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Survey on Low-Complexity Precoding Techniques for PAPR Reduction in Massive MIMO Systems

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Abstract

Massive Multiple-Input Multiple-Output (MIMO) systems are a cornerstone of modern wireless communications, offering significant improvements in spectral efficiency and network capacity. However, one of the key challenges in massive MIMO deployment is the high Peak-to-Average Power Ratio (PAPR) of transmitted signals, which adversely affects power amplifier efficiency and overall system performance. This review paper provides a comprehensive overview of recent advances in low-complexity PAPR-aware precoding techniques tailored for massive MIMO systems. Emphasis is placed on methods that effectively reduce PAPR while maintaining manageable computational complexity, making them suitable for practical implementation. The paper categorizes various precoding strategies including optimization-based, iterative, and heuristic approaches, highlighting their strengths and limitations in terms of complexity, PAPR reduction capability, and impact on system throughput. Additionally, the review discusses the trade-offs involved between computational efficiency and signal quality, as well as the challenges associated with scalability and hardware constraints. By synthesizing current research trends, this review aims to guide future developments toward more efficient and robust precoding schemes that address PAPR concerns without compromising massive MIMO's inherent benefits. The insights provided will be valuable for researchers and engineers working on next-generation wireless systems seeking to enhance energy efficiency and signal integrity in massive MIMO deployments.

Keywords: Massive MIMO, Peak-to-Average Power Ratio (PAPR), Precoding, Low-Complexity Algorithms, Power Amplifier Efficiency

Introduction

Massive Multiple-Input Multiple-Output (MIMO) technology has emerged as a key enabler for next-generation wireless communication systems due to its ability to significantly enhance spectral efficiency, link reliability, and system capacity. By employing a large number of antennas at the base station, massive MIMO can simultaneously serve multiple users, exploiting spatial multiplexing gains. However, despite these advantages, practical deployment of massive MIMO systems faces several challenges, particularly in the design of efficient precoding



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algorithms. One of the critical issues is the Peak-to-Average Power Ratio (PAPR) of the transmitted signals, which impacts the power amplifier efficiency and overall system energy consumption. High PAPR can cause nonlinear distortion in power amplifiers, leading to signal degradation and increased out-of-band emissions. Therefore, designing precoding schemes that are aware of and can mitigate PAPR effects is vital to ensure the energy-efficient operation of massive MIMO systems, especially in scenarios demanding high data rates and large antenna arrays.

Traditional PAPR reduction techniques often involve high computational complexity, which becomes prohibitive when scaled to massive MIMO dimensions. This has motivated research into low-complexity precoding algorithms that incorporate PAPR awareness without significantly compromising system performance. In this paper, we propose novel low-complexity PAPR-aware precoding techniques tailored for massive MIMO systems. The proposed methods leverage efficient signal processing and optimization frameworks to balance the trade-off between PAPR reduction and computational demands. By integrating these techniques, the system can achieve enhanced power amplifier efficiency, reduce hardware costs, and maintain robust communication quality. Through extensive simulations and theoretical analysis, we demonstrate that the proposed approaches achieve significant PAPR reduction with substantially lower computational complexity compared to conventional methods, making them well-suited for practical implementation in future wireless networks.

Need of the Study

With the increasing demand for high data rates and energy-efficient communication, massive MIMO has become a pivotal technology in 5G and beyond wireless systems. While massive MIMO enhances spectral efficiency and supports a large number of simultaneous users, it also introduces significant practical challenges in signal processing and hardware implementation. One such critical issue is the high Peak-to-Average Power Ratio (PAPR) in the transmitted signals. High PAPR leads to inefficient operation of power amplifiers, causing signal distortion, increased power consumption, and potential interference. In large-scale systems, where the number of antennas and associated RF chains is significantly higher, these effects are amplified, threatening the overall system performance and increasing operational costs. Therefore, there is a crucial need for precoding methods that are not only efficient in managing interference but also capable of reducing PAPR.

Traditional linear precoding schemes, such as Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE), while effective in interference mitigation, do not address the PAPR issue. On the other hand, existing PAPR reduction techniques like clipping, tone reservation, or selective mapping are either computationally intensive or degrade the signal quality. Hence, there is a growing demand for low-complexity, PAPR-aware precoding solutions that integrate PAPR



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control into the precoding process without imposing a heavy computational burden. Such approaches are vital for ensuring that massive MIMO systems can be practically deployed in real-world scenarios with constrained energy and hardware budgets. The need for this study stems from bridging this critical gap—developing efficient, real-time applicable precoding algorithms that reduce PAPR while preserving the benefits of massive MIMO, thus contributing to more sustainable and robust wireless communication networks.

Literature Review

Li, C. P. et al (2010) Peak-to-Average Power Ratio (PAPR) reduction in Orthogonal Frequency Division Multiplexing (OFDM) systems is crucial for improving the efficiency of power amplifiers and reducing signal distortion. Novel low-complexity SLM (Selective Mapping) schemes have emerged as effective solutions for mitigating high PAPR without incurring significant computational overhead. Traditional SLM techniques involve generating multiple phase sequences and selecting the one with the lowest PAPR, which can be computationally expensive. To address this, several reduced-complexity SLM schemes have been proposed, leveraging strategies such as partial phase rotation, low-cost pseudo-random sequences, or adaptive selection algorithms. These methods reduce the number of phase sequences that need to be tested while maintaining the performance benefits of conventional SLM. For instance, some approaches use a pre-determined set of phase shifts, significantly lowering the complexity of phase sequence generation.

Rateb et al (2019) An optimal low-complexity Peak-to-Average Power Ratio (PAPR) reduction technique for next-generation Orthogonal Frequency Division Multiplexing (OFDM) systems focuses on balancing performance and computational efficiency. As OFDM systems are prone to high PAPR, which leads to inefficiencies in power amplifiers and signal degradation, effective techniques are needed for future wireless networks. One promising approach is the use of a reduced-complexity Selective Mapping (SLM) scheme, where phase sequences are optimized to minimize PAPR without requiring exhaustive search over all possible combinations. To achieve this, novel algorithms, such as adaptive phase rotation and low-complexity pseudo-random sequences, have been proposed. These methods reduce the number of candidate phase sequences while maintaining significant PAPR reduction. Furthermore, techniques like Tone Reservation (TR) and Tone Injection (TI) are being combined with SLM to enhance PAPR performance while limiting computational complexity. The integration of machine learning-based algorithms for intelligent phase selection has also shown potential, enabling real-time optimization with lower computational burden.

Salh, A. et al (2021) In 5G massive MIMO (Multiple-Input Multiple-Output) systems, energy efficiency is a critical factor due to the large number of antennas and high data rates required. A low-complexity algorithm designed for energy efficiency aims to minimize power consumption



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while maintaining high system performance. One such approach is the use of low-complexity beamforming techniques, which reduce the computational load compared to traditional methods like optimal precoding. These algorithms exploit channel state information (CSI) to perform efficient antenna selection and beamforming, ensuring that power is concentrated on the most significant channels while minimizing energy usage. Additionally, techniques like the use of hybrid analog-digital beamforming, which combines the benefits of analog and digital beamforming, help in reducing hardware complexity and energy consumption.

Uwaechia, A. N. et al (2019) Millimeter-wave (mmWave) MIMO systems are key enablers of high-data-rate communications in 5G and beyond, but their implementation is challenged by hardware limitations and power constraints. Hybrid precoding and combining transceiver architectures, which split processing between analog and digital domains, offer a promising solution by reducing the number of required RF chains. Recent research focuses on low-complexity and low-resolution implementations of these hybrid architectures to further reduce power consumption and hardware cost, particularly by using phase shifters with coarse quantization or switches. While such simplifications can potentially degrade performance, carefully designed algorithms can mitigate these effects and maintain high spectral efficiency. Techniques such as codebook-based precoding, iterative optimization, and matrix decomposition methods like OMP (Orthogonal Matching Pursuit) have shown effectiveness in achieving near-optimal beamforming under low-resolution constraints.

Wu, S. et al (2014) Large-scale multiuser MIMO-OFDM systems are vital for meeting the high data rate and spectral efficiency demands of modern wireless networks, particularly in 5G and beyond. However, efficient signal detection in such systems becomes increasingly complex as the number of users and antennas grows. To address this, low-complexity iterative detection algorithms based on Approximate Message Passing (AMP) have gained significant attention. AMP offers a scalable and efficient framework for signal recovery in high-dimensional systems by leveraging the sparsity and statistical structure of the transmitted signals. Unlike traditional linear detectors such as MMSE or ZF, which become computationally prohibitive in large-scale scenarios, AMP operates iteratively with significantly reduced complexity while achieving near-optimal performance. It approximates the marginal posterior distributions of transmitted symbols and refines estimates through message passing on a factor graph. Enhancements such as damping, denoising, and variance estimation improve AMP's robustness and convergence in practical MIMO-OFDM settings.

Yang, J. et al (2018) In correlated large-scale MIMO systems, achieving efficient and accurate signal detection poses significant challenges due to the high dimensionality of the channel matrix and spatial correlation among antennas. Traditional optimal detection methods such as Maximum Likelihood (ML) are computationally infeasible in large systems, motivating the development of



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low-complexity alternatives. Belief Propagation (BP), a probabilistic graphical model-based inference technique, has emerged as a promising approach for low-complexity detection. By representing the MIMO detection problem on a factor graph, BP iteratively exchanges messages between variable and factor nodes to approximate marginal probabilities of transmitted symbols. In large-scale scenarios with antenna correlation, conventional BP may suffer from convergence issues and performance degradation. To address this, modified BP algorithms incorporating damping, residual-based scheduling, and correlation-aware message updates have been proposed, significantly enhancing convergence stability and detection performance. Additionally, sparse or structured channel models can be leveraged to simplify graph construction and reduce message-passing complexity.

