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An Analysis of PAPR Reduction from the Point of View of BER Performance in Next-Generation MIMO-OFDM Wireless Systems

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Abstract: In today's society, high-speed and reliable wireless communication is a crucial requirement. With the rapid increase in mobile applications and users, there is a pressing need for more dependable and high-speed wireless networks that can address the limitations of existing systems in a multiuser environment. Wireless systems often face challenges such as noise, interference, inter-symbol interference (ISI), and inter-carrier interference (ICI), all of which can degrade signal quality due to multi-path fading. Additionally, performance issues such as poor bit error rates (BER) and high peak-to-average power ratio (PAPR) further impact signal power and spectral efficiency. One promising solution to these challenges is the combination of Orthogonal Frequency Division Multiplexing (OFDM) and Multi-Input Multi-Output (MIMO) antenna systems, known as MIMO-OFDM systems. This approach enhances the quality of service and increases throughput, meeting the demands of future wireless communication. This review article focuses on various technologies explored by researchers to improve bit error rates, peak-to-average power ratio, signal-to-noise ratio, and spectral efficiency in wireless systems. It provides an overview of the limitations of conventional methods and compares the results of different schemes and algorithms proposed by researchers. Additionally, the article highlights the role of multiple antenna systems (MIMO) in enhancing capacity and throughput, aiming to improve service quality in future multiuser environments.

Keywords: 5G, Wireless, Antenna, Interference, Multicarrier, modulation, MIMO, OFDM, PAPR, BER.

1. Introduction:

In the modern era, digital communications over wireless links have advanced significantly, connecting the entire world with ultra-high-speed digital networks. As mobile users, applications, and protocols evolve rapidly, the world is shifting towards next-generation 5G technologies. This transition to new generations brings numerous challenges, particularly as it involves integrating various wireless communication standards such as IEEE 802.11a, IEEE 802.16a, and their associated protocols. The primary goals for next-generation communication systems are to simplify system complexity, reduce power consumption, optimize bandwidth usage, and ensure error-free, reliable high-speed wireless communication.

To address these challenges, the integration of Multi-Input Multi-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) technologies is crucial. The MIMO-OFDM system effectively handles frequency-selective fading and eliminates the need for complex equalizers, making it a robust technology for reliable communication with good spectral efficiency. MIMO-OFDM leverages spatial diversity to deliver exceptionally high capacity, throughput, and resilience against Inter-Symbol Interference (ISI). This technology is already incorporated into several standards, including Wi-Fi (Wireless Fidelity), LTE (Long-Term Evolution), LTE Advanced (3GPP), WiMAX (Worldwide Interoperability for Microwave Access / IEEE 802.16m), and WLAN (Wireless Local Area Network / IEEE 802.11n).

However, MIMO-OFDM systems are not immune to challenges such as Bit Error Rate (BER), Symbol Error Rate (SER), Framing Error Rate (FER), Interference (including ISI and Inter-Carrier Interference, ICI), and high Peak-to-Average Power Ratio (PAPR). In Additive White Gaussian Noise (AWGN) environments, error rates can be improved by 1 to 2 dB higher Signal-to-Noise Ratio (SNR) using advanced constellation techniques and coding. In multipath fading environments, however, improving error rates may require increasing the SNR by up to 10 dB. Thus, addressing multipath fading effects is critical for effective wireless communication.

This review article specifically focuses on the error performance analysis and PAPR reduction schemes for MIMO-OFDM systems, as investigated by various researchers. The paper is organized as follows: Section II describes the basic MIMO-OFDM system model; Section III reviews enhancements in BER performance; Section IV covers different PAPR reduction methods; Section V discusses expected results; and Section VI concludes the article.

2. System Model

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MIMO-OFDM is a highly effective technology for ensuring reliable wireless communication, offering spatial diversity, high spectral efficiency, and enhanced capacity and throughput, all while maintaining robustness against various impairments.

A. MIMO Antenna System

The capacity of a MIMO system increases linearly with the number of transmit (mt) and receive (mr) antennas. This spatial diversity provided by MIMO significantly boosts spectral efficiency (SE). By deploying additional antennas at either the transmitter or receiver, it is possible to maximize the received power, thereby enhancing the overall performance of the system.

