Space-Time Indexed Multiple-LED Complex Modulation Schemes for VLC Systems

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***Abstract*—This paper proposes two index modulation schemes for multiple-input multiple-output (MIMO) visible light communication (VLC) systems, referred to as time index modulated DCM (TIM-DCM) and space-time index modulated DCM (STIM-DCM) schemes. The proposed schemes use dual-LED complex modulator (DCM) as a basic unit (termed as DCM block) to transmit complex modulation symbols. In TIM-DCM scheme, a time slot in given frame can be used or unused, and the pattern in which the slots are used for transmission also conveys information bits (referred to as slot index bits) besides the information bits conveyed through complex modulation symbols. In STIM-DCM scheme, in addition to the slot index bits and modulation bits, spatial index bits are conveyed by activating one among the available DCM blocks in every used time slot. Hence, the proposed schemes can achieve high rates. We study the bit error rate (BER) performance of the proposed schemes and compare with that of the state-of-art modulation schemes such as spatial modulation DCM (SM-DCM) scheme. Results show that the proposed schemes can achieve better BER performance. Also, results on the spatial distribution of best performing modulation scheme indicates that the proposed schemes are favorable for different receiver locations across the room.**

Keywords – *Visible light communication, MIMO VLC, complex modulation, time indexing, spatial indexing.*

I. Introduction

With the tremendous rise in the usage of mobile electronic devices such as smart phones/tablets that have high data rate and bandwidth requirements, the available RF spectrum is getting heavily crowded. Millimeter wave communication that uses millimeter wave frequencies with large available bandwidths is a popular RF communication approach to meet the growing demands for wireless data capacity. Visible light communication (VLC) that uses visible light spectrum for wireless transmissions is emerging as an attractive alternative to the RF communication technology [1].

The transmitter in VLC systems uses light emitting diodes (LED) to transmit data wirelessly in visible light wavelengths (400nm to 700nm). The received signals are detected by the photo detectors (PD) at the receiver. Intensity modulation (IM) of the LED at the transmitter and direct detection (DD) of intensities by PD at the receiver are extensively used in VLC systems. Real and non-negative signals are used to modulate the LEDs as information is conveyed by varying the light intensity. Use multiple LEDs and multiple PDs in multiple-input multiple-output (MIMO) configurations can offer increased rates.

In OFDM based indoor VLC systems, complex signal sets such as M-ary quadrature amplitude modulation (QAM) are often used. Variants of OFDM for VLC such as dc-biased optical (DCO) OFDM, asymmetrically clipped optical (ACO) OFDM, flip OFDM, and index modulation for NDC-OFDM are known in the literature [2]-[4]. These schemes use Hermitian symmetry operation to convert complex modulation symbols to real non-negative signals, which reduces the transmission rate. Complex modulation schemes reported in the recent literature eliminate the use of Hermitian symmetry operation through the use of multiple LEDs. These schemes include quad-LED complex modulation (QCM) and dual-LED complex modulation (DCM) [5]. Moreover, the performance of the QCM and DCM schemes have been shown to be better than other MIMO modulation schemes such as SMP, SM, GSM [5].

In RF communications, the use of time indexing and spatial indexing has been shown to improve performance [6],[7]. A multi-antenna modulation scheme termed as space-time index modulation (STIM) performs indexing in spatial and time domains and achieve good performance compared to the conventional OFDM scheme [6]. In [7], media based modulation (MBM) scheme with time indexing has been shown to achieve improved performance compared to conventional MBM scheme. Against this background, in this paper, we propose two new multiple-LED complex modulation schemes, referred to as time index modulated DCM (TIM-DCM) and space-time index modulated DCM (STIM-DCM), suited for VLC systems. The proposed schemes employ dual-LED complex modulator as the basic unit (termed as DCM block) to transmit complex modulation symbols.

