A Color Space Exploration in Optical Spatial Modulation

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***Abstract*—In order to increase spectrum efficiency, two-dimensional signal space in conventional modulation schemes is expanded by LED transmitter indices in the Optical Spatial Modulation (OSM) scheme, and a combination of transmitter and modulation indices in the Index-based Optical Spatial Modulation (IOSM) scheme. In this paper, we proposed a novel Spatial Modulation called Optical Color-Transmission modes Index-based Spatial Modulation scheme (OCTI-SM) which explore one more dimension – color dimension by using white Laser Diode (LD) light bulb which consists of four color laser sources. With the color space exploration, the proposed scheme achieves higher data rate than the SM schemes. Using computer simulations and mathematical analysis, the system performance of the proposed OCTI-SM is compared with the conventional OSM and the IOSM schemes, and results show that the OCTI-SM achieves a significant improvement in increasing spectral efficiency.**

Keywords—Visible Light Communications (VLC), Optical Spatial Modulation (OSM), RGYB-Laser Diodes (RGYB-LDs).

I. INTRODUCTION

One of the trends in next communication network generations is deploying new available spectrum range due to the exhaustion of RF spectrum resource. Millimeter-wave and visible light ranges are candidates to expand spectrum for wireless data transmission. The key main problem of Millimeter-wave communications is electronic circuit design to generate high carrier frequency and high bandwidth of 60 GHz band. Because high transmit power and huge bandwidth cause severe nonlinear distortion of power amplifiers (PAs) [1]. By using Intensity Modulation/Direct Detection (IM/DD), Visible Light Communications gains low-complexity of hardware and low-cost implementation because of carrying information bits on the intensity of optical power [2].

However, the complex receiver is required in conventional MIMO systems to deal with the high level Inter-Carrier Interference (ICI) due to simultaneous transmission on all transmitters. To improve the system performance, Beamforming technique is applied in VLC systems to deal with the ICI problem. A Beamforming-VLC system is proposed in [3] concentrates carrying information light on specific region while illuminate to the surround environment. However, the reported spectrum efficiency of the beamforming technique is reduced [4]. Spatial Modulation technique is proposed as an alternative of MIMO technique which can eliminate the ICI completely while still maintain spectrum efficiency by conveying information bit stream to both transmitter indices and conventional two-dimensional signal constellations. Moreover, the lower complexity of receiver, no inter-antenna synchronization and power efficiency are other advantages of the SM over the traditional MIMO.

In SM, spectral efficiency is evaluated by number of information bits carried per symbols. To increase spectral efficiency of the SM, there are number of SM variations proposed recently such as Generalized Spatial Modulation (GSM) [5, 6], Index based Optical Spatial Modulation (IOSM) [7], OSM-OFDM [8]. In GSM, spectral efficiency is improved by increasing the number of transmit antennas being active simultaneously, but not all to convey a longer part of information bit stream [6]. The GSM scheme includes both special cases of the OSM [9] and SMP [10] when N_a = 1 and $N_a = N_t$, alternately, where N_a is number of simultaneous LED transmitters and N_t is number of all LED transmitters. However, there is a tradeoff between data code rate and influence of the ICI in GSM. The IOSM scheme is our previous work where not only LED transmitter indices, but also the selection indices of the modulation schemes are utilized to convey the first portion of data bit stream. In contrast to the GSM and IOSM, OSM-OFDM maintains only active LED transmitter at time and uses OFDM to instead of conventional singer-carrier modulation schemes to convey the later portion of information [8].

So far, white light LEDs using blue chips and yellow phosphor to generate white light are utilized in most VLC systems [11]. It is due to this technique is the simplest and most cost-effective approach. However, the achieved data rate by using LEDs is still low because of narrow modulation bandwidth of 25 MHz [10], the maximum data 100-230 Mbps was the result of using phosphorescent LEDs with the simple On-Off keying (OOK) modulation [12]. To increase data rate, a complex transceiver is required to implement advanced modulation techniques [5]-[10]. The second method is to combine red, green, blue LEDs (RGB LEDs) in the proper proportion to achieve a white color [13]-[15]. This approach achieves significant enhancements in data rate which are reported in [13] with 1.25 Gbps in a single-color transmission mode and in [14] with 1.5 Gbps by using a new design of µ LED array. The highest data rate achieved 3 Gbps is demonstrated recently by using OFDM technique in the µ LED VLC systems [15]. Main concerns in such VLC systems are complexity in design and implementation.

