The Index-based Optical Spatial Modulation Scheme in Optical MIMO

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***Abstract*— Optical Multi-input Multi-output (O-MIMO) is considered as an effective solution in order to achieve high performance for Visible Light Communication (VLC) systems. However, O-MIMO systems are faced with the impact of Inter-Channel Interference (ICI) which results in system performance decrease. In this paper, a novel Index-based Optical Spatial Modulation (IOSM) is proposed to remove ICI and increase spectrum efficiency for indoor VLC systems applying O-MIMO. In our proposed scheme, the signals are DC biased for intensity modulation and direct detection (IM/DD) and a Maximum-likelihood (ML) decoder decision to maximize the signal-to-noise ratio (SNR) at the receiver. Computer simulation results show that the proposed scheme outperforms previously proposed spatial modulation schemes in O-MIMO systems.**

Keywords*— *Visible Light Communications (VLC), Optical multiple input multiple output (O-MIMO), Beamforming, Optical Spatial Modulation.

I. INTRODUCTION

The potential challenges of OWC are *i*) the limited modulation capabilities of lighting-grade LEDs, *ii)* the directional nature of light, and *iii)* dealing with the complexity of an optical receiver, especially a mobility receiver. Recently, O-MIMO techniques are applied to the indoor Optical wireless communications (OWC) systems in order to improve the capacity and throughput by distributing the signal power over multiple simultaneous links. The O-MIMO systems can achieve a higher speed transmission than the Optical Single Input Single Output (O-SISO) systems by setting the optical transmitters and receivers and the transmit semi-angle appropriately [1].

A major disadvantage of the O-MIMO systems is Inter-Channel Interference (ICI) because of the simultaneous transmissions on the information source from multiple transmit LEDs. The University of South Florida has developed an information beamforming technique for Visible Light Communication (VLC) systems and such a technique is well known in RF MIMO beamforming communications. The Optical information beamforming technique concentrates the carrying information light on a specific region exist in the literature while broadcasting the illumination to the surrounding environment. This results in no ICI appearing at the receiver and the data is directionally transmitted in VLC without hurting the ability to illuminate a space [2]. The bit error rate (BER) performance for the same total transmit optical power beamforming MIMO in VLC is significantly improved when compared to the traditional O-MIMO equal power allocation [3].

To obtain good system performance under the presence of such ICI requires a complex receiver structure. Another technique called Optical Spatial Modulation (OSM) with a power and bandwidth efficient pulsed modulation technique for OWC was proposed in [4] where there are multiple transmit units but only one LED is active at any transmission time. The spatially separated transmit units are considered as spatial constellation points. Each unique sequence of incoming data bits is mapped to one of the spatial constellation points, i.e., activating one of the transmit units. Therefore, no ICI appears at the receiver and detection can be performed with very low complexity.

Ertugrul Basar in Istanbul Technical University and Erdal Panayırci in Kadir Has University, Turkey proposed Optical Orthogonal Frequency Division Multiplexing with Index Modulation (O-OFDM-IM) for VLC systems employing light emitting diodes (LEDs) and photodetectors (PDs) [5]. The authors 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 simulation results that O-OFDM-IM can be considered as an alternative to classical optical OFDM for VLC systems.

Ye Shan, Ming Li and Minglu Jin proposed the enhanced Spatial Modulation (en-SM) scheme for Indoor VLC in which two LEDs are activated at one time, and half the brightness levels are used to maintain a constant transmission rate [6]. For each LED, the transmission power is reduced by the square root of two in order to provide the same signal-to-noise ratio (SNR). In the range of high SNR, the enhanced SM exhibits better improvement in system performance than the conventional SM. But the performance of the en-SM is worse in the case of low SNR.

Spatial diversity in MIMO transmissions for OWC with Intensity Modulation/Direct Detection (IM/DD) has been considered in [4, 5]. In [5], the signal processing for index SM at the receiver is based on the Minimum Mean Square Error (MMSE) criterion. In [4], received signals use the maximum ratio combining (MRC) method to maximize the Signal-to-Noise (SNR) ratio, which in turns minimizes the BER.