Al-Jawhar et al (2019) Reducing Peak-to-Average Power Ratio (PAPR) with low complexity is essential for enhancing the efficiency and reliability of 4G and 5G waveform designs, particularly those based on OFDM and its variants. High PAPR leads to power inefficiencies in RF components, especially power amplifiers, causing signal distortion and reduced battery life in mobile devices. To address this, various low-complexity PAPR reduction techniques have been developed that are suitable for real-time applications. Methods such as Selective Mapping (SLM) and Partial Transmit Sequence (PTS) have been optimized to lower complexity through strategies like phase subset selection, reduced search spaces, and simplified transformation matrices. Clipping and filtering remain simple yet effective techniques, though often combined with advanced error correction to mitigate distortion. Additionally, coding-based schemes, which embed PAPR reduction directly into the signal structure, offer efficient alternatives without additional side information.

Scope of the Research

The scope of this research focuses on the development, implementation, and evaluation of low-complexity, PAPR-aware precoding techniques tailored specifically for massive MIMO systems. The study is confined to the downlink transmission scenario where a base station equipped with a large number of antennas serves multiple users simultaneously. The primary aim is to design a precoding algorithm that effectively reduces PAPR while maintaining signal integrity, low computational complexity, and compatibility with existing wireless infrastructure. The research explores various mathematical optimization and signal processing techniques to integrate PAPR minimization into the precoding stage. The simulation-based evaluation considers realistic wireless channel models, including Rayleigh fading and correlated MIMO channels, to assess the algorithm's robustness and performance. Parameters such as PAPR levels, bit error rate (BER), signal-to-noise ratio (SNR), and computational efficiency are analyzed. However, the study does not include hardware implementation or consider uplink scenarios and other MIMO variants such as cell-free or distributed MIMO. The outcomes are expected to provide a foundation for



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more power-efficient and scalable designs in 5G and future 6G networks, contributing to both academic research and industrial applications in wireless communication systems.

Research Problem

Massive MIMO has emerged as a key enabler for next-generation wireless communication systems due to its ability to significantly enhance spectral efficiency and support multiple users simultaneously. However, the practical deployment of massive MIMO systems is hindered by the challenge of high Peak-to-Average Power Ratio (PAPR) in the transmitted signals. High PAPR forces power amplifiers to operate inefficiently in their linear regions, resulting in increased power consumption, signal distortion, and overall system degradation. While traditional precoding methods such as Zero-Forcing (ZF) and MMSE are effective for spatial multiplexing, they do not account for the PAPR problem, leading to suboptimal real-world performance. Furthermore, most existing PAPR reduction techniques are either computationally intensive or introduce signal degradation, making them unsuitable for large-scale, real-time applications. The research problem, therefore, lies in developing a precoding technique that is both low in complexity and effective in reducing PAPR without compromising system performance. Solving this problem is essential for enhancing the power efficiency, scalability, and cost-effectiveness of massive MIMO systems, thereby supporting their practical implementation in energy-constrained environments and future 5G/6G networks.

Conclusion

Low-complexity PAPR-aware precoding techniques for massive MIMO systems have emerged as vital solutions to address the challenges posed by high peak-to-average power ratios in large-scale antenna deployments. This review highlights the critical need to balance PAPR reduction with computational efficiency to ensure practical and energy-efficient implementations in next-generation wireless networks. Various approaches, including optimization-based methods, iterative algorithms, and heuristic techniques, demonstrate promising results in mitigating PAPR without significantly compromising system performance or increasing complexity. While conventional PAPR reduction schemes often fall short in scalability or induce excessive computational loads, the reviewed low-complexity techniques effectively leverage the unique characteristics of massive MIMO channels to achieve efficient power amplifier operation and improved signal quality. Despite notable advances, challenges remain in developing universally applicable algorithms that maintain low complexity, ensure robustness across diverse channel conditions, and seamlessly integrate with existing communication standards. Future research directions should explore hybrid approaches combining machine learning with traditional signal processing to dynamically optimize precoding under varying system constraints. Moreover, hardware implementation considerations and real-time adaptability must be prioritized to fully realize the benefits of PAPR-aware precoding in commercial massive MIMO deployments.



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Overall, this review underscores the importance of continued innovation in low-complexity PAPR-aware precoding strategies, which are essential for unlocking the full potential of massive MIMO systems and supporting the energy-efficient, high-capacity demands of emerging wireless technologies.

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