Generalized Spatial Multiplexing for Optical Wireless Communication Systems

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Abstract—**Spatial Multiplexing (SMP) is one of the most commonly used multiple-input multiple-output (MIMO) techniques in optical wireless communication (OWC) systems. Although SMP can achieve high spectral efficiency, it suffers from severe inter-channel interference (ICI). In this paper, we for the first time propose a novel MIMO technique, i.e., generalized SMP (GSMP), for intensity modulation/direct detection (IM/DD) OWC systems. Differing from conventional SMP which activates all the transmitters to transmit signals, GSMP selects a variable number of transmitters for signal transmission. The information bits of GSMP can be carried by both the spatial index symbols via variable-number transmitter selection and the constellation symbols transmitted by the activated transmitters. Compared with SMP, GSMP has the advantages of reduced ICI and enhanced spectral efficiency. The obtained analytical and simulation results show that GSMP can achieve greatly improved bit error rate performance than conventional SMP to achieve the same spectral efficiency in indoor 2 × 2 and 4 × 4 MIMO-OWC systems.**

Keywords-optical wireless communication; multiple-input multiple-output; generalized spatial multiplexing

I. INTRODUCTION

Recently, the involvement of new technologies such as cloud-based technologies, Internet of things and artificial intelligence results in higher demand for data rates. Due to the exhaustion of radio frequency (RF) spectrum resources, the utilization of high frequency resources becomes a development trend. In the fifth generation (5G) wireless systems, the wireless communication industry has responded to this challenge by considering millimeter-wave, sub-6 GHz and the optical spectrum [1]. Among them, optical wireless communication (OWC) using infrared, visible light or ultra-violet light-emitting diodes (LEDs) has been considered as a promising candidate to satisfy the ever-increasing data demand in indoor environments. OWC systems have many attractive advantages such as license-free spectrum, high data rate, inherent physical-layer security and no electromagnetic interference [2], [3]. Although the commercial off-the-shelf (COTS) LEDs have many advantages such as high energy efficiency, long lifetime, low cost and small size, they usually have limited electrical bandwidth. To improve the capacity of bandlimited OWC systems, many capacity-enhancing techniques have been proposed in the literature. Among them, multiple-input multiple-output (MIMO) transmission is one of the most popular techniques, which can provide substantial diversity or multiplexing gain for OWC systems [4]-[7]. There are mainly three types of MIMO schemes that have been applied in OWC systems for achieving diversity or multiplexing gains, including repetition coding (RC), spatial modulation (SM) and spatial multiplexing (SMP) [5], [8]. As the simplest MIMO scheme, RC activates all the LED transmitters to deliver the same signal in order to achieve transmit diversity, but it has the smallest spectral efficiency. SM can be considered as the combination of MIMO and digital modulation, which activates one LED to transmit signal at each time slot and additional bits can be transmitted by selecting the index of the activated LED [9]. Nevertheless, it is challenging for SM to achieve high spectral efficiency [10]. SMP is the most widely used MIMO scheme in OWC systems, which can achieve high spectral efficiency, but suffers from severe inter-channel interference (ICI).

In this paper, we propose a novel MIMO technique, i.e., generalized SMP (GSMP), for intensity modulation/direct detection (IM/DD) OWC systems. GSMP can be seen as the combination of digital modulation and SMP, which activates a variable-number of LEDs to transmit different signals and the information bits can be carried by both the spatial index symbols through variable-number LED selection and the constellation symbols delivered by the activated LEDs. Therefore, GSMP can achieve enhanced spectral efficiency with reduced ICI in comparison to conventional SMP. The superiority of GSMP over SMP in typical indoor MIMO-OWC systems has been verified by analytical and simulation results.

The rest of this paper is organized as follows. In Section II, we describe the model of a typical MIMO-OWC system. The principle of GSMP-based MIMO-OWC system is described in Section III. The analytical and simulation results are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

In the following, we consider a typical MIMO-OWC system equipped with N_t ED transmitters and N_r photo-diode (PD) receivers. Let $\mathbf{s} = [s_1, s_2, \cdots, s_{N_t}]^T$ be the transmitted signal vector, $\mathbf{H}$ represent the $N_r \times N_t$ MIMO channel matrix and $\mathbf{n} = [n_1, n_2, \cdots, n_{N_r}]^T$ denote the additive noise vector. The received signal vector $\mathbf{y} = [y_1, y_2, \cdots, y_{N_r}]^T$ can be given by

$$\mathbf{y} = \mathbf{Hs} + \mathbf{n}, \quad (1)$$

where the channel matrix of the $N_r \times N_t$ MIMO-OWC system can be expressed as follows:

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r1} & \cdots & h_{N_rN_t} \end{bmatrix}, \qquad (2)$$

where h_{rt} $(r = 1, 2, \cdots, N_r;\ t = 1, 2, \cdots, N_t)$ is the direct current channel gain between the *r*-th PD and the *t*-th LED. We assume that each LED transmitter follows the Lambertian radiation pattern and only the line-of-sight (LOS) transmission is considered [4]. Hence, h_{rt} is calculated by

$$h_{rt} = \frac{(l+1)\rho A}{2\pi d_{rt}^2} cos^m(\varphi_{rt}) T_s(\theta_{rt}) g(\theta_{rt}) cos(\theta_{rt}), \quad (3)$$

where $l = -ln2/ln(cos(\Psi))$ is the Lambertian emission order and Ψ denotes the semi-angle at half power of the LED; ρ and A are the responsivity and the active area of the PD, respectively; d_{rt} is the distance between the r-th PD and the t-th LED; φ_{rt} and θ_{rt} are the emission angle and the incident angle, respectively; $T_s(\theta_{rt})$ is the gain of optical filter; $g(\theta_{rt}) = n^2/sin(\Phi)$ is the gain of optical lens, where n and Φ are the refractive index and the half-angle field-of-view (FOV) of the optical lens, respectively.

The additive noise usually consists of both shot and thermal noises, which can be reasonably modeled as a real-valued zero-mean additive white Gaussian noise (AWGN) with power $P_n = N_0 B$, where N_0 and B denote the noise power spectral density (PSD) and the signal bandwidth, respectively.

III. GSMP-Based MIMO-OWC

In this section, the principle of the proposed GSMP technique is first introduced. Then, MIMO-OWC systems using GSMP and *M*-ary pulse amplitude modulation (*M*-PAM) is described and the corresponding analytical error bound is also derived.

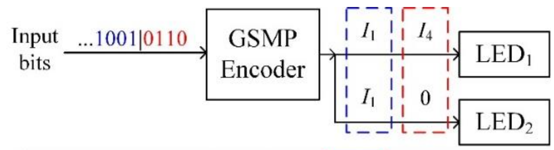
A. Principle of GSMP

In conventional SMP, all the LEDs are activated to transmit different signals. Hence, for SMP systems with N_t transmitters and *M*-ary constellation, the spectral efficiency R_{SMP} with unit bits/s/Hz is given by

$$R_{\text{SMP}} = N_t \, log_2 M = log_2(M^{N_t}). \qquad (4)$$

Although SMP can achieve relatively high spectral efficiency, it suffers from severe ICI which greatly degrades the achievable multiplexing gain [8].

In order to reduce ICI while maintaining a high spectral efficiency, we propose a novel GSMP technique as follows. In GSMP, a variable-number of LEDs are activated to transmit signal and the information bits are carried by both the spatial index symbols via variable-number LED selection and the constellation symbols transmitted by the activated LEDs.



Input bits	0000	0001	0011	0010	0110	0111	0101	0100
LED$_1$	0	I_1	I_2	I_3	I_4	0	0	0
LED$_2$	0	0	0	0	0	I_1	I_2	I_3
Input bits	1100	1101	1111	1110	1010	1011	1001	1000
LED$_1$	0	I_1	I_1	I_2	I_2	I_3	I_3	I_4
LED$_2$	I_4	I_1	I_2	I_2	I_3	I_3	I_1	I_4

Figure 1. Schematic diagram of the GSMP-enabled MIMO-OWC transmitter by taking $R_{\text{GSMP}} = 4$ bits/s/Hz with $N_t = 2$ and $M = 4$ as an example.

Therefore, the achievable spectral efficiency of GSMP systems with N_t transmitters and M-ary constellation can be obtained by

$$R_{\text{GSMP}} = \left\lfloor log_2\left(1 + \sum_{i=1}^{N_t} C_{N_t}^{i} M^{i}\right)\right\rfloor, \qquad (5)$$

where $\lfloor \cdot \rfloor$ denotes the floor function and $C_{N_t}^{i}$ represents the binomial coefficient.

B. MIMO-OWC Using GSMP with M-PAM

In this subsection, we apply the proposed GSMP technique into MIMO-OWC systems using *M*-PAM constellation. Due to the IM/DD nature of OWC, unipolar *M*-PAM is adopted. Since spatial index symbols via variable-number LED selection are used to transmit information bits, the intensity level of the *M*-PAM constellation cannot be zero, otherwise the spatial information would be lost [5]. As a result, the following intensity levels are utilized for *M*-PAM mapping:

$$I_m = \frac{2I}{M+1} m, \qquad m = 1, \cdots, M, \qquad (6)$$

where I denotes the average optical power emitted.

Fig. 1 shows the schematic diagram of the GSMP-enabled MIMO-OWC transmitter, where we take R_{GSMP} = 4 bits/s/Hz with $N_t = 2$ and $M = 4$ as an example. As we can see, the input information bits are first fed into a GSMP encoder, whose outputs are subsequently used to drive the two LEDs. The corresponding mapping table is shown at the bottom of Fig. 1. Due to the variable-number LED selection of GSMP, the number of activated LEDs can be zero, one or two. For example, when the input bits are "0000", both the two LEDs are deactivated; when the input bits are "0110", only the first LED, i.e., LED1, is activated to transmit intensity I_4; when the input bits are "1001", both LED1 and LED2 are activated to transmit intensities I_3 and I_1, respectively.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Room dimension	5 m × 5 m × 3 m
Height of ceiling	2.5 m
LED spacing	2 m
Height of receiving plane	0.85 m
PD spacing	10 cm
Semi-angle at half power of LED	60°
Responsivity of the PD	1 A/W
Active area of PD	1 cm^2
Refractive index	1.5
Half-angle FOV of optical lens	72°
Noise PSD	10^{-22} A^2/Hz
Signal bandwidth	20 MHz

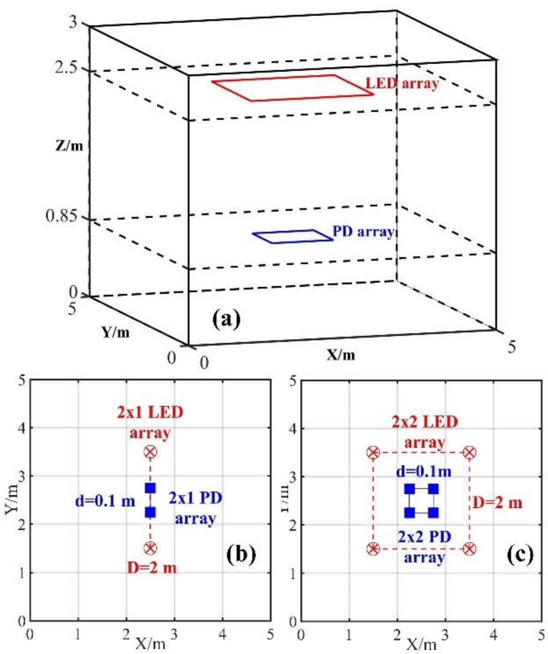


Figure 2. (a) Geometric setup, (b) top view of the 2 × 2 MIMO-OWC system and (c) top view of the 4 × 4 MIMO-OWC system.

At the receiver side, the maximum-likelihood (ML) detector is used for signal detection with perfect channel state information and ideal time synchronization, which is expressed by

$$\hat{\mathbf{s}} = \underset{\mathbf{s}}{arg\,min}\ \|\mathbf{y} - \mathbf{Hs}\|^2, \tag{7}$$

where $\|\cdot\|$ denotes the Euclidean norm.

C. Analytical Error Bound

In the following, we derive the analytical error bound of a general MIMO-OWC system. According to [11], the pairwise error probability (PEP), which denotes the probability that the receiver mistakes the transmitted signal vector $\boldsymbol{c}_{m^{(1)}}$ for $\boldsymbol{c}_{m^{(2)}}$ for a given transmit signal-to-noise ratio (SNR) γ_t, can be calculated by

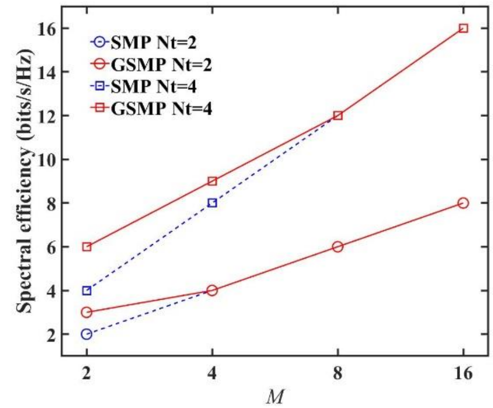


Figure 3. Shows the spectral efficiency versus M for SMP and GSMP with N_t = 2 and 4.