A DCM block consists of two LEDs to transmit a complex modulation symbol, where one LED conveys the magnitude and the other LED conveys the phase information of the symbol [5]. The proposed schemes are block transmission schemes where the transmission is carried out in frames and each frame consists of certain number of time slots. Each slot can be used or unused for transmission. The proposed TIM-DCM scheme uses only one DCM block and the complex symbols are transmitted from that DCM block in every used time slot. In TIM-DCM scheme, the pattern in which the time slots are used for transmission convey information bits through time slot indexing. The proposed STIM-DCM scheme uses multiple DCM blocks where in addition to the time slot indexing, spatial indexing is performed by activating one among the available DCM blocks and the complex symbol is sent from the active DCM block in every used time slot. We compare the BER performance of the proposed TIM-DCM and STIM-DCM schemes with the basic DCM scheme without indexing and DCM with spatial modulation (SM-DCM) scheme proposed in [5]. Simulation results show that the proposed schemes can achieve better performance. Also, the spatial distribution of best performing modulation scheme indicate that the proposed schemes are favorable for different receiver locations across the room.

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by $\overline{\gamma} = \frac{a^2}{\sigma^2 n_r}\sum_{i=1}^{n_r}\mathbb{E}\{(\mathbf{H}_i\mathbf{x})^2\}$ where $\mathbb{E}\{.\}$ is the expectation operator and the expectation is w.r.t. the signal vector $\mathbf{x}$, and $\|.\|$ is the Euclidean norm operator.

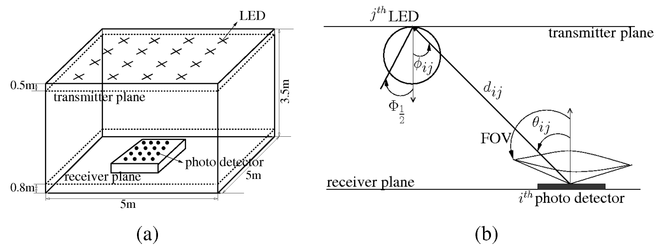

Fig. 1. (a) Geometric setup of a typical indoor MIMO VLC system. (b) LOS channel between jth LED and ith PD.

II. Indoor MIMO VLC System Model

Consider an indoor MIMO VLC system inside a room of size 5m×5m×3.5m as shown in Fig. 1(a). The transmitter consists of n_t LEDs located in the transmitter plane which is 0.5m below the ceiling. LEDs convert the data stream in the electrical domain to optical domain. Assume that each LED emits unpolarized white light with Lambertian radiation pattern. In a given channel use, each LED emits light with certain intensity based on the MIMO modulation scheme used. Let x_j denotes the light intensity emitted by the jth LED so that the $n_t\times 1$ transmit signal vector $\mathbf{x}$ is $\mathbf{x} = [x_1\ x_2\ \cdots x_{n_t}]^T$. The receiver consists of n_r PDs that are placed on a table located at 0.8m above the ground. The PDs receive the optical signals and convert them to electrical domain to detect the transmitted data. The line-of-sight (LOS) channel gain between the jth LED and ith PD, denoted by h_{ij}, can be calculated as (see Fig. 1(b)):

$$h_{ij} = \frac{m+1}{2\pi}\cos^m\phi_{ij}\,\cos\theta_{ij}\frac{A}{d_{ij}^2}\mathrm{rect}\Big(\frac{\theta_{ij}}{FOV}\Big), \tag{1}$$

where ϕ_{ij} is the angle of emergence for jth LED with respect to its normal, θ_{ij} is the angle of incidence at the ith PD, d_{ij} is the LOS distance between jth LED and ith PD, m is the mode number of the radiating lobe given by $m = \frac{-\ln(2)}{\ln\cos\Phi_{\frac{1}{2}}}$, A is the area of the PD, FOV is the field-of-view of the PD, and $\mathrm{rect}(x) = 1$, if $|x| \leq 1$, and $\mathrm{rect}(x) = 0$, if $|x| > 1$, $\Phi_{\frac{1}{2}}$ is the half-power semi-angle of the LEDs. The $n_r \times n_t$ MIMO channel matrix $\mathbf{H}$ is given by

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \cdots & h_{1n_t} \\ h_{21} & h_{22} & h_{23} & \cdots & h_{2n_t} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ h_{n_r1} & h_{n_r2} & h_{n_r3} & \cdots & h_{n_rn_t} \end{bmatrix}. \tag{2}$$