In this paper, a novel Index-based OSM (IOSM) is proposed in order to enhance data rate by the index defined multiple active scheme for spatial modulation in which several LEDs carrying different information symbols are active during each time slot. In IOSM, a Maximum-likelihood (ML) decoder with linear complexity is utilized to recover information. Simulation results demonstrate the superior performance of IOSM when applied to several communication systems. This is done by comparing it against several widely used algorithms.

The rest of this paper is organized as follows: In section II we introduce the system model of an Optical MIMO channel and the novel IOSM scheme. The numerical results are calculated in section III. In section IV, computer simulations are carried out to compare the proposed scheme with exiting O-MIMO schemes. Finally, Section V summarizes this paper.

Notation: Bold letters are used for column vectors, while capital bold letters are for matrices. The operators $(.)^*$, $(.)^T$ and $(.)^H$ denote complex conjugation, transposition and Hermitian transposition, respectively. $\|.\|$, tr(.) and det(.) stand for the Frobenius norm, trace and determinant of a matrix. Pr(.) and E{.} denote the probability of an event and expectation.

II. System Model

Consider a system model of MIMO channels in an indoor Visible Light Communication network shown in Fig. 1. Four LED arrays are used to illuminate the room, each of which transmits an independent data stream simultaneously. Light from each of the LED arrays is received by all the separate receivers, but with different strengths. The receiver used two Photodetector elements.

A. System Parameters

The MIMO VLC system has the following parameters:

- N_T: number of LED (transmitters).
- N_R: number of Photodetector elements used by the receivers.
- **s**: data symbol to be transmitted.
- T: data symbol interval (s).
- $\boldsymbol{P}_T$: total transmit optical power (W).
- h_{ij}: channel loss factor from the transmitter i^{th} to the photodetector j^{th}.
- **H**: $N_R \times N_T$ MIMO channel matrix.

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{N_R1} \\ \vdots & \ddots & \vdots \\ h_{1N_T} & \cdots & h_{N_RN_T} \end{bmatrix} \tag{1}$$

  In our system model, $N_T = 4$ and $N_R = 2$ so that **H** is the 4×2 MIMO channel matrix.

- η_T: source conversion factor for IM (LED drive current converted into transmit optical power, in W/A).
- η_R: source conversion factor for DD (received optical power converted into photocurrent, in A/W).
- **n**: Gaussian noise vector.

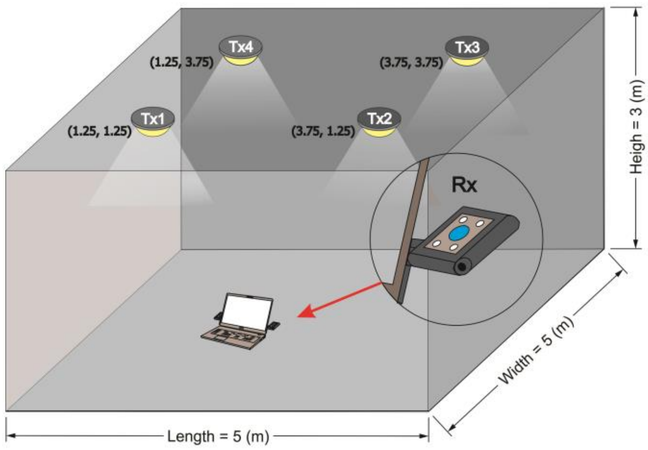

Fig. 1. O-MIMO system model.

Given the data symbol **s**, the NT transmit signal values (in the form of optical intensities) are given by $N_T s \eta_T/\sqrt{T}$. For IM/DD, we must have unipolar signals. The condition makes MIMO signal processing for IM/DD fundamentally different from existing methods for bipolar signals [7].

