cases} x(n), & \text{if } x(n) < 0 \\ 0, & \text{if } x(n) \geq 0. \end{cases}$$

If the selected BLOCK is BLOCK 1, $x^+(n)$ drives LED1 and $-x^-(n)$ drives LED2. Similarly, if BLOCK 2 is selected, $x^+(n)$ drives LED3 and $-x^-(n)$ drives LED4. So, the light intensity emitted by each LED is either $|x(n)|$ or 0. Since $|x(n)| \sim \mathcal{N}_+\left(\frac{\sigma_x}{\sqrt{2\pi}}, \frac{\sigma_x^2(\pi-2)}{2\pi}\right)$, the intensity I is such that

$$I \in \left\{\mathcal{N}_+\left(\frac{\sigma_x}{\sqrt{2\pi}}, \frac{\sigma_x^2(\pi-2)}{2\pi}\right)\right\}.$$

Achieved data rate: In I-NDC OFDM, $\left(\frac{N}{2}-1\right)$ QAM symbols are sent per OFDM symbol. In addition, $\lfloor \log_2 N_p \rfloor$ number of bits are used to select the active BLOCK per channel use. Therefore, the achieved data rate in I-NDC OFDM is

$$\begin{aligned} \eta_{\text{indc}} &= \left(\frac{\frac{N}{2}-1}{N}\right)\log_2 M + \frac{N\lfloor \log_2 N_p \rfloor}{N} \\ &= \underbrace{\left(\frac{N-2}{2N}\right)\log_2 M}_{\text{modulation bits}} + \underbrace{\lfloor \log_2 N_p \rfloor}_{\text{index bits}} \text{ bpcu.} \end{aligned} \tag{5}$$

I-NDC OFDM Receiver: The block diagram of I-NDC receiver is illustrated in Fig. 3. We assume perfect channel state information at the receiver. Assuming perfect synchronization, the $N_r \times 1$ received signal vector at the receiver is given by

$$\mathbf{y} = r\mathbf{H}\mathbf{x} + \mathbf{n}, \tag{6}$$

where $\mathbf{x}$ is the $N_t \times 1$ transmit vector, r is the responsivity of the detector, and $\mathbf{n}$ is the noise vector of dimension $N_r \times 1$. Each element in the noise vector $\mathbf{n}$ can be modeled as i.i.d. real AWGN with zero mean and variance σ^2. Note that the transmit vector $\mathbf{x}$ has only one non-zero element, and the remaining $N_t - 1$ elements are zeros. The non-zero element in $\mathbf{x}$ represents the light intensity I emitted by the active LED, where $I \sim \mathcal{N}_+\left(\frac{\sigma_x}{\sqrt{2\pi}}, \frac{\sigma_x^2(\pi-2)}{2\pi}\right)$. The average received signal-to-noise ratio (SNR) is given by $\overline{\gamma} = \frac{r^2 P_r^2}{\sigma^2}$, where

$$P_r^2 = \frac{1}{N_r}\sum_{i=1}^{N_r}\mathbb{E}[|\mathbf{H}_i\mathbf{x}|^2] = \frac{\sigma_x^2}{2N_r}\sum_{i=1}^{N_r}\sum_{j=1}^{N_t} h_{ij}^2, \tag{7}$$

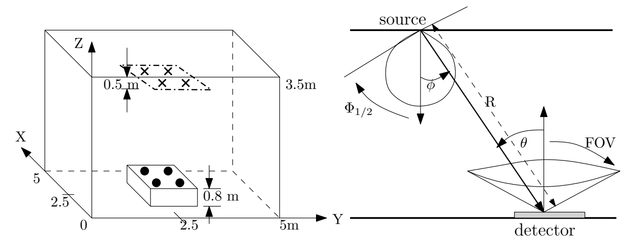

Fig. 4. Geometric set-up of the considered indoor VLC system. A dot represents a photo detector and a cross represents an LED.

and $\mathbf{H}_i$ is the ith row of $\mathbf{H}$. The received optical signals are converted to electrical signals by the PDs. The output of these PDs are then fed to the ADCs. The output of the ADCs is given by the vector $\mathbf{y} = [y_1(n)\quad y_2(n)\quad y_3(n)\quad y_4(n)]^T$, which is fed to the SM detector. The bipolar output of the SM detector is fed to the N-point FFT. The SM detector can be a ZF detector. That is, the SM detector output, denoted by $y(n),\ n = 0,1,\cdots,N-1$, is

$$|y(n)| = \max_{i=1,2,3,4} |z_i(n)| \tag{8}$$

$$\text{sign}\{y(n)\} = \begin{cases} +\text{ve}, & \text{if } \arg\max\limits_{i=1,2,3,4} |z_i(n)| = 1 \\ -\text{ve}, & \text{if } \arg\max\limits_{i=1,2,3,4} |z_i(n)| = 2 \\ +\text{ve}, & \text{if } \arg\max\limits_{i=1,2,3,4} |z_i(n)| = 3 \\ -\text{ve}, & \text{if } \arg\max\limits_{i=1,2,3,4} |z_i(n)| = 4, \end{cases} \tag{9}$$