At the receiver, in the electrical domain, the received signal vector of dimension $n_r \times 1$ is given by

$$\mathbf{y} = a\mathbf{H}\mathbf{x} + \mathbf{z}, \tag{3}$$

where $\mathbf{z}$ is the noise vector of dimension $n_r \times 1$, $\mathbf{x}$ is the transmit signal vector, and a is the responsivity of the PD (in Amp/Watt). The transmit signal vector $\mathbf{x}$ consists of optical intensity values that are determined based on the modulation scheme used. Each element in the noise vector $\mathbf{z}$ is the sum of received thermal noise and noise due to ambient light, and is modeled as i.i.d. real AWGN with zero mean and variance σ^2. The average received SNR in the electrical domain is given by $\overline{\gamma} = \frac{a^2}{\sigma^2 n_r}\sum_{i=1}^{n_r}\mathbb{E}\{(\mathbf{H}_i\mathbf{x})^2\}$ where $\mathbb{E}\{.\}$ is the expectation operator and the expectation is w.r.t. the signal vector $\mathbf{x}$, and $\|.\|$ is the Euclidean norm operator.

A. Normalized minimum Euclidean distance metric

For a given $\mathbf{H}$ and the the transmit signal set $\mathbb{S}_{\text{Tx}}$, let $\mathbb{S}_{\text{Rx}} = \{\mathbf{H}\mathbf{x}_1, \mathbf{H}\mathbf{x}_2, \cdots, \mathbf{H}\mathbf{x}_L\}$ denote the received signal set in the absence of noise. The vectors in $\mathbb{S}_{\text{Rx}}$ are normalized by the average received signal power to get normalized received signal set $\tilde{\mathbb{S}}_{\text{Rx}} = \{\tilde{\mathbf{y}}_1, \tilde{\mathbf{y}}_2, \cdots, \tilde{\mathbf{y}}_L\}$, where $\tilde{\mathbf{y}}_i = \frac{\mathbf{H}\mathbf{x}_i}{\sqrt{\frac{1}{Ln_r}\sum_{i=1}^{L}||\mathbf{H}\mathbf{x}_i||^2}}$. The minimum Euclidean distance of the normalized received signal set is

$$\tilde{d}_{\text{min},\mathbf{H}} = \min_{\tilde{\mathbf{y}}_i,\tilde{\mathbf{y}}_j \in \tilde{\mathbb{S}}_{\text{Rx}}, i\neq j} \|\tilde{\mathbf{y}}_i - \tilde{\mathbf{y}}_j\|. \tag{4}$$

The relative performance of the modulation schemes in the high SNR regime can be evaluated using $\tilde{d}_{\text{min},\mathbf{H}}$. Let $\mathbb{S}_{\text{Tx}}^{(1)}$ and $\mathbb{S}_{\text{Tx}}^{(2)}$ denote the signal sets of two different modulation schemes, and let $\tilde{d}^{(1)}_{\text{min},\mathbf{H}}$ and $\tilde{d}^{(2)}_{\text{min},\mathbf{H}}$ denote their corresponding normalized minimum Euclidean distances, for a given $\mathbf{H}$. In the high SNR regime, if $\tilde{d}^{(1)}_{\text{min},\mathbf{H}} > \tilde{d}^{(2)}_{\text{min},\mathbf{H}}$, then the BER performance of modulation scheme with signal set $\mathbb{S}_{\text{Tx}}^{(1)}$ will be better than that of the scheme with $\mathbb{S}_{\text{Tx}}^{(2)}$. Also, the SNR gap between the BER performance of the two modulation schemes in the high SNR regime is given by $20\log\big(\tilde{d}^{(1)}_{\text{min},\mathbf{H}}/\tilde{d}^{(2)}_{\text{min},\mathbf{H}}\big)$.

B. DCM scheme

DCM scheme in [5] uses two LEDs to implement a complex modulator unit suited for VLC. It exploits the polar representation of complex numbers to transmit complex modulation symbols. One LED conveys the magnitude and the other LED conveys the phase of a complex symbol. The complex modulation symbol s can be written in the form

$$s = re^{j\phi}, \tag{5}$$

where $r = |s|$, $r \in \mathbb{R}^+$, and $\phi = \angle s$, $\phi \in [0, 2\pi)$. One LED emits intensity value r and the other LED emits intensity value ϕ. Hence, the 2×1 dimension transmit vector $\mathbf{x}$ is given by $\mathbf{x} = [r \quad \phi]^T$. The proposed modulation schemes (presented in the next section) use DCM blocks for signaling complex modulation symbols.