The optical received signal is expressed as follows:

$$\mathbf{y} = \eta_T \eta_R \mathbf{H}\mathbf{s} + \mathbf{n} \tag{2}$$

where the noise **n** is an additive white Gaussian noise (AWGN) with a double-sided power spectral density σ^2, which is the sum of the variance of the thermal noise σ_{th}^2 at the receiver hardware and shot light noise σ_{sh}^2 of intense ambient lights. We have [8]:

$$\sigma^2 = \sigma_{th}^2 + \sigma_{sh}^2 \tag{3}$$

$$\sigma_{sh}^2 = 2qA_z\eta_R R_b B_n \tag{4}$$

$$\sigma_{th}^2 = \frac{4k_B T_{abs}}{R_F} R_b B_n \tag{5}$$

where q is the electronic charge, $\boldsymbol{A}_z$ is light detector area, k_B is the Boltzmann's constant, T_{abs} is the absolute temperature, R_F is the feedback resistance, R_b is the bit rate and B_n is the noise-bandwidth factor. Assume n is independent of P_T.

When the channel state information (CSI) is perfectly known at the receiver, the maximum-likelihood (ML) decoder [9] estimates the transmitted symbol vector and the value of combined signal for symbol detection is computed as:

$$\mathbf{s}' = \arg\min_{s \in S} \|\mathbf{y} - \mathbf{H}\mathbf{s}\|^2. \tag{6}$$

Here, S denotes the constellation of the normalized transmitted symbols, and the minimization is performed over all possible transmitted symbol vectors.

B. VLC Channel Model

LOS propagation paths of information light are assumed in this paper. Hence, h_{ij} is one element of the matrix **H** which denotes the respective channel loss factor of the link between the transmitter i^{th} and the receiver j^{th} and is defined as in [10]:

$$h_{ij} = \begin{cases} \frac{A_{rz}^{j}}{d_{ij}^{2}} R_0(\theta) T_s(\varphi) g(\varphi) cos(\varphi) & 0 \le \varphi \le \varphi_c \\ 0 & \varphi > \varphi_c \end{cases} \quad (7)$$

where A_{rz}^{j} is light detector area of the PD receiver j^{th}, d_{ji} is the distance of the link, θ is the angle of irradiance, φ is the angle of incidence, $T_s(\varphi)$ is the gain of an optical filter, $g(\varphi)$ is the gain of an optical concentrator, and φ_c denotes the width of the field of vision (FOV) at a receiver, usually $\varphi_c \le \pi/2$. $R_0(\theta)$ is the transmitter radiant intensity given as below:

$$R_0(\theta) = [(m+1)/2\pi] cos^2\theta \quad (8)$$

where *m* is the order of Lembertian emission defined as in [10]. The gain of the optical concentrator at the receiver is defined by:

$$g(\theta) = \begin{cases} \frac{n_{opt}^2}{sin^2\varphi_c} & 0 \le \varphi \le \varphi_c \\ 0 & \varphi > \varphi_c \end{cases} \quad (9)$$

where n_{opt} is the refractive index.

C. *The Index Optical SM (IOSM)*

Although the term OSM was used in [4], various researchers independently investigated this strategy. Focusing on the case that two LEDs are active among available transmitted LEDs, and that is the state-of-the-art schemes introduced by Basar et al. in [5] and Ye Shan in [6].

Our proposed scheme can increase the data rate by making use of the high-rate index OSM in [5, 6]. The diagram of the proposed IOSM is depicted in Fig. 2 where not only indices of the active LEDs transmitters, but also through the selection of the modulation schemes are utilized to convey a part of information bits. Indeed, the data bit streams convert into blocks or code-words. There are three types of information for each code-words. The first information is number of modulation groups or called modulation index. The first modulation group is the primary modulation group which activates only one transmitter at any time (OSM mode). The others are the secondary modulation group in which they activate two transmitters simultaneously. The second information is the number of LEDs for data transmission and the last one is the size of constellations using for the first group. Each information above needs some different bits up to modulation index.

For example, a IOSM 4x2 system with 6 bit per channel unit (bpcu) has three modulation groups g_1, g_2 and g_3 (three modulation indices) where g_1 is called the primary modulation group, g_2 and g_3 are the secondary modulation group. We arrange two bits containing that information. In each modulation group, the minimum Euclidean distance must be near the same for all signal constellations used in decoding. It is given by $\delta_0 = 2$. Obviously, δ_0 is also the minimum distance between two signal vectors corresponding to the same combination.

