An Improved Generalized Spatial Modulation Scheme for Indoor Visible Light Communications

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***Abstract*—This paper proposes an improved generalized spatial modulation (iGSM) scheme for indoor visible light communication (VLC), which can significantly improve the spectral efficiency (SE) of traditional generalized spatial modulation. The iGSM uses N_t transmitters, i.e., light emitting diodes (LEDs), and activates N_a $(0 < N_a \leq N_t)$ LEDs to transmit the signal. The proposed iGSM can achieve 2^{N_t} LED groups by activating all LEDs for twice, and these two LED groups are distinguished by setting different intensity levels. This paper also compares the SE between iGSM and other modulation techniques, such as spatial modulation (SM), quadrature spatial modulation (QSM), enhanced spatial modulation (ESM), and traditional generalized spatial modulation. We get the conclusion that the SE of iGSM can achieve more than 60% increase compared with the generalized spatial modulation. At last, we compare the bit error rate (BER) performance between iGSM and generalized spatial modulation when the SE is 5 $bpcu$ and 6 $bpcu$ (the $bpcu$ is the term of SE and it means bits per channel use), and the proposed iGSM scheme can achieve about 3 dB gain than the generalized spatial modulation when the BER is about 10^{-4}.**

***Index Terms*—Visible light communication, generalized spatial modulation, quadrature spatial modulation, spatial modulation, spectral efficiency.**

I. Introduction

Multiple-input multiple-output (MIMO) systems achieve a high-speed transmission by activating all transmitters at every time slot [1]. However, all transmitters are activated at same time on the same transmission frequency would cause the inter-channel interference (ICI) and inter-antenna synchronization (IAS) at the receivers.

A new transmission approach named spatial modulation (SM) proposed in [2] entirely avoids ICI and IAS at the receivers. The key feature of the SM is that only one of the transmitters is activated to transmit the information at every time slot instead of all transmitters are activated in MIMO, this is the reason why SM can avoid the ICI and IAS. In [3], SM is applied to the optical wireless communications, the transmitters, i.e., LEDs, are considered as the spatial constellation points, and the incoming bit steam would mapping to one of the LED and activate it to transmit information. But SM has two bottlenecks: a) the number of LED has to be the power of 2, b) the SE of SM is low because it does not efficiently make use of the transmitters. In order to overcome these two bottlenecks of SM, some schemes such as generalized spatial modulation [4], ESM [5], and QSM [6] have been proposed.

Generalized spatial modulation activates more than one LEDs and the activated LEDs transmit the same information at every time slot. Therefore, the SE of generalized spatial modulation is higher than SM because the number of LED groups used in the generalized spatial modulation is more than the number of LEDs used in SM in the same system, that is $\binom{N_t}{N_a} = \frac{N_t!}{N_a!(N_t - N_a)!} > N_t$. This reason also causes the elimination of the limit on the number of LEDs used in generalized spatial modulation. But the number of activated LEDs cannot be 0 $(N_a \neq 0)$, and the number of LED groups must be power of 2, so generalized spatial modulation cannot use all $\binom{N_t}{N_a}$ LED groups.

The number of activated transmitters in ESM will vary with the selected signal constellation. For example, the ESM will use the primary signal constellation on the single activated antenna and use the secondary signal constellation on the two activated antennas. That is, ESM conveys the information by the combination of selected signal constellation and corresponding antenna(s). As for QSM, this scheme improves the SE by extending the real part of SM constellation to the in-phase and quadrature constellation. The selected complex symbol from the QSM constellation is divided into real and imaginary parts, and these two parts will be transmitted by two different antennas. Compared with the SM, the QSM has a chance to choose second antenna, so the SE of QSM is higher than that of SM.

The contributions of this paper can be summarized as follows: a) this paper proposes a new scheme which can improve the SE of generalized spatial modulation, b) we analyse and compare the SE of iGSM and other modulation techniques, c) we compare the BER performance between iGSM and generalized spatial modulation.