III. Proposed modulation schemes

In this section, we present the proposed TIM-DCM and STIM-DCM schemes using DCM as the basic building block.

A. Time index modulated DCM (TIM-DCM) scheme

The transmitter of the proposed TIM-DCM scheme is shown in Fig. 2. It consists of a DCM block that uses two LEDs to transmit complex modulation symbols. In TIM-DCM, transmission is carried out in frames. Each frame consists of N time slots (i.e, N channel uses). Out of these N slots, only k slots are used for transmission of complex modulation symbols using the DCM block. These slots are called as active slots. The remaining $N-k$ slots are called as inactive slots during which the DCM block remains silent (i.e, the two LEDs will remain OFF). There are $\binom{N}{k}$ ways of choosing which

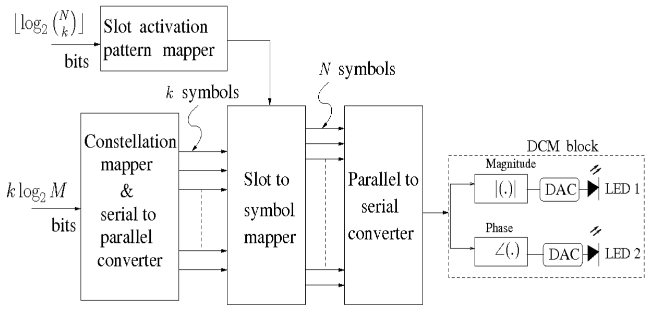

Fig. 2. Proposed TIM-DCM transmitter.

k slots are active and which $N-k$ slots are inactive. Let a given realization of active/inactive status of N slots in a frame be called as 'slot activation pattern (SAP)'. There are $\binom{N}{k}$ possible SAPs out of which $2^{\lfloor \log_2 \binom{N}{k} \rfloor}$ SAPs are used for slot indexing and are conveyed by $\lfloor \log_2 \binom{N}{k} \rfloor$ slot index bits. In each active time slot, a complex modulation symbol chosen from the M-ary modulation alphabet $\mathbb{M}$ is transmitted by the DCM block. As $\log_2 M$ bits are used to choose a modulation symbol, $k\log_2 M$ information bits are used to choose k complex symbols for transmission in k active slots. Hence, $\lfloor \log_2 \binom{N}{k} \rfloor + k\log_2 M$ information bits are transmitted in a frame. The achieved rate of TIM-DCM scheme, therefore, is given by

$$\eta_{\text{tim-dcm}} = \frac{1}{N}\Bigg\{ \underbrace{\Big\lfloor \log_2 \binom{N}{k} \Big\rfloor}_{slot\ index\ bits} + \underbrace{k\log_2 M}_{modulation\ bits} \Bigg\} \text{ bpcu.} \quad (6)$$

The transmit signal vector $\mathbf{x}$ of TIM-DCM is of size $2N \times 1$ and consists of the intensity values emitted by the two LEDs in the DCM block in N slots of the frame.

Example: Let $N=5$, $k=4$, and 4-QAM be the modulation alphabet. Here, $\binom{N}{k} = \binom{5}{4} = 5$ possible SAPs are: [1 1 1 1 0], [1 1 1 0 1], [1 1 0 1 1], [1 0 1 1 1], [0 1 1 1 1], where the 1's indicate the locations of the active time slots and the 0's indicate the locations of inactive time slots. Out of the 5 possible SAPs, the first four SAPs are used for slot indexing to convey 2 information bits. In this system, 10 information bits are transmitted per frame and the achieved rate is 2 bpcu. Let 1000100110 be the input bit sequence to be transmitted. The first two bits (i.e, 10) are slot index bits and [1 0 1 1 1] is the SAP. The remaining 8 bits are used to choose symbols $-1+j$, $1+j$, $-1-j$, and $1+j$, with 2 bits being used to chose each symbol. These four complex symbols are transmitted in the four active slots using the DCM block. Hence, the 10×1 transmit signal vector for this example is $\mathbf{x} = [\sqrt{2}\ \ 3\pi/4\ \ 0\ \ 0\ \ \sqrt{2}\ \ \pi/4\ \ \sqrt{2}\ \ 5\pi/4\ \ \sqrt{2}\ \ \pi/4]^T$.