By a IOSM 4x2 system uses 4 LEDs for transmission, so that we need $\log_2(N_T) = \log_2(4) = 2$ bits to contain that information so that only one LED could be active at any time for the primary modulation group.

For the 2-bits remains, they are used to design the size of the primary constellations for the primary modulation group. In this case, QPSK constellations is chosen as the primary modulation. For the secondary modulation groups which actives two LEDs simultaneously at any time, the size of constellations can reduce (e.g: BPSK) and we have to choose so that constellation points do not match other constellations of the remaining groups and having the same the minimum Euclidean distance [6]. The modulation scheme BPSK ($\mathfrak{B}_0 = \{\pm 1\}$) is chosen for the second group and π/2-shifted BPSK ($\mathfrak{B}\pi_{/2} = \pm i$) is chosen for the third modulation, respectively.

Table I shows an example for IOSM 4x2 system with 6 (bpcu). The number of transmission modes are sixteen to be arranged in three modulation groups.

TABLE I. TRANSMISSION MODES IN THE CASE OF 4 TRANSMITTERS

Modulation 1		**Modulation 2**		**Modulation 3**	
Source Bits	**Trans. Modes**	**Source Bits**	**Trans. Modes**	**Source Bits**	**Trans. Modes**
0000	LED1	0100	LED1, LED2	1010	LED1, LED2
0001	LED2	0101	LED1, LED3	1011	LED1, LED3
0010	LED3	0110	LED1, LED4	1100	LED1, LED4
0011	LED4	0111	LED2, LED3	1101	LED2, LED3
		1000	LED2, LED4	1110	LED2, LED4
		1001	LED3, LED4	1111	LED3, LED4

By the same way, a IOSM 4x2 system with 8 (bpcu) obtains 3 modulation groups and uses 16-QAM for the primary constellation in transmission modes of the first group and QPSK and π/4-shifted QPSK for the secondary constellation remaining transmission modes.

The general framework of the proposed IOSM scheme for an arbitrary number of transmit LEDs is described as follows:

1. Determine the number of signal constellation points *M* of the primary modulation scheme to select a particular symbol **s**.
2. Determine the total number of bit *q* to select the index of the active LED as $q = \log_2(N_T)$.
3. Determine the number of bit *p* to select the indices of the modulation mode groups *k* for LEDs so that p = Ceil($\log_2(k)$) and the number of transmission modes for IOSM in this case calculated as $2^{(p+q)}$.

Given the number of codewords, the total of $m_{IOSM} = p + q + log_2 M$ information bits are sent per channel (bpcu) for IOSM, which is higher than $m_{OSM} = q + log_2 M$ (bpcu) for OSM and in [6].

III. NUMERICAL ANALYSIS

A. *Calculating the* **H** *matrix:*

The proposed O-MIMO system which is set up in the 5×5×3 (m) room in Fig. 1 consists of four LED transmitters located at {(1.25_x, 1.25_y); (3.75_x, 1.25_y); (3.75_x, 3.75_y); (1.25_x, 3.75_y)} on the ceiling and two PD of receivers which is separated 30 (cm). By move the user to different places in the room, we can derive the channel gains of different indoor setup scenarios:

