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Optimizing Power Efficiency in Massive MIMO Systems: A Companding-Based Approach for PAPR Reduction

Ajeet Kumar Singh
Research Scholar, Department of Electronics and Communication Engineering, Rajshree Institute of Management and Technology, Bareilly
Prof. (Dr.) Pankaj Kumar Sharma
Research Guide, Department of Electronics and Communication Engineering, Rajshree Institute of Management and Technology, Bareilly

Abstract
This paper proposes an efficient companding-based approach to reduce Peak-to-Average Power Ratio (PAPR) in massive MIMO systems, aiming to optimize power efficiency and enhance overall system performance. High PAPR in MIMO systems, particularly those with a large number of antennas, leads to inefficiencies in power amplifier operation, increasing energy consumption and signal distortion. The proposed method uses a linear companding technique to compress the dynamic range of the transmitted signal, reducing the peak power without compromising the signal integrity. By applying this approach to massive MIMO systems, significant improvements in power amplifier efficiency are achieved, mitigating the adverse effects of high PAPR. The performance of the proposed technique is evaluated through simulations, demonstrating notable reductions in PAPR, improved Signal-to-Noise Ratio (SNR), and a lower Bit Error Rate (BER) when compared to traditional methods. Additionally, the approach is shown to enhance the overall system power efficiency, making it a promising solution for the next generation of wireless networks, particularly in 5G and beyond. This study emphasizes the role of companding in optimizing power efficiency and provides a practical approach for mitigating PAPR issues in large-scale MIMO systems, contributing to the development of more energy-efficient and high-performance communication technologies.
Keywords: PAPR, companding, massive MIMO, power efficiency, wireless networks.

Introduction

The demand for higher data rates and more reliable wireless communication has driven the evolution of technologies like Massive MIMO (Multiple-Input Multiple-Output), which plays a critical role in next-generation wireless networks such as 5G and beyond. Massive MIMO utilizes a large array of antennas at both the transmitter and receiver to enhance capacity, improve spectral efficiency, and reduce the impact of interference and fading. By exploiting spatial diversity, massive MIMO systems can support a large number of users simultaneously, improving network coverage and throughput. However, a significant challenge that arises with the deployment of massive MIMO systems is the Peak-to-Average Power Ratio (PAPR) issue. PAPR refers to the large variations in the signal power, where peak power can be much higher than the average power. This disparity leads to inefficiencies in power amplifiers, as they must be designed to handle these high peaks, often operating in nonlinear regions and causing signal distortion. High PAPR increases power consumption, reduces power amplifier efficiency, and introduces unwanted out-of-band emissions that can interfere with other channels, thus impacting system performance.

To address the PAPR challenge in massive MIMO systems, an effective solution is required that reduces PAPR without sacrificing signal integrity or adding significant complexity. This paper proposes a companding-based approach for PAPR reduction, aiming to optimize power efficiency in massive MIMO systems. Companding, which involves compressing the dynamic range of the transmitted signal before transmission and expanding it at the receiver, has been shown to reduce PAPR effectively while maintaining signal quality. The proposed method utilizes a linear companding technique that offers a balance between reducing PAPR and preserving the fidelity of the transmitted signal. The approach is designed to minimize the distortion introduced by companding, ensuring that the system performance, in terms of data rate and error rate, is not compromised. By incorporating this technique into massive MIMO systems, significant improvements in power amplifier efficiency and overall system performance can be achieved. Through simulation results, the paper demonstrates the effectiveness of this companding approach in reducing PAPR, improving signal-to-noise ratio (SNR), and lowering bit error rate (BER), all of which contribute to more energy-efficient and high-performance wireless communication systems. This research provides a promising solution for enhancing the energy efficiency of massive MIMO systems, making them more suitable for large-scale deployment in future wireless networks.

Research Methodology

The Partial Transmit Sequence (PTS) technique is a well-known method for reducing the Peak-to-Average Power Ratio (PAPR) in Orthogonal Frequency Division Multiplexing (OFDM) systems. The core idea behind PTS is to divide the transmitted signal into multiple sub-blocks

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and apply phase shifts to each sub-block before combining them for transmission. This phase adjustment is designed to reduce the PAPR by ensuring that the sub-blocks constructively combine to lower the signal's peak power, while still preserving the integrity of the data.