A typical MIMO antenna system, illustrated in Figure 1, employs a configuration of mt×mr \times mt×mr antennas, where mt denotes the number of transmit antennas and mr denotes the number of receive antennas. The presence of multiple antennas at both the transmitter and receiver improves spatial diversity, which in turn enhances the quality of service (QoS) and throughput of the communication system.

Despite these advantages, MIMO antenna systems face certain limitations. These include inter-channel interference (ICI), increased transmit power requirements, and the complexity of system implementation. Addressing these challenges is crucial for optimizing the performance of MIMO-OFDM systems.

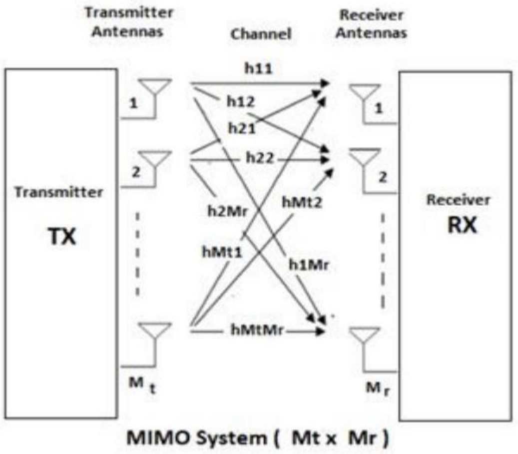

Fig. 1. MIMO ($m_t \times m_r$) antenna System

B. OFDM System.

Orthogonal Frequency Division Multiplexing (OFDM) transforms frequency-selective fading channels into multiple flat fading channels, thereby eliminating the need for complex equalization techniques and reducing receiver complexity.

In an OFDM system, the available bandwidth WWW is divided into NNN narrowband frequency subbands or subcarriers. This subdivision ensures that each subcarrier experiences flat fading rather than frequency-selective fading. Each subcarrier is spaced at equidistant frequencies, specifically at 1Ts\frac{1}{T_s}Ts1, where TsT_sTs is the symbol duration, calculated as Ts=NWT_s = \frac{N}{W}Ts=WN. The subcarriers are arranged orthogonally to prevent Inter-Symbol Interference (ISI), thus maintaining the integrity of the transmitted signal and improving system performance.

C. MIMO-OFDM System model.

The integration of MIMO and OFDM technologies, known as MIMO-OFDM, stands out as a leading approach in wireless communication due to its ability to deliver high data rates, efficiently utilize available bandwidth, enhance signal quality, and mitigate various channel impairments. Figure 2 illustrates the architecture of a MIMO-OFDM system.

The process begins with the modulation of the message signal. This modulation can be performed using various constellation schemes such as Binary Phase Shift-Keying (BPSK), Quadrature Phase Shift Keying (QPSK), or M-ary Quadrature Amplitude Modulation (M-QAM). After modulation, the complex output is converted into a parallel set of symbols through a serial-to-parallel converter. This parallelization prepares the signal for processing through multiple antennas, enabling the full advantages of MIMO technology combined with OFDM's robustness against frequency-selective fading.

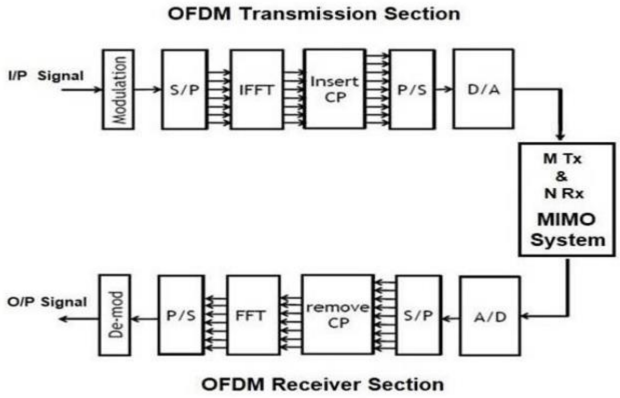

Fig. 2. MIMO-OFDM Architecture

In a MIMO-OFDM system, the process of data transmission begins with the modulation of the message signal using techniques such as Binary Phase Shift-Keying (BPSK), Quadrature Phase Shift Keying (QPSK), or M-ary Quadrature Amplitude Modulation (M-QAM). The modulated symbols are then converted into parallel streams through a serial-to-parallel converter.