The rest of this paper is organized as follows: a VLC system model is presented in Section II. In Section III, we describe the use of the iGSM in the VLC systems. In Section IV, we compare the spectral efficiency of iGSM with other modulation techniques and have a BER performance comparison between iGSM and generalized spatial modulation. Finally,

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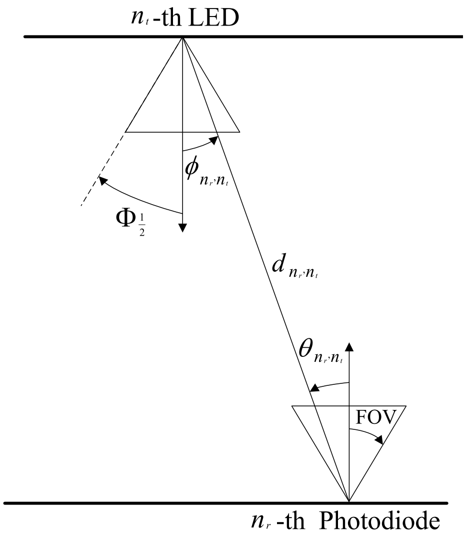

Fig. 1. Various angles between the LED and the photodiode.

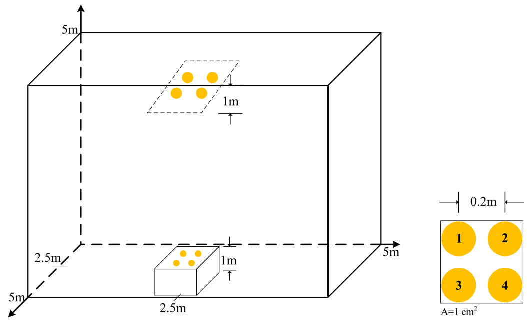

Fig. 2. Geometric set-up and the layout of transmitters (receivers) of the considered indoor VLC system.

the conclusions and future work are presented in Section V.

II. System Model

In this section, we consider an indoor VLC system which consists of N_t transmitters (LEDs) and N_r receivers (photodiodes). In this system, the intensity modulation and direct detection (IM/DD) are used because of the characteristic of VLC system, and we just focus on the line-of-sight (LOS) component which is dominant in the channel gain [7]. At last, we can get the VLC MIMO system equation:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{1}$$

where $\mathbf{y}$ and $\mathbf{w}$ denote the $N_r \times 1$ received signal vector and additive white gaussian noise (AWGN) vector, respectively. $\mathbf{x}$ is the $N_t \times 1$ transmitted signal vector, and the number of the nonzero elements in it is equal to the number of activated LEDs in every time slot , i.e., N_a. the $\mathbf{H}$ in (1) denotes the $N_r \times N_t$ optical MIMO channel gain matrix which is represented by:

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r1} & \cdots & h_{N_rN_t} \end{pmatrix} \tag{2}$$

where the (n_r, n_t) element h_{n_r,n_t} represents the channel gain between the n_t-th LED and the n_r-th photodiode. We only consider the LOS component between the transmitters and the receivers, so the channel gain h_{n_r,n_t} can be calculated by [8] as below (see Fig. 1 for the details of various angles between the LED and the photodiode)

$$h_{n_r,n_t} = \frac{A(k+1)}{2\pi\, d^2_{n_r,n_t}} \left(\cos\phi_{n_r,n_t}\right)^k \cos\theta_{n_r,n_t}\, \mathrm{rect}\left(\frac{\theta_{n_r,n_t}}{FOV}\right) \tag{3}$$

where A is the area of the photodiodes (in m^2), d_{n_r,n_t} is the distance between the n_t-th LED and the n_r-th photodiode. ϕ_{n_r,n_t} is the angle of emission of the n_t-th LED to the n_r-th photodiode with the normal at the n_t-th LED. θ_{n_r,n_t} represents the angle of incidence at the n_r-th photodiode. The FOV means the field of view of the photodiode. k represents the mode number of the radiating lobe and is given by