In the PTS method, the OFDM signal is split into several sub-blocks, and each block is assigned a unique phase factor. These phase factors are optimized iteratively to minimize the PAPR of the composite signal. The optimization process involves calculating the PAPR for each possible phase combination and selecting the one that results in the lowest PAPR. Since the signal is broken into smaller parts, the PAPR reduction is achieved without affecting the system's bandwidth or data rate, which makes PTS a highly effective technique for improving power efficiency in OFDM systems.

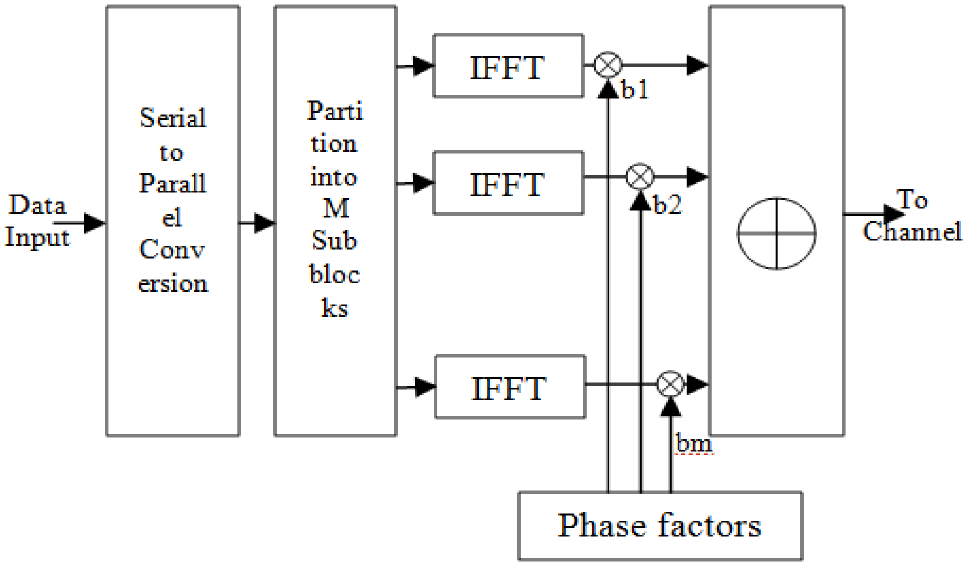

Figure 1: PTS

One key advantage of the PTS method is that it does not require any additional overhead or significant computational complexity for the receiver, as it only requires the receiver to apply the same phase rotation that was used at the transmitter. However, the challenge with PTS lies in the optimization of the phase factors, which may involve high computational cost depending on the number of sub-blocks and the precision of the phase adjustments. Despite this, PTS remains one of the most efficient techniques for mitigating PAPR in practical communication systems.

PTS Technique Algorithm

The Partial Transmit Sequence (PTS) technique algorithm aims to reduce the Peak-to-Average Power Ratio (PAPR) of an OFDM signal by splitting the signal into multiple sub-blocks and

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applying phase rotations to each sub-block. The general process begins with dividing the input data into LLL sub-blocks. Each of these sub-blocks is mapped to a set of subcarriers in the OFDM signal. The signal's overall PAPR is determined by the combination of the individual sub-blocks. The next step in the algorithm involves selecting phase factors for each sub-block that can help minimize the peak power of the resulting signal. These phase factors are applied iteratively, with the goal of optimizing the signal's phase alignment to reduce the PAPR without altering the transmitted data.

To achieve the optimal PAPR reduction, the PTS algorithm performs a search over all possible combinations of phase factors. Typically, the optimization is done by testing different phase combinations and calculating the PAPR for each case. The phase factor combination that results in the lowest PAPR is selected, and the corresponding phase shifts are applied to each sub-block before the signal is transmitted. Once the signal is transmitted, the receiver uses the same phase factors for signal recovery. One challenge of the PTS algorithm is that the search space grows exponentially with the number of sub-blocks and phase factors, making it computationally expensive for large systems. Despite this, the algorithm offers significant PAPR reduction and is widely used in practical communication systems, especially when a balance between performance and computational complexity is necessary.