Recently, Laser Diodes (LDs) is proposed to replace LEDs because of more efficiency in illumination and communications [16]. A prototype of four-color laser sources (Red, green, yellow and blue) was demonstrated by Neumann *et al.* that provides a practical white illuminant like other light sources, such as incandescent and white LEDs light by using diffusers [17]. With the approximate tenfold higher bandwidth than LEDs (maximum 245 MHz [18]), LDs achieves higher data rate to Gigabits/second. Moreover, other characteristics of high optical power and light beam convergence made LDs to be preferred than LEDs [16].

In this paper, we propose an Optical MIMO system which explores color space in the OSM scheme by using RGYB Laser Diode (RGYB-LD) transmitters. The key of the proposed scheme is activating only one color light source of one RGYB-LD transmitter at instance compared to the traditional OSM scheme. By using spatial modulation for each color, the advantage of spatial modulation in traditional Optical MIMO can be exploited in OSM and OCTI-SM, i.e., avoiding ICI between symbols in the same colors at different LEDs. Using spatial modulation also increases the transmission rate of OCTI-SM as compared to IOSM since more information bits are conveyed by color indices. Performance analysis is carried out to determine the diversity gains of the proposed scheme. Numerical results and comparison with existing schemes such as IOSM and OCTT-SM demonstrate the efficiency of the proposed OCTI-SM.

The rest of this paper is organized as follows: In section II, we introduce the system model of the proposed Spatial Modulation scheme. The detail of the OCTI-SM scheme is described in section III. In next section, numerical analysis and computer simulations are implemented to compare the proposed scheme with the exiting SM schemes. Finally, Section V concludes this paper.

Notation: Bold letters are used for column vectors, while capital bold letters are for matrices. $\|.\|_F$ stand for the Frobenius norm.

II. System Model

Consider a system model of the proposed OCTI-SM scheme in an indoor Visible Light Communication network shown in Fig. 1.

The system model in Fig. 1 uses four white LD light bulbs (transmitters) to provide illumination for the whole room. In communications purpose, each white LD light bulb transmits an independent data stream simultaneously. All the separate receivers at the user side receives white light from the LD transmitters in different strengths. For each receiver, four Photo-detectors (PDs) with four-color filters (Red, Green, Yellow, and Blue) in front of them to decompose different color sources from incoming white light.

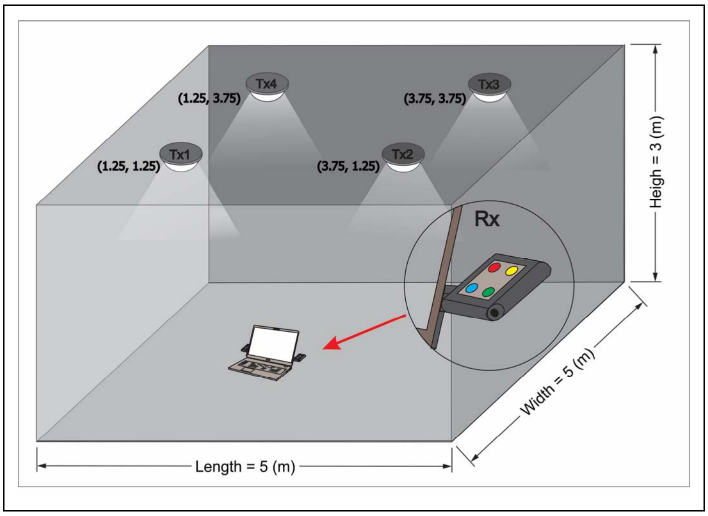

Fig 1. The system model of the proposed OCTI-SM scheme.

A. *Architecture of a RGYB-LD transmitter*

Four laser sources which are used to create white light have wavelengths as following: Red-635nm, Green-532nm, Yellow-589nm, and Blue-457nm. This architecture of the RGYB-LD transmitter is proposed the study in [17]. All color laser sources are mixed using beam combiners, then passed through a ground glass diffuser to reduce speckle before illuminating the room. To obtain the exact color and set the total emitted power, the emitted power of each laser source must be controlled and monitored by beam-splitters and detectors.