$$k = \frac{-\ln 2}{\ln\cos\Phi_{\frac{1}{2}}} \tag{4}$$

where $\Phi_{\frac{1}{2}}$ represents LEDs half-power semi-angle [9],

$$\mathrm{rect}\left(\frac{\theta_{n_r,n_t}}{FOV}\right) = \begin{cases} 0 & \frac{\theta_{n_r,n_t}}{FOV} > 1; \\ 1 & 0 \le \frac{\theta_{n_r,n_t}}{FOV} \le 1. \end{cases} \tag{5}$$

as shown in (5), the rectangle function in (3) is used to determine whether the photodiode can receive the signal from LEDs, that is, if $\theta_{n_r,n_t} > FOV$, the n_r-th photodiode cannot receive the signal from the n_t-th LED.

In order to simplify the model, we assume $N_r = N_t = 4$, and a room of size 5m×5m×5m where the LEDs are placed at a plane which is lower 1m than the ceiling, and the photodiodes are placed on a one-meter-high table, the distance of each LED or photodiode is 0.2m. Other parameters in this system are shown in Table I.

The angles of emission of the LED and the angles of incidence of photodiode can be calculated by (4) and (5) in [10]. Then we notice the angles of incidence of photodiodes are smaller than the FOV, this means the photodiodes can receive the signal from every LED, that is, $\mathrm{rect}(\frac{\theta_{n_r,n_t}}{FOV}) = 1$. At last, we can get the optical MIMO channel gain matrix $\mathbf{H}$ of consider system which is shown as below:

$$\mathbf{H} = 10^{-5} \begin{pmatrix} 3.7125 & 3.6716 & 3.6716 & 3.6313 \\ 3.6716 & 3.7125 & 3.6313 & 3.6716 \\ 3.6716 & 3.6313 & 3.7125 & 3.6716 \\ 3.6313 & 3.6716 & 3.6716 & 3.7125 \end{pmatrix}. \tag{6}$$

TABLE I
THE PARAMETERS OF THE SYSTEM.

Transceiver	Coordinate
LED1	(2.4,2.4,4)
LED2	(2.4,2.6,4)
LED3	(2.6,2.4,4)
LED4	(2.6,2.6,4)
Photodiode1	(2.4,2.4,1)
Photodiode2	(2.4,2.6,1)
Photodiode3	(2.6,2.4,1)
Photodiode4	(2.6,2.6,1)
Other parameters	Value
A	0.0001m^2
$\Phi_{\frac{1}{2}}$	15°
FOV	30°

On the basis of system equation in (1), the optimum maximum likelihood (ML) detector is used for detecting signal under the condition of perfect channel state information (CSI) which can be expressed as:

$$\hat{x} = \arg\min_{x} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|_F^2 \tag{7}$$

where $\hat{x}$ is detected symbol, and $\|\cdot\|_F$ is Frobenius norm.

III. iGSM MAPPING SCHEME IN VLC SYSTEM

Like generalized spatial modulation, iGSM transmits the information not only by the intensity level of activated LEDs, but also by the indices of them. What difference between iGSM and generalized spatial modulation is that a) the generalized spatial modulation just considers the case of N_a =2 or N_a =3 while iGSM focuses on every case of $N_a(0 < N_a \le N_t)$, and b) the iGSM activates all transmitters for twice by setting different intensity levels to achieve 2^{N_t} groups of LEDs.

Under the condition of VLC system setup mentioned in the Section II, and two intensity levels are used in the generalized spatial modulation while four intensity levels are used in the iGSM. The first two intensity levels which used in the iGSM are for the case of $N_a = 4$ when transmitters are activated by the bits "0000" and the other two intensity levels are used in the other cases.

The mapping scheme of other cases is similar to the traditional generalized spatial modulation (N_a =2 or N_a =3) and SM (N_a =1), therefore we just discuss the two special cases of N_a =4 in iGSM, and the iGSM mapping table for N_a =4 and pulse amplitude modulation (PAM) is shown in Table II.