These parallel streams are fed into an N-point Inverse Fast Fourier Transform (IFFT), which transforms the signal from the frequency domain into the time domain. This transformation enables the transmission of the signal over N subcarriers. The output of the IFFT is appended with a Cyclic Prefix (CP)—a copy of the last P samples from the previous symbol. This CP ensures that each OFDM symbol consists of N+PN + PN+P samples and helps to mitigate inter-symbol interference.

After adding the CP, the data block is converted back into a serial form using a parallel-to-serial converter. The serial data is then processed by a Digital-to-Analog Converter (DAC), which transforms the digital data into an analog signal. This analog signal is then up-converted to the transmission frequency and sent through MIMO transmitting antennas. The

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signal travels through the wireless channel and is received by the MIMO receiver antennas.

At the receiver, the analog signal is converted back into a digital form using an Analog-to-Digital Converter (ADC). This step includes timing synchronization of the received symbols. The ADC output is then converted into a parallel data stream with a serial-to-parallel converter. The Cyclic Prefix is removed from each OFDM symbol, and the resultant signal is processed by an N-point Fast Fourier Transform (FFT) to convert it back into the frequency domain.

Finally, the parallel signal is converted to serial form again using a parallel-to-serial converter and demodulated to retrieve the original information.

3. Literature Review:

In digital wireless communication, the Bit Error Rate (BER) measures the number of erroneous bits received per symbol per unit time through a communication channel. BER performance is crucial for comparing different OFDM modulation schemes. Due to multipath fading in wireless channels, signals are received through multiple paths and may combine destructively, which degrades system performance and leads to higher BER. To mitigate this, receiver diversity and transmit diversity schemes, such as Alamouti's scheme and Maximum Ratio Combining (MRC) with modulation techniques like BPSK, QPSK, and M-QAM, can effectively reduce BER.

A. H. Alqahtani et al. examined BER performance in MIMO-OFDM systems using a 2x2 antenna configuration with Rate-less Space-Time Block Codes (RSTBC). They utilized QPSK and 16-QAM modulation and applied a guard signal or Cyclic Prefix (CP) to minimize Inter-Symbol Interference (ISI). Their study demonstrated that RSTBC can maintain signal reliability even at loss rates of 10% to 25% for specific encoded data amounts. They found that BER performance improves with an increasing number of RSTBC blocks, particularly for 16-QAM modulation, with blocks L=1, 2, 4, 6, and 8.

M. El-Absi et al. proposed a Transmit Antenna Selection (TAS) method for MIMO-OFDM systems, either through bulk selection or per-subcarrier selection. This approach aims to enhance the sum rate and error rate performance under challenging channel conditions. They employed two antenna selection techniques, Maximum Sum Rate (Max-SR) and Minimum Error Rate (Min-ER), and validated their results through indoor experiments. Their findings showed improved BER performance at a Signal-to-Noise Ratio (SNR) of 10 dB or higher.

S. A. Nambi and K. Giridhar introduced an OFDM Index Modulation (OFDM-IM) scheme to enhance BER performance using QPSK and M-QAM modulation techniques. Their approach demonstrated better performance compared to conventional schemes without compromising the spectral efficiency of OFDM. They compared BER results for OFDM-IM with 16-QAM and 8-QAM modulation techniques, finding that 8-QAM provided better BER performance with reduced complexity at the receiver.

A. Afana et al. presented a MIMO scheme incorporating Quadrature Spatial Modulation (QSM) in a cooperative Decode and Forward (DF) diversity scheme. Their analytical and simulation results indicated that QSM offers a 3 dB gain over conventional spatial modulation schemes. They evaluated average bit error probability (ABEP) versus SNR for different antenna configurations and spectral efficiencies, showing that QSM with 4-QAM modulation achieves 4 bits/s/Hz spectral efficiency and an ABEP at an SNR of 20 dB. Similarly, the QSM-DF system with a 4x4 configuration and 4-QAM modulation also achieved notable results. Compared to conventional spatial modulation with 4x4 antennas and 16-QAM, QSM provided a 3 dB gain.