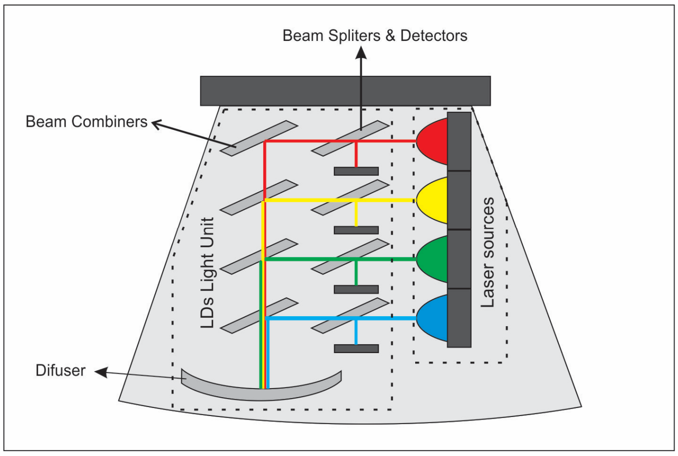

Fig 2. The architecture of a RGYB-LD transmitter.

The power generated internally by an LED may be determined by consideration of the excess electrons and holes. The generated power in terms of wavelength is given by;

$$P_T = \eta_R \frac{ihc}{e\lambda} \quad (W) \tag{1}$$

where η_R internal quantum efficiency, i is the forward-biased current into the LED, h is Planck's constant and e is the charge on an electron.

Although the possible internal quantum efficiency can be relatively high, the radiation geometry for an LED being reflected by mirrors, is emitted through a diffuser surface. It has the Lambertian distribution (W.sr^{-1}.m^{-2}) which is constant in all directions. In the Lambertian intensity distribution, the maximum intensity I_0 is perpendicular to the diffuser surface and is reduced on the sides in proportion to the cosine of the irradiance angle θ.

B. Signal Transmission

Without loss of generality, the Fig. 3 illustrates an Optical MIMO system consisting of N_t RGYB-LD transmit units and N_r receive units. The input bit stream is grouped as row signal vectors of **s**(t) which are transmitted at time instances:

$$\mathbf{s}(t) = \{c_1, c_2\} \tag{2}$$

where c_1 denotes the signal space, modulation indices and number of transmitters which are described in [7]. Here, the color space is explored and denoted as c_2 which decides the color LD source being utilized to transmit at one time instance.

In the optical wireless network (OWC) systems using the IM/DD, we have the optical received signal under the LOS condition expressed as:

$$\mathbf{y} = \eta_T \eta_R \mathbf{Hs} + \mathbf{n} \tag{3}$$

where **s** is a transmitted data vector, η_T is a source conversion factor for IM (LD drive current converted into transmit optical power, in W/A), η_R is a source conversion factor for DD (received optical power converted into photocurrent, in A/W), **H** is a $N_R \times N_T$ MIMO channel matrix

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R 1} & \cdots & h_{N_R N_T} \end{bmatrix} \tag{4}$$

where N_T is number of RGYB-LD transmitters, N_R is number of receivers used by the user, h_{ij} is a channel loss factor from the transmitter i^{th} to the photo-detector j^{th}

$$h_{ij} = \begin{cases} \frac{A_{rz}^j}{d_{ij}^2} R_0(\theta) T_s(\varphi) g(\varphi) cos(\varphi) & 0 \le \varphi \le \varphi_c \\ 0 & \varphi > \varphi_c \end{cases} \tag{5}$$

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 follows:

$$R_0(\theta) = [(m+1)/2\pi] cos^2\theta \tag{6}$$

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

$$g(\theta) = \begin{cases} \frac{n_{opt}^2}{sin^2\varphi_c} & 0 \le \varphi \le \varphi_c \\ 0 & \varphi > \varphi_c \end{cases} \tag{7}$$

where n_{opt} is the refractive index.