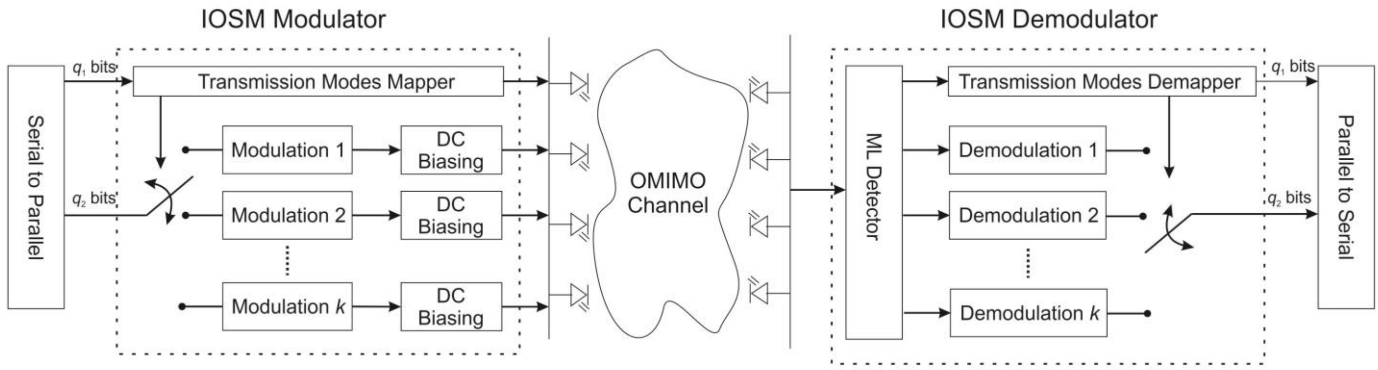

Fig. 2. Block diagram of the proposed IOSM scheme.

Scen. 1: Rec. at $\{(0_x, 2.5_y, 0.85_z); (0.3_x, 2.5_y, 0.85_z)\}$

Scen. 2: Rec. at $\{(1.15_x, 2.5_y, 0.85_z); (1.35_x, 2.5_y, 0.85_z)\}$

Scen. 1: Rec. at $\{(2.35_x, 2.5_y, 0.85_z); (2.65_x, 2.5_y, 0.85_z)\}$

Light propagates from each of the LEDs to the receiver, and there are generally two types of propagation. Each LED has a line-of-sight (LOS) component that propagates to the receiver, and there is also a diffuse component that propagates via reflections from the surfaces within the room.

Given the data rates are substantially less than channel bandwidth, the difference between LOS components are ignored in these simulations and the DC channel gains are used to describe the channel matrix **H**.

By using Equations (7), (8) and (9), the channel matrix is generated as follows when the half-power angle is set to 65°:

$$\begin{aligned}\mathbf{H}_{Scen.1} &= 10^{-7}\begin{bmatrix}0.7608 & 0.1137 & 0.1137 & 0.7068\\ 0.8372 & 0.1409 & 0.1409 & 0.8372\end{bmatrix}\\ \mathbf{H}_{Scen.2} &= 10^{-6}\begin{bmatrix}0.1082 & 0.0266 & 0.0266 & 0.1082\\ 0.1082 & 0.0310 & 0.0310 & 0.1082\end{bmatrix}\\ \mathbf{H}_{Scen.3} &= 10^{-7}\begin{bmatrix}0.7722 & 0.6426 & 0.6426 & 0.7722\\ 0.6426 & 0.7722 & 0.7722 & 0.6426\end{bmatrix}\end{aligned} \tag{11}$$

The multiple received signals have to be linearly combined by a mechanism, which is called a *Maximal Ratio Combiner* (MRC). This mechanism can maximize the SNR. With channel matrix **H** given, the coefficients of $\boldsymbol{c_T}$ vector for the MRC combiner are chosen $c_i = h_i/\sqrt{N_0}$ which maximizes SNR. The resulting maximized SNR at the output of the MRC is:

$$SNR = \frac{2\left(\eta_T\eta_R \|\mathbf{H}\boldsymbol{c_T}\|^2 E[\mathbf{s^2}]\right)}{N_0} \tag{12}$$

Without any illumination requirement, the constant parameters η_T, η_R and E[$\boldsymbol{s}^2$] can be omitted from the objective function without loss of optimality. Fig. 3 plots the SNR distribution in Equation (12) based on simulation parameters above.

B. *Analytical BER Calculation*

For modulation, the term T is the inverse of the transmission bit rate. Without loss of generality, assume that the total power constraint E[**s**] must be set equal to $\sqrt{T}P_T^{total}/\eta_T$. It follows that η_T is always cancelled out in the performance analysis, and its value need not be specified.