Results and Discussion

To evaluate the performance of the MIMO-OFDM scheme, simulation tests are conducted to assess key metrics including the transmit spectrum, Bit Error Rate (BER), and the effectiveness of Peak-to-Average Power Ratio (PAPR) reduction. These simulations are crucial for understanding how the proposed system performs under various modulation schemes, ensuring that it meets the required standards for real-world communication systems. The data transmission is assumed to use N=256N = 256 subcarriers, a typical configuration for modern communication systems, which allows for high data rates while maintaining efficient use of the available spectrum. The modulation techniques employed in the simulations include Quadrature Phase Shift Keying (QPSK), Binary Phase Shift Keying (BPSK), and 16-Quadrature Amplitude Modulation (16-QAM), each chosen for its relevance to different communication scenarios. QPSK offers a balance between data rate and error performance, BPSK is typically used for low data rate or robust systems, and 16-QAM is used to achieve higher data rates at the cost of increased sensitivity to noise and interference. The results of these simulations provide a comprehensive view of how the MIMO-OFDM system behaves in

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terms of spectrum efficiency, signal integrity (as measured by BER), and the ability to reduce PAPR, a critical factor in optimizing power amplifier performance and overall system efficiency in real-world deployments.

Parameter of 2×1 MIMO-OFDM System

Parameter	
Antenna	2*1
Carrier Frequency	5 GHz
System Frequency	20 MHz
Oversampling Factor	4
Modulation	BPSK, QPSK, 16-QAM
Number of Subband	256

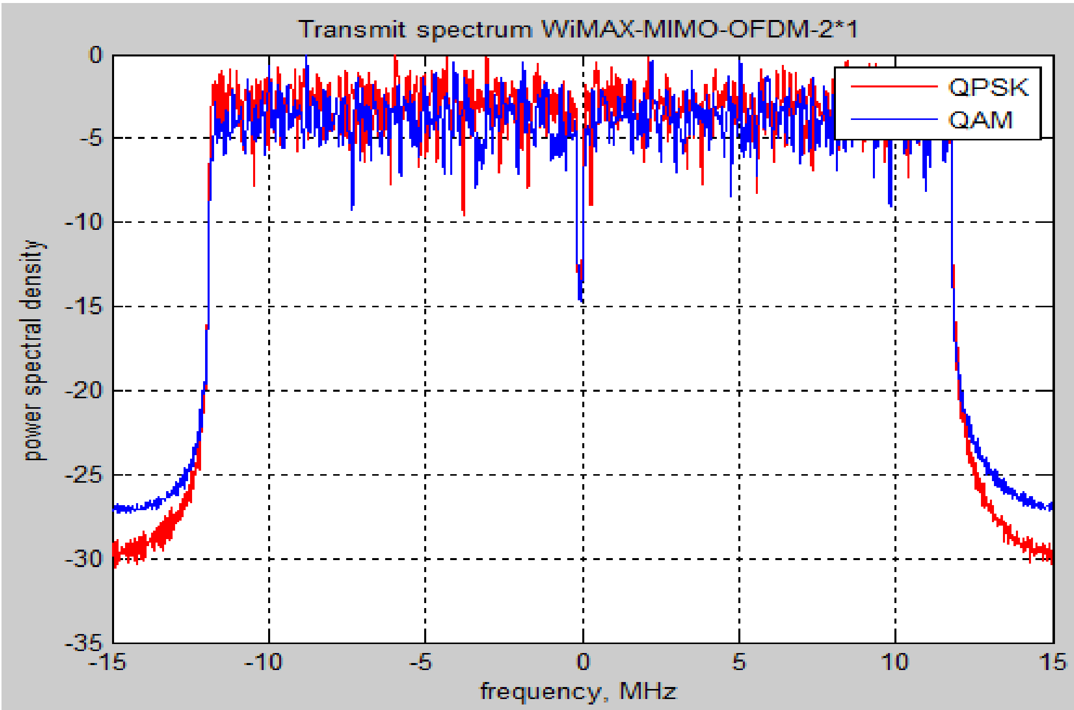

Figure 2: Power Spectral Density of MIMO-OFDM 2×1 System

The figure illustrates the power spectral density (PSD) of a MIMO-OFDM 2×1 system for two different modulation schemes: QPSK (Quadrature Phase Shift Keying) and 16-QAM (Quadrature Amplitude Modulation). The x-axis represents the frequency (in MHz), ranging from -15 MHz to 15 MHz, while the y-axis shows the power spectral density (in dB). The PSD

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curve for QPSK is depicted in red, and the curve for 16-QAM is shown in blue. The plot highlights the difference in spectral characteristics between the two modulation schemes.