where

$$\begin{bmatrix} z_1(n) \\ z_2(n) \\ z_3(n) \\ z_4(n) \end{bmatrix} = \begin{bmatrix} (\mathbf{h}_1^T\mathbf{h}_1)^{-1}\mathbf{h}_1^T\ \mathbf{y} \\ (\mathbf{h}_2^T\mathbf{h}_2)^{-1}\mathbf{h}_2^T\ \mathbf{y} \\ (\mathbf{h}_3^T\mathbf{h}_3)^{-1}\mathbf{h}_3^T\ \mathbf{y} \\ (\mathbf{h}_4^T\mathbf{h}_4)^{-1}\mathbf{h}_4^T\ \mathbf{y} \end{bmatrix}, \tag{10}$$

and $\mathbf{h}_i$ is the ith column of channel matrix $\mathbf{H},\ i = 1,2,3,4$. The SM detector output $y(n)$ is fed to the N-point FFT. The subcarriers 1 to $\left(\frac{N}{2}-1\right)$ at the FFT output and demodulated to get back the transmit data. The index bits $b(n)$s are detected as $\hat{b}(n) = 0$ if $\arg\max\limits_{i=1,2,3,4}|z_i(n)| = 1$ or 2. $\hat{b}(n) = 1$ if $\arg\max\limits_{i=1,2,3,4}|z_i(n)| = 3$ or 4.

B. Performance of I-NDC OFDM

Here, we present the BER performance of the proposed I-NDC OFDM scheme for various system parameters. he indoor VLC system set up is shown in Fig. 4. The system parameters of the indoor VLC system considered in the simulation are given in Table I. We also compare the performance of the proposed I-NDC OFDM with that of NDC OFDM. We fix the

Room	Length (X)	5m
	Width (Y)	5m
	Height (Z)	3.5m
Transmitter	Height from the floor	3m
	Elevation	$-90°$
	Azimuth	$0°$
	$\Phi_{1/2}$	$60°$
	Mode number, n	1
	d_{tx}	1m
Receiver	Height from the floor	0.8m
	Elevation	$90°$
	Azimuth	$0°$
	Responsivity, r	1 Ampere/Watt
	FOV	$85°$
	d_{rx}	0.1m

TABLE I
SYSTEM PARAMETERS IN THE CONSIDERED INDOOR VLC SYSTEM.

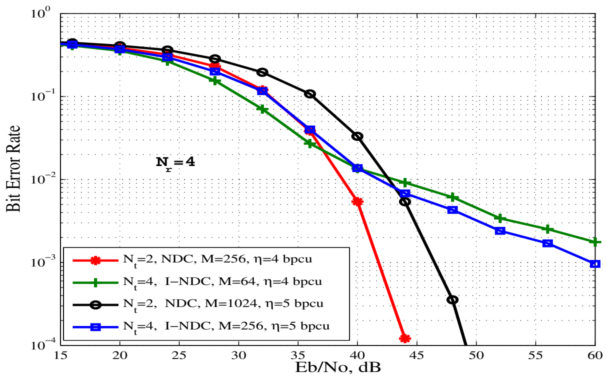

Fig. 5. Comparison of the BER performance of NDC OFDM and the proposed I-NDC OFDM for $\eta = 4,\ 5$ bpcu, $N_r = 4$.

number of LEDs in I-NDC OFDM to be $N_t = 4$ (see Fig. 2), and the number of PDs to be $N_r = 4$. The PDs are kept symmetrical on top of a table with respect to the center of the floor with a d_{rx} of 0.1m. The LEDs are kept symmetrical with respect to the center of the room at 1m apart and at 3m height(i.e., $d_{tx} = 1$m and $z = 3$m). Two among the four LEDs are used for NDC OFDM. The channel gain between jth LED and ith PD is calculated as [1]

$$h_{ij} = \frac{n+1}{2\pi} \cos^n \phi_{ij} \cos\theta_{ij} \frac{A}{R_{ij}^2} \mathrm{rect}\Big(\frac{\theta_{ij}}{FOV}\Big), \qquad (11)$$

where ϕ_{ij} is the angle of emergence with respect to the jth source (LED) and the normal at the source, n is the mode number of the radiating lobe given by $n = \frac{-\ln(2)}{\ln\cos\Phi_{\frac{1}{2}}}$, $\Phi_{\frac{1}{2}}$ is the half-power semiangle of the LED [15], θ_{ij} is the angle of incidence at the ith photo detector, A is the area of the detector, R_{ij} is the distance between the jth source and the ith detector, FOV is the field of view of the detector, and $\mathrm{rect}(x) = 1$ if $|x| \leq 1$ and $\mathrm{rect}(x) = 0$ if $|x| > 1$.