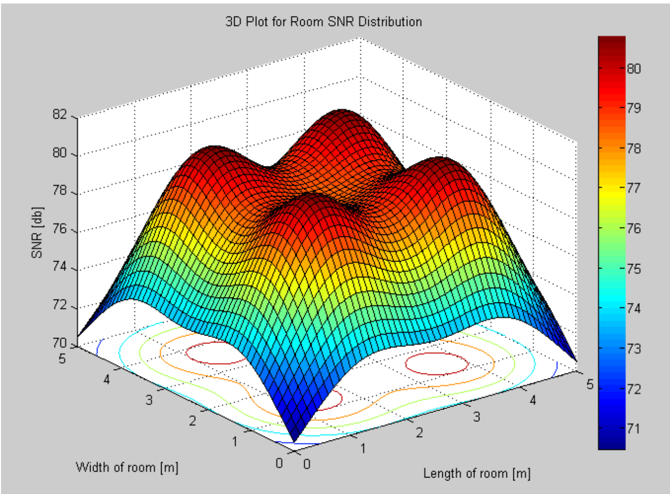

Fig. 3. The received power distribution of the proposed IOSM scheme.

The receiver employs the optimal maximum likelihood (ML) detection after MRC-based receiver [9]. We define the pairwise error probability (PEP) as the probability that the ML decoder decodes a symbol vector **s**' instead of the transmitted symbol vector **s**. The average PEP (APEP) can be computed by using the union bound as follows:

$$APEP \le \frac{1}{|S|}\sum_{\mathbf{s}\in S}\sum_{\mathbf{s}\in S} PEP(\mathbf{s}\to\mathbf{s}'). \tag{13}$$

In [9], the researchers demonstrated that this is the optimal detection of SM. The detector decides the vector with the minimum Euclidean distance by using the following equation:

$$\mathbf{s}' = \arg\max_{s} p_y(\mathbf{y}|\mathbf{s}.\mathbf{H}) \tag{14}$$

where $p_{\mathbf{y}}$ denotes the probability density function of **y** conditioned on **s**, which can be expressed as:

$$p_y(\mathbf{y}|\mathbf{s}.\mathbf{H}) = \pi^{-N_R} exp(-\|\mathbf{y}-\mathbf{Hs}\|_F^2) \tag{15}$$

where $\|.\|_F^2$ denotes the Frobenius norm. The PEP for Gaussian given channels at Hamming distance d is given by:

$$PEP(\mathbf{s} \rightarrow \mathbf{s}') = PEP(d) = Q\left(\sqrt{2dSNR}\right) \approx \frac{e^{-dSNR}}{2\sqrt{\pi dSNR}} \quad (16)$$

where Q(x) is the Gaussian tail function.

The asymptotic system performance is determined by the worst-case PEP, which corresponds to the minimum value of the squared Euclidean distance between symbol vectors in the signal space:

$$d_{min}^2 = \min_{s \neq s'} \|\mathbf{s} - \mathbf{s}'\|^2 = \frac{1}{E_s} \min_{x \neq x'} \|x - x'\|^2 \quad (17)$$

Next, we analyze asymptotic performance with different O-MIMO schemes at hand in terms of the squared minimum Euclidean distance between transmit symbol vectors. Following Equation (13), the BER with normalized distance d can be expressed as:

$$BER = Q\left(\sqrt{SNR}/2\right). \quad (18)$$

The analytical BER of the first scenario is the worst which is $6.23\text{x}10^{-5}$ recorded at 70 dBm because the distance between the transmitters and receiver is the largest. On the contrary, the second scenario where the receiver is closest to the first and fourth transmitters achieves the best BER of 1.26×10^{-6} and the third scenario obtains the average BER of 1.5×10^{-5}.

IV. SIMULATION RESULTS

In this section, Monte Carlo simulations are carried out to evaluate performance of the proposed IOSM scheme compared to the others modulation schemes in O-MIMO systems. The Other relevant system parameters used in the investigation is listed in Table II.

TABLE II. TRANSMISSION SYSTEM PARAMETERS

Parameter	Notation	Value
Number of LEDs	N_T	4
Number of photo-detector	N_R	2
Transmit optical power	P_T	10-100 dBm
Transmit bit rate	-	10 Mbps
Received FOV	φ_c	60^0
Received Response	η_R	0.55 A/W
Modulation format	-	IM/DD

The simulation scenario with the spectrum efficiency 6 (bpcu) is investigated. The system configuration mentioned in previous section is applied for both scenarios where the number of transmitters N_T = 4 and receivers N_R = 2. The data rate of the considered system is set to 6 (bpcu). For such a spectrum efficiency, the OSM scheme must use 16-QAM to modulate four data source bits while the two bits left represents indices of transmitters and the beamforming scheme requires 32-QAM. Meanwhile, in order to achieve such a modulation rate, the proposed IOSM requires only 4-QAM or BPSK.

