OFDM-Based Generalized Spatial Modulation for Optical Wireless Communication

Xin Zhong\textsuperscript{1}, Chen Chen\textsuperscript{1,*}, Shu Fu\textsuperscript{1}, Xin Jian\textsuperscript{1}, Min Liu\textsuperscript{1}, and Xiong Deng\textsuperscript{2}

\textsuperscript{1}School of Microelectronics and Communication Engineering
Chongqing University, Chongqing 400044, China
\textsuperscript{2}Department of Electrical Engineering
Eindhoven University of Technology (TU/e), 5600MB Eindhoven, Netherlands
\textsuperscript{*}c.chen@cqu.edu.cn

Abstract—In this paper, we propose two orthogonal frequency division multiplexing (OFDM)-based generalized spatial modulation (GSM) techniques, i.e., frequency domain GSM (FD-GSM) and time domain GSM (TD-GSM), for indoor multiple-input multiple-output optical wireless communication (MIMO-OWC) systems. Specifically, FD-GSM selects a subset of parallel OFDM modulators to transmit the same quadrature amplitude modulation (QAM) constellation symbol in the subcarrier level, while TD-GSM selects a subset of light-emitting diode (LED) transmitters to transmit the same time domain sample after OFDM modulation. Compared with the existing OFDM-based spatial modulation (SM) scheme, OFDM-based GSM can provide additional transmit diversity. For both FD-GSM and TD-GSM, maximum-likelihood (ML) detectors are employed to recover the spatial and constellation symbols. Moreover, TD-GSM usually requires a secondary direct current (DC) bias to work properly. The simulation results show that in a typical indoor 4 × 4 MIMO-OWC system, OFDM-based TD-GSM outperforms OFDM-based FD-GSM by adding a proper secondary DC bias.

Index Terms—Optical wireless communication (OWC), multiple-input multiple-output (MIMO), generalized spatial modulation (GSM).

I. INTRODUCTION

Recently, the involvement of new technologies such as virtual/augmented reality (VR/AR), Internet of things (IoT) and artificial intelligence (AI) 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]. Since the light emitted by LEDs is generally not coherent, typical OWC systems adopt intensity modulation with direct detection (IM/DD). Nevertheless, LEDs usually have a small electrical bandwidth, which greatly limit the achievable capacity of OWC systems.

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 [3]–[5]. 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) [4], [6]. Although RC can provide substantial diversity gain, its spectral efficiency is low. In contrast, SMP can achieve high spectral efficiency, but suffers from severe inter-channel interference. SM has been shown to be a promising MIMO scheme, which can be seen as the combination of MIMO and digital modulation [7]. Nevertheless, it is challenging for SM to achieve high spectral efficiency [8]. In order to enhance the spectral efficiency of conventional SM, generalized SM (GSM) has been further proposed in [9], which can transmit the same symbol from more than one transmit antenna. Moreover, as a multi-carrier modulation technology, orthogonal frequency division multiplexing (OFDM) can make full use of limited bandwidth, and hence OFDM can be combined with SM to enhance the capacity of SM-based OWC systems. Generally, OFDM-based SM for OWC systems can be divided into two categories: one is OFDM-based frequency domain SM (FD-SM) and the other is OFDM-based time domain SM (TD-SM) [10], [11]. To the best of our knowledge, the combination of OFDM with GSM has not yet been considered for OWC systems.

In this paper, we propose two OFDM-based GSM techniques for indoor MIMO-OWC systems, including FD-GSM and TD-GSM. The superiority of OFDM-based GSM over OFDM-based SM in typical indoor MIMO-OWC systems has been verified by simulation results. The rest of this paper is organized as follows. In Section II, we describe the channel model of a typical MIMO-OWC system. The principle of OFDM-based GSM techniques is described in Section III. The simulation results are presented in Section IV. Finally, Section V concludes the paper.

This work was supported by the National Natural Science Foundation of China under Grant 61901065.
II. MIMO CHANNEL MODEL

In the following, we consider a typical MIMO-OWC system which consists of \( N_r \) LED transmitters and \( N_t \) photo-diodes (PDs). The received signal vector \( y = [y_1, y_2, \cdots, y_N] \) can be expressed by:

\[
y = Hs + n,
\]

where \( s = [s_1, s_2, \cdots, s_N] \) is the transmitted signal vector and \( n = [n_1, n_2, \cdots, n_N] \) denotes noise vector, which can be assumed as a real-valued additive white Gaussian noise (AWGN) with zero mean and a variance \( \sigma^2 \). The noise power is \( P_n = N_0B_m \), where \( N_0 \) is the power spectral density (PSD) and \( B_m \) is the modulation bandwidth [4]. \( H \) represents the \( N_r \times N_t \) MIMO channel matrix, where its element \( h_{rt} \) (\( r = 1, \cdots, N_r; t = 1, \cdots, N_t \)) denotes the direct current channel gain between the \( r \)-th PD and the \( t \)-th LED. Assuming the LEDs follow the Lambertian radiation pattern and only considering the line-of-sight (LOS) component, \( h_{rt} \) can be calculated by:

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

where \( l = -\ln(2/\ln(\cos(\Psi))) \) is the Lambertian emission order, \( \rho \) and \( A \) are the responsivity and the active area of the PD, respectively; \( \Psi \) denotes the semi-angle at half power of the LED; \( d_{rt} \) is the distance between the \( r \)-th PD and the \( t \)-th LED; \( \varphi_{rt} \) and \( \theta_{rt} \) are the emission angle and the incident angle, respectively; \( T_s(\theta_{rt}) \) is the gain of optical filter; \( g(\theta_{rt}) = \frac{n^2}{n^2 + \Phi} \) is the gain of optical lens, where \( n \) and \( \Phi \) are the refractive index and the half-angle field-of-view (FOV) of the optical lens, respectively. If the incident light is outside the FOV of the receiver, \( h_{rt} \) becomes zero. At receiver side, zero forcing (ZF) equalization can be applied to recover the transmitted signal vector \( s \):

\[
\hat{s} = H^\dagger y = s + H^\dagger n,
\]

where \( H^\dagger \) is the pseudo inverse of \( H \).

III. OFDM-BASED GSM TECHNIQUES

In this section, we first review the principle of OFDM for IM/DD OWC systems, and then describe the principle of the proposed two OFDM-based GSM techniques.

A. OFDM for IM/DD OWC

Due to the non-coherence nature of LEDs, IM/DD is generally adopted in OWC systems, and hence only real-valued non-negative signals can be successfully transmitted [12]. To generate IM/DD-compatible real-valued OFDM signals, the Hermitian symmetry constraint is usually imposed at the input of the \( N \)-pint inverse fast Fourier transform (IFFT) and hence resultant the input vector can be expressed by:

\[
X = \left[ X_1, X_2, \cdots, X_N, 0, X_N, 0, \cdots, X_1 \right]^T,
\]

where \( X_k^* \) denotes the Hermitian conjugate of \( X_k \) with \( k = 1, \cdots, N/2 - 1 \). As we can see, due to the imposing of the Hermitian symmetry constraint, only \( N/2 - 1 \) subcarriers can be used for valid data transmission. A real-valued bipolar time-domain signal can be generated at the output of IFFT:

\[
x_m = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_m \exp \left( \frac{j2\pi km}{N} \right), m = 0, 1, \cdots, N - 1.
\]

For a relatively large value of \( N \), \( x_m \) can be assumed to follow a Gaussian distribution with zero mean and variance \( \sigma^2 \). To obtain a non-negative signal to modulate the LEDs, the bipolar
OFDM-based FD-GSM with \( N_t \) LEDs, \( N_a \) selected OFDM modulators and \( M \)-ary QAM constellation is given by:

\[
SE_{\text{FD-GSM}} = \frac{N}{2} - \frac{1}{N} \left( \log_2(M) + \left| \log_2 \left( C(N_t, N_a) \right) \right| \right)
\]

\[
\approx \frac{1}{2} \log_2(M) + \frac{1}{2} \log_2 \left( C(N_t, N_a) \right),
\]

where \([\cdot]\) denotes the floor operation. Subsequently, the received signals are equalized and further fed into OFDM demodulators. The output signal matrix \( \mathbf{S}_r \) is subsequently detected by a maximum-likelihood (ML) detector. The detailed procedures of ML detection are described in Algorithm 1. The multipliers of the elements in \( \hat{s}_m \) (\( m = 1, \ldots, N/2 - 1 \)) are first calculated and then sorted in the descending order. Hence, we can obtain the sorted index vector \( \hat{i} = [\hat{i}_1, \hat{i}_2, \ldots, \hat{i}_{N_a}]^T \). Then, the first \( N_a \) elements of \( \hat{i} \) are abstracted and an index vector \( \hat{\mathbf{i}}' = [\hat{i}_1, \hat{i}_2, \ldots, \hat{i}_{N_a}]^T \) is obtained. By further sorting \( \hat{\mathbf{i}}' \) in the ascending order, we can obtain the sorted index vector \( \hat{\mathbf{c}}_m = [\hat{c}_1, \ldots, \hat{c}_{N_a}]^T \) and the constellation symbol \( \hat{x}_m = [\hat{x}_{\hat{c}_1}, \ldots, \hat{x}_{\hat{c}_{N_a}}]^T \). Finally, the averaged signal \( \hat{x}_{\hat{c}} = \frac{1}{N_a} \sum_{i=1}^{N_a} \hat{x}_{\hat{c}_i} \) can be obtained.

Algorithm 1 ML detection for FD-GSM

**Input:** \( \hat{\mathbf{S}}_r = [\hat{s}_1, \ldots, \hat{s}_{N/2-1}] \)

**Output:** \( \hat{\mathbf{C}}_r = [\hat{c}_1, \ldots, \hat{c}_{N/2-1}] \), \( \hat{x}_{\hat{c}} = [\hat{x}_{\hat{c}_1}, \ldots, \hat{x}_{\hat{c}_{N_a}}] \) for \( m = 1 \) to \( N/2 - 1 \)

1. Calculate the modulus of the elements in \( \hat{s}_m \) and sort them in the descending order.
2. Obtain the sorted index vector \( \hat{i} = [\hat{i}_1, \hat{i}_2, \ldots, \hat{i}_{N_a}]^T \) and abstract \( \hat{\mathbf{i}}' = [\hat{i}_1, \hat{i}_2, \ldots, \hat{i}_{N_a}]^T \).
3. Sort the elements of \( \hat{\mathbf{i}}' \) in the ascending order.
4. Obtain the sorted index vector \( \hat{\mathbf{c}}_m = [\hat{c}_1, \ldots, \hat{c}_{N_a}]^T \) and the constellation symbol \( \hat{x}_m = [\hat{x}_{\hat{c}_1}, \ldots, \hat{x}_{\hat{c}_{N_a}}]^T \).
5. Obtain the averaged signal \( \hat{x}_{\hat{c}} = \frac{1}{N_a} \sum_{i=1}^{N_a} \hat{x}_{\hat{c}_i} \).

**end for**

C. OFDM-Based TD-GSM

Fig. 1(b) shows the block diagram of the \( N_c \times N_t \) OFDM-based TD-GSM system. Compared with OFDM-based FD-GSM, Gaussian is performed in the time domain in OFDM-based TD-GSM and LED is selected after OFDM modulation. Hence, only \( N_a \) out of totally \( N_t \) LEDs are activated for valid data transmission and the others are just driven by DC biases for the purpose of illumination. The mapping table of spatial bits for OFDM-based TD-GSM is similar to that of OFDM-based FD-GSM, as shown in Table I, which is omitted here for brevity. Since GSM is performed in the time domain, the spatial symbol \( c_T \) is not constrained by the Hermitian symmetry and...
TABLE II
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of LEDs</td>
<td>4</td>
</tr>
<tr>
<td>Number of PDs</td>
<td>4</td>
</tr>
<tr>
<td>Room dimension</td>
<td>5 m × 5 m × 3 m</td>
</tr>
<tr>
<td>Height of ceiling</td>
<td>3 m</td>
</tr>
<tr>
<td>LED spacing</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Height of receiving plane</td>
<td>0.85 m</td>
</tr>
<tr>
<td>PD spacing</td>
<td>10 cm</td>
</tr>
<tr>
<td>Position of PDs</td>
<td>(2m, 2m, 0.85m)</td>
</tr>
<tr>
<td>Semi-angle at half power of LED</td>
<td>60°</td>
</tr>
<tr>
<td>Responsivity of the PD</td>
<td>1 A/W</td>
</tr>
<tr>
<td>Active area of PD</td>
<td>1 cm²</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.5</td>
</tr>
<tr>
<td>Half-angle FOV of optical lens</td>
<td>72°</td>
</tr>
<tr>
<td>Noise PSD</td>
<td>10⁻²² A²/Hz</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Gain of the optical filter</td>
<td>0.9</td>
</tr>
<tr>
<td>Number of activated LEDs</td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>

hence the spectral efficiency of OFDM-based TD-GSM can be obtained by

\[
SE_{\text{TD-GSM}} = \frac{N}{N_t} - \frac{1}{N} \log_2(M) + \left[ \log_2(N_t, N_a) \right] \\
\approx \frac{1}{2} \log_2(M) + \left[ \log_2(N_t, N_a) \right]. \tag{9}
\]

In OFDM-based TD-GSM, only the selected \( N_a \) LEDs transmit the valid data and the rest of them are unmodulated. As a result, when \( N_a < N_t \), OFDM-based TD-GSM suffers from reduced inter-channel-interference (ICI) in comparison to OFDM-based FD-GSM. However, according to (6), if the DC bias we define is relatively small, the output time samples will have a large number of zero samples, which will cause the loss of spatial information. In order to obtain non-zero time domain samples, a secondary bias can be added after clipping so as to guarantee that all the time-domain samples have positive values. Hence, (6) can be modified as

\[
s_m = \begin{cases} 
\epsilon, & x_m < -b \\
\frac{1}{2} (x_m + b + \epsilon), & x_m \geq -b 
\end{cases}, \tag{10}
\]

where \( \epsilon = \rho b \) is the value of the secondary DC bias with \( \rho \) denoting the ratio between the secondary DC bias (i.e., \( \epsilon \)) and the primary DC bias (i.e., \( b \)).

At receiver side, ML detection is performed before OFDM demodulation. The detailed procedures are similar to that of OFDM-based FD-GSM, as given by Algorithm 1, and the main differences are that: (i) the number of elements in \( \hat{S}_T \), \( C_T \) and \( \hat{x}_T^{\text{av}} \) is increased to \( N \) and (ii) we can directly sort the elements of \( \hat{s}_m \) without the need to calculate the moduli.

IV. SIMULATION RESULTS

In this section, we evaluate and compare the performance of OFDM-based FD-GSM and TD-GSM in a typical indoor MIMO-OWC system.

![Fig. 2. Spectral efficiency (bits/s/Hz) vs. log₂ M for OFDM-based FD-GSM and TD-GSM.](image)

(a) FD-GSM

(b) TD-GSM

A. Simulation Setup

In our simulations, we consider an indoor 4 × 4 MIMO-OWC system with a dimension of 5 m × 5 m × 3 m, where the LED array is mounted in the ceiling which is 3 m above the floor, and the PD array is located within the receiving plane which is 0.85 m above the floor. The LED array is located at the center of the ceiling and the LED spacing between two adjacent LEDs is 2.5 m while the PD spacing is 10 cm. The position coordinates of the receiver are (2m, 2m, 0.85m). The semi-angle at half power of LED is 60°. The responsivity and active area of PD are 1 A/W and 1 cm², 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 gain of the optical filter is 0.9. The potential number of activated LEDs is $N_a = 1, 2, 3, 4$. The detailed simulation parameters are summarized in Table II.

**B. Spectral Efficiency**

Figs. 2(a) and (b) show the spectral efficiency versus $\log_2 M$ for OFDM-based FD-GSM and TD-GSM, respectively. In OFDM-based FD-GSM, the achievable spectral efficiencies for $N_a = 1$ (green line), 2 (blue line) and 3 (red line) are the same, which are higher than that for $N_a = 4$. Similarly, OFDM-based TD-GSM with $N_a = 1, 2$ and 3 achieves the same spectral efficiency and outperforms that for $N_a = 4$. By comparing Figs. 2(a) and (b), we can see that OFDM-based TD-GSM achieves higher spectral efficiencies than OFDM-based FD-GSM for $N_a = 1, 2$ and 3, since TD-GSM can get twice as many spatial bits as FD-GSM. When $N_a = 4$, both FD-GSM and TD-GSM become RC, so they have the same spectral efficiency.

**C. BER performance**

Fig. 3 shows the BER performance of OFDM-based FD-GSM for different spectral efficiencies, where the DC bias $b_{dB}$ is set to 10 dB. For the spectral efficiency of 4 bits/s/Hz, FD-GSM with $N_a = 4$ (i.e., RC) has the best BER performance, while FD-GSM with $N_a = 1, 2$ and 3 achieves comparable BER performance. It can be seen that FD-GSM with $N_a = 4$ outperforms FD-GSM with $N_a = 2$ by an SNR gain of 7 dB at BER $= 10^{-3}$. Moreover, an error floor of about $6.3 \times 10^{-4}$ occurs for FD-GSM with $N_a = 4$ when the transmit SNR is relatively large, which is mainly caused by the clipping noise during the OFDM modulation. However, when the spectral efficiency is improved to 5 bits/s/Hz, FD-GSM with $N_a = 4$ cannot reach the BER of $10^{-3}$ since its error floor is about $4.4 \times 10^{-3}$. In contrast, FD-GSM with $N_a = 3$ achieves the best BER performance, which outperforms FD-GSM with $N_a = 2$ by an SNR gain of 2 dB at BER $= 10^{-3}$.

Fig. 4(a) shows the BER performance of OFDM-based TD-GSM for a spectral efficiency of 4 bits/s/Hz, where the DC bias $b_{dB}$ is 10 dB and two secondary DC bias ratio values $\rho = 0$ and 0.2 are considered. When $\rho = 0$, i.e., no secondary DC bias is added, TD-GSM gets the best performance for $N_a = 4$, while the worst BER performance is obtained by $N_a = 1$. It can be observed that, for TD-GSM with $N_a = 1, 2$ and 3, the error floors might occur due to high spatial errors caused by the zero samples in the time domain signals. For TD-GSM with $N_a = 4$, it also becomes RC and the error floor occurs due to the clipping noise. When $\rho = 0.2$, the spatial errors can be efficiently reduced and hence the BER performance can be improved. Specifically, TD-GSM with $N_a$
= 3 achieves the best BER performance, which outperforms $N_a = 4$ at a BER of $10^{-3}$ by about 2 dB. It also performs about 3 dB and 6 dB better than $N_a = 2$ and 1, respectively. Due to the use of a relatively large secondary DC bias, the number of zero samples in the time domain signals is significantly reduced and hence the spatial errors caused by zero samples can be efficiently eliminated. Therefore, the error floors no longer exist for TD-GSM with $N_a = 1, 2$ and 3. Fig. 4(b) presents the BER performance of OFDM-based TD-GSM for a spectral efficiency of 5 bits/s/Hz, where the DC bias $b_{dB}$ is 10 dB and $\rho = 0$ and 0.2. As we can observe, TD-GSM with $N_a = 4$ cannot reach the BER of $10^{-3}$ with an error floor of about $3.1 \times 10^{-3}$, and TD-GSM with $N_a = 3$ achieves the best BER performance than others for both $\rho = 0$ and 0.2. When $\rho = 0$, TD-GSM with $N_a = 3$ obtains SNR gains of 4 dB and 8 dB at BER = $10^{-3}$ compared with TD-GSM with $N_a = 2$ and TD-GSM with $N_a = 1$, respectively. Moreover, error floors of about $2.9 \times 10^{-4}$ occur for TD-GSM with $N_a = 1, 2$ and 3. When $\rho = 0.2$, TD-GSM with $N_a = 3$ outperforms TD-GSM $N_a = 2$ and TD-GSM $N_a = 1$ by SNR gains of 5 dB and 9 dB at BER = $10^{-3}$, respectively. It also can be seen that, for TD-GSM with $N_a = 3$, an SNR gain of 2 dB is achieved when $\rho$ is increased from 0 to 0.2.

Finally, we compare the BER performance versus transmit SNR between OFDM-based FD-GSM and TD-GSM for different spectral efficiencies, where the optimal value of $N_a$ is selected for each case according to the above results. As we can see, for SE = 4 bits/s/Hz, FD-GSM with $N_a = 4$ outperforms TD-GSM with $N_a = 3$ and $\rho = 0$ by an SNR gain of 5 dB at BER = $10^{-3}$. However, TD-GSM with $N_a = 3$ and $\rho = 0.2$ performs better than FD-GSM with $N_a = 4$ with an SNR gain of 2 dB. For the spectral efficiency of 5 bits/s/Hz, whether it has secondary DC bias or not, TD-GSM with $N_a = 3$ is always superior than FD-GSM with $N_a = 3$. When $\rho = 0$, it outperforms FD-GSM with $N_a = 3$ at a BER of $10^{-3}$ by an SNR gain of 5 dB, which is increased to 7 dB, when $\rho$ is increased to 0.2.

V. CONCLUSION

In this paper, we have proposed and evaluated two OFDM-based GSM techniques, including FD-GSM and TD-GSM, for indoor IM/DD MIMO-OWC systems. Compared with conventional SM, multiple LEDs can be selected to transmit the same symbol when applying GSM in the system, which can provide transmit diversity. The obtained simulation results show that, for both OFDM-based FD-GSM and TD-GSM, there exist optimal numbers of the activated OFDM modulators and LED transmitters, respectively. In a typical indoor 4 × 4 MIMO-OWC system, FD-GSM outperforms TD-GSM without adding a secondary DC bias for a spectral efficiency of 4 bits/s/Hz, while TD-GSM always achieves better BER than FD-GSM when a proper secondary DC bias is applied. In conclusion, OFDM-based FD-GSM might be a promising technique for energy-efficient OWC systems since it does require a secondary DC bias, while OFDM-based TD-GSM has the potential for visible light communication (VLC) systems since a large secondary DC bias is generally required to ensure efficient illumination.

REFERENCES