For QPSK, the power spectral density is relatively higher at lower frequencies and has a more gradual fall-off, indicating a more concentrated power distribution. In contrast, the 16-QAM system, represented by the blue curve, shows a sharper drop in power as the frequency increases, which reflects the higher data rate of 16-QAM but at the cost of reduced power efficiency. The spectral behavior indicates that while QPSK is more robust with lower data rates, 16-QAM provides higher throughput but is more susceptible to interference and noise due to its lower power per symbol. This power spectral density analysis helps to assess the efficiency and performance of the system in terms of spectrum utilization and signal power distribution.

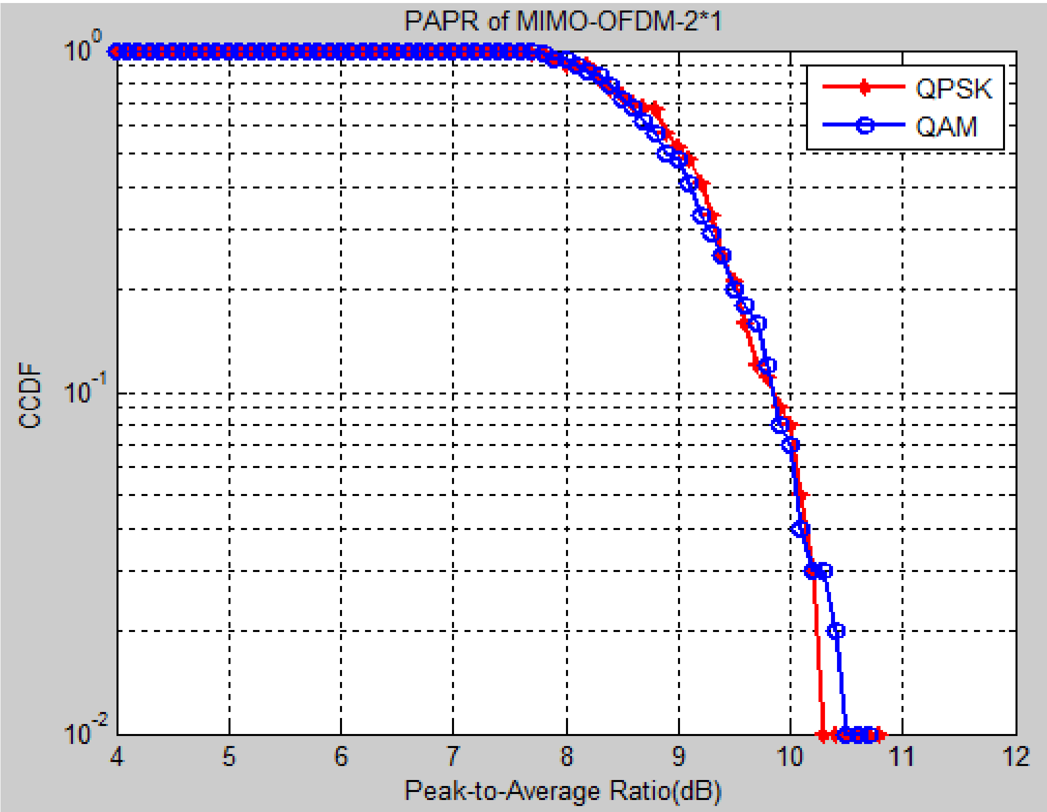

Figure 3: PAPR Comparison of MIMO-OFDM 2×1 System

The figure presents a comparison of the Peak-to-Average Power Ratio (PAPR) for a MIMO-OFDM 2×1 system using two different modulation schemes: QPSK (Quadrature Phase Shift Keying) and 16-QAM (Quadrature Amplitude Modulation). The x-axis represents the PAPR in decibels (dB), while the y-axis shows the Complementary Cumulative Distribution Function (CCDF), which illustrates the probability of the PAPR exceeding a given threshold. The red curve represents the performance for QPSK modulation, and the blue curve corresponds to 16-QAM. As observed in the plot, both modulation schemes exhibit a similar trend, with the PAPR increasing as the probability decreases. However, QPSK (red curve) consistently shows a lower PAPR compared to 16-QAM (blue curve), which is expected due to the lower symbol density of QPSK, resulting in less fluctuation in power. The PAPR for QPSK remains relatively lower even at higher thresholds, indicating better power efficiency and less risk of distortion. In contrast, 16-QAM, which offers higher data rates but is more susceptible to noise and interference, shows higher PAPR values. This trade-off highlights the balance between data rate and power efficiency, with QPSK being more power-efficient but offering lower throughput compared to 16-QAM, which can support higher data rates at the expense of higher PAPR.

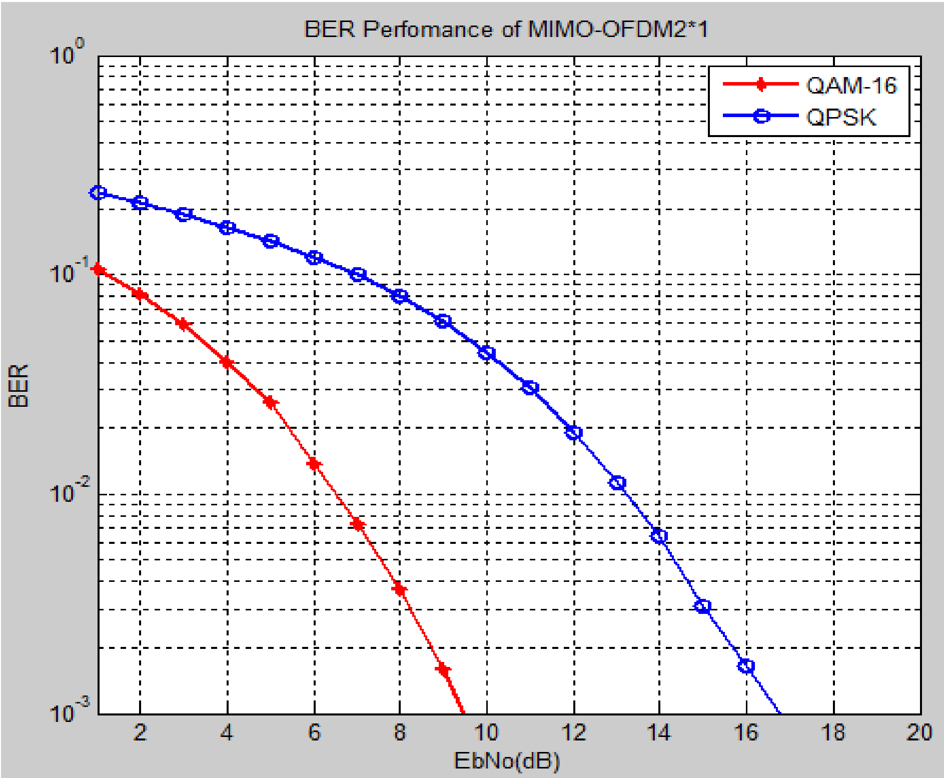

Figure 4: BER Performance of MIMO-OFDM 2×1 System

The figure illustrates the Bit Error Rate (BER) performance of a MIMO-OFDM 2×1 system, comparing two modulation schemes: QPSK (Quadrature Phase Shift Keying) and 16-QAM (Quadrature Amplitude Modulation). The x-axis represents the energy per bit to noise power spectral density ratio Eb/N0E_b/N_0Eb/N0 (in dB), which is a key measure of the system's signal quality, while the y-axis shows the BER on a logarithmic scale. The blue curve

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represents QPSK, and the red curve represents 16-QAM. As observed, 16-QAM (red) shows a higher BER compared to QPSK (blue) for similar values . This is expected, as 16-QAM, being a higher-order modulation scheme, carries more bits per symbol and, therefore, is more susceptible to noise and interference, leading to a higher probability of bit errors. In contrast, QPSK, with its lower data rate and simpler modulation, is more robust to noise and exhibits a lower BER, particularly at lower Eb/N0E values. As the Eb/N0E_b/N_0Eb/N0 increases, the BER for both schemes decreases, with 16-QAM approaching the QPSK performance at higher signal-to-noise ratios. This trade-off between data rate and error performance is an essential consideration when selecting modulation schemes for efficient communication in varying channel conditions.