Investigating the performance of the proposed modulation scheme, BER in two cases of spectral efficiency 6 (bpcu) and 8 (bpcu) are shown in the Fig.6. The QPSK is chosen for the first modulation scheme of the proposed IOSM which achieves 6 (bpcu). While the 16-QAM is applied to obtain 8 (bpcu). As shown the system performance in the case of 6 (bpcu) is better than the 8 (bpcu) about 4.8 dB at same BER value 10^{-6}.

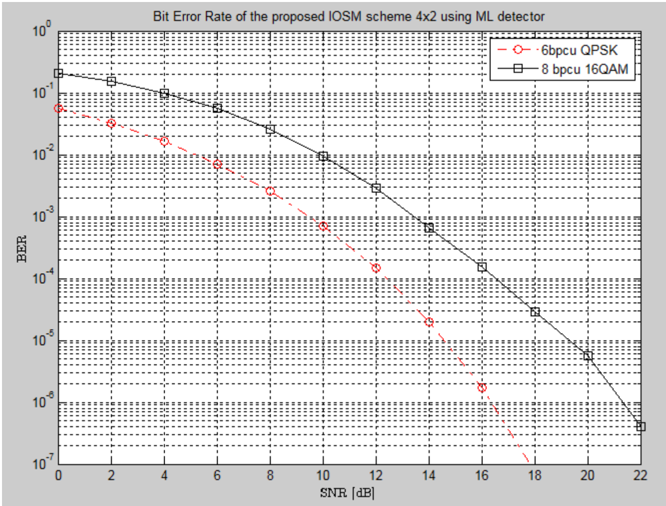

Fig. 4. BER Comparison between the spectral efficiency 6 and 8 bpcu.

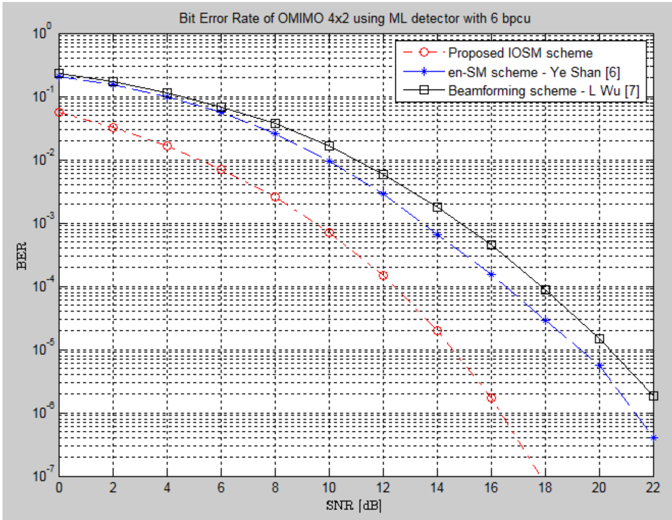

Fig. 5. System performance compared between the proposed IOSM and the other modulation schemes in O-MIMO systems at 6 (bpcu).

For the same spectral efficiency 6 (bpcu) considered, the performance of the proposed IOSM scheme is reported much better than the other modulation schemes. It is higher 5.5 dB than the en-SM scheme which was proposed by Y. Shan and 6.5 dB than the Beamforming scheme of L. Wu at BER = 10^{-6} as shown as Fig. 5. While the en-SM scheme outperforms only 1 dB than the Beamforming scheme.

V. CONCLUSION

In this paper, a novel transmission scheme for a IOSM system is developed by combining optical spatial modulation and enhanced optical spatial modulation. Aiming at a system implementation that requires only two active transmit LEDs, and operating at high spectral efficiencies. It was demonstrated that the proposed scheme performs better than previously-proposed schemes that are based on OSM or en-SM .

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