In LOS condition, the additive white Gaussian noise (AWGN) vector **n** has 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:

$$\sigma^2 = \sigma_{th}^2 + \sigma_{sh}^2 \tag{8}$$

$$\sigma_{sh}^2 = 2qA_z \eta_R R_b B_n \tag{9}$$

$$\sigma_{th}^2 = \frac{4k_B T_{abs}}{R_F} R_b B_n \tag{10}$$

where q is the electronic charge, 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 $\boldsymbol{P}_T$ which is the total optical transmit power.

III. Optical Color-TransmiSSION modes Index-based Modulation

In our previous work, the Index-based OSM in [7] was motivated from the conventional optical spatial modulation, but not only transmitter indices, but also the modulation modes indices are used to convey information bits. The information for each codeword in the IOSM scheme can be split to three types of sub information. The first sub-information is number of modulation groups or called modulation index. The second sub-information is the number of LEDs for data transmission

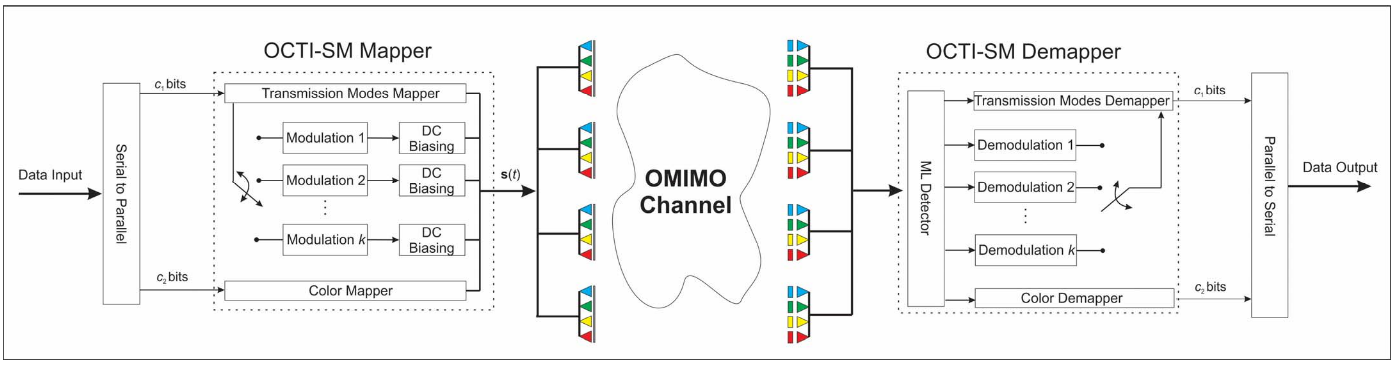

Fig. 3. Block diagram of the proposed OCTI-SM scheme.

and the last one is the size of constellations using in the first modulation group. It results in higher diversity gain than the classical OSM.

In this paper, one more dimension – color dimension by using RGYB-Laser Diode (LD) light bulb is explored from the IOSM scheme to increase spectrum efficiency. The proposed SM scheme is called Optical Color-Transmission Modes Index-based Spatial Modulation scheme (OCTI-SM) which is illustrated in Fig. 3. The input bit stream is divided into bit blocks which have same length of N bits. These bit blocks are passed through Serial-to-Parallel component before being mapped by the OCTI-SM mapper component. In the proposed OCTI-SM scheme, one more sub information is used to convey a portion of input data stream compared to the IOSM scheme. Indeed, the input bit sequence is organized into each block shown in Table I.

TABLE I. MAPPING TABLE OF THE PROPOSED OCTI-SM SCHEME.

Indices	**Transmission modes**		**Signal Constellation**	**Color**
Value	$\log_2(N_t)$	$\log_2(N_M)$	$\log_2(M)$	$\log_2(N_c)$
Notations	α	β	μ	ν
	$\zeta = \alpha + \beta$			
	$c_1 = \zeta + \mu$			$c_2 = \nu$

The general process of the proposed OCTI-SM scheme is described as follows:

1. Determine number of signal constellation points M of the primary modulation scheme to represent a particular symbol **s** ($\mu = \log_2(M)$).
2. Determine number of bits which represent indices of LD transmitters $\alpha = \log_2(N_T)$.
3. Determine number of bits to indicate the modulation indices $\beta = \log_2(N_M)$ where N_M is the number of modulation groups. Hence, number of transmission modes in the OCTI-SM system is $2^{\zeta} = 2^{(\alpha+\beta)}$.
4. Determine number of color LD sources using in each transmitter N_c.

In the OCTI-SM system, the total information bits sent per channel unit (bpcu) is $m_{OCTI\_SM} = c_1 + c_2 = \log_2(N_t) + \log_2(N_M) + \log_2(M) + \log_2(N_c)$. It is clearly that data rate of the OCTI-SM is higher than $m_{IOSM} = c_1 = \log_2(N_t) + \log_2(N_M) + \log_2(M)$ (bpcu) of the IOSM [7] and $m_{OSM} = \log_2(N_t) + \log_2(M)$ (bpcu) of the OSM [9].

For example, an OCTI-SM 4×2 system with four LD color sources (RGYB-LDs) achieves a data rate of eight bits per channel unit (bpcu) (see Fig. 4) by using the four constellation points for the primary modulation. The first two bits carries the color information, or in other words, it represents the index of the active color LD source. The next four bits indicate sixteen transmission modes in the case of four RGYB-LD transmitters and three modulation groups. The sixteen transmission modes in this case are shown as in Table I in [7].

Note that 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

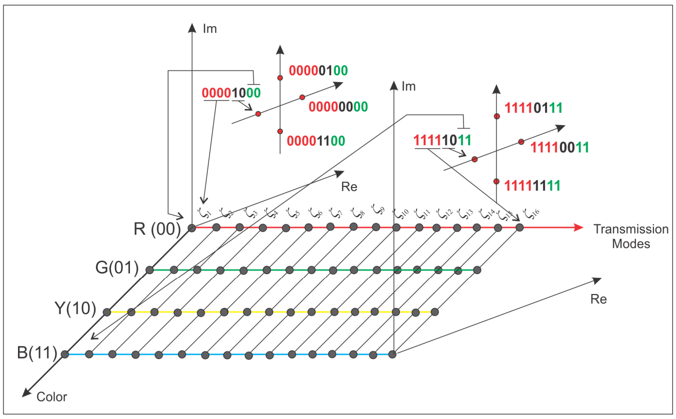

Fig. 4. The 4D constellation diagram of the OCTI-SM scheme.

vectors corresponding to the same combination. The size of the primary constellations for the primary modulation group is represented by the last two bits. Corresponding to the case of two bits, QPSK or 4-QAM is considered as the primary modulation. The constellation size of secondary modulation groups which actives two RGYB-LD transmitters simultaneously at any time, must be half-fold reduced (i.e., BPSK). The key point of choosing secondary modulation groups are that their constellation points must be not matched other constellation points of the remaining groups and had the same the minimum Euclidean distances [7]. Hence, 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. By increasing the constellation points to sixteen, the data rate of the OCTI-SM system is raised by 2 (bpcu). 16-QAM, QPSK, and π/4-shifted QPSK are chosen for the first, second and third modulation groups, respectively to gain the data rate of 10 (bpcu) [7].

IV. NUMERICAL ANALYSIS AND SIMULATION

A. BER Analysis

In IM/DD VLC systems, the bipolar-unipolar conversion is required to create unipolar transmit signal. Asymmetrical clipping (AC) or DC biasing are well-known techniques to implement the conversion. For AC, the negative samples in the signal vector **s** are clipped at zero without data loss to obtain a unipolar signal $\mathbf{s}_U$. While a suitable DC bias value B_{DC} is added to the transmit signal vector **s** in DC biasing technique

$$B_{DC} = \rho\sqrt{E[s^2]} \tag{11}$$

where ρ is a constant and B_{DC} is defined as a bias of $10\log_{10}(\mu^2+1)$ dB.

For high data rate VLC system, a maximal ratio combiner (MRC) is utilized to maximize the SNR by combining multiple received signals consisting of the LOS and NLOS signals linearly. With channel matrix H given, the coefficients of $\mathbf{c}_T$ vector for the MRC combiner are chosen $c_i = h_i/\sqrt{N_0}$ maximized 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 can be omitted from the objective function without loss of optimality. E[$\mathbf{s}^2$] is the average received electrical energy per bit which is dependent on symbol transmission for AC and DC biasing, respectively. E[$\mathbf{s}^2$] is equal 0.5 for AC bias and $\left((1+B_{DC})^2\left(1-Q(B_{DC})\right)\right)$ for DC bias. The power received distribution based simulation with $\mathbf{P}_T$ = 1 dB plot in Fig. 5.

The average pairwise error probability (APEP) can be computed by using the union bound as follows:

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

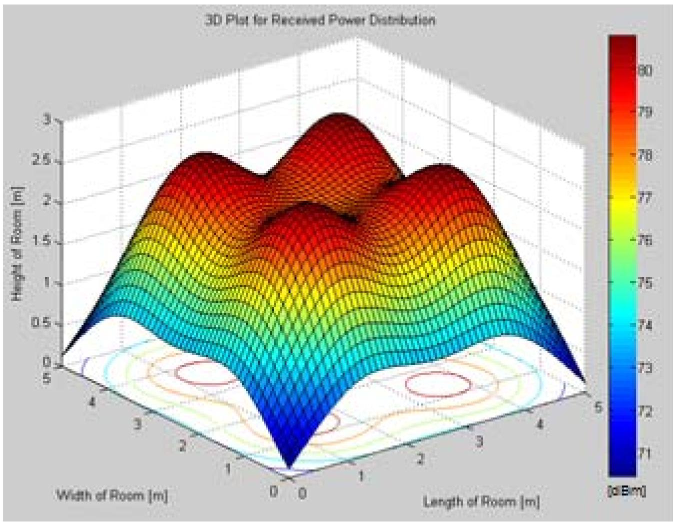

Fig.5: The received power distribution of the proposed OCTI-SM scheme in a room of 5×5×3 (m) with four RGYB-LD transmitters located at {(1.25x, 1.25y); (3.75x, 1.25y); (3.75x, 3.75y); (1.25x, 3.75y)} on the ceiling and two color-filtered receivers in 30 cm separately.

The detector of receiver decides the vector with the minimum Euclidean distance by

$$\mathbf{s}' = \arg\max_{s}\{\pi^{-N_R}exp(-\|\mathbf{y}-\mathbf{Hs}\|_F^2)\} \tag{14}$$

where $\|.\|_F^2$ denotes the Frobenius norm. J.G. Proakis shown that the PEP for a given Gaussian channel at Hamming distance d is:

$$PEP(\mathbf{s}\rightarrow\mathbf{s}') = PEP(d) = Q\left(\sqrt{2dSNR}\right) \approx \frac{e^{-dSNR}}{2\sqrt{\pi dSNR}} \tag{15}$$

where $Q(x)$ is the Gaussian tail function.

Asymptotic performance of the proposed OCTI-SM scheme is analyzed in terms of the squared minimum Euclidean distance between transmit symbol vectors. The Bit Error Rate (BER) with normalized distance d can be expressed as:

$$BER = Q\left(\sqrt{SNR}/2\right) \tag{16}$$

B. Simulation Results

In the following section, computer simulations are executed to evaluate the system performance of the OCTI-SM scheme in the cases of combining with the ACO-QAM and DCO-QAM schemes by applying Monte Carlo method. In addition, the system performance of the proposed OCTI-SM scheme is compared to the other Spatial Modulation schemes and Beamforming scheme. System parameters using in the simulations are listed in the following table.

TABLE II. TRANSMISSION SYSTEM PARAMETERS

Parameter	Notation	Value
Number of color	N_c	4
Number of RGYB-LD transmitters	N_T	4
Number of four-color filtered receivers	N_R	2
Transmit optical power	P_T	10-100 dBm
Transmit bit rate	-	20 Mbps
Received FOV	φ_c	60^0
Received Response	η_R	0.55 A/W
Modulation format	-	IM/DD

The BER performance of the proposed OCTI-SM scheme using AC and DC biasing techniques with ML detection are revealed in Fig. 6. Simulation scenarios with the spectrum efficiency 8 (bpcu) and 10 (bpcu) are investigated, respect-tively. The system configuration mentioned in previous section is applied for both scenarios where the number of RGYB-LD transmitters N_T = 4 and color-filtered receivers N_R = 2. To achieve the data rate of 8 (bpcu), the OCTI-SM scheme uses the QPSK modulation as the primary modulation and the BPSK modulation as the secondary modulation. Meanwhile, the OCTI-SM scheme with data rate of 10 (bpcu) must use 16-QAM for the primary and the QPSK for the secondary. It can be seen clearly that the better BER performance of the proposed scheme is achieved in the case of lower data rate. Moreover, it is interesting to note that for the same considered spectral efficiency, the OCTI-SM system using the DC biasing technique outperforms the AC technique.

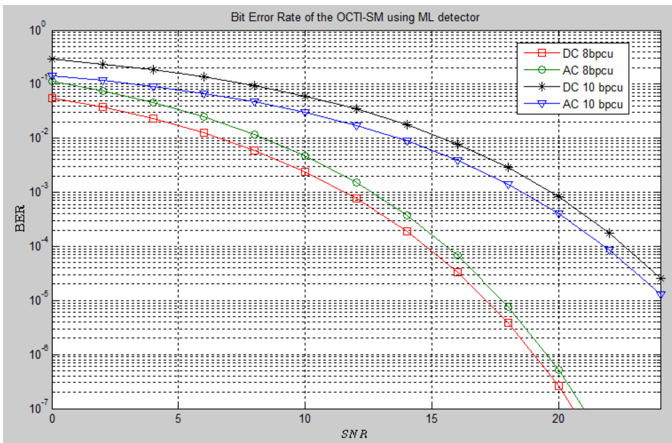

Fig. 6: The performance of DC/AC-OCTI-SM scheme with 8 vs. 10 (bpcu).

For the spectrum efficiency is 6 (bpcu), the conventional OSM scheme uses 16-QAM to modulate the first four data source bits and indices of LED transmitters represents the left of two bits. The beamforming scheme in [4] requires 32-QAM. Meanwhile, the IOSM scheme in [7] requires only the 4-QAM or QPSK for the primary modulation and the BPSK for the secondary modulation. With the above modulation groups setup, the data rate of the OCTI-SM scheme is higher than the IOSM scheme by two bits representing the indices of the color LD sources per each RGYB-LD transmitter.

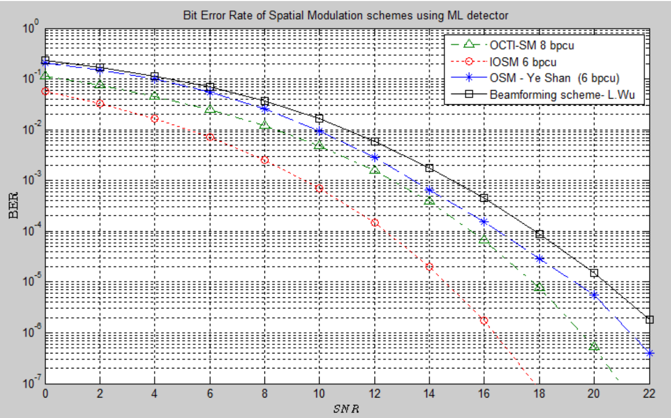

Fig.7: Comparison of system performance between the OCTI-SM and the other spatial modulation schemes.

Fig. 7 shows that the system performance of IOSM scheme in [7] is higher 5.5 dB than the en-SM scheme proposed by Y. Shan in [19] and 6.5 dB higher than the Beamforming scheme of L.Wu at BER = 10^{-6} in [4]. It is seen easily that the en-SM scheme outperforms only 1 dB than the Beamforming scheme. However, the system performance of OCTI-SM scheme in the case of 8 (bpcu) is not as good as the 6 (bpcu) IOSM scheme with the same modulation groups setup due to the dependencies of SNR with emitting color LD source. Indeed, the value of photodiode response $\eta_R(\lambda)$ are dissimilar with different colors (or wavelengths). It results in the change of SNR by wavelengths. It is no doubt that the system performance of the OCTI-SM scheme is better than the IOSM scheme for the same data rate 10 (bpcu).

V. CONCLUSION

In this paper, an enhancement of the IOSM scheme has been revealed by exploring the color space. RGYB-LD transmitters are utilized in the proposed OCTI-SM scheme to represent two more bits compared to the previous IOSM scheme. The proposed OCTI-SM scheme provides an incensement of data rate by logarithm base 2 of number of colors in each light bulb. It was also investigated that the OCTI-SM scheme outperforms other SM schemes and the beamforming scheme via computer simulations.

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