S.M. Alamouti's Approach: Alamouti introduced a transmit diversity technique with a 2x1 antenna system. His analysis demonstrated that both 2x1 and Maximal Ratio Receiver Combining (MRRC) 1x2 schemes offer similar diversity orders. Alamouti's scheme does not require additional bandwidth or feedback from the receiver to the transmitter. However, the proposed 2x1 antenna system with BPSK modulation yields a 3 dB lower gain compared to the MRRC technique. With 1 and 2 receive antennas, the diversity gains were observed to be 15 dB and 24 dB, respectively, at a BER of 10^-3 in a Rayleigh fading channel.

K. Tiwari and D. S. Saini: They applied Alamouti’s transmit diversity and Maximum Ratio Combining (MRC) receive diversity to improve error performance in MIMO-OFDM systems. They used BPSK, QPSK, and 16-QAM modulation schemes along with Space-Time Block Coding (STBC) to enhance BER performance over fading channels. Their results showed significant BER improvement from an SNR of 0 to 20 dB.

T.V. Luong and Y. Ko: Their investigation focused on BER performance in OFDM-Index Modulation (OFDM-IM) schemes. They employed MRC with Greedy Detector (MRC-GD) and compared it with MRC using Maximum Likelihood (MRC-ML) detection. Their findings indicated that BER results were nearly identical for both detectors under perfect and variable channel state information (CSI), with the number of receive antennas varying from 1 to 8. The BER values ranged from 10^-4 to 10^-2 at SNRs from 0 to 20 dB.

P. Bento et al.: They analyzed BER performance using Phase Shift Keying (PSK) signals obtained through Magnitude Modulation (MM) techniques. Their analytical BER expression, dependent on modulation order and the Kullback–Leibler divergence of the MM factors' PDF from a Gaussian distribution, proved to be very accurate. Their experimental and analytical results showed BER values in the range of 10^-4 to 10^-2 at SNRs from 0 to 18 dB.

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General Observation: Spatially modulated OFDM systems generally exhibit better BER performance compared to other OFDM schemes at lower spectral efficiencies. However, at higher spectral efficiencies, BER performance is notably affected due to the trade-off between spatial diversity and constellation size.
These studies highlight the ongoing advancements and evaluations in MIMO-OFDM systems aimed at improving BER performance across various modulation schemes and configurations.

Peak-to-Average Power Ratio (PAPR) is a significant challenge in Orthogonal Frequency Division Multiplexing (OFDM) systems, as it represents the ratio of peak signal power to average signal power. High PAPR can lead to out-of-band radiation and signal distortions, necessitating the use of highly linear analog devices like Digital-to-Analog Converters (DACs) and Power Amplifiers (PAs). However, managing high PAPR often results in decreased efficiency and degraded Signal-to-Noise Ratio (SNR) if the PA saturates.

To address the PAPR issue, several reduction techniques have been developed. One such technique is the Bayesian approach proposed by H. Bao et al., which employs surplus degrees-of-freedom in the transmit array through an adaptive method that combines Generalized Approximate Message Passing (GAMP) with Expectation-Maximization (EM). This approach reduces computational complexity while enhancing PAPR performance. The EM-GTM-GAMP algorithm achieved a PAPR of 0.8 dB, significantly outperforming traditional methods such as FITRA, Clipping, and Zero Forcing (ZF), which yielded PAPR values of 2.4 dB, 4.3 dB, and 10.6 dB, respectively. Additionally, the Bayesian approach showed improved Symbol Error Rate (SER) performance at lower SNR levels compared to these conventional methods.

Another effective technique is the Enhanced Iterative Clipping and Error Filtering (E-ICEF) and Fast Convolution (FC) processing, introduced by S. Gokceli et al. The E-ICEF algorithm not only minimizes PAPR but also cancels out Inter-Numerology Interference (INI) between different Bandwidth Parts (BWPs) through iterative processes. The FC algorithm performs block-wise PAPR minimization. Both methods demonstrated significant PAPR reduction, with E-ICEF and FC-ICEF achieving PAPR values of 5.2 dB and 5.1 dB, respectively, against a target PAPR of 5 dB. These techniques offer substantial improvements in PAPR reduction while balancing computational complexity and overall system performance.

