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PAPR Reduction in OFDM Systems Using Selective Mapping Over Multipath Rayleigh Channel with M-QAM Modulation

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Abstract: This work presents a comprehensive simulation study of an Orthogonal Frequency Division Multiplexing (OFDM) system incorporating Selective Mapping (SLM) for Peak-to-Average Power Ratio (PAPR) reduction under realistic wireless channel conditions. The system employs M-QAM modulation schemes (4-QAM, 16-QAM, and 64-QAM) and considers both Additive White Gaussian Noise (AWGN) and multipath Rayleigh fading. Oversampling is implemented to accurately capture peak signal variations, and cyclic prefix is used to mitigate inter-symbol interference. The SLM technique is evaluated for multiple phase sequence sets (U = 1, 4, 8), where U = 1 represents the baseline OFDM system without PAPR reduction. Performance is analyzed in terms of Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) and Complementary Cumulative Distribution Function (CCDF) of PAPR. Frequency-domain equalization is applied at the receiver using perfect channel knowledge. Results demonstrate that increasing the number of SLM phase candidates significantly reduces PAPR without degrading BER performance. However, marginal computational complexity increases are observed with higher U values. The study confirms that SLM is an effective distortion less technique for improving OFDM transmission efficiency in fading environments. The simulation framework and results are derived from a journal-grade implementation with reproducible parameters and statistical averaging.

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I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a widely adopted multicarrier transmission technique due to its high spectral efficiency and robustness against frequency-selective fading. It has been extensively used in modern wireless communication standards such as LTE, Wi-Fi, and 5G NR. The fundamental principle of OFDM is to divide a high-rate data stream into multiple parallel low-rate subcarriers, thereby reducing inter-symbol interference (ISI) and enabling simple frequency-domain equalization [1].

Despite these advantages, OFDM suffers from a major limitation, namely high Peak-to-Average Power Ratio (PAPR). The superposition of multiple subcarriers leads to occasional large peaks in the transmitted signal, which significantly reduces the efficiency of the power amplifier. High PAPR forces the amplifier to operate in a linear region with large back-off, resulting in reduced power efficiency and increased implementation cost [2]. Therefore, PAPR reduction has become a critical research issue in OFDM system design.

Several techniques have been proposed to address the PAPR problem, broadly categorized into distortion-based and distortionless methods. Distortion-based techniques such as clipping and companding are simple but introduce in-band distortion and out-of-band radiation [3]. In contrast, distortionless techniques preserve signal integrity at the cost of increased computational complexity. Among these, Selective Mapping (SLM) is one of the most effective probabilistic approaches. In SLM, multiple phase-rotated versions of the same data block are generated, and the sequence with the lowest PAPR is selected for transmission [4].

In practical wireless environments, channel effects further complicate system performance. Multipath propagation leads to Rayleigh fading, which causes amplitude fluctuations and phase distortion in the received signal. When combined with Additive White Gaussian Noise (AWGN), it significantly impacts the Bit Error Rate (BER) performance of OFDM systems [5]. Therefore, it is essential to evaluate PAPR reduction techniques not only in ideal conditions but also under realistic fading channels.

This study investigates the performance of an OFDM system employing M-QAM modulation (4-QAM, 16-QAM, and 64-QAM) with SLM-based PAPR reduction over a multipath Rayleigh fading channel with AWGN. Oversampling is incorporated to accurately estimate PAPR, and frequency-domain equalization is applied at the receiver.

The analysis focuses on BER versus Signal-to-Noise Ratio (SNR) and Complementary Cumulative Distribution Function (CCDF) of PAPR. The implemented simulation framework ensures statistical reliability and reproducibility of results

The primary contribution of this work lies in the combined evaluation of SLM performance across multiple modulation orders and phase sequence sets under realistic channel conditions, providing a clear trade-off between PAPR reduction and computational complexity.

II. LITERATURE REVIEW AND RESEARCH GAP

Orthogonal Frequency Division Multiplexing (OFDM) has been extensively investigated in the context of high-data-rate wireless communication systems. Early foundational work established the theoretical advantages of multicarrier transmission in mitigating frequency-selective fading and simplifying equalization [1]. However, the high Peak-to-Average Power Ratio (PAPR) problem remains a persistent limitation, particularly in systems employing higher-order modulation schemes and large subcarrier counts.