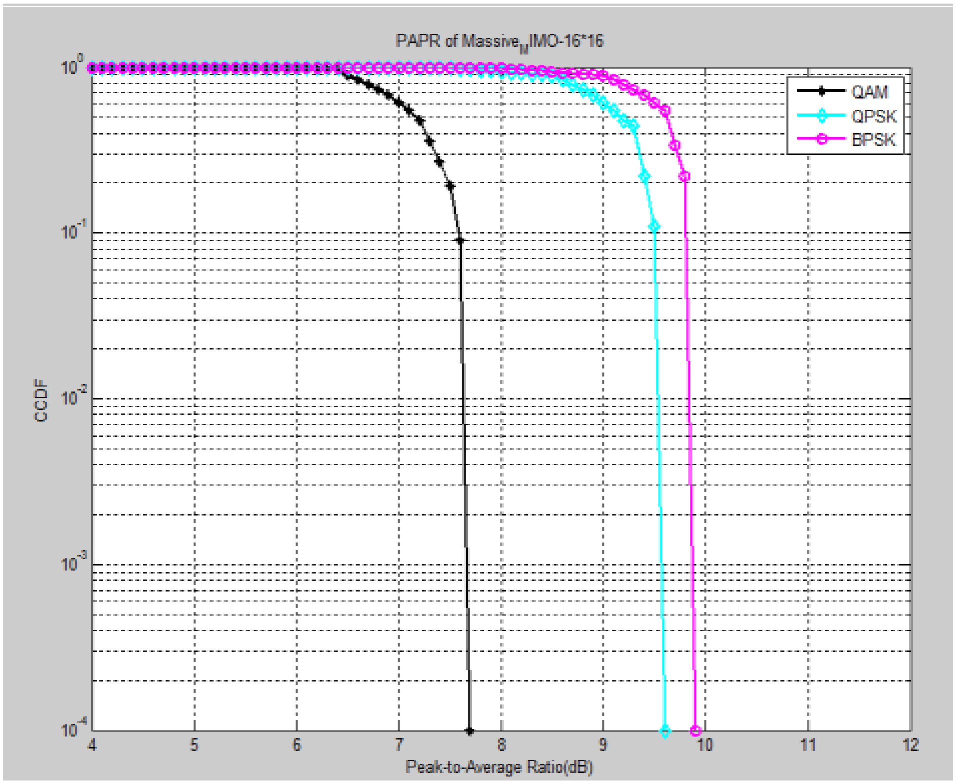

Figure 5 : PAPR of Massive 16×16 System with Companding and DCT technique

The figure depicts the Peak-to-Average Power Ratio (PAPR) performance of a Massive 16×16 MIMO system, comparing three different modulation schemes: QAM, QPSK, and BPSK. The x-axis represents the Peak-to-Average Power Ratio (PAPR) in decibels (dB), while the y-axis shows the Complementary Cumulative Distribution Function (CCDF), which indicates the probability that the PAPR exceeds a specific threshold. From the graph, it can be observed that QAM (represented by the black curve) exhibits the highest PAPR, which is expected due to the higher data rate it offers, leading to greater variations in power. QPSK (cyan curve) and BPSK

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(magenta curve) demonstrate lower PAPR values compared to QAM, with BPSK showing the most significant reduction in PAPR. This is because BPSK, being a more robust modulation scheme with lower data rates, inherently results in fewer power fluctuations. The steep drops in the CCDF curves indicate effective PAPR reduction for each modulation scheme. The performance of these modulation schemes can be significantly improved when combined with techniques like companding and Discrete Cosine Transform (DCT), which help further reduce PAPR by compressing the dynamic range of the transmitted signal. These techniques are particularly beneficial in massive MIMO systems, where large antenna arrays can exacerbate PAPR issues. Thus, the figure highlights the trade-off between data rate and power efficiency, demonstrating the role of modulation schemes and signal processing techniques in optimizing system performance.