S. Gökceli et al. proposed a PAPR reduction scheme tailored for frequency-selective fading channels, where clipping noise is controlled and filtered within the transmitter's passband. Their simulation results targeted a PAPR of 6 dB, using QPSK and 16-QAM modulation, and demonstrated that their Iterative Clipping and Error Filtering (ICEF) algorithm effectively reduced PAPR over 1 to 20 iterations. However, the RBMC (Root-based μ-Law Companding) technique, which simultaneously compresses and amplifies OFDM signals, was found to outperform traditional companding methods. For a μ value of 30, the RBMC technique achieved a PAPR of 4.6 dB at a CCDF of 0.01% and maintained a desirable BER performance at 16 dB SNR.

F. Gao et al. introduced a hybrid Partial Transmit Sequence (PTS) model that combines Iterative Partial Transmit Sequence (IPTS) and clipping methods for PAPR reduction. This approach provided superior results compared to conventional PTS and clipping methods separately. Their proposed scheme optimized the PAPR reduction by 1.01 dB and 4.09 dB compared to PTS splicing and IPTS, and by 2.60 dB and 0.08 dB compared to conventional PTS and clipping methods, respectively.

Lahcen Amhaimar et al. developed a PTS scheme integrated with the Firework Algorithm (FWA) to reduce PAPR in MIMO-OFDM systems. The PTS-FWA method achieved improved PAPR performance with minimal computational complexity. Simulation results indicated that PTS-FWA outperformed other methods, including Standard Particle Swarm Algorithm (SPSO), Simulated Annealing (SA), Genetic Algorithm (GA), and Selective Mapping (SLM).

P. Gupta et al. proposed a novel PAPR optimization scheme using Discrete Cosine Transform (DCT) combined with the SLM technique. This SLM-DCT scheme demonstrated significant improvement in PAPR reduction without adversely affecting BER performance. Simulation results, covering various subcarrier numbers and phase sequences, revealed a PAPR gain of 1.35 dB at CCDF values for different phase sequences ranging from 1 to 8.

S.H. Wang et al. introduced a new PAPR reduction technique utilizing frequency-domain phase rotation, cyclic shifting, complex conjugation, and sub-carrier reversal operations to enhance signal diversity. Analytical and experimental results showed that this method significantly reduces PAPR compared to traditional SLM schemes.

K.H. Kim proposed an OFDM-IM multicarrier scheme that employs multi-level dither signals in idle subcarriers to minimize PAPR. By distributing symbol amplitudes variably across different sub-blocks, this method achieved better BER performance than single-level dither signals, with a PAPR of 6 dB at the CCDF level.

B. Tang et al. developed a clipping-noise compression scheme that simplifies the computational process by requiring only one FFT. This approach demonstrated improved PAPR and BER performance relative to conventional Iterative Clipping and Filtering (ICF) methods, achieving a PAPR of 4.5 dB at the

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CCDF and providing BER values within a range of 10 to 15 dB SNR.

4. Conclusions:

This article examines the enhancement of MIMO-OFDM system performance while maintaining system stability and key parameters. Implementing Space-Time Block Codes (STBC), such as the Rate-less Space-Time-Block Code (RSTBC) and Alamouti's scheme, optimizes error rate performance and reduces packet loss and data link degradation. Literature indicates that BER values range from 10−310^{-3}10−3 to 10−510^{-5}10−5 at SNR values between 8 dB and 15 dB. Prominent techniques for PAPR reduction, including Iterative Clipping and Filtering (ICF), Iterative Companding Transform Filtering (ICTF), Partial Transmit Sequence (PTS), Selective Mapping (SLM), and Bayesian approaches, have been evaluated. Among these, the ICF technique remains effective, achieving satisfactory PAPR reduction with minimal impact on BER. MIMO technology proves to be a strong candidate for providing spatial diversity, thereby enhancing Quality of Service (QoS) and system channel capacity. Error rate performance in MIMO-OFDM systems can be significantly improved by adopting various schemes, antenna configurations, and algorithms such as Maximal Ratio Combining (MRC) and Alamouti's scheme. These methods offer better error rates and throughput with fewer antennas at the receiver and transmitter. Specifically, configurations like 2x2 and 2x1 antennas or MRC schemes are highly suitable for improving both BER and PAPR performance, aligning with the requirements of next-generation wireless systems (5G) using 16-QAM or QPSK modulation. Furthermore, using MIMO-OