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Enhancing MIMO-OFDM Performance: Innovative Techniques for PAPR Reduction and BER Optimization

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ABSTRACT

Increased channel capacity and enhanced BER performance are two benefits of integrating MIMO and OFDM methods in a MIMO-OFDM wireless communication system. Because of this, the method for high data-rate transmission is now very compatible with both present and next generations of communication systems. Nevertheless, the method also bears the significant PAPR issue related to OFDM signals, which still needs a workable solution. An technique for reducing PAPR is presented in this study to address the issue of excessive PAPR in MIMO-OFDM systems. The suggested technique combines the original transmit signal with a created peak-cancelling signal using a low-complexity signal mixing idea. The suggested method's computational complexity, $O(M)$, is much smaller than the FFT techniques' $O(N \log 2\ N)$. This is due to the fact that the FFT window size, N, is much larger than the number of nonzero peak-cancelling samples, represented by M. The suggested technique did not appreciably alter the transmitted signal's strength and was shown to produce large PAPR reductions with just a small number of nonzero peak-cancelling samples. For instance, a high PAPR reduction of 5.9 dB might be achieved at a tiny power loss of 0.09 dB with M = 5% of 256-point IFFT samples, which corresponds to a data rate loss of 4.8%. The suggested strategy was shown to perform better in terms of BER performance and PAPR reductions when compared to other ways that have been offered in the literature.

Keywords- PAPR, High power amplifier, BER, MIMO-OFDM.

I. OVERVIEW OF MIMO-OFDM SYSTEMS

MIMO-OFDM (Multiple Input Multiple Output - Orthogonal Frequency Division Multiplexing) systems are pivotal in modern wireless communication, combining MIMO’s capacity and diversity gains with OFDM’s robustness against multipath interference. MIMO technology utilizes multiple antennas at both the transmitter and receiver to enhance spectral efficiency and coverage, while OFDM divides the spectrum into multiple carriers, each modulated by a low data rate stream, making it resilient to frequency-selective fading and inter-symbol interference. Enhancing MIMO-OFDM performance involves innovative techniques for PAPR (Peak-to-Average Power Ratio) reduction and BER (Bit Error Rate) optimization. PAPR reduction techniques include Selective Mapping (SLM), which generates multiple versions of the OFDM signal and selects the one with the lowest PAPR, and Partial Transmit Sequences (PTS), which divides the OFDM signal into sub-blocks and optimizes their phase to reduce PAPR [1]. Clipping and filtering methods, as well as hybrid techniques like combining PTS with Gaussian pulse-based Tone Reservation (TR), are also effective [2]. For BER optimization, channel equalization techniques such as MMSE (Minimum Mean Square Error) and MLSE (Maximum Likelihood Sequence Estimation) are employed to mitigate ISI and improve BER [3]. Adaptive algorithms, like Adaptive Fruit Fly Optimization (FOA), dynamically select the best equalization method, while advanced error correction codes like LDPC (Low-Density

Parity-Check) and Turbo Codes correct errors and enhance BER. These techniques collectively enhance the performance of MIMO-OFDM systems, making them suitable for next-generation communication standards, ensuring high data rates and reliable communication.

II. IMPORTANCE OF PAPR REDUCTION AND BER OPTIMIZATION

PAPR (Peak-to-Average Power Ratio) reduction and BER (Bit Error Rate) optimization are critical for enhancing MIMO-OFDM (Multiple Input Multiple Output - Orthogonal Frequency Division Multiplexing) performance. High PAPR in MIMO-OFDM systems can lead to significant power inefficiencies and signal distortion due to the non-linear characteristics of power amplifiers. This distortion not only degrades signal quality but also increases out-of-band radiation, which can interfere with adjacent channels. Techniques such as Selective Mapping (SLM), Partial Transmit Sequences (PTS), and Clipping and Filtering are employed to mitigate these issues by reducing the PAPR, thereby improving the efficiency and reliability of the power amplifiers.

On the other hand, BER optimization is essential for ensuring data integrity and reliable communication. High BER indicates a higher number of errors in the transmitted data, which can severely impact the performance of communication systems. Techniques like channel equalization (e.g., MMSE and MLSE), adaptive algorithms (e.g., Adaptive Fruit Fly Optimization), and advanced error correction codes (e.g., LDPC and Turbo Codes) are utilized to minimize BER[31]. These methods help in mitigating the effects of inter-symbol interference (ISI) and other channel impairments, thereby enhancing the overall data transmission quality. Together, PAPR reduction and BER optimization play a pivotal role in maximizing the performance of MIMO-OFDM systems, making them more efficient and reliable for next-generation wireless communication standards. These enhancements ensure high data rates, improved spectral efficiency, and robust communication, which are essential for modern wireless networks.

III. PAPR REDUCTION TECHNIQUES IN MIMO-OFDM

Conventional PAPR Reduction Methods

Conventional Peak-to-Average Power Ratio (PAPR) reduction methods are crucial for enhancing the performance of MIMO-OFDM systems. Techniques such as Clipping and Filtering, Selective Mapping (SLM), Partial Transmit Sequences (PTS), and Tone Reservation are widely used. Clipping and Filtering involve cutting off signal peaks and then filtering to reduce out-of-band emissions, though this can introduce distortion and affect Bit Error Rate (BER). SLM generates multiple signal versions and selects the one with the lowest PAPR, but it is computationally intensive. PTS divides the signal into sub-blocks and optimizes their phases to minimize PAPR, offering good reduction at the cost of increased complexity. Tone Reservation reserves certain subcarriers to create a peak-canceling signal, which is simple but reduces data throughput. These conventional methods, while effective, often involve trade-offs between PAPR reduction, computational complexity, and BER performance, necessitating innovative approaches for optimal results.

Advanced Signal Processing Techniques

Advanced signal processing techniques are essential for enhancing MIMO-OFDM performance, particularly in reducing Peak-to-Average Power Ratio (PAPR) and optimizing Bit Error Rate (BER). Hybrid methods, such as combining Selective Mapping (SLM) with companding, offer significant PAPR reduction while maintaining manageable computational complexity [4]. Probabilistic algorithms, like the Fireworks Algorithm, dynamically adjust signals to minimize PAPR and maintain efficiency [5]. Low-complexity additive methods provide straightforward approaches to PAPR reduction without heavily taxing computational resources. Additionally, machine learning approaches are emerging as powerful tools for predicting and adjusting signals to achieve optimal PAPR and BER performance. These innovative techniques not only address the limitations of conventional methods but also pave the way for more efficient and robust MIMO-OFDM systems. By integrating these advanced signal processing strategies, researchers can significantly enhance the reliability and efficiency of wireless communication networks [6].

Hybrid Approaches for PAPR Reduction

Hybrid approaches for Peak-to-Average Power Ratio (PAPR) reduction are gaining traction in enhancing MIMO-OFDM performance, offering a balance between efficiency and complexity. These methods combine traditional techniques like Partial Transmit Sequences (PTS) with innovative strategies such as Gaussian pulse-based Tone Reservation (TR) to achieve superior PAPR reduction [5]. For instance, integrating PTS with adaptive optimization algorithms like Gray Wolf Optimization and Artificial Bee Colony can significantly lower PAPR while maintaining system performance [7]. Additionally, hybrid methods employing convolutional codes and iterative companding techniques have shown promise in reducing PAPR and controlling out-of-band radiation. These approaches not only mitigate the drawbacks of conventional methods but also enhance Bit Error Rate (BER) performance, making them ideal for next-generation wireless communication systems. By leveraging these hybrid techniques, researchers can achieve more robust and efficient MIMO-OFDM systems, paving the way for advanced wireless communication networks [8].

Comparative Analysis of PAPR Reduction Techniques

Peak-to-Average Power Ratio (PAPR) reduction is crucial for enhancing the performance of MIMO-OFDM systems, which are widely used in modern wireless communication due to their high spectral efficiency and robustness against multipath fading. Various techniques have been developed to address the high PAPR issue, including Selective Mapping (SLM), Partial Transmit Sequence (PTS), and clipping and filtering. These methods aim to optimize the Bit Error Rate (BER) while maintaining system efficiency. SLM and PTS are particularly effective as they do not introduce distortion, unlike clipping and filtering, which can degrade signal quality. Recent advancements also explore hybrid approaches combining multiple techniques to achieve better performance. Comparative analysis of these methods reveals that while SLM and PTS offer significant PAPR reduction, their computational complexity can be a drawback. Therefore, ongoing research focuses on balancing PAPR reduction, BER optimization, and computational efficiency to enhance overall system performance [9,10].

IV. INNOVATIVE APPROACHES FOR COMBINED PAPR REDUCTION AND BER OPTIMIZATION

Innovative approaches for combined Peak-to-Average Power Ratio (PAPR) reduction and Bit Error Rate (BER) optimization in MIMO-OFDM systems are pivotal for advancing wireless communication technologies. Joint optimization frameworks are at the forefront of these innovations, integrating multiple techniques to simultaneously address PAPR and BER challenges. These frameworks often employ hybrid methods, such as combining Selective Mapping (SLM) with Partial Transmit Sequence (PTS), to achieve significant PAPR reduction while maintaining low BER. By leveraging the strengths of different techniques, joint optimization frameworks provide a balanced solution that enhances overall system performance. Machine learning-based techniques have emerged as powerful tools for optimizing PAPR and BER. Algorithms such as neural networks and reinforcement learning can dynamically adapt to varying channel conditions and system requirements. These techniques can predict and mitigate high PAPR scenarios while optimizing BER, offering a flexible and efficient approach to system optimization [11]. For instance, deep learning models can be trained to identify optimal signal processing strategies that minimize PAPR without compromising BER. This adaptability makes machine learning-based techniques particularly effective in real-time communication environments.

Resource allocation and power control strategies are crucial for managing PAPR and BER in MIMO-OFDM systems. By intelligently allocating resources such as power and bandwidth, these strategies can enhance signal quality and reduce PAPR. Power control mechanisms, for example, can adjust the transmission power of individual subcarriers to minimize PAPR while ensuring reliable communication. Additionally, adaptive resource allocation can dynamically distribute resources based on real-time system demands, further optimizing performance. These strategies are essential for maintaining the balance between PAPR reduction and BER optimization, especially in complex and dynamic communication environments.

The trade-offs and performance metrics associated with PAPR reduction and BER optimization are critical for evaluating the effectiveness of different techniques. While techniques like clipping and filtering can significantly reduce PAPR, they may introduce distortion, leading to higher BER. Conversely, methods such as SLM and PTS offer distortion-free PAPR reduction but can be computationally intensive. Performance metrics such as computational complexity, spectral efficiency, and energy consumption must be considered when assessing the trade-offs between PAPR reduction and BER optimization [12]. By carefully balancing these factors, researchers can develop innovative solutions that enhance MIMO-OFDM performance.

V. PAPR IN MIMO-OFDM SYSTEM

With the consideration that each branch of a MIMO- OFDM system is equivalent to a SISO-OFDM system, the IFFT output during one-symbol duration is the baseband signal given by

$$x_i(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_i(k)\, e^{\frac{j2\pi kn}{N}}$$

Here, $Xi(k)$ is the modulation symbol from binary phase-shift keying (BPSK) or M-ary quadrature amplitude modulation (M-QAM), N is the total number of subcarriers, and i = 1 or 2 is the branch index. For each branch signal $xi(n)$, the ratio of the peak power to the average power is given by

$$\mathrm{PAPR}\{x_i(n)\} = \frac{\max_{0\le n\le N-1}\{|x_i(n)|^2\}}{E\{|x_i(n)|^2\}}$$

Where, E{.} is the expectation operator. For the MIMO- OFDM system, we are interested with the maximum PAPR among all branches, which for the 2 × 2 system is given by

$$PAPR_{MIMO} = \max(\mathrm{PAPR}\{x_1(n)\}, \mathrm{PAPR}\{x_2(n)\})$$

Because the input to the HPA is a continuous-time signal $xi(t)$, in the calculation of PAPR, signal $xi(n)$ should be oversampled with a factor ≥ 4. This avoids skipping the peak value of the continuous-time signal and in turn helps to closely estimate the continuous-time PAPR [13].

It is clear that each branch signal is a summation of N signals and therefore can have large amplitude fluctuations resulting from constructive and destructive additions. These amplitude fluctuations can result into high PAPR and nonlinear amplification effects.

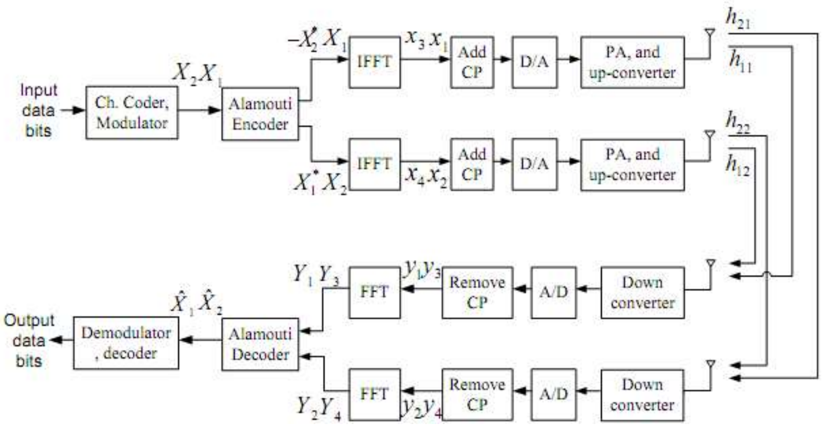

Fig.1. MIMO-OFDM system deploying 2×2 Alamouti STBC

After the HPA processes the signal. Analytically, a signal's distribution of amplitude magnitudes, or $|xi(n)|$, may indicate whether or not it exhibits large power fluctuations and, therefore, high PAPR. The central limit theorem states that the real and imaginary parts of the amplitudes are Gaussian-distributed, resulting in Rayleigh-distributed signal magnitudes $|xi(n)|$, provided that N is large enough and that the signal amplitudes are identically and statistically independent. As a result, signal $xi(n)$ may exhibit significant PAPR. The complementary cumulative distribution function (CCDF), which is the likelihood that a PAPR will be higher than a specified threshold γ and is provided by the equation, may be used to determine how high a PAPR is

$$\Pr\{\mathrm{PAPR}\{x_i(n)\} > \gamma\} = 1 - (1 - e^{-\gamma})^N$$

Where, Pr{.} is the probability operator.

According to the preceding equation, a high threshold value denotes a high PAPR for fixed values of CCDF and N, and vice versa. This means that the difference between any two threshold values, for a particular CCDF value, may be used as a metric of PAPR reduction and to show how effectively any suggested strategy decreases PAPR.

VI. METHODOLOGY

In this research, we present a low-complexity approach to generate additive peak-cancelling signals to lower high signal amplitudes in transmitted signals, hence reducing PAPR in MIMO-OFDM systems. The suggested technique is called the ASM PAPR reduction approach, or "low-complexity additive signal mixing." A few samples of the peak-cancelling signals are added to the broadcast signals for the restoration of clipped amplitudes at the receiver, preventing BER deterioration caused by clipping of high signal amplitudes. Taking into account the maximum power that the HPA can tolerate without causing signal distortion, the peak-cancelling signals are generated from MIMO-OFDM transmit signals.

Proposed Algorithm

A peak-cancelling signal should only include samples of signal peaks that above a clipping threshold in order to precisely cancel the highest peaks in a transmit signal without adding new ones. Generally speaking, the system's intended PAPR level may be used to determine the clipping threshold. The appropriate peak-cancelling signal for signal $xi(n)$ may be constructed using the equation for a particular clipping threshold xt.

$$d_i(n) = \begin{cases} \frac{x_i(n)}{|x_i(n)|}(|x_i(n)| - x_{th}), & |x_i(n)| > x_{th} \\ 0, & |x_i(n)| \leq x_{th} \end{cases}$$

In vector form this signal can be expressed as $\boldsymbol{di} = [di(0), di(1), \ldots, di(N-1)]T$. The signal has both zero and nonzero samples. A simplified discrete-time signal $ci(k)$ containing only the nonzero entries can be written as

$$\boldsymbol{c}_i = [c_i(0), c_i(1), \ldots, c_i(M-1)]^T$$

where M is the number of nonzero samples in $di(n)$.

An estimated signal may be produced by generating a peak-cancelling signal using the tone reservation idea described in [14]. To achieve this, set aside the L subcarriers and use the following system of linear equations to solve for the frequency-domain peak-cancelling coefficients:

$$\widehat{\boldsymbol{Q}}\boldsymbol{C}_i = \boldsymbol{d}_i$$

where the IDFT matrix $\boldsymbol{Q} \in \mathbb{C}N\times N$, whose components are supplied by $(1/\sqrt{N})\exp(j2\boldsymbol{\kappa}kn/N)$, and $\boldsymbol{C}i \in \mathbb{C}N\times L$ is the submatrix composed of L columns, which correspond to the positions of reserved subcarriers in the IDFT matrix $y \in \mathbb{C}N\times N$. The following ratio shows that there is a loss in data rate as a result of the reserve of L subcarriers that do not carry user data:

$$R_{l,f} = \frac{L}{N}$$

A very low value of L, much less than N, is preferable to decrease the data rate loss, but this may adversely influence the tone-reservation method's capacity to reduce PAPR.

The system in equation is overdetermined since $L \geq N$, and the only way to solve it is via least-squares minimization of the residual error [15–17].

$$\boldsymbol{\epsilon}_i = \widehat{\boldsymbol{Q}}_i\boldsymbol{C}_i - \boldsymbol{d}_i$$

resulting in the closed form solution

$$\boldsymbol{C}_i = \left[\widehat{\boldsymbol{Q}}_i^H\widehat{\boldsymbol{Q}}_i\right]^{-1}\widehat{\boldsymbol{Q}}_i^H\boldsymbol{d}_i$$

After finding the frequency-domain coefficients, the time-domain peak-cancelling signal is obtained using the equation

$$\widehat{\boldsymbol{d}}_i = \widehat{\boldsymbol{Q}}_i\boldsymbol{C}_i$$

and the PAPR-reduced signal is then given by

$$s_i(n) = x_i(n) - \hat{d}_i(n)$$

The peak-cancelling signal $\hat{\boldsymbol{d}}i$ is not identical to the intended signal $\boldsymbol{d}i$ due to the over-deterministic character of the mechanism calculating peak-cancelling coefficients. It contains nonzero elements even in places with zeros in the desired signal. To achieve $\hat{\boldsymbol{d}}i \cong \boldsymbol{d}i$, raise L towards N, however this may result in unacceptably significant data rate loss.

Figure 2 displays two example peak-cancelling signals for a 2x2 MIMO-OFDM system. Peak-cancelling signals for the second transmit antenna include 13 nonzero samples, whereas the first antenna signal has 10. The second antenna signal peaks too. The transmit signal from the second antenna requires a larger PAPR reduction than the one from the first. Additionally, oversampling by 4 results in N = 1024/4 = 256 and data rate loss Rl,t = 0.048.

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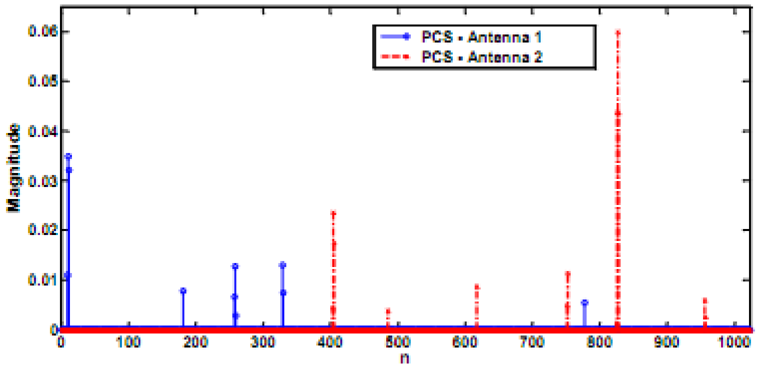

Fig 2. Peak-cancelling signals in 2 × 2 MIMO-OFDM system.

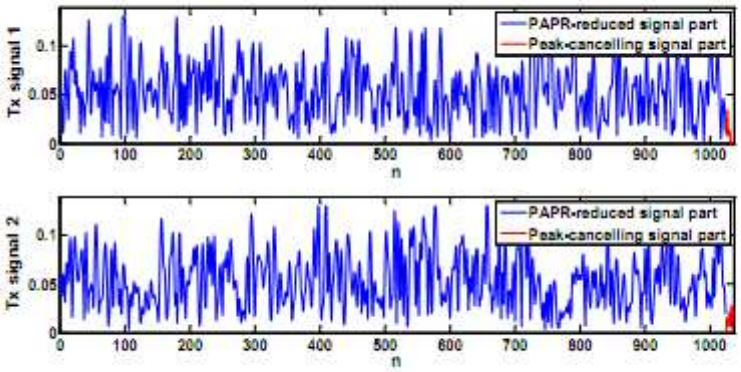

Fig. 3. Composite transmit signals in 2×2 MIMO-OFDM system.

The composite signals from the two transmit antennas are presented in Fig. 3. Figure shows that adding M peak-cancelling signal samples scarcely affects the PAPR-reduced signal waveform when M ≭ N. This implies that the average transmit power is unaffected by M sample transmission.

VII. RESULTS AND DISCUSSION

The suggested ASM PAPR reduction approach reduced MIMO-OFDM PAPR. MIMO-OFDM simulations were done in MATLAB. Table I lists important simulation parameters. Over Rayleigh flat-fading channels, an Alamouti space-time code was utilized with 2 send and 2 receiver antennas. Simulations employed the HPA Rapp model. Each simulation scenario used the suggested method for 10^4 symbols.

Table 1: Simulation Parameters

FFT window size	128, 256
Modulation	QPSK
Number of OFDM symbols	10^4
Oversampling factor F_s	4
Power amplifier model	Rapp model, $p = 2$
Guard interval	1/4
Channel model	Rayleigh flat-fading

As seen in the table, all subcarriers were modulated using QPSK. This is enough to evaluate the approach and compare it to others since modulation type does not effect PAPR reduction performance. Both PAPR reduction and BER were examined. The initial simulations assessed the suggested method's PAPR lowering capacity. This job used a N = 256 subcarrier system. The system received M = 3, 6, 13, 19, and 26 peak-cancelling samples. Data-rate losses are 1.2%, 2.3%, 4.8%, 6.9%, and 9.2% for these M values. Fig. 4 shows the CCDF evaluation of PAPR decrease for each example.

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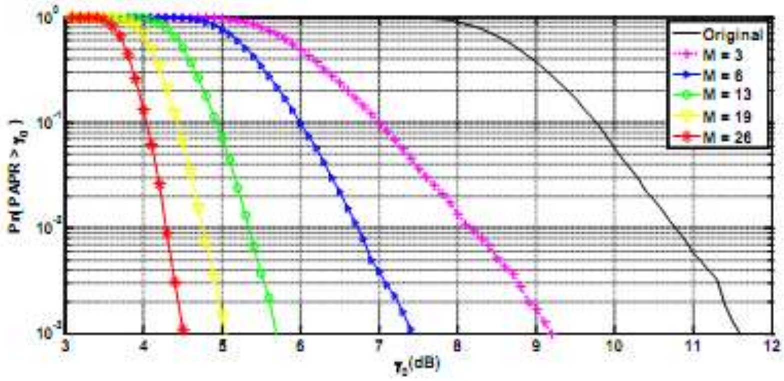

Fig. 4. CCDF for MIMO-OFDM system with QPSK data and N= 256

Table 2: PAPR Reductions at CCDF = 10^{-3}, N = 256

M	3	6	13	19	26
$R_{l,t}$ (%)	1.2	2.3	4.8	6.9	9.2
PAPR Reduction (dB)	2.4	4.2	5.9	6.5	7.1
Power Change (dB)	-0.02	-0.04	-0.09	-0.13	-0.18

Table 2 displays PAPR reductions at CCDF = 10−3 and transmit power decreases from varying peak-cancelling sample counts. This table shows that the number of peak-cancelling samples determines how well the suggested strategy reduces PAPR. But even with a few peak-cancelling samples, PAPR reductions may be considerable, as 4.2 dB with only 6.

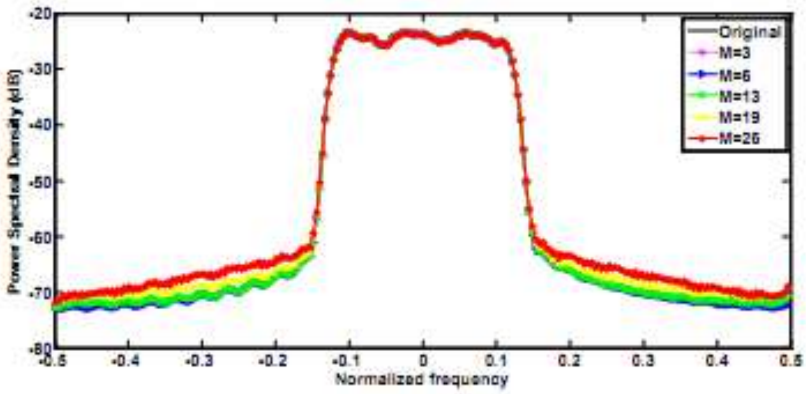

Fig. 5. Power spectral densities for different PAPR-reduced signals.

Furthermore, it is evident from the average power tabulation findings that the signal's transmit power is essentially maintained both before and after PAPR reduction. The average transmit power, for instance, is 99.3% of the value prior to the PAPR decrease for M = 26. Furthermore, it is evident from the power spectral density graphs in Figure 5 that the out-of-band radiations are minimal because of the little amount of clipping on a limited number of signal amplitudes.

Following confirmation that the suggested ASM approach could lower PAPR, it was contrasted with four additional viable PAPR reduction strategies that had previously been suggested in the literature and were designated with the initials SCS-SLM, STR, ACT, and CSC. A MIMO-OFDM system with QPSK-modulated subcarriers and M = 23 samples—or a 15% data rate loss—was used for the comparison. For CCDF = 10^{-3}, the results illustrating the PAPR reduction performances of the various approaches are shown in Table III and Fig. 6.

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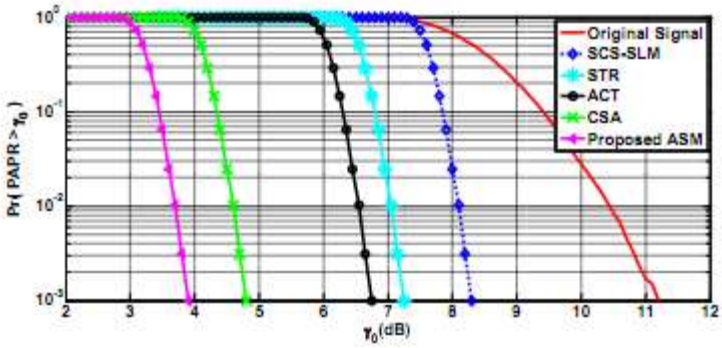

Fig. 6. PAPR reduction by different methods, N = 128.

Based on the available findings, it seems that the suggested technique has a superior capacity for PAPR reduction than the other four methods. According to Table 3's findings, for instance, the suggested ASM approach reduces PAPR by 0.9, 2.85, 3.35, and 4.4 dB more than the comparable reductions made by the CSC, ACT, STR, and SCS-SLM methods.

Table 3: PAPR reductions at CCDF =10^{-3}, N = 128

Method	ASM	CSA	ACT	STR	SCS-SLM
PAPR reduction (dB)	7.30	6.40	4.45	3.95	2.90

VIII. CONCLUSION

To sum up, there are potential paths for combining PAPR reduction with BER optimization when joint optimization frameworks, machine learning-based methods, and resource allocation algorithms are integrated. Through the consideration of trade-offs and the use of sophisticated performance measurements, these novel techniques have the potential to greatly improve MIMO-OFDM systems' dependability and efficiency. In order to satisfy the increasing requirements of contemporary wireless communication networks, more research and development in these fields are necessary.

This research proposes a novel approach for MIMO-OFDM systems to reduce PAPR. The technique first designs a peak-cancelling signal for each MIMO diversity arm, which is then added to the transmit signal of each arm using a low-complexity additive signal-mixing idea to minimize PAPR. A few samples of the peak-cancelling signal are attached to the transmit signal to be utilized for amplitude reconstructions at the receiver, preventing BER deterioration caused by peak reductions. As a result, the technique saves resources for peak-cancelling in the time domain as opposed to the frequency domain. Because of this, the technique has a smaller data rate loss than when using a traditional tone reservation approach, which reserves resources for peak-cancelling in the frequency domain.

The suggested approach might realistically preserve the average transmission powers of the original MIMO-OFDM signals while achieving large PAPR reductions with extremely minimal data rate losses, according to an analysis of its capacity for PAPR reduction. Furthermore, the computational difficulty of the approach is just O(M), significantly lower than the FFT complexity of O(N log2 N). Furthermore, the technique preserves the original MIMO-OFDM system's BER. Overall, the suggested technique provides superior PAPR reduction and BER performances when compared to the four other PAPR reduction methods, ACT, STR, SCS-SLM, and CSC.

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