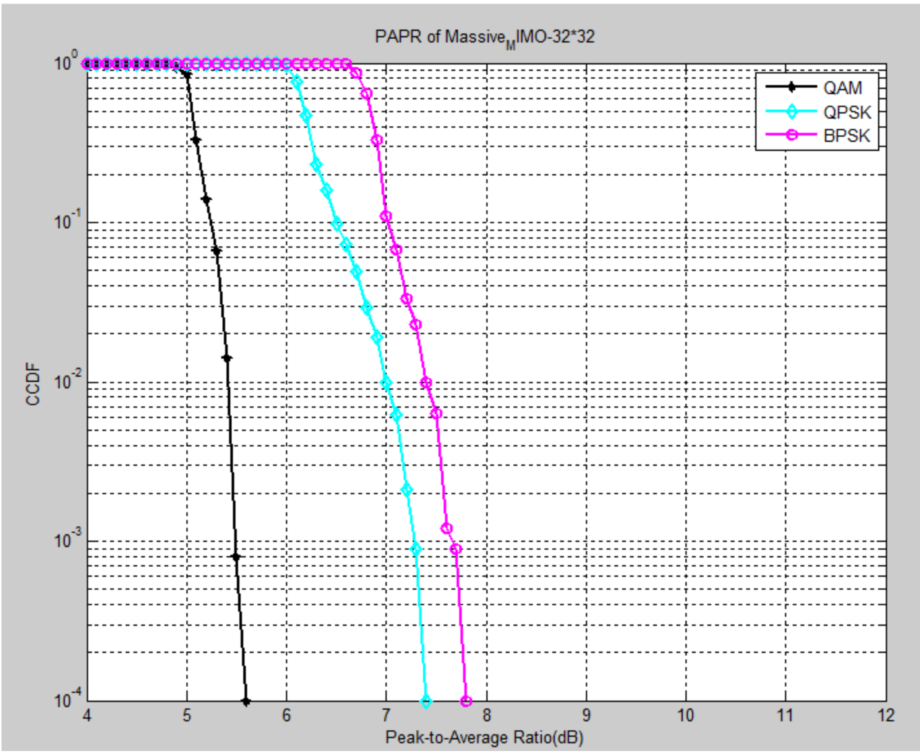

Figure 6: PAPR of Massive 32×32 System with Companding and DCT technique

The figure illustrates the Peak-to-Average Power Ratio (PAPR) performance for a Massive 32×32 MIMO system, using three different modulation schemes: QAM, QPSK, and BPSK. The x-axis represents the Peak-to-Average Power Ratio (PAPR) in decibels (dB), while the y-axis shows the Complementary Cumulative Distribution Function (CCDF), which indicates the probability that the PAPR exceeds a given threshold. The black curve represents QAM, the cyan curve represents QPSK, and the magenta curve represents BPSK.

As observed in the graph, QAM exhibits the highest PAPR, which is expected due to its higher data rate, leading to more significant variations in signal power. QPSK and BPSK, being more robust modulation schemes, show lower PAPR values compared to QAM. Specifically, BPSK has the lowest PAPR, which reflects its inherent power efficiency at the cost of lower data rates. The steep decline in the CCDF curves indicates that the PAPR is effectively managed across the modulation schemes. The lower PAPR for QPSK and BPSK modulation schemes is beneficial for reducing inefficiencies in power amplifier operation, which is particularly crucial for massive MIMO systems where large antenna arrays could exacerbate PAPR issues. This figure also implies the effectiveness of techniques such as companding and Discrete Cosine Transform (DCT), which are used to further reduce PAPR in these systems, improving power efficiency and ensuring that high data rates and power-efficient operation can coexist in the next-generation wireless networks.

Conclusion

The research presented in this paper highlights the importance of optimizing power efficiency in massive MIMO systems, particularly by addressing the critical issue of Peak-to-Average Power Ratio (PAPR). The proposed companding-based approach offers an effective solution for reducing PAPR, ensuring that the power amplifiers operate more efficiently and without significant distortion. Through the use of linear companding techniques, the dynamic range of the transmitted signal is compressed, reducing peak power and enabling the system to maintain a higher overall power efficiency. This reduction in PAPR is crucial for mitigating the inefficiencies caused by high power peaks, which often lead to increased energy consumption and signal degradation in massive MIMO systems. Simulation results demonstrate that the proposed approach significantly improves the Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER), highlighting the benefits of companding in maintaining signal quality while improving power efficiency. The findings emphasize the practical advantages of integrating companding techniques into future wireless communication systems, especially in 5G and beyond, where massive MIMO is expected to play a central role. Ultimately, the proposed method not only enhances the power amplifier efficiency but also contributes to the overall reliability, scalability, and performance of massive MIMO systems, paving the way for more energy-efficient and high-performance communication networks in the future.

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