$$P_e\left(\boldsymbol{c}_{m^{(1)}} \to \boldsymbol{c}_{m^{(2)}}, \gamma_t\right) \leq \frac{1}{6}e^{-\frac{\|\mathbf{H}\|^2}{2}\gamma_t} + \frac{1}{12}e^{-\frac{\|\mathbf{H}\|^2}{4}\gamma_t} + \frac{1}{4}e^{-\frac{\|\mathbf{H}\|^2}{8}\gamma_t}, \tag{8}$$

where $\mathbf{H}$ is channel matrix given by (3) and $\gamma_t = \frac{P_s}{P_n}$ with P_s and P_n being the electrical powers of the transmitted M-PAM signal and the additive noise, respectively.

For the MIMO-OWC system with a spectral efficiency of R, the tight upper-bounded can be obtained as follows:

$$BER_{\text{upper}} \leq \frac{1}{2^R R}\sum_{m^{(1)}=1}^{2^R}\sum_{m^{(2)}=1}^{2^R} d_{\text{H}}\left(\boldsymbol{c}_{m^{(1)}}, \boldsymbol{c}_{m^{(2)}}\right) \times \left(\frac{1}{6}e^{-\frac{\|\mathbf{H}\|^2}{2}\gamma_t} + \frac{1}{12}e^{-\frac{\|\mathbf{H}\|^2}{4}\gamma_t} + \frac{1}{4}e^{-\frac{\|\mathbf{H}\|^2}{8}\gamma_t}\right), \tag{9}$$

where $d_{\text{H}}\left(\boldsymbol{c}_{m^{(1)}}, \boldsymbol{c}_{m^{(2)}}\right)$ gives the Hamming distance between $\boldsymbol{c}_{m^{(1)}}$ and $\boldsymbol{c}_{m^{(2)}}$. It should be noted that the BER upper bound given in (9) is applicable to the MIMO-OWC systems using both SMP and GSMP.

IV. RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of GSMP in typical MIMO-OWC systems and compared it with conventional SMP though Monte Carlo simulation. In our simulation, we consider an indoor room with a dimension of 5 m × 5 m × 3 m and the detailed simulation parameters are summarized in Table I. The heights of the ceiling and the receiving plane are 2.5 and 0.85 m, respectively. The LED spacing is 2 m while the PD spacing is 10 cm. The semi-angle at half power of LED is 60°. The responsivity and active area of PD are 1 A/W and 1 cm^2, respectively. The refractive index and the half-angle FOV of optical lens are 1.5 and 72°, respectively. The signal bandwidth is 20 MHz and the noise PSD is 10^{-22} A^2/Hz. The geometric setup of the MIMO-OWC system is shown in Fig. 2(a), where the LED array is placed at the center of the ceiling and the PD array is placed

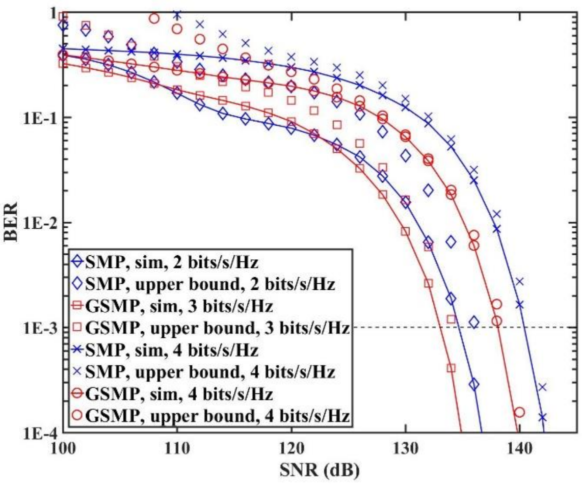


Figure 4. BER vs. transmit SNR for SMP and GSMP in the 2 × 2 MIMO-OWC system with different spectral efficiencies.