Figure 5 presents the BER performance comparison of I-NDC OFDM and NDC OFDM for $\eta = 4,\ 5$ bpcu. We fix the number of PDs to be $N_r = 4$ for both I-NDC OFDM and NDC OFDM. The parameters considered in these systems for $\eta = 4$ bpcu are: 1) NDC OFDM: $N_t = 2$, $N_r = 4$, $M = 256$, and 2) I-NDC OFDM: $N_t = N_r = 4$, $M = 64$. Similarly, the system parameters considered for $\eta = 5$ bpcu are: 1) NDC OFDM: $N_t = 2$, $N_r = 4$, $M = 1024$, and 2) I-NDC OFDM: $N_t = N_r = 4$, $M = 256$. From Fig. 5, it can be seen that the I-NDC OFDM outperforms NDC OFDM at low SNRs. This is because, to achieve the same spectral efficiency, I-NDC OFDM uses a smaller-sized QAM compared to that in NDC OFDM. But, as the SNR increases, the NDC OFDM outperforms I-NDC OFDM. This is because, as the number of LEDs is increased, the channel correlation increases which affects the detection performance. Note that, though only one LED will be active at a time in both NDC OFDM as well as I-NDC OFDM, NDC OFDM has 2 LEDs whereas I-NDC OFDM has 4 LEDs.

C. Proposed CI-NDC OFDM

Motivation for CI-NDC OFDM: While investigating the poor performance of I-NDC OFDM at high SNRs, we observed from the simulation results that reliability of the index bits is far inferior compared to the reliability of the modulation bits. This is illustrated in Fig. 6. As can be seen, the reliability of the index bits is so poor relative to the that of the modulation bits, the overall performance is dominated by the performance of the index bits. This is because while the modulation bits have the benefit of OFDM signaling to achieve good performance, the index bits did not have any special physical layer care. This has motivated the need to provide some physical layer protection in the form of coding, diversity, etc. Indeed, as can be seen from Fig. 6, in the ideal case of error-free reception of index bits, the I-NDC OFDM has the potential of outperforming NDC-OFDM even at high SNRs; see the plots of I-NDC OFDM (error-free index bits) and NDC OFDM. Motivated by this observation, we propose to use coding to improve the reliability of index bits.

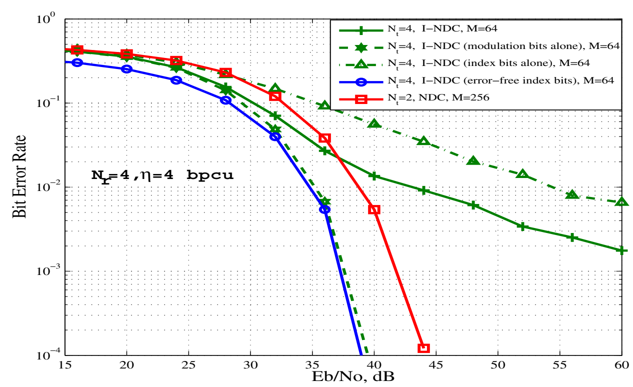

Fig. 6. Reliability of modulation bits and index bits in the proposed I-NDC OFDM for $\eta = 4$ bpcu, $N_r = 4$.

LDPC coding for index bits: We propose to use a rate-r LDPC code to encode k_c uncoded index bits and obtain n_c coded index bits, $r = \frac{k_c}{n_c}$. At the transmitter, k_c uncoded index bits are accumulated to obtain n_c LDPC coded index bits. Now, the n_c coded index bits are used to select the index of the active LED block. Thus, one LDPC codeword of size n_c is transmitted in $\frac{n_c}{\lfloor\log_2 N_p\rfloor}$ channel uses. Therefore, the overall spectral efficiency achieved by the CI-NDC scheme is

$$\eta_{\text{cindc}} = r\lfloor\log_2 N_p\rfloor + \frac{N-2}{2N}\ \log_2 M_c\ \ \text{bpcu}, \qquad (12)$$

where M_c is the size of the QAM alphabet used.

Walsh coding for index bits: Though LDPC codes provide excellent error correction capabilities, their complexity and

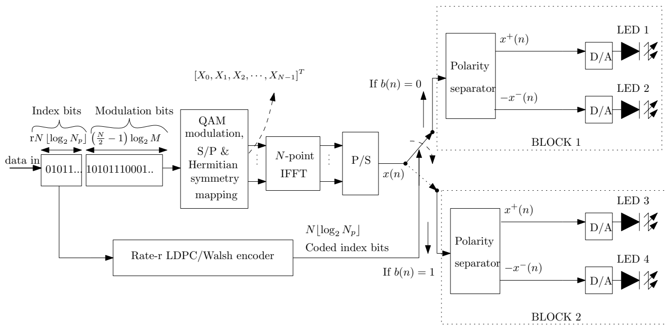

Fig. 7. Proposed CI-NDC OFDM transmitter.

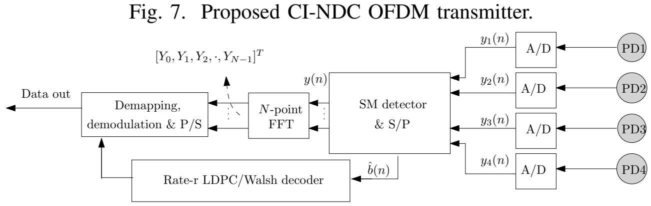

Fig. 8. Proposed CI-NDC OFDM receiver.

delay in decoding are higher. To reduce this, we propose to use Walsh codes for encoding index bits. We encode k_c uncoded index bits to obtain $n_c = 2^{k_c}$ coded index bits, and rate $r = \frac{k_c}{2^{k_c}}$. At the transmitter, k_c uncoded bits choose one of the 2^{k_c} columns of the Walsh matrix of size $2^{k_c} \times 2^{k_c}$, the 2^{k_c} entries of the chosen column become the coded index bits to be transmitted. Thus, the achieved spectral efficiency is

$$\eta_{cindc} = \frac{k_c}{2^{k_c}} \lfloor \log_2 N_p \rfloor + \frac{N-2}{2N} \log_2 M_c \quad \text{bpcu}. \tag{13}$$

For small values of k_c, this scheme achieves very low-complexity of encoding, decoding and smaller delay in decoding, while providing very good performance.

The proposed CI-NDC OFDM transmitter and receiver are shown in Figs. 7 and 8, respectively.

D. Performance of CI-NDC OFDM

In Fig. 9, we compare the performance of the proposed C-INDC OFDM with that of NDC OFDM. We compare the following configurations: 1) NDC OFDM: $N = 64$, $M = 256$, $N_t = 2$, $N_r = 4$, $\eta_{ndc} = 3.875$ bpcu, 2) C-INDC OFDM with LDPC: $N = 64$, $M_c = 128$, $N_t = 4$, $N_r = 4$, $r = \frac{1}{2}$, $k_c = 504$, $n_c = 1008$, $\eta_{cindc} = 3.891$ bpcu, and 3) C-INDC OFDM with Walsh: $N = 64$, $M_c = 128$, $N_t = 4$, $N_r = 4$, $k_c = 5$, $n_c = 32$, $\eta_{cindc} = 3.547$ bpcu. From Fig. 9, we observe that, for approximately the same spectral efficiency of about 3.8 bpcu, the proposed CI-NDC OFDM performs better than NDC OFDM. For example, to achieve a BER of 10^{-5}, CI-NDC OFDM requires about 1.3 dB less SNR compared to NDC OFDM. This is because of the improved reliability of the index bits achieved through coding of index bits.

IV. Conclusions

We proposed an efficient multiple LED OFDM scheme, termed as coded index non-DC-biased OFDM, for VLC. In the proposed scheme, additional information bits were conveyed through indexing in addition to QAM bits. The channel

Walsh matrices of size n_c consists of 1's and 0's such that they are orthogonal in the binary field. This enables low-complexity of decoding [16].

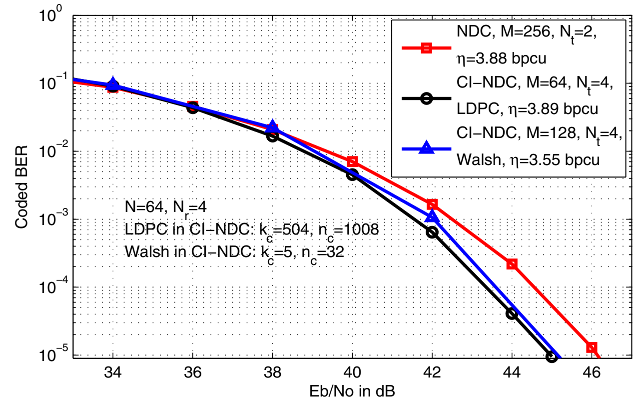

Fig. 9. BER performance of the proposed CI-NDC OFDM and NDC OFDM at $\eta = 3.8$ bpcu, $N_r = 4$.

correlation in multiple LED settings was found to significantly degrade the reliability of index bits recovery. To overcome this, we proposed coding of index bits. This was found to serve the intended purpose of achieving better performance compared to other OFDM schemes for VLC. Investigation of the proposed signaling architecture for higher-order index modulation using multiple pairs of LEDs can be a topic of further study.

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