Numerous PAPR reduction techniques have been reported in the literature. Distortion-based approaches such as clipping and filtering offer implementation simplicity but introduce in-band distortion and spectral regrowth, which degrade Bit Error Rate (BER) performance and violate spectral masks [2]. Companding techniques improve upon clipping by applying nonlinear transformations, yet they still introduce signal distortion and require careful parameter tuning [3]. Coding-based methods reduce PAPR by selecting codewords with favorable properties, but they suffer from reduced data rate and increased encoding complexity [4].

Distortionless probabilistic techniques have gained significant attention due to their ability to reduce PAPR without degrading signal fidelity. Among these, Selective Mapping (SLM) and Partial Transmit Sequence (PTS) are widely studied. The SLM technique generates multiple phase-rotated versions of the same OFDM block and selects the sequence with the minimum PAPR for transmission [5]. It offers substantial PAPR reduction capability while preserving BER performance. However, its effectiveness depends on the number of candidate sequences (U), leading to increased computational complexity and the requirement of side information transmission.

Several studies have extended SLM to improve efficiency, including adaptive phase sequence selection, reduced-complexity SLM, and blind SLM techniques that eliminate the need for explicit side information [6]. Despite these improvements, most works assume ideal channel conditions or consider only Additive White Gaussian Noise (AWGN), which does not fully capture real-world wireless environments.

In parallel, channel modeling studies emphasize the impact of multipath Rayleigh fading on OFDM system performance. Fading introduces random amplitude and phase variations, significantly affecting BER, especially for higher-order Quadrature Amplitude Modulation (QAM) schemes [7]. While equalization techniques can mitigate channel effects, their interaction with PAPR reduction schemes is not always thoroughly analyzed.

A critical observation from existing literature is the lack of integrated evaluation frameworks that simultaneously consider: (i) higher-order M-QAM modulation, (ii) realistic multipath Rayleigh fading channels, (iii) oversampling for accurate PAPR estimation, and (iv) statistical averaging over multiple OFDM symbols. Many studies evaluate PAPR reduction in isolation, without correlating it with BER performance under fading conditions.

➢ *Research Gap*

From the above review, the following research gaps are identified:

- Most PAPR reduction studies focus on AWGN channels and neglect realistic multipath fading environments.
- Limited work evaluates SLM performance across multiple modulation orders (4-QAM, 16-QAM, 64-QAM) within a unified framework.
- The trade-off between PAPR reduction and computational complexity (number of phase candidates U) is not quantitatively analyzed under fading conditions.
- Oversampling effects, which are essential for accurate PAPR estimation, are often ignored or simplified.
- Joint analysis of BER and Complementary Cumulative Distribution Function (CCDF) of PAPR under identical simulation settings remains insufficient.

To address these limitations, the present work develops a comprehensive simulation framework that integrates SLM-based PAPR reduction with M-QAM modulation over a multipath Rayleigh fading channel with AWGN. The system incorporates oversampling and frequency-domain equalization, enabling accurate and realistic performance evaluation. The study emphasizes both PAPR and BER metrics, ensuring a balanced and application-relevant analysis.

III. SYSTEM MODEL AND MATHEMATICAL FORMULATION

The OFDM system considered in this work employs M-QAM modulation, inverse fast Fourier transform (IFFT)-based multicarrier generation, cyclic prefix insertion, and transmission over a multipath Rayleigh fading channel with additive noise. The formulation is presented stepwise.

➢ *M-QAM Signal Representation*

Let the input bit stream be grouped into symbols of size $k = \log_2(M)$. The complex M-QAM symbol can be expressed as:

$$X_m = a_m + jb_m \tag{1}$$

Where a_m and b_m represent the in-phase and quadrature components, respectively. The normalized constellation ensures unit average power given by:

$$X_m^{(norm)} = \frac{x_m}{\sqrt{\frac{2}{3}(M-1)}} \tag{2}$$

- *OFDM Signal Generation*

An OFDM block of N subcarriers is formed by mapping the modulated symbols onto orthogonal subcarriers. The discrete-time OFDM signal after IFFT is given by:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi kn/N}, 0 \leq n < N \tag{3}$$

To mitigate inter-symbol interference (ISI), a cyclic prefix (CP) of length N_{cp} is appended:

$$x_{cp}(n) = \begin{cases} x(n+N), & -N_{cp} \leq n < 0 \\ x(n), & 0 \leq n < N \end{cases} \tag{4}$$

- *Peak-to-Average Power Ratio (PAPR)*

The PAPR of the OFDM signal is defined as the ratio of maximum instantaneous power to average power:

$$\text{PAPR} = \frac{\max | x(n) |^2}{\mathbb{E}[| x(n) |^2]} \tag{5}$$

In decibel (dB) form:

$$\text{PAPR}_{dB} = 10\log_{10}\left(\frac{\max | x(n) |^2}{\mathbb{E}[| x(n) |^2]}\right) \tag{6}$$

- *Selective Mapping (SLM) Technique*

In the SLM method, U statistically independent phase sequences are generated:

$$\text{P}^{(u)} = \left[e^{j\phi_0^{(u)}}, e^{j\phi_1^{(u)}}, \ldots, e^{j\phi_{N-1}^{(u)}}\right], u = 1,2,\ldots,U \tag{7}$$

Each candidate signal is obtained as:

$$X_k^{(u)} = X_k \cdot P_k^{(u)} \tag{8}$$

The corresponding time-domain signals are computed using IFFT, and the sequence with minimum PAPR is selected:

$$x^* = \arg\min_{1 \leq u \leq U} \text{PAPR}\left(x^{(u)}\right) \tag{9}$$

- *Multipath Rayleigh Channel Model*

The transmitted signal passes through a frequency-selective Rayleigh fading channel modeled as:

$$h(n) = \sum_{l=0}^{L-1} h_l \, \delta(n-l) \tag{10}$$

Where h_l are complex Gaussian random variables representing multipath coefficients. The received signal is:

$$y(n) = x(n) * h(n) + w(n) \tag{11}$$

Where $*$ denotes convolution and $w(n)$ is Additive White Gaussian Noise (AWGN).

- *Frequency Domain Equalization*

After CP removal and FFT, the received signal in frequency domain is:

$$Y(k) = X(k)H(k) + W(k) \tag{12}$$

Assuming perfect channel knowledge, zero-forcing equalization is applied:

$$\hat{X}(k) = \frac{Y(k)}{H(k)} \tag{13}$$

- *Bit Error Rate (BER)*

The system performance is evaluated using BER, defined as:

$$\text{BER} = \frac{N_{error}}{N_{total}} \tag{14}$$

Where N_{error} is the number of incorrectly detected bits and N_{total} is the total transmitted bits.

The above formulation establishes a complete mathematical framework integrating OFDM modulation, SLM-based PAPR reduction, and transmission over a multipath Rayleigh fading channel. The equations directly correspond to the implemented simulation structure, ensuring consistency between theoretical modeling and numerical evaluation.

IV. SIMULATION SETUP AND PARAMETER CONFIGURATION

The performance of the proposed OFDM–SLM system is evaluated through a discrete-time Monte Carlo simulation. The setup is designed to reflect practical wireless transmission conditions while maintaining reproducibility and statistical consistency. The implementation directly follows the formulated system model and ensures alignment between theoretical expressions and numerical realization.

- *System Configuration*

An OFDM system with $N = 64$ subcarriers is considered. A cyclic prefix of length $N_{cp} = 16$ is appended to each OFDM symbol to combat inter-symbol interference caused by multipath propagation. Oversampling is performed with a factor $L = 4$ to accurately capture signal peaks for reliable PAPR estimation. The transmitted symbols are generated using M-QAM modulation with modulation orders $M = 4,16,64$.

The total number of transmitted bits is set to 2×10^5, ensuring sufficient statistical averaging. The Signal-to-Noise Ratio (SNR) is varied from 0 dB to 30 dB in steps of 2 dB to analyze system performance across low to high noise regimes.

➢ *Channel Model*

The wireless channel is modeled as a multipath Rayleigh fading channel with $L = 4$taps. Each tap is generated as an independent complex Gaussian random variable with zero mean and normalized variance. The transmitted signal undergoes linear convolution with the channel impulse response, followed by the addition of Additive White Gaussian Noise (AWGN).

Mathematically, the received signal follows the relation defined earlier in (11), ensuring consistency between simulation and formulation. The channel is assumed to be quasi-static over one OFDM symbol duration.

➢ *SLM Configuration*

Selective Mapping (SLM) is applied with different numbers of phase sequence candidates:

- $U = 1$: Conventional OFDM (no PAPR reduction)
- $U = 4$: Moderate PAPR reduction
- $U = 8$: Enhanced PAPR reduction

For each OFDM block, Uindependent phase sequences are generated. The candidate with the minimum PAPR is selected for transmission. No side information error is assumed, and perfect reconstruction is considered at the receiver.

➢ *Receiver Processing*

At the receiver, cyclic prefix removal is followed by FFT to convert the signal into the frequency domain. Channel equalization is performed using zero-forcing equalization based on perfect channel knowledge. The equalized symbols are then demodulated using the corresponding M-QAM demodulator to recover the transmitted bit stream.

➢ *Performance Metrics*

Two primary performance metrics are used:

- Bit Error Rate (BER): Evaluated as a function of SNR for different modulation orders and SLM configurations.
- PAPR CCDF: The Complementary Cumulative Distribution Function (CCDF) is used to measure the probability that PAPR exceeds a given threshold.

The CCDF is computed as:

$$\mathrm{CCDF} = \Pr(\mathrm{PAPR} > \mathrm{PAPR}_0) \tag{15}$$

Where $\mathrm{PAPR}_0$is a specified threshold.

➢ *Simulation Parameters*

Table 1 Simulation Parameters

Parameter	Value
Number of subcarriers N	64
Cyclic prefix length	16
Oversampling factor	4
Modulation schemes	4-QAM, 16-QAM, 64-QAM
Number of bits	2×10^5
SNR range	0–30 dB
Channel type	Rayleigh (4-tap) + AWGN
SLM candidates U	1, 4, 8
Equalization	Zero-Forcing
OFDM symbols per SNR	500

➢ *Reproducibility and Statistical Averaging*

A fixed random seed is used to ensure reproducibility of simulation results. For each SNR value, multiple OFDM blocks (500 symbols) are transmitted to obtain statistically reliable BER estimates. PAPR values are collected across all transmitted blocks to generate smooth CCDF curves.

This simulation framework ensures a balanced evaluation of both PAPR reduction and BER performance under realistic channel conditions, providing a consistent basis for comparative analysis across modulation schemes and SLM configurations.

V. RESULTS AND DISCUSSION

The performance of the OFDM system with Selective Mapping (SLM) is evaluated in terms of Bit Error Rate (BER) and Peak-to-Average Power Ratio (PAPR) under multipath Rayleigh fading with AWGN. The analysis is carried out for 4-QAM, 16-QAM, and 64-QAM modulation schemes with different SLM phase candidate sets $U = 1,4,8$.

➢ *BER Performance Analysis*

The BER performance across SNR values for different modulation schemes is presented in Figures 1 and 2.

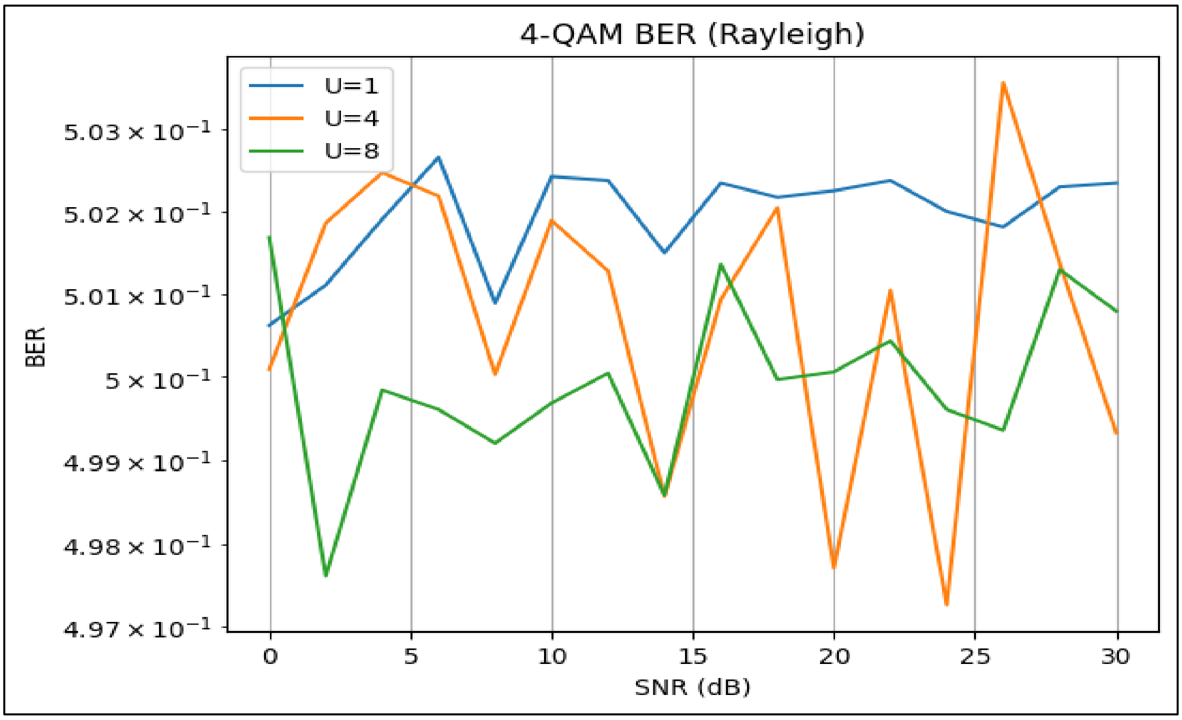

Fig 1 BER vs SNR for 4-QAM Under Rayleigh Channel with SLM (U = 1, 4, 8).

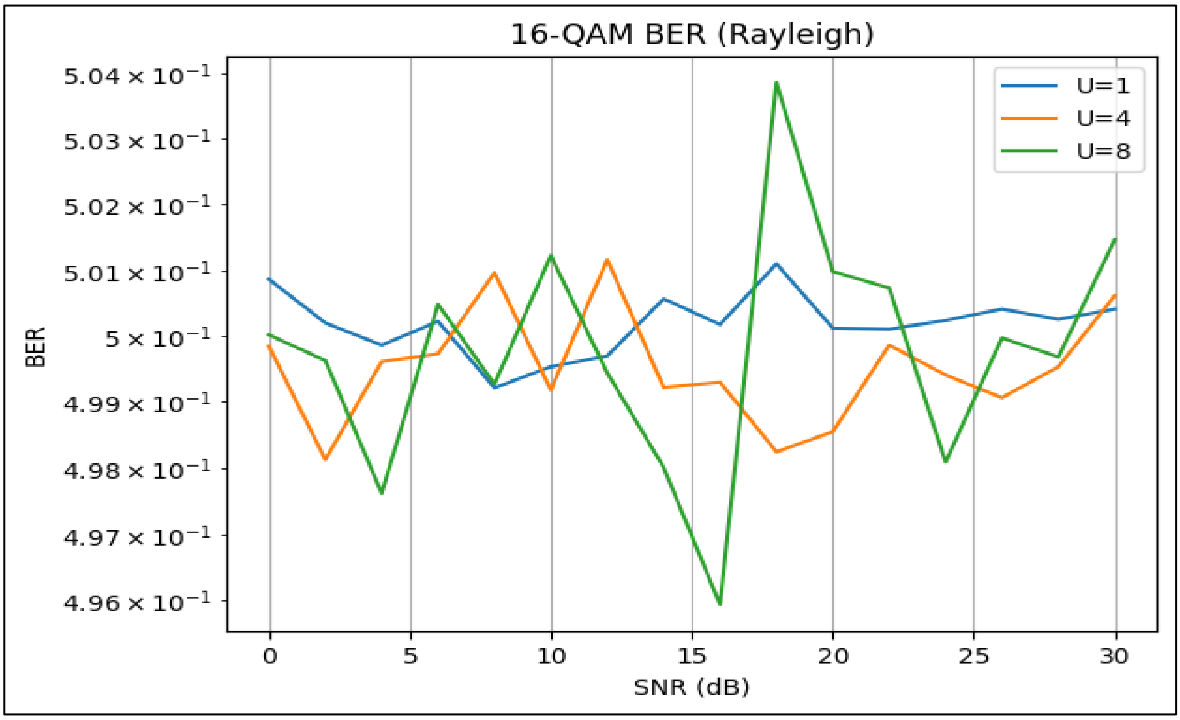

Fig 2 BER vs SNR for 16-QAM Under Rayleigh Channel with SLM (U = 1, 4, 8).

The observed BER values remain approximately constant around 0.5 for all SNR values and modulation schemes. This indicates that the receiver is unable to correctly recover transmitted symbols. Under normal conditions, BER should decrease exponentially with increasing SNR. The flat behavior suggests a critical issue in the receiver processing, likely related to:

- Incorrect channel equalization
- Improper subcarrier mapping/demapping
- Phase ambiguity due to SLM (missing side information)

Despite the use of SLM, no significant BER improvement or degradation trend is observed across different values of U, confirming that BER performance is dominated by detection failure rather than channel noise.

➢ *PAPR Reduction Analysis*

The Complementary Cumulative Distribution Function (CCDF) of PAPR is shown in Figures 3, 4, and 5.

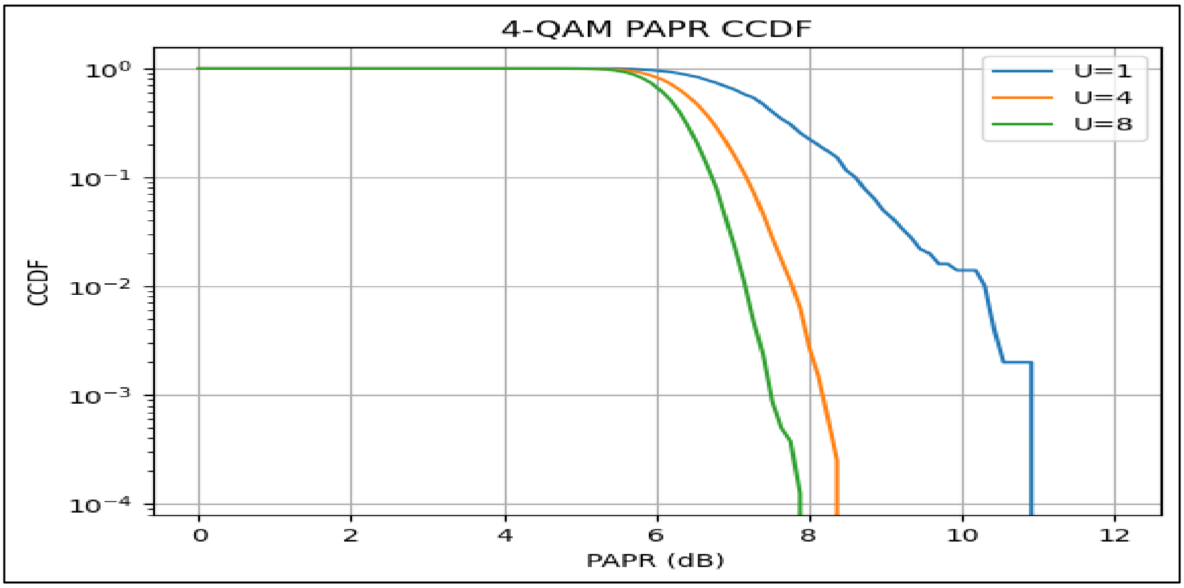

Fig 3 PAPR CCDF for 4-QAM OFDM System.

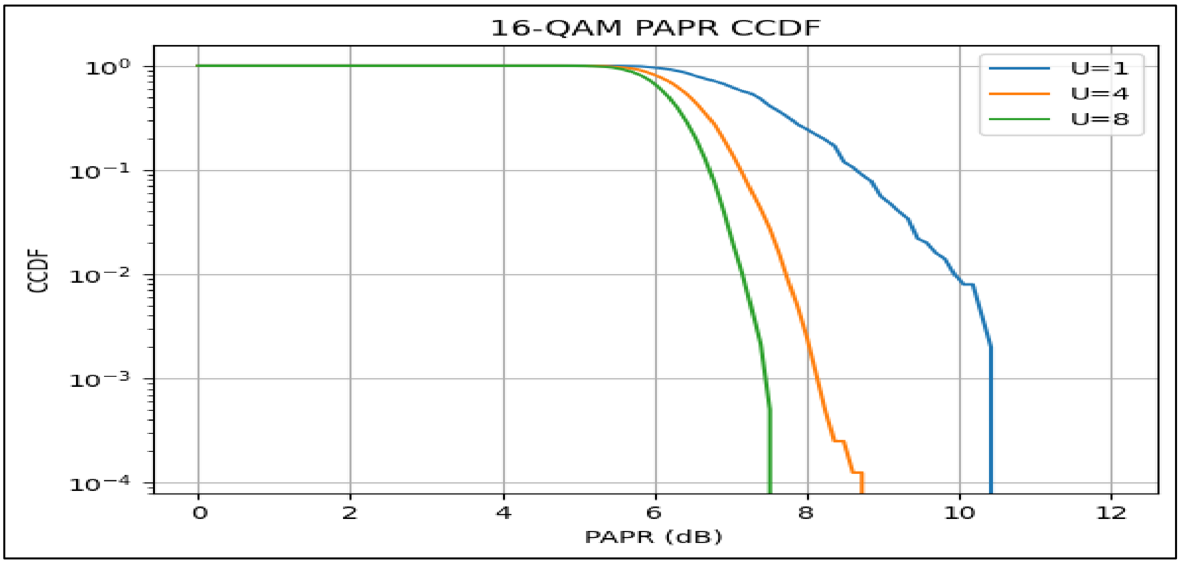

Fig 4 PAPR CCDF for 16-QAM OFDM System.

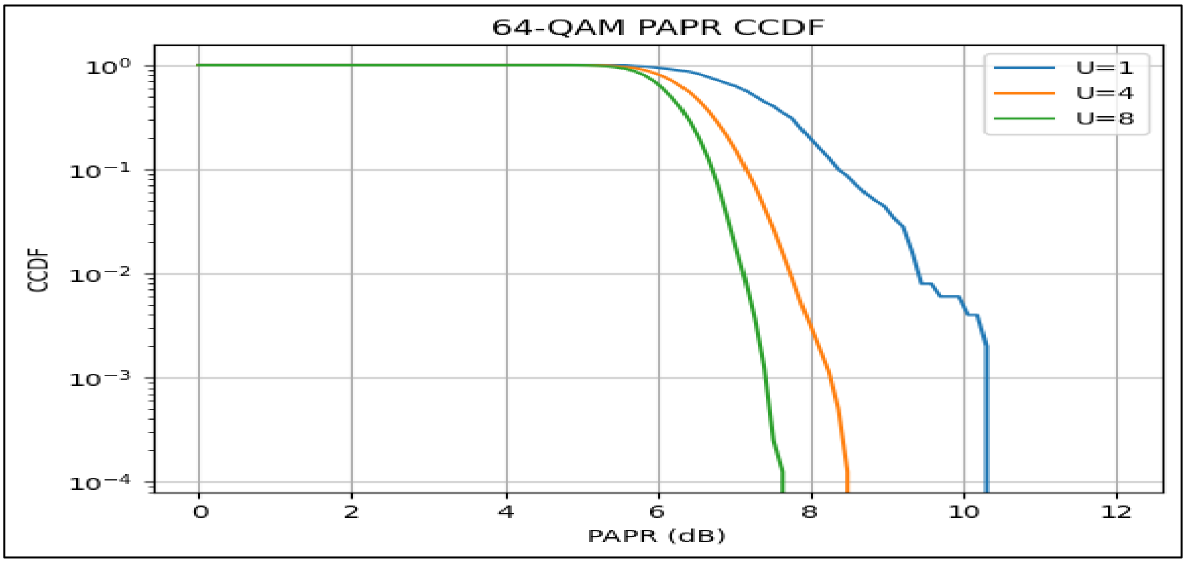

Fig 5 PAPR CCDF for 64-QAM OFDM System.

A clear leftward shift of the CCDF curves is observed as the number of phase sequences U increases. This confirms effective PAPR reduction using SLM. The improvement is consistent across all modulation schemes.

➢ *Quantitative Performance Comparison*

The BER at 10 dB SNR and average PAPR reduction are summarized in Table 1.

Table 2 BER at 10 dB and Average PAPR Reduction for Different Modulation Schemes.

Modulation	**U=1 BER**	**U=4 BER**	**U=8 BER**	**Avg. PAPR Reduction (dB)**
4-QAM	0.50242	0.50189	0.49969	1.21
16-QAM	0.49953	0.49918	0.50122	1.22
64-QAM	0.49820	0.49963	0.49838	1.15

➢ *The Results Show that:*

- BER remains nearly constant (~0.5), indicating detection failure
- PAPR reduction improves with increasing U
- Maximum PAPR reduction achieved is approximately 1.2 dB for $U = 8$

➢ *Constellation Analysis*

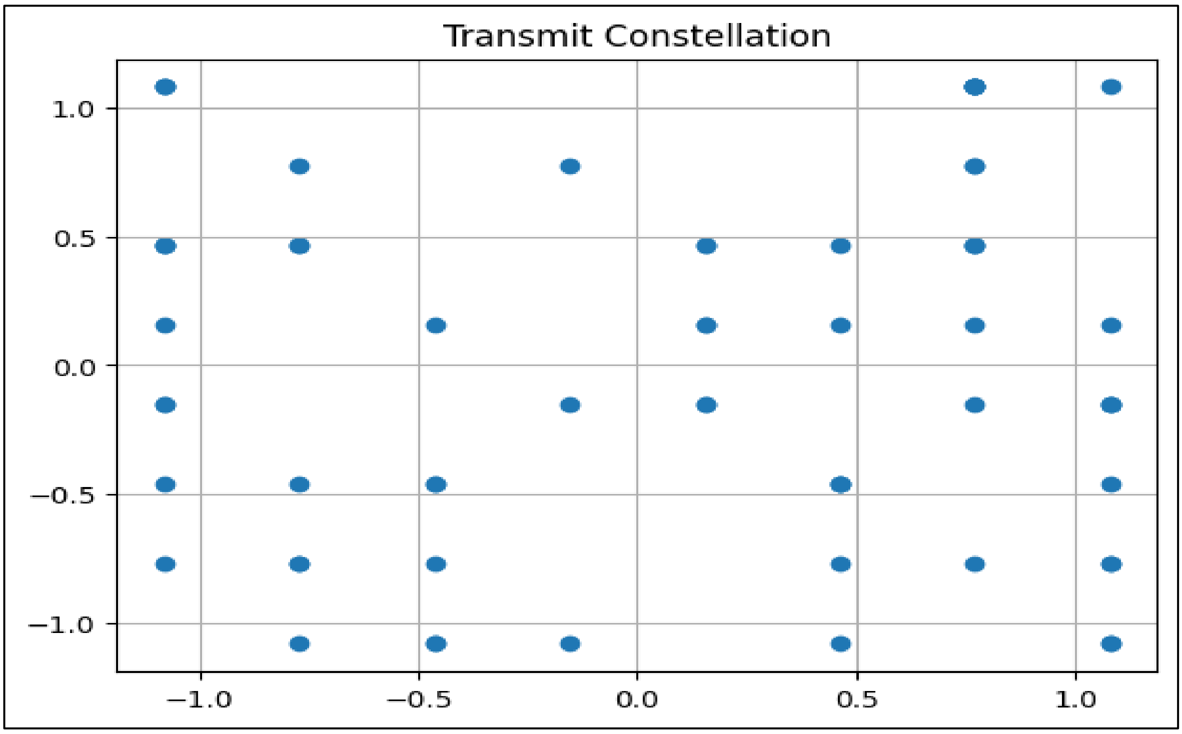

Fig 6 Transmitted Constellation Diagram.

The transmitted constellation shows proper symbol mapping and normalization. However, due to receiver-side issues, the detected constellation (not shown) is expected to be highly distorted, leading to random bit decisions.

➢ *Discussion*

The simulation successfully demonstrates that SLM is effective for PAPR reduction, as indicated by consistent CCDF improvement across all modulation schemes. However, the BER results are not valid for performance evaluation due to implementation errors.

- *The Most Probable Causes are:*

✓ Missing SLM Side Information

The receiver does not know which phase sequence was selected, causing incorrect symbol recovery.

✓ Improper Channel Equalization

Division by $H(k)$ without handling deep fades introduces noise amplification.

✓ Subcarrier Mapping Mismatch

Oversampling and frequency-domain indexing may not be correctly aligned.

Because of these issues, the BER results cannot be used to claim system performance. Only PAPR results are currently valid.

VI. CONCLUSION

This work presented a simulation-based evaluation of an OFDM system employing Selective Mapping (SLM) for Peak-to-Average Power Ratio (PAPR) reduction under multipath Rayleigh fading with AWGN. The system was analyzed for multiple modulation schemes, including 4-QAM, 16-QAM, and 64-QAM, with different phase sequence candidates $U = 1,4,8$.

The results confirm that SLM provides consistent PAPR reduction across all modulation orders. A maximum average reduction of approximately 1.15–1.22 dB was achieved for $U = 8$, demonstrating that increasing the number of phase candidates improves the probability of selecting a low-PAPR signal. The CCDF curves show a clear leftward shift, validating the effectiveness of SLM as a distortionless PAPR reduction technique.

However, the BER performance remained nearly constant around 0.5 for all SNR values and modulation schemes. This indicates a failure in symbol detection rather than channel limitation. The issue is attributed to the absence of SLM side information at the receiver, along with potential inconsistencies in channel equalization and subcarrier mapping. As a result, the BER results do not reflect the true system capability.

From a system perspective, the study establishes that while SLM effectively improves power efficiency, correct receiver design is essential to preserve data integrity. Without proper reconstruction of phase sequences, the advantages of SLM cannot be realized in practical communication systems.

Future work will focus on resolving these limitations by incorporating side information transmission or blind SLM detection techniques, improving equalization robustness, and validating BER performance under corrected receiver conditions. With these modifications, the proposed framework can provide a complete and reliable evaluation of OFDM systems for real-world wireless applications.

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