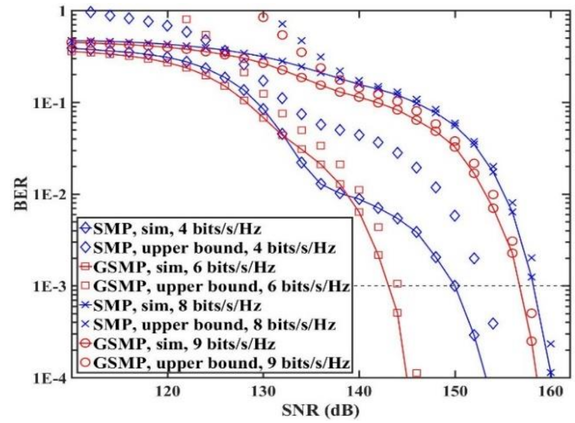


Figure 5. BER vs. transmit SNR for SMP and GSMP in the 4 ×4 MIMO-OWC system with different spectral efficiencies.

at the center of the receiving plane. Two MIMO settings, i.e., 2 × 2 and 4 × 4, are considered in the following. The top views of the 2 × 2 and 4 × 4 MIMO-OWC systems are shown in Figs. 2(b) and (c), respectively.

Fig. 3 shows the spectral efficiency versus M for SMP and GSMP with $N_t = 2$ and 4. As we can see, when M is relatively small, GSMP can achieve a higher spectral efficiency than conventional SMP. Specifically, for $N_t = 2$ with $M = 2$, the achievable spectral efficiency is improved from 2 to 3 bits/s/Hz when SMP is replaced by GSMP. The spectral efficiency improvement is more significant for $N_t = 4$. When M is relative large, SMP and GSMP can achieve comparable spectral efficiencies.

Fig. 4 shows the BER versus transmit SNR for SMP and GSMP in the 2 × 2 MIMO-OWC system with different spectral efficiencies. As we can see, the simulation results agree well with the derived analytical upper bounds in the high SNR region. It can also be found that GSMP with a spectral efficiency of 3 bits/s/Hz can outperform SMP with a spectral efficiency of 2 bits/s/Hz, and an SNR gain of 2 dB can be obtained at the BER of 10^{-3}. Moreover, to achieve the same spectral efficiency of 4 bits/s/Hz, an SNR gain of 3.9 dB can be achieved at the BER of 10^{-3} by using GSMP in comparison to SMP. The BER versus transmit SNR for SMP and GSMP in the 4 × 4 MIMO-OWC system with different spectral efficiencies is shown in Fig. 5. Similarly, the analytical upper bounds closely match the simulation results, which can provide an accurate estimation of the BERs in the high SNR region. It can be seen from Fig. 5 that GSMP with a spectral efficiency of 6 bits/s/Hz outperforms SMP with a spectral efficiency of 4 bits/s/Hz by an SNR gain of 7 dB at the BER of 10^{-3}. Moreover, a 1.5-dB SNR gain can also be achieved for GSMP with a spectral efficiency of 9 bits/s/Hz compared with SMP with a spectral efficiency of 8 bits/s/Hz. These results indicate that substantial SNR gains can be achieved by GSMP in comparison to SMP for small and moderate spectral efficiencies, and the achievable SNR gain becomes less significant for larger spectral efficiencies.

V. CONCLUSION

In this paper, we have proposed and evaluated a novel GSMP technique for IM/DD MIMO-OWC systems. GSMP can be considered as the combination of digital modulation and SMP, where the information bits can be carried by both the spatial index symbols via variable-number LED selection and the constellation symbols transmitted by the activated LEDs. Compared with conventional SMP, the proposed GSMP can achieve enhanced spectral efficiency with reduced ICI. The performance of GSMP has been evaluated in typical 2 × 2 and 4 × 4 MIMO-OWC systems via Monte Carlo simulations. The obtained simulation results agree well with the derived analytical upper bounds in the high SNR region. In the 2 × 2 MIMO-OWC system, GSMP achieves a 3.9-dB SNR improvement in comparison to SMP at the BER of 10^{-3}. In the 4 × 4 MIMO-OWC system, a significant 7-dB SNR gain at BER = 10^{-3} can be obtained by GSMP with a spectral efficiency of 6 bits/s/Hz over SMP with a spectral efficiency of 4 bits/s/Hz. The analytical and simulation results demonstrate the superiority of GSMP compared with conventional SMP. In conclusion, the proposed GSMP technique can be a promising candidate for future high-speed MIMO-OWC systems. In our future work, we will consider to apply more advanced modulation schemes such as orthogonal frequency division multiplexing (OFDM) in GSMP-enabled MIMO-OWC systems.

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