Let $\mathbf{H}$ be the $n_r \times 2$ size channel gain matrix computed by following the system model described in Sec. II. As the transmission occurs in frames consisting of N channel uses, the equivalent channel gain matrix in TIM-DCM scheme ($\mathbf{H}_{eq}$) is a block diagonal matrix of size $Nn_r \times 2N$, where each block diagonal element is the channel gain matrix $\mathbf{H}$. The received signal vector $\mathbf{y}$ of size $Nn_r \times 1$ at the receiver is given by

$$\mathbf{y} = a\mathbf{H}_{eq}\mathbf{x} + \mathbf{z}, \quad (7)$$

where $\mathbf{z}$ is noise vector of size $Nn_r \times 1$, $\mathbf{z} \sim \mathcal{N}(0, \sigma^2 I_N)$, and $\mathbf{x}$ is the TIM-DCM transmit signal vector of size $2N \times 1$. Assuming that $\mathbf{H}_{eq}$ is known at the receiver, the maximum likelihood (ML) estimate of the transmit vector is given by

$$\hat{\mathbf{x}}_{\text{ML}} = \underset{\mathbf{x} \in \mathbb{S}_{\text{TIM-DCM}}}{\text{argmin}} \ \|\mathbf{y} - a\mathbf{H}_{eq}\mathbf{x}\|^2. \quad (8)$$

where $\mathbb{S}_{\text{TIM-DCM}}$ is the transmit signal set of TIM-DCM scheme. The detected signal vector $\hat{\mathbf{x}}_{\text{ML}}$ is demapped to recover the information bits.

B. Space-time index modulated DCM (STIM-DCM) scheme

Here, we shall construct the STIM-DCM scheme by extending the TIM-DCM scheme to include multiple DCM blocks. The transmitter of the proposed STIM-DCM scheme is shown in Fig. 3. It consists of n_t LEDs, where $n_t = 2^q$ and q is an integer ≥ 2. The n_t LEDs are grouped into $n_p = \frac{n_t}{2}$ DCM blocks, each with two LEDs. In STIM-DCM scheme, in additional to the indexing of the time slots, spatial indexing of the DCM blocks is performed during the active time slots to transmit additional information bits. During the active time slot, a complex modulation symbol chosen from M-ary modulation alphabet $\mathbb{M}$ is transmitted from one among the n_p DCM blocks and the remaining DCM blocks will remain OFF. Thus, in a active time slot, $\log_2 M$ information bits are used to choose a complex symbol and $\log_2 n_p$ information bits are used to determine the index of active DCM block that transmits the complex symbol. During the inactive time slot, all the DCM blocks will be OFF (i.e., LEDs emit with zero intensity level). Hence, in a given frame, $\lfloor \log_2 \binom{N}{k} \rfloor$ information bits are used as slot index bits, $k\log_2 M$ bits are used as modulation bits, and $k\log_2 n_p$ bits are used as spatial index bits. The achieved rate of STIM-DCM scheme is given by

$$\eta_{\text{stim-dcm}} = \frac{1}{N}\Bigg\{ \underbrace{\Big\lfloor \log_2 \binom{N}{k} \Big\rfloor}_{slot\ index\ bits} + \underbrace{k\log_2 n_p}_{spatial\ index\ bits} + \underbrace{k\log_2 M}_{modulation\ bits} \Bigg\} \text{ bpcu.} \quad (9)$$

The transmit signal vector $\mathbf{x}$ of STIM-DCM scheme is of size $Nn_t \times 1$ and consists of the intensity values emitted by the n_t LEDs in N slots of the frame.