As shown in Table II, all transmitters can be activated by the bits "0000" and "1111". If the LEDs are activated by "0000", they transmit bit "0" by intensity level I_1 and transmit bit "1" by intensity level I_2 while they transmit bit "0" by intensity level I_3 and transmit bit "1" by intensity level I_4 when they are activated by "1111". That is, the transmitted vector is $\mathbf{x} = \begin{bmatrix} I_1 & I_1 & I_1 & I_1 \end{bmatrix}^T$ if incoming bit stream is "00000", and the transmitted vector will be $\mathbf{x} = \begin{bmatrix} I_4 & I_4 & I_4 & I_4 \end{bmatrix}^T$ if incoming bit stream is "11111". Moreover, if incoming bit stream is "01010", the indices of activated LED are 2 and 4, and the transmitted vector will be $\mathbf{x} = \begin{bmatrix} 0 & I_3 & 0 & I_3 \end{bmatrix}^T$. The $[\mathbf{x}]^T$ denotes the transpose operation to vector $\mathbf{x}$.

The I_j is the intensity level which can be calculated by [11]

$$I_j = \frac{2\,I_p\,j}{M+1} \qquad j = 1, 2, 3, \ldots, M \tag{8}$$

where I_p is the average optical power of LED, and M is M -levels PAM signals, that is, the number of intensity levels.

The iGSM activates all LEDs for twice, thus the achievable number of LED groups by N_t LEDs which denotes G can be calculated as

$$G = \sum_{N_a=1}^{N_t} \begin{pmatrix} N_t \\ N_a \end{pmatrix} + 1 = 2^{N_t} \tag{9}$$

therefore, the total number of bits transmitted by iGSM at every time slot can be calculated as

$$\eta_{iGSM} = N_t + \log_2 M \qquad bpcu. \tag{10}$$

IV. SPECTRAL EFFICIENCY ANALYSIS AND BER PERFORMANCE COMPARISON

A. Spectral efficiency analysis between iGSM and other modulation techniques

In this section, we compare the SE of some modulation techniques. Specifically, we set up the number of intensity levels M=64, and the number of transmitters N_t increases from 2 to 32.

Spatial modulation transmits the information by the symbol and spatial domain, and the SE of it can be calculated as

$$\eta_{SM} = \lfloor \log_2 N_t \rfloor + \log_2 M \qquad bpcu \tag{11}$$

where $\lfloor x \rfloor$ is floor function which means the greatest integer less than or equal to real number x.

The generalized spatial modulation improves the SE by activating N_a LEDs at every time slot. Therefore generalized spatial modulation has $\begin{pmatrix} N_t \\ N_a \end{pmatrix}$ groups of LEDs, but the number of bits to mapping the LED groups must be the integer, so the SE of generalized spatial modulation can be calculated as

$$\eta_{GeSM} = \left\lfloor \log_2 \begin{pmatrix} N_t \\ N_a \end{pmatrix} \right\rfloor + \log_2 M \qquad bpcu \tag{12}$$

where GeSM is abbreviation of generalized spatial modulation.

It is important to note that we make N_a and N_t follow (13) according to the theorem of combination in order to maximize the number of LED groups.

$$N_a = \left\lfloor \frac{1}{2} N_t \right\rfloor. \tag{13}$$

The ESM improves the SE by employing multiple signal constellations, that is, ESM uses the primary signal constellation when the single antenna is activated to transmit the

TABLE II
iGSM MAPPING TABLE FOR N_a =4 AND PAM MODULATION.

Number of activated LED	Index of LED groups	Index of intensity level	LED1	LED2	LED3	LED4
N_a =4	0000	0	I_1	I_1	I_1	I_1
	0000	1	I_2	I_2	I_2	I_2
N_a =4	0000	0	I_3	I_3	I_3	I_3
	0000	1	I_4	I_4	I_4	I_4

information and some other secondary constellations are used for two active transmit antennas. Although ESM uses different signal constellation to transmit information, the total number of bits can be transmitted by every constellations is similar because the size of secondary constellation is half of primary signal constellation, so we can focus on the one of signal constellations to calculate the SE of ESM as below

$$\eta_{ESM} = N_t + \log_2 M \qquad bpcu. \tag{14}$$

The QSM is a variant of SM, it can improve the SE of SM by extending the spatial constellation symbols to in-phase and quadrature components. Compared with SM, the QSM has a chance to choose another antenna, then the SE of QSM is more $\lfloor \log_2 N_t \rfloor$ $bpcu$ than SM and can be calculated as

$$\eta_{QSM} = 2\lfloor \log_2 N_t \rfloor + \log_2 M \qquad bpcu. \tag{15}$$

The results of the SE analysis are depicted in Fig. 3. As we can see, the SM, QSM and generalized spatial modulation have a stepped upward trend because the floor operations are used in the calculation of SE. Moreover, the SM has the lowest of SE because it does not make efficient use of the transmitters, and the QSM obtains the enhancement compared the SM because it extends the spatial constellation symbols to in-phase and quadrature components. Generalized spatial modulation has a significantly improvement than SM and QSM because a much larger spatial domain (LED groups) is used to transmit information. However, the SE of generalized spatial modulation is still limited by the logarithmic algorithm, that is, the overall increase in the SE of generalized spatial modulation is related to the base 2 logarithm of the number of transmitters. The SE of ESM is equal to iGSM, but the ESM employs two constellations with different sizes (one of which is half the size of the other). Therefore the ESM is more complex than iGSM.

At last, in the consider system, the SE of generalized spatial modulation ($N_a = 2$) is

$$\eta_{GeSM} = \left\lfloor \log_2 \begin{pmatrix} 4 \\ 2 \end{pmatrix} \right\rfloor + \log_2 2 = 3 \qquad bpcu \tag{16}$$

and the SE of iGSM is

$$\eta_{iGSM} = 4 + \log_2 2 = 5 \qquad bpcu. \tag{17}$$

Thus, the SE of iGSM increases by more than 60% compared with generalized spatial modulation in the consider system.

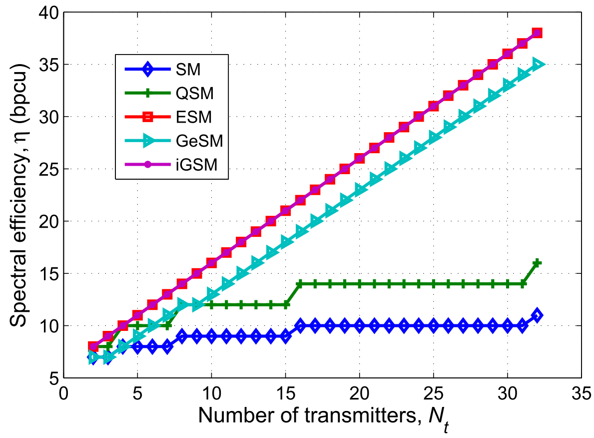

Fig. 3. The spectral efficiency analysis of different modulation techniques.

B. Performance comparison between iGSM and generalized spatial modulation

The iGSM is a scheme which can improve the SE of generalized spatial modulation, therefore we focus on the BER performance comparison between these two modulation techniques.In order to fairly compare the performance of iGSM and generalized spatial modulation, we set the spectral efficiency equals 5 $bpcu$ and 6 $bpcu$. Moreover, the signal-to-noise ratio (SNR) is defined as $SNR = \frac{E_\mathbf{x}}{E_\mathbf{w}}$ where $E_\mathbf{x}$ and $E_\mathbf{w}$ are the energy of transmitted signals and AWGN respectively.

As previously mentioned, the generalized spatial modulation has 6 LED groups when N_t =4 and $N_a = 2$, but we can only use 4 LED groups, and the LED groups mapping table is shown in Table III. As we can see, the 1st and 2nd LEDs would be activated when the incoming bit stream is “00”, and other cases are similar to this.

TABLE III
GENERALIZED SPATIAL MODULATION LED GROUPS MAPPING TABLE.

Index of LED groups	Activated LED groups
00	(1,2)
01	(1,3)
10	(2,3)
11	(3,4)

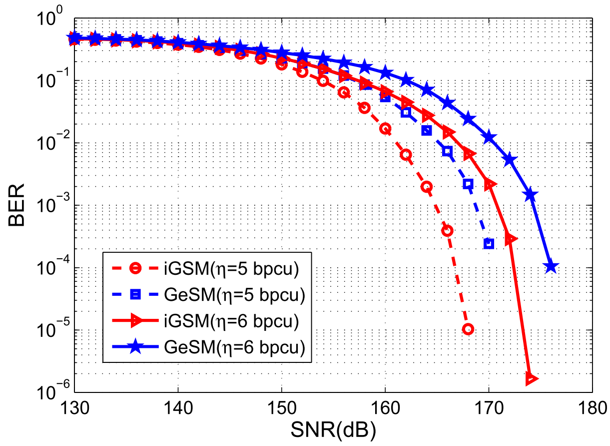

Fig. 4. BER performance comparison between iGSM and generalized spatial modulation under the condition of different spectral efficiency.

Taking 5 *bpcu* as an example, the intensity levels which are used in generalized spatial modulation can be calculated by (8) where $M = 8$, and these eight levels are mapped by 3 bits. It means the first two bits mapping the LED groups and the next three bits mapping the intensity levels in the five bits of incoming bit stream. For example, if the incoming bit stream is "01001", then the 1st and 3rd LEDs will be activated and transmit information by intensity level I_1^*. At last, the transmitted signal vector is $\mathbf{x}^* = \begin{bmatrix} I_1^* & 0 & I_1^* & 0 \end{bmatrix}^T$. The $\mathbf{x}^*$ and I_1^* are used to distinguish from the signal vectors and intensity levels used in iGSM, i.e.,$\mathbf{x}$ and I_1.

The BER performance comparison between iGSM and generalized spatial modulation is depicted in Fig. 4. The performance of iGSM is better about 3 dB gain than generalized spatial modulation when the BER is about 10^{-4}, this is because traditional generalized spatial modulation would employ more intensity levels to achieve the same spectral efficiency with iGSM, and this makes each intensity level is closer to each other, thereby increases the difficulty of the detection, at last these results in much more errors of detection appeared at receivers. This also reflects the benefits of effective use of LED groups in iGSM. The more LED groups can be used, the less intensity levels would be employed, and the better performance can be achieved.

V. Conclusions and Future Work

In this paper, a new modulation scheme named iGSM has been proposed, which can improve the SE of the VLC system. All LEDs in iGSM can be activated by the bit stream "0000" or "1111" in the considered system. We distinguish these two LED groups by setting different intensity levels, and other LED groups mapping scheme is similar to traditional generalized spatial modulation. Therefore, the VLC system equipped with N_t LEDs can achieve 2^{N_t} LED groups, and this expands the spatial domain of iGSM. This paper also shows the comparisons of SE between iGSM and other modulation techniques, and comes to a conclusion that the iGSM can achieve great performance. Moreover, the SE of iGSM increases by more than 60% compared with generalized spatial modulation in the consider system. As for BER performance, this paper compares it between iGSM and generalized spatial modulation at the SE equals 5 *bpcu* and 6 *bpcu*, then gets the conclusion that the performance of iGSM is better than generalized spatial modulation under the condition of the same SE, furthermore the former performs better about 3 dB gain than the latter when the BER is about 10^{-4}. Our future work will focus on the upper bound of BER of iGSM as well as in-depth analysis of the performance of iGSM, and compare it with other modulation techniques in different systems.

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