PAPR Reduction in OTSM Systems: A Comparative Analysis of SLM Techniques with Novel Phase Matrix Designs

Hsin-Ying Liang and Chuan-Bi Lin

***Abstract*—Orthogonal Time Sequency Multiplexing (OTSM) represents a pivotal advancement in wireless communication technology. Nevertheless, its high Peak-to-Average Power Ratio (PAPR) imposes significant constraints on its practical applications and future development. The definition of PAPR refers to the ratio of the maximum instantaneous power to the average power of a signal, and it is commonly used to assess the performance of high-power amplifiers. When PAPR values are excessively high, they reduce the efficiency of high-power amplifiers and increase the complexity of the transmission system. To mitigate this challenge, this paper explores and evaluates the efficacy of the Selective Mapping (SLM) technique for enhancing PAPR performance in OTSM systems. Leveraging the unique two-dimensional data structure inherent to OTSM, a specialized SLM approach is introduced in this paper. The proposed SLM method incorporates a Phase Generation Mechanism (PGM) that utilizes a pre-constructed perturbation phase matrix. This matrix undergoes cyclic shifts to produce multiple perturbation phase matrices. To assess the effectiveness of the proposed SLM technique, this paper investigates three distinct perturbation phase matrix generation mechanisms: Zadoff-Chu Transform (ZCT) matrices, Discrete Cosine Transform (DCT) matrices, and Randomly Generated Phase (RGP) matrices. Additionally, for evaluating PAPR performance improvement, the Complementary Cumulative Distribution Function (CCDF) is used, a statistical method that estimates the probability of high PAPR occurrences. Simulation results indicate that the RGP-based phase generation mechanism consistently outperforms the other methods in achieving significant PAPR reduction.**

***Index Terms*—OTSM, PAPR, ZCT matrices, DCT matrices.**

I. Introduction

Addressing the stringent demands of 5G and future wireless communication for high throughput and enhanced spectral efficiency necessitates advanced physical layer technologies[1][2]. Filter Bank Multi-Carrier (FBMC) modulation, a key 5G enabler, improves spectral efficiency and bandwidth conservation over Orthogonal Frequency Division Multiplexing (OFDM), especially in SUI-6 multipath fading channels, where it can outperform OFDM by up to 20%[1]. Concurrently, Sparse Code Multiple Access (SCMA)[2], a non-orthogonal multiple access (NOMA) technique, augments multi-user processing capability. SCMA codebook design utilizing chaotic interleaving based on Arnold's Cat map can reduce computational complexity by up to 32% for $M = 16$ codewords while maintaining performance[2]. For high-mobility wireless communication environments demanding superior transmission stability and reduced system complexity, Orthogonal Time Sequency Multiplexing (OTSM) is introduced to fulfill these specialized requirements[3][4][5].

Orthogonal Time Sequency Multiplexing (OTSM) is a novel single-carrier modulation technology designed for high-mobility wireless communication environments. OTSM not only achieves comparable performance to Orthogonal Time Frequency Space (OTFS) modulation but also significantly reduces the system's implementation complexity [3][4][5]. The core concept of OTSM is multiplexing in the delay-sequency domain, utilizing Walsh-Hadamard Transform (WHT) to convert signals into the delay-time domain, and finally transmitting and receiving signals in the time domain. This modulation technique demonstrates exceptional transmission stability in high-mobility channels while maintaining system implementation simplicity.

At the transmitter, OTSM arranges information symbols into a two-dimensional delay-sequency domain matrix. Each row undergoes WHT to transform it into the delay-time domain, and the transformed matrix rows are sequentially transmitted. At the receiver, the received time-domain signals are reconstructed into a delay-time domain matrix, and each row is processed by WHT to recover the original delay-sequency domain symbols. By leveraging the simplicity of WHT, which only requires addition and subtraction operations, OTSM achieves significant simplification in modulation and demodulation compared to OTFS, which relies on Fast Fourier Transform (FFT). In addition to reduced computational complexity, OTSM also exhibits similar performance to OTFS in high-mobility scenarios and outperforms conventional Orthogonal Frequency Division Multiplexing (OFDM) [3][4][5]. OTSM can be seamlessly integrated with existing OFDM systems, where Inverse WHT (IWHT) and FFT are used to generate time-frequency signals for OFDM transmission. Compared to OTFS, OTSM can be seen as a simplified version, primarily replacing FFT with WHT for domain transformations. Notably, both techniques effectively separate delay and Doppler effects at the receiver, granting them significant advantages in high-mobility channels. Moreover, WHT's low complexity makes OTSM particularly suitable for future high-mobility communication systems sensitive to computational load, showcasing substantial application potential.

Peak-to-Average Power Ratio (PAPR) is a critical performance metric in wireless communication systems[6][7][8][9].

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It is defined as the ratio of the maximum instantaneous power of a signal to its average power. Signals with high PAPR are prone to nonlinear distortions when passed through high-power amplifiers (HPAs), thereby affecting energy efficiency and system performance. Consequently, effective PAPR reduction is essential to improving system robustness and influences the design, cost, and efficiency of HPAs. While both OTSM and OTFS are considered promising candidate technologies for future wireless systems, one shared drawback is their inherently high PAPR. In general, the PAPR characteristics of OTSM systems are closely related to the arrangement of data symbols within the delay-sequency grid and the properties of the WHT. In contrast, the PAPR characteristics of OTFS systems are primarily influenced by how data symbols in the delay-Doppler domain are expanded into the time-frequency domain via unitary transformations, typically involving FFT operations. Since traditional PAPR reduction techniques are designed specifically for OFDM-based systems, they are not directly applicable to OTFS or OTSM due to fundamental differences in modulation and signal structure. This limitation has prompted growing interest in adapting or re-designing PAPR reduction schemes tailored specifically for OTFS and OTSM systems. In addition to PAPR reduction, minimizing bit error rate (BER) and computational complexity (CC) are also active areas of research within the OTFS and OTSM domains. Nevertheless, the primary focus of the present paper is to investigate a PAPR reduction technique specifically designed for OTSM systems. This work does not aim to directly optimize BER or computational complexity. Instead, it proposes a method for enhancing PAPR performance in OTSM systems, providing a foundation for future research that may explore integrated solutions capable of jointly improving PAPR and BER performance while maintaining low computational complexity. PAPR is one of the primary drawbacks of OTSM and is a critical factor affecting system performance and efficiency[7][8][9]. High PAPR primarily results in nonlinear distortion, decreased transmission efficiency, and elevated power consumption, all of which significantly constrain the practical implementation of OTSM. In addressing PAPR reduction, Al Ahsan et al. [7] proposed an Adapted Tone Reservation (A-TR) method and analyzed its performance in the delay domain (A-TR-DD), frequency domain (A-TR-SD), and delay-frequency domain (A-TR-BD). The study indicated that A-TR techniques effectively reduce PAPR while maintaining good BER performance. However, the authors focused solely on A-TR methods without considering alternative PAPR reduction techniques. To address this, Neelam and Sahu [8] proposed an SIP-based method that reduces pilot data interference (PDI) and inter-block interference (IBI) through effective channel estimation and data detection techniques. They also analyzed the linear relationship between PAPR and the number of frequency-domain resource blocks, but the design and parameter optimization of the SIP technique remain unexplored. Additionally, Doosti-Aref et al. [9] introduced PSeIM-OTSM, which leverages index modulation to further reduce PAPR and BER, improving energy efficiency. However, its adaptability to more complex scenarios, such as MIMO systems or multi-user environments, has yet to be studied.

Based on the aforementioned literature, OTSM remains an active field of research, with numerous new discoveries being published regularly. As indicated in the aforementioned literature, research aimed at simultaneously optimizing both the PAPR and BER performance of OTSM systems presents significant challenges. Optimizing various performance metrics of the OTSM system may inadvertently lead to an increase in circuit complexity. Furthermore, a holistic solution that addresses the optimization of PAPR, BER, and circuit complexity concurrently remains an open problem. For example, the traditional Selective Mapping (SLM) technique has primarily focused on optimizing the PAPR performance of OFDM systems. While it has proven effective in improving the PAPR of OFDM systems, the identification of an optimal phase generation mechanism for PAPR reduction continues to be a popular research topic. However, unlike OFDM systems, the development of an SLM technique to optimize PAPR in OTSM systems remains an unresolved issue, primarily due to the structural differences between OFDM and OTSM. For instance, OFDM is a multi-carrier technique, while OTSM is a single-carrier technique. Additionally, the appropriate phase generation mechanism for applying the SLM technique to OTSM systems is also still to be determined. This paper proposes a modified SLM[10] technique for OTSM systems, utilizing Zadoff-Chu Transform (ZCT)[11] matrices, Discrete Cosine Transform (DCT)[11] matrices and Randomly Generated Phase (RGP) matrices to construct phase perturbation matrices. By applying cyclic shifts, multiple distinct phase perturbation matrices are generated. The SLM technique uses these matrices to create multiple candidate signals and selects the signal with the lowest PAPR for transmission. Simulation results indicate that the proposed method achieves optimal PAPR reduction performance using RGP matrices, outperforming ZCT or DCT matrices.

This work builds upon the precoding techniques proposed in Reference [11] for application in OTFS systems. In particular, this paper investigates how the two precoding techniques introduced in [11], namely ZCT and DCT, can be integrated with the conventional SLM technique to address the PAPR issue in OTSM systems. Unlike OTFS, which employs a multicarrier modulation scheme, OTSM is based on single-carrier modulation, resulting in notable differences in system architecture. Given that OTSM systems also experience the high PAPR problem, this paper proposes a PAPR reduction approach tailored to the specific characteristics of OTSM. The effectiveness of the proposed method in improving PAPR performance is analyzed and evaluated through simulations. The main contributions of this paper are summarized as follows:

- Modified Phase Perturbation Mechanism in the SLM Technique
  The conventional SLM technique employs a phase perturbation mechanism that generates U phase sequences of the same size as the input data, where each sequence is multiplied element-wise with the input to produce U candidate signals. For example, if the input data size in OTSM is $M \times N$, the phase perturbation sequences are

also of size $M \times N$. The proposed method introduces two modifications:

- Precoding-Based Phase Perturbation: Rather than using element-wise multiplication, the proposed method applies an N×N precoding matrix to the input data via matrix multiplication, achieving phase perturbation through a structural transformation.
- Circular Shift Generation of Phase Sequences: Unlike the traditional method that requires generating U distinct phase sequences, the proposed method creates only one perturbation matrix and obtains the remaining $U-1$ sequences via circular shifting.

These modifications aim to reduce the computational complexity associated with phase sequence generation and introduce a structurally efficient mechanism using precoding and circular shifting.

- Phase Sequence Generation Mechanisms and Their Impact on PAPR
  The design of phase perturbation sequences is a critical area of SLM-related research due to its influence on PAPR reduction performance. This paper investigates three phase sequence generation mechanisms—ZCT, DCT, and RGP—within the framework of the proposed method. Their effectiveness is evaluated through simulations tailored to the OTSM system. The results indicate that the proposed method can achieve PAPR reduction under the evaluated conditions, while maintaining transmission performance comparable to that of the original OTSM system.
- Design of an SLM Technique Adapted for OTSM Systems
  Since the OTSM system already incorporates the Walsh–Hadamard Transform (WHT), as described in Reference [11], this paper presents an enhanced SLM technique that combines both SLM and precoding. The aim is to preserve the respective advantages of both methods.

Furthermore, based on the structure of the OTSM system, three types of phase perturbation matrices are analyzed within the proposed framework, and simulation results are provided to assess their applicability and performance in the OTSM context.

The chapter organization of this paper is structured as follows. Section II presents the mathematical definitions of OTSM signals and PAPR. Section III introduces the proposed method for improving the conventional SLM technique and its application in OTSM systems. Additionally, the definitions of the ZCT and DCT matrices are provided to demonstrate how the proposed method constructs an enhanced Phase Generation Mechanism (PGM) for the SLM technique. Sections IV and V focus on the discussion of simulation results and the conclusion, respectively.

II. Definition of OTSM Signals and PAPR

OTSM is a wireless communication signal modulation technique based on the Walsh-Hadamard Transform (WHT). This technique primarily utilizes WHT for signal processing in the delay-sequency domain and combines it with pulse-shaping filters to generate time-domain signals. The mathematical representation and generation method of OTSM signals are introduced as follows. OTSM signals are computed through the following steps. First, the information symbols to be transmitted are mapped onto a two-dimensional Delay-Sequency (DS) domain matrix $\mathbf{X}_{DS}$. Subsequently, each row of $\mathbf{X}_{DS}$ undergoes an N-point Walsh-Hadamard Transform, transforming the data into the delay-time domain to form a new matrix $\tilde{\mathrm{s}}$. This process is critical for OTSM signal processing as it achieves the conversion from the delay-sequency domain to the delay-time domain. The mathematical expression for any OTSM signal in the delay-time domain can be described as:

$$\tilde{s}[m+nM] = \sum_{k=0}^{N-1} X_{DS}[m,k] W_N[k,n], \quad (1)$$

where $X_{DS}[m,k]$ is the information symbol matrix in the delay-sequency domain, and $W_N[k,n]$ represents the normalized N-point Walsh-Hadamard Transform matrix. The index m corresponds to the delay dimension, ranging from 0 to $M-1$, and n corresponds to the sequency dimension, ranging from 0 to $N-1$, where M and N are the total numbers of delays and sequences, respectively. In the delay-sequency domain, zero-symbol vectors are typically inserted into the data matrix to mitigate inter-block interference (IBI) caused by channel delay spread. Channel delay spread leads to signal leakage between adjacent blocks, resulting in interference. To address this issue, OTSM technology introduces zero-symbol vectors into the data matrix, analogous to inserting guard bands in the time domain to prevent signal overlap. In OTSM systems, zero-symbol vectors are generally placed in the last few rows (z_l) of the data matrix, with the number of rows being equal to or greater than the channel delay spread index. This approach reduces the computational complexity at the receiver and enhances system performance in high-mobility environments. However, the inclusion of zero symbols reduces spectral efficiency as these symbols occupy transmission resources. Consequently, zero-padding offers a balanced solution between performance improvement and resource utilization, making it suitable for various application scenarios.

Next, OTSM applies pulse shaping to the time-domain vector $\tilde{\mathrm{s}}$ by using a pulse-shaping filter $g(t)$. This process converts the signal $\tilde{\mathrm{s}}$ into a form suitable for wireless transmission, generating the final time-domain signal $s(t)$. The representation of the OTSM signal in the time domain can be described as:

$$s(t) = \sum_{0 \le n < N, 0 \le m < M} \tilde{s}[m+nM] g(t-nT), \quad (2)$$

where $s(t)$ is the time-domain signal, $\tilde{s}[m+nM]$ represents the signal in the delay-time domain, $g(t)$ is the pulse-shaping filter, and T denotes the symbol period.

The primary advantage of OTSM lies in its lower computational complexity. Specifically, compared to traditional OFDM, OTSM employs WHT for modulation and demodulation, whereas OFDM uses the Fast Fourier Transform (FFT). As FFT requires extensive adders and multipliers, while WHT involves only addition and subtraction operations, OTSM reduces computational complexity and implementation costs effectively. Despite its advantages, OTSM signals exhibit the drawback of a high PAPR. PAPR is an important metric for evaluating system performance and design. It is defined as the ratio of the peak power to the average power of a signal. A high PAPR value indicates significant peak power, which can have a profound impact on OTSM system performance. The calculation method and implications of PAPR for OTSM systems are discussed below.

The PAPR of OTSM signals can be calculated as follows. First, based on the time-domain representation of OTSM signals, as shown in Equation (2), the signal $s(t)$ is sampled at an appropriate time to obtain a discrete time-domain sample sequence $s[u]$, where $u = m + nM$ and $u = 0, 1, \ldots, MN-1$. After obtaining the time-domain sample sequence $s[u]$, the maximum absolute value among all samples is identified, and its squared value is taken as the signal's peak power. The average power of the signal is computed by summing the squared values of all samples and dividing by the total number of samples. Finally, the PAPR of the OTSM signal is determined by dividing the peak power by the average power and converting it to decibel (dB) units, as expressed by:

$$\text{PAPR}(s[u]) = 10log_{10}\left(\frac{\max_{u}|s[u]|^2}{P_{avg}}\right) \quad (3)$$

where $\max_{u}|s[u]|^2$ represents the peak power of the OTSM signal, and P_{avg} is the average power.

The Complementary Cumulative Distribution Function (CCDF) is a statistical tool used to quantify the probability that a random variable exceeds a specified value. More precisely, the CCDF represents the likelihood that a random variable is greater than or equal to a particular threshold. In communication systems, the CCDF is widely applied, especially in analyzing the PAPR of signals. Mathematically, the CCDF is defined as follows: for a random variable V and a given threshold v, the CCDF is expressed as

$$\text{CCDF}(v) = P(V > v) \quad (4)$$

where $P(V > v)$ denotes the probability that the random variable V exceeds v. In communication systems, the CCDF is widely employed to evaluate the PAPR of signals. It facilitates an effective comparison of the performance of various PAPR reduction techniques.

III. Proposed Method

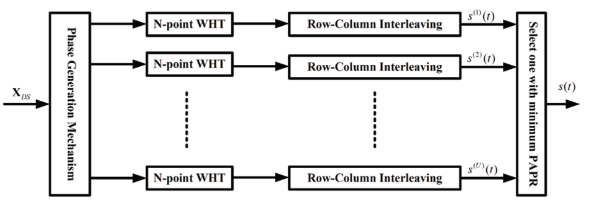

Fig. 1. Block Diagram of the Proposed Method.

Figure 1 illustrates the block diagram of the proposed method when applied to the OTSM system. In this figure, the primary focus of this paper is on the application of the SLM technique to the OTSM system, where phase perturbation is applied to the two-dimensional matrix of data. The phase generation mechanism is central to the main research topic of this paper. Additionally, this section will provide a brief review of the SLM technique's principles, followed by a discussion of the unresolved research challenges associated with phase generation mechanisms. Subsequently, the paper will present a low-complexity phase generation mechanism and use three commonly employed phase perturbation matrices for PAPR reduction to construct an enhanced phase generation method. In the next section, the PAPR performance of three low-complexity phase perturbation schemes will be evaluated.

High PAPR signals necessitate the use of power amplifiers with high linearity to avoid signal distortion. However, high-linearity amplifiers typically have lower efficiency, leading to increased power consumption and reduced system performance. Addressing high PAPR signals often requires more expensive linear power amplifiers, directly increasing system hardware costs, particularly in large-scale deployments. Conversely, using nonlinear power amplifiers to amplify high PAPR signals can result in nonlinear distortion, degrading signal quality. This not only affects system reliability but may also increase the bit error rate, reducing communication performance. Furthermore, high PAPR signals have a larger dynamic range, which implies a higher resolution requirement for Analog-to-Digital Converters (ADCs). If the ADC resolution is insufficient, signal distortion or information loss may occur, adversely affecting overall system performance. In summary, high PAPR introduces a range of negative effects, including low amplifier efficiency, increased system costs, degraded signal quality, and higher ADC resolution requirements. Therefore, developing effective PAPR suppression techniques is crucial for enhancing OTSM system performance and reducing costs.SLM is an effective approach for mitigating the PAPR in communication systems and is categorized under multiple signal representation (MSR) techniques. MSR techniques operate by generating multiple candidate signals through phase manipulation of the transmitted data, followed by the selection of the candidate signal with the lowest PAPR for transmission. In alignment with this principle, SLM generates U candidate signals by multiplying the transmitted data with U predesigned phase perturbation sequences. These modified signals are then processed further, often through OFDM modulation, to produce the final set of candidate signals. Ultimately, the signal exhibiting the minimum PAPR is chosen for transmission.

It is important to note that the modified SLM technique proposed in this paper primarily focuses on reducing the PAPR of OTSM systems, while attempting to introduce a phase generation mechanism that offers both low computational complexity and improved PAPR performance. The main goal is not to enhance the error correction capability of the transmitted signal. Furthermore, for the conventional SLM technique used in OFDM systems, the size of the phase perturbation sequence is consistent with the size of the input data and is represented as a row vector. In contrast, for the traditional SLM technique applied to OTSM systems, the size of the phase perturbation sequence must also match the input data size, but it will be represented as a two-dimensional matrix. Therefore, the design of a phase generation mechanism to create phase perturbation sequences that optimize PAPR performance will differ from the OFDM system case, making this an entirely new and important research topic. Reference [11] demonstrates the use of precoding techniques to reduce the PAPR of OTFS systems, with simulation results showing that the application of a precoding matrix effectively improves the PAPR performance of OTFS systems. Based on this, this paper proposes an enhanced SLM technique that combines precoding and SLM techniques. Specifically, the precoding matrix is employed as the phase perturbation matrix to apply phase disturbance to the transmitted data, and cyclic shifts are used to generate multiple phase perturbation matrices. However, it should be noted that while the precoding matrix can effectively improve the PAPR performance of OTFS systems, it does not necessarily yield the same improvement for OTSM systems.

In this paper, the authors have adopted a precoding matrix from reference [11] and modified it to serve as the phase generation mechanism for the SLM technique. The performance of the proposed method in reducing PAPR is specifically demonstrated in the simulation results section, which aims to evaluate whether the precoding matrix, originally used for OTFS systems, can serve as a viable phase generation mechanism to improve the PAPR performance of OTSM systems. To compare whether the precoding matrix described in reference [11] can improve the PAPR performance of OTSM systems in the same manner as it does for OTFS systems, the ZCT matrix and DCT matrix described in reference [11] will be introduced as follows. Given the limited exploration of SLM in the context of OTSM systems, this paper proposes an advanced SLM approach specifically adapted to OTSM. Conventional SLM methods typically employ randomly generated phase perturbation sequences, which, while effective, tend to increase system circuit complexity. Consequently, the development of low-complexity PGMs capable of maintaining or improving PAPR reduction performance remains a significant area of investigation. To address this issue, this paper evaluates conventional random PGMs and introduces two alternative mechanisms utilizing the ZCT matrix and the DCT matrix. These mechanisms are assessed for their ability to enhance PAPR performance while minimizing complexity. The definitions of the ZCT and DCT matrices are provided below[11].

1) **ZCT Matrix**
A Zadoff-Chu sequence of length K is expressed as:

$$z[k] = \begin{cases} \exp\left(j\frac{2\pi r}{K}\left(\frac{k^2}{2}+qk\right)\right), & \text{if } K \text{ is even,} \\ \exp\left(j\frac{2\pi r}{K}\left(\frac{k(k+1)}{2}+qk\right)\right), & \text{if } K \text{ is odd.} \end{cases}$$

From this sequence, a ZCT matrix of size $M \times M$ is constructed as:

$$z_M[m,l] = z[m+lK], \quad m,l = 0,1,\dots,M-1.$$

For example, with $M = 4$, $q = 7$, and $r = 1$, the ZCT matrix is given by:

$$\begin{bmatrix} 1 & i & -1 & -i \\ -0.98+0.20i & 0.98-0.20i & -0.98+0.20i & 0.98-0.20i \\ 1 & -i & -1 & i \\ -0.83-0.56i & -0.83-0.56i & -0.83-0.56i & -0.83-0.56i \end{bmatrix}$$

2) **DCT Matrix**
A Discrete Cosine Transform matrix C_M of size $M \times M$ is defined as:

$$C_M[m,l] = \begin{cases} \sqrt{\frac{1}{M}}, & m=0,\ 0 \le l \le M-1, \\ \sqrt{\frac{2}{M}}\cos\left(\frac{(2l+1)m\pi}{2M}\right), & 1 \le m \le M-1,\ 0 \le l \le M-1. \end{cases}$$

For $M = 4$, the DCT matrix is represented as:

$$\begin{bmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ 0.6533 & 0.2706 & -0.2706 & -0.6533 \\ 0.5000 & -0.5000 & -0.5000 & 0.5000 \\ 0.2706 & -0.6533 & 0.6533 & -0.2706 \end{bmatrix}$$

The proposed method modifies the phase of the data matrix $\mathbf{X}_{\text{DS}}$ in the delay-sequency domain by multiplying it with a phase perturbation matrix $\mathbf{P}^{(u)}$, resulting in U candidate signals as:

$$s^{(u)}(t) = \sum_{\substack{0\le k<N \\ 0\le n<N \\ 0\le m<M}} \mathbf{P}^{(u)} X_{\text{DS}}[m,k] W_N[k,n] g(t-nT), \tag{5}$$

where $u = 1,\dots,U$ and $\mathbf{P}^{(u)}$ denotes an $M \times M$ phase perturbation matrix. To reduce circuit complexity, these phase perturbation matrices are generated using the ZCT and DCT matrices, which are then modified through cyclic right shifts. Furthermore, as shown in Equation (1), the generation of OTSM signals involves the superposition of multiple modulation symbols. When several of these symbols exhibit phase alignment, constructive interference may occur, resulting in signal peaks with significantly elevated amplitudes. This phenomenon directly contributes to the high PAPR characteristic of OTSM signals. To address this, a phase perturbation matrix is introduced, whose primary function is to impose deliberate phase variations on the transmitted symbols. This phase diversity disrupts potential phase alignment, thereby reducing the probability of peak formation and lowering the resulting PAPR. To illustrate the construction method of such a phase perturbation matrix, consider the use of a 4×4 DCT matrix. Based on this reference matrix, four phase perturbation matrices $\mathbf{P}^{(u)}$, where $u = 0,1,2,3$, are derived by applying successive circular shifts along the columns. These matrices are expressed as follows:

$$\mathbf{P}^{(0)} = \begin{bmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ -0.6533 & 0.6533 & 0.2706 & -0.2706 \\ -0.5000 & -0.5000 & 0.5000 & 0.5000 \\ -0.2706 & 0.2706 & -0.6533 & 0.6533 \end{bmatrix},$$

$$\mathbf{P}^{(1)} = \begin{bmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ -0.2706 & -0.6533 & 0.2706 & 0.6533 \\ 0.5000 & 0.5000 & -0.5000 & -0.5000 \\ 0.6533 & -0.2706 & -0.6533 & 0.2706 \end{bmatrix},$$

$$\mathbf{P}^{(2)} = \begin{bmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ 0.2706 & -0.2706 & -0.6533 & 0.6533 \\ -0.5000 & 0.5000 & -0.5000 & 0.5000 \\ -0.6533 & -0.6533 & 0.2706 & 0.2706 \end{bmatrix},$$

$$\mathbf{P}^{(3)} = \begin{bmatrix} 0.5000 & 0.5000 & 0.5000 & 0.5000 \\ 0.6533 & 0.2706 & -0.6533 & -0.2706 \\ 0.5000 & -0.5000 & -0.5000 & 0.5000 \\ 0.2706 & -0.6533 & 0.6533 & -0.2706 \end{bmatrix}.$$

The above method demonstrates that multiple distinct phase perturbation matrices can be generated without the need for additional arithmetic operations such as multiplication or addition. These matrices can be employed to modulate the transmission sequence, generating a set of candidate signals. Subsequently, the transmitter selects the candidate signal with the lowest PAPR for actual transmission. More specifically, this approach generates U distinct phase perturbation matrices, where U is at most M. Furthermore, unlike the traditional SLM technique, which requires the generation of U phase perturbation matrices in the OTSM system, the proposed method only requires one phase perturbation matrix. This simplification reduces the hardware complexity required for the phase generation mechanism in circuit design. Additionally, the proposed method uses $U-1$ cyclic shifts to generate $U-1$ phase perturbation matrices. Since cyclic shifts do not require adders or multipliers, this further alleviates the hardware implementation complexity. In summary, the proposed method is an enhanced SLM technique based on the OTSM system architecture, offering suboptimal PAPR improvement performance with low circuit complexity for PAPR reduction. On the receiver side, the proposed method follows the same procedure as the conventional SLM technique. Since both the transmitter and receiver have prior knowledge of the U phase perturbation matrices, the amount of side information required remains $\log_2(U)$ bits, as in conventional SLM. No additional bits are needed to indicate which of the U candidate signals is selected for transmission. Thus, after signal processing at the OTSM receiver, the proposed method can be recovered using the standard SLM demodulation procedure.

IV. Simulation Results

This paper proposes a modified SLM technique to improve the PAPR performance of OTSM systems, achieved by combining traditional SLM with precoding techniques. The proposed method simplifies the complexity of phase perturbation generation in traditional SLM techniques by employing cyclic shifting, and optimizes PAPR performance using precoding techniques. In this section, the paper compares the PAPR performance of the modified SLM technique with that of the conventional SLM technique to assess whether the proposed method can retain the PAPR improvement benefits of the traditional SLM technique. To assess the PAPR reduction performance of the proposed method in OTSM systems, simulations are conducted using the following parameters. A total of $10,000$ OTSM signals are generated randomly, employing digital modulation schemes of 4-QAM and 16-QAM. The total number of delays (M) and sequences (N) are configured to 64 and 256, respectively. For the number of candidate signals, values of $\{4, 16\}$ are utilized. In the conventional SLM approach, two randomly generated phase variations $\{-1, 1\}$ are applied. For the proposed method, the ZCT matrix parameters are set as $q = 7$ and $r = 1$. Additionally, the number of zero symbols inserted into the last row of the data matrix (z_l) is configured to 3. All simulation outcomes in this section are illustrated using CCDF curves. The CCDF curves for various methods are compared and analyzed to provide a thorough evaluation of their relative PAPR reduction performance.

Figure 2 and Figure 3 compare the performance of three PAPR reduction techniques in a 4QAM-modulated OTSM system. These techniques include the traditional SLM technique, the proposed method based on the RGP matrix, the proposed method based on the DCT matrix, and the proposed method based on the ZCT matrix. As shown in Figure 2 and Figure 3, the RGP-based method demonstrates superior PAPR reduction performance compared to the ZCT-based method and DCT-based method. Additionally, the PAPR reduction performance of the RGP-based method improves significantly with an increasing number of candidate signals. To analyze the impact of the total delay number (M) and the total sequency number (N) on the PAPR reduction performance of the proposed methods, Figures 4 and 5 present simulation results under the condition of four candidate signals, while Figure 6 shows results for 16 candidate signals. These results are obtained by varying the total sequency number (or total delay number) while fixing the total delay number (or total sequency number) at 64. In Figure 4, when $M = 64$ and $N = 128$ or $N = 256$, both the DCT-based and ZCT-based methods exhibit a slight degradation in PAPR reduction performance as the total sequency number increases. Similarly, in Figure 5, when $N = 64$ and $M = 128$ or $M = 256$, the PAPR reduction performance of both methods slightly decreases with an increase in the total delay number. Nevertheless, the results presented in Figures 4, 5, and 6 demonstrate that, regardless of variations in M or N, the RGP-based method consistently outperforms both the ZCT-based and DCT-based methods in terms of PAPR reduction. It is noteworthy that when M is smaller than N, the proposed method yields improved PAPR performance, whereas, when M exceeds N, the improvement in PAPR performance decreases. To further investigate whether the proposed method's PAPR reduction performance is influenced by variations in the T-value of T-ary QAM modulation, this paper simulated and analyzed the performance of the proposed method in a 16-QAM-modulated OTSM system. Figure 7 and 8 presents a comparison of three PAPR reduction techniques in the 16-QAM-modulated OTSM system. Consistent with the results shown in Figure 2 and Figure 3, the RGP-based method demonstrates superior PAPR reduction performance in the 16-QAM system compared to the ZCT-based method and the DCT-based method. The overall simulation results confirm that the RGP-based method consistently outperforms both the ZCT-based method and the DCT-based method in terms of PAPR reduction performance in both 4-QAM and 16-QAM-modulated OTSM systems. Figure 9 compares the bit error rate (BER) curves of the proposed method and the OTSM system over an additive white Gaussian noise (AWGN) channel. The results in Figure 9 show that when $M \leq N$, the RGP-based proposed method performs slightly worse than the OTSM system in the AWGN channel; however, when $M > N$, the RGP-based proposed method outperforms the OTSM system. Therefore, from the perspective of both PAPR performance improvement and channel transmission performance, the RGP-based proposed method effectively combines the advantages of both SLM and precoding techniques in improving PAPR. Additionally, the integration of precoding techniques helps reduce the complexity of the phase perturbation mechanism in traditional SLM techniques and provides a better phase perturbation matrix for PAPR improvement.

V. Conclusion

To mitigate the issue of high PAPR in OTSM systems and enhance overall transmission performance, this paper introduces an improved Selected Mapping (SLM) technique specifically designed for OTSM systems. The proposed approach constructs the phase generation matrix (PGM) using ZCT, DCT, and RGP matrices, in conjunction with cyclic shifts, to generate multiple candidate signals for selecting the optimal transmission signal. Simulation results show that the PGM based on the RGP matrix outperforms the ZCT-based and DCT-based mechanisms, as well as conventional SLM techniques, in terms of PAPR reduction. Moreover, the proposed method, utilizing the RGP-based PGM, consistently delivers significant PAPR reduction in OTSM systems, regardless of whether 4-QAM or 16-QAM modulation schemes are employed. The findings of this paper may serve as a reference

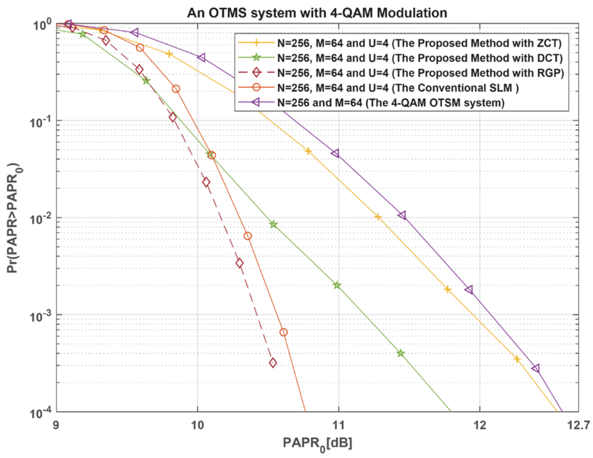

Fig. 2. Performance Comparison of PAPR Reduction Techniques in 4QAM-modulated OTSM Systems with $M = 64$ and $N = 256$.

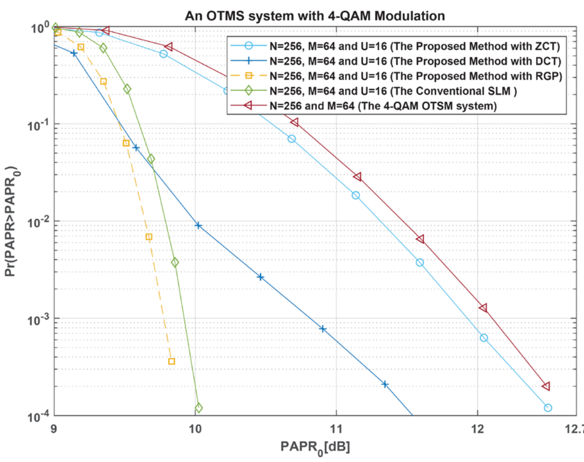

Fig. 3. Performance Comparison of PAPR Reduction Techniques in 4QAM-modulated OTSM Systems with $M = 64$ and $N = 256$.

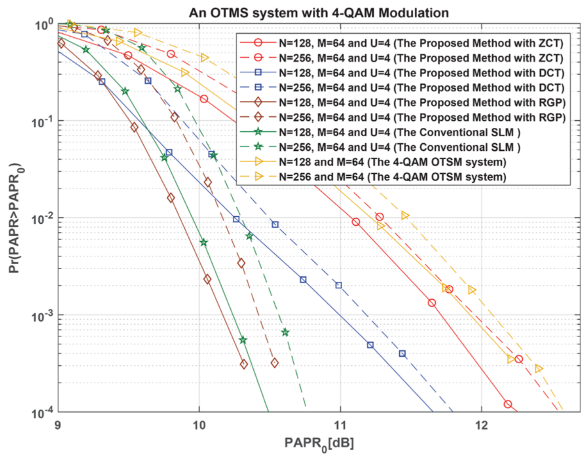

Fig. 4. PAPR Reduction Performance Comparison of the Proposed Method in 4QAM-modulated OTSM systems with $M = 64$ and $N = 128$ or 256.

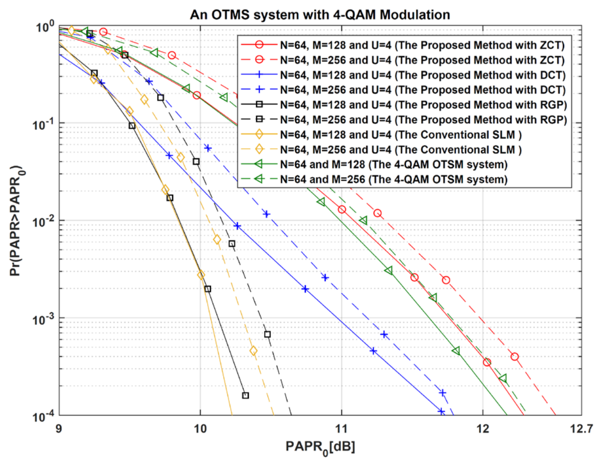

Fig. 5. PAPR Reduction Performance Comparison of the Proposed Method in 4QAM-modulated OTSM systems with $N = 64$ and $M = 128$ or 256.

for improving OTSM system performance in areas such as channel efficiency and circuit design. These insights can also contribute to the optimization of key issues in OTSM systems, including channel performance, circuit implementation, and PAPR reduction.

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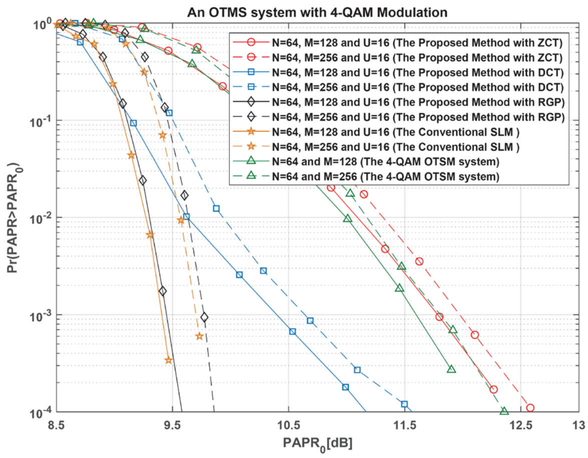

Fig. 6. PAPR Reduction Performance Comparison of the Proposed Method in 4QAM-modulated OTSM systems with $N = 64$ and $M = 128$ or 256.

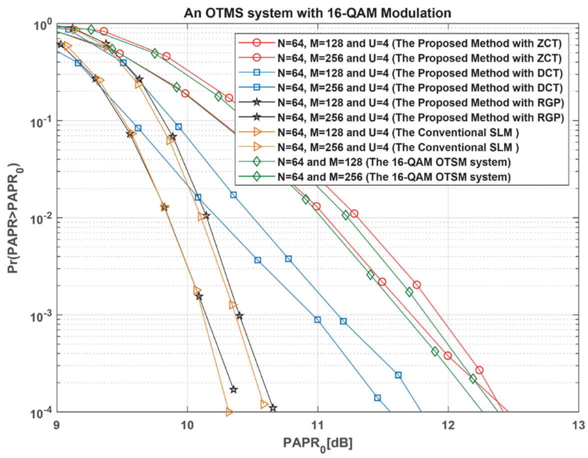

Fig. 8. PAPR Reduction Performance Comparison of the Proposed Method in 16QAM-modulated OTSM systems with $N = 64$ and $M = 128$ or 256.

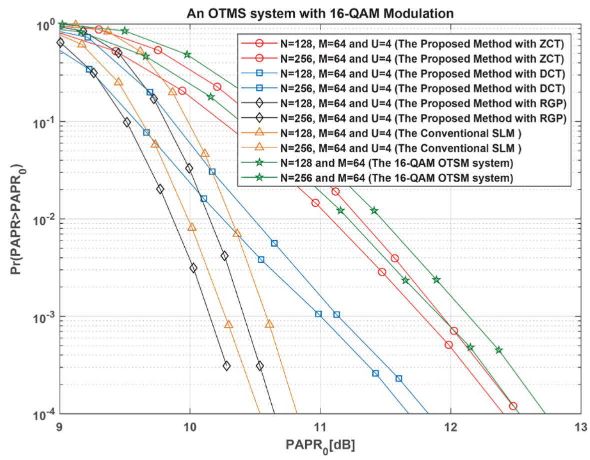

Fig. 7. PAPR Reduction Performance Comparison of the Proposed Method in 16QAM-modulated OTSM systems with $M = 64$ and $N = 128$ or 256.

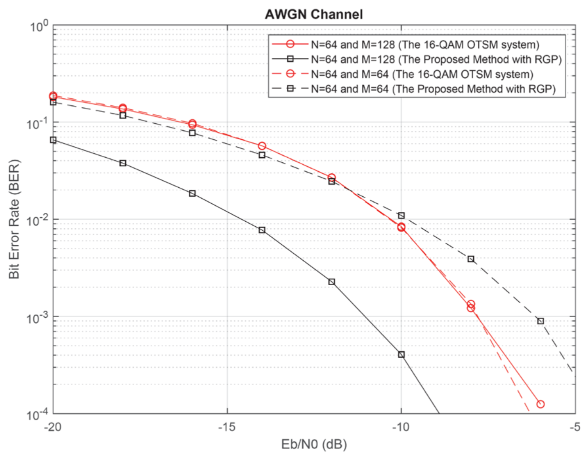

Fig. 9. BER Performance of OTSM Systems with and without the Proposed Method under AWGN

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