Example: Let $n_p = 2$, $N = 4$, $k = 3$, and 4-QAM be the modulation alphabet. Here, $\binom{N}{k} = \binom{4}{3} = 4$ possible SAPs are: [1 1 1 0], [1 1 0 1], [1 0 1 1], [0 1 1 1]. In this system, 11 information bits are transmitted per frame and the achieved rate is $(11/4) = 2.75$ bpcu. Let 01110001001 be the input bit sequence to be transmitted. The first two bits (i.e., 01) are slot index bits and [1 1 0 1] is the SAP. The next 6 bits (i.e., 110001) are used to choose symbols $1-j$, $-1+j$, and $1+j$, with 2 bits being used to chose each symbol. The remaining 3 bits (i.e., 001) are used to determine the index of active DCM blocks that transmits the complex symbols. In the first and second time slots, DCM Block 1 transmits the symbols $1-j$ and $-1+j$, whereas the DCM Block 2 remains OFF. In the third slot, both the DCM blocks are OFF. In the fourth slot, DCM Block 2 transmits $1+j$, whereas DCM Block 1 remains

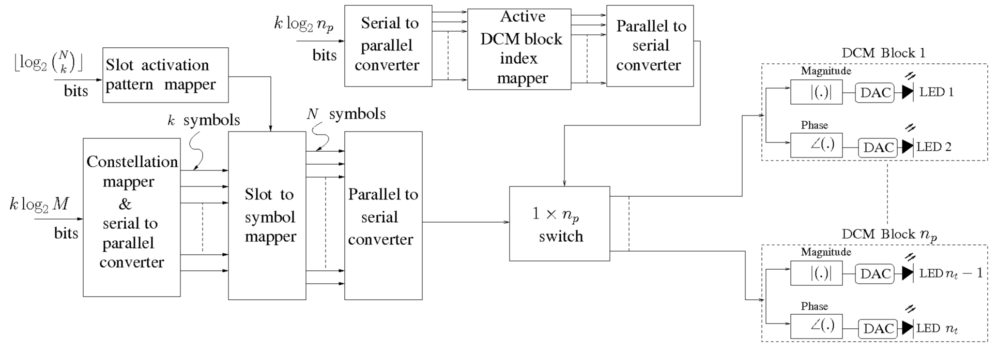

Fig. 3. Proposed STIM-DCM transmitter.

Room	Length × Width × Height	5m × 5m × 3.5m
2 × 4 system transmitter	No. of LEDs (n_t)	2
	Height from the floor	3m
	Mode number (m)	1
	d_{tx}	3m
4 × 4 system transmitter	No. of LEDs (n_t)	4
	Height from the floor	3m
	Mode number (m)	1
	d_{tx}	3m
2 × 4 and 4 × 4 system receiver	No. of PDs (n_r)	4
	Height from the floor	0.8m
	Responsivity of PD (a)	0.4 Ampere/Watt
	Field-of-view (FOV)	85°
	d_{rx}	0.1m

TABLE I
SYSTEM PARAMETERS FOR DIFFERENT CONFIGURATIONS OF INDOOR MIMO VLC SYSTEM.

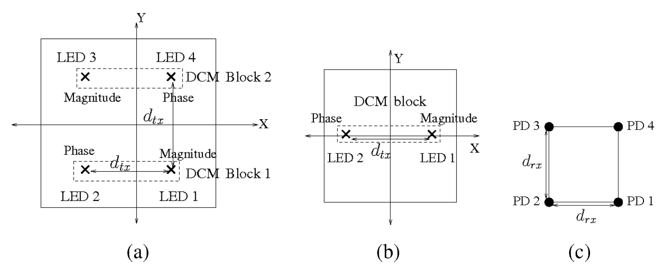

Fig. 4. Arrangement of (a) LEDs in 4×4 system, (b) LEDs in 2×4 system, and (c) PDs in 2×4 and 4×4 systems.

OFF. Hence, the 16×1 transmit signal vector for this example is

$$\mathbf{x} = [\sqrt{2} \;\; 7\pi/4 \;\; 0 \;\; 0 \; \sqrt{2} \;\; 3\pi/4 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; \sqrt{2} \;\; 5\pi/4]^T.$$

The equivalent channel gain matrix $\mathbf{H}_{eq}$ in STIM-DCM is a $Nn_r \times Nn_t$ size block diagonal matrix in which each block diagonal element is the $n_r \times n_t$ size channel gain matrix $\mathbf{H}$ computed by following the system model described in Sec. II.

IV. Results and Discussions

In this section, we present the BER performance and spatial performance results of the proposed TIM-DCM and STIM-DCM schemes. We compare the BER performance results of the proposed TIM-DCM scheme with that of the DCM scheme, and the results of the proposed STIM-DCM scheme with that of the SM-DCM scheme in [5]. We consider 2×4 and 4×4 MIMO configurations. TIM-DCM and DCM schemes using one DCM block in 2×4 MIMO configuration, and

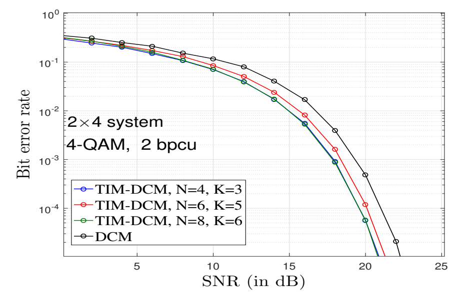

Fig. 5. BER vs SNR performance comparison between the proposed TIM-DCM scheme and the DCM scheme at 2 bpcu.

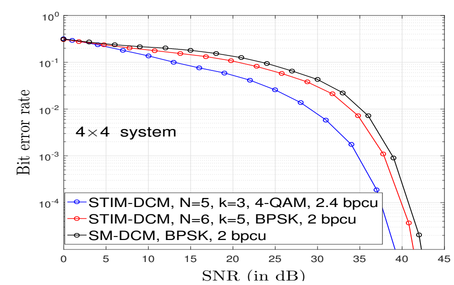

Fig. 6. BER vs SNR performance comparison between the proposed STIM-DCM scheme and the SM-DCM scheme at 2 bpcu.

STIM-DCM and SM-DCM schemes with $n_p = 2$ (i.e., two DCM blocks) in 4×4 MIMO configuration are considered. The positions of LEDs and PDs in 2×4 and 4×4 MIMO configurations are shown in Fig. 4. Table I shows the system parameters used in the simulation. The receiver is located at the center of the room on the receiver plane (i.e., on a table located 0.8m above the ground) and ML detection is used at the receiver. The spatial distribution of best performing modulation scheme based on the minimum euclidean distance metric is also presented.

BER vs SNR performance: We present the BER performance of the proposed modulation schemes obtained through simulation. Figure 5 shows the BER performance comparison of various configurations of the proposed TIM-DCM scheme and the DCM scheme at 2 bpcu. TIM-DCM scheme with three different configurations are considered: (i) $N = 4$ and $k = 3$, (ii) $N = 6$ and $k = 5$, and (iii) $N = 8$ and $k = 6$. 4-QAM is used as the modulation alphabet in DCM scheme and all the three configurations of TIM-DCM scheme. At 10^{-5} BER, the proposed TIM-DCM schemed with configurations (i) and

Modulation scheme		$\tilde{d}_{\min,\mathbf{H}}$
TIM-DCM	$N=4$ and $k=3$, 4-QAM, 2 bpcu	0.7435
	$N=6$ and $k=5$, 4-QAM, 2 bpcu	0.7053
	$N=8$ and $k=6$, 4-QAM, 2 bpcu	0.7435
STIM-DCM	$N=5$ and $k=3$, 4-QAM, 2.4 bpcu	0.0777
	$N=6$ and $k=5$, BPSK, 2 bpcu	0.0660
DCM (4-QAM, 2 bpcu)		0.6439
SM-DCM (BPSK, 2 bpcu)		0.0603

TABLE II
$\tilde{d}_{\text{MIN},\mathbf{H}}$ VALUES FOR DIFFERENT CONFIGURATIONS OF TIM-DCM AND STIM-DCM SCHEMES, DCM SCHEME AND SM-DCM SCHEME.

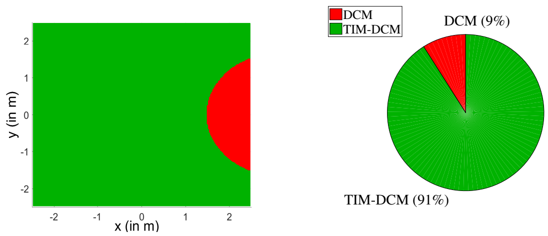

Fig. 7. Spatial distribution of best performing modulation scheme among TIM-DCM and DCM schemes at 2 bpcu.

(iii) outperform DCM scheme by 1.5 dB, whereas the scheme with configuration (ii) outperform by 1 dB. This can also be verified with the $\tilde{d}_{\min,\mathbf{H}}$ values presented in the Table II, where we observe that the $\tilde{d}_{\min,\mathbf{H}}$ values are higher for TIM-DCM compared to those of DCM.

Figure 6 shows the BER performance comparison between the proposed STIM-DCM scheme with two different configurations: (i) $N=5$ and $k=3$ (ii) $N=6$ and $k=5$, and the SM-DCM scheme. The STIM-DCM scheme with configuration (ii) and SM-DCM scheme achieve rate of 2 bpcu with BPSK as the modulation alphabet, whereas the STIM-DCM scheme with configuration (i) achieves rate of 2.4 bpcu with 4-QAM as the modulation alphabet. At 10^{-5} BER, compared to the SM-DCM scheme, performance gains up to 3 dB and 1 dB can be achieved by the STIM-DCM scheme with configurations (i) and (ii), respectively. Also, the $\tilde{d}_{\min,\mathbf{H}}$ values presented in the Table II verifies the same.

Spatial distribution of best performing modulation scheme: The channel gain matrix in MIMO VLC systems depends upon the relative positions of transmitter and receiver. As the receiver location changes, the channel gain matrix also changes, which, in turn, may result in the variation of BER performance. As discussed in Sec. II, in the high SNR regime, the modulation scheme with higher $\tilde{d}_{\min,\mathbf{H}}$ value has better BER performance than the scheme with lower $\tilde{d}_{\min,\mathbf{H}}$ value. In this subsection, we present the best performing modulation scheme in the high SNR regime among TIM-DCM (with $N=4$, $k=3$, and 4-QAM) and DCM schemes at 2 bpcu for various receiver locations across the room based on their $\tilde{d}_{\min,\mathbf{H}}$ values. We also present the spatial distribution of best performing modulation scheme among STIM-DCM (with $N=6$, $k=5$, and BPSK) and SM-DCM schemes at 2 bpcu. A grid of 200×200 points is obtained by dividing the receiver plane and each grid point is considered as a receiver location. For each receiver location, we compute channel gain matrix from using (1), (2), and then compute $\tilde{d}_{\min,\mathbf{H}}$ values for the modulation schemes considered using (4). The modulation scheme with highest $\tilde{d}_{\min,\mathbf{H}}$ is the best performing modulation scheme for that receiver location. Each modulation scheme is assigned a particular color (e.g., TIM-DCM: green, DCM: red) in the spatial distribution plots. For the given receiver location, the corresponding grid point is filled with the color of best performing modulation scheme in the spatial distribution plot. Figure 7 shows the spatial distribution plot of best performing modulation scheme among TIM-DCM and DCM schemes at 2 bcpu. It is observed that TIM-DCM is the most favorable scheme as it performs best across 91% of the room area whereas DCM scheme performs best across only 9% of the room area. Similarly, Fig. 8 shows the spatial distribution plot of best performing modulation scheme among STIM-DCM and SM-DCM schemes at 2 bcpu. Here, it is observed that both the STIM-DCM and SM-DCM schemes are favorable schemes as they perform best across 49.25% and 50.75% of room area, respectively.

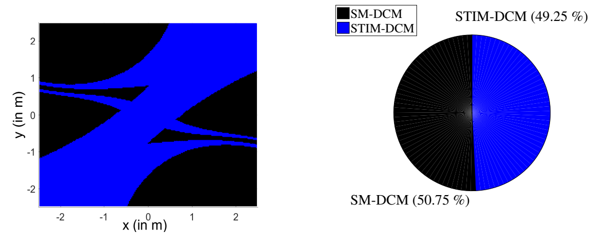

Fig. 8. Spatial distribution of best performing modulation scheme among STIM-DCM and SM-DCM schemes at 2 bpcu.

V. Conclusions

Two index modulation schemes that use dual-LED complex modulator (DCM) as the basic building block to transmit complex symbols in MIMO VLC systems were proposed. The proposed schemes were termed as TIM-DCM and STIM-DCM schemes. In TIM-DCM, the pattern in which the slots are used for transmission conveyed additional information bits. In STIM-DCM, besides time slot indexing, spatial indexing is performed by activating one among the available DCM blocks in every used time slot. The proposed schemes were shown to achieve high rates and improved performance compared to the DCM and SM-DCM schemes known in the literature. Also, the spatial distribution of best performing modulation scheme indicated that the proposed modulation schemes are favorable for different receiver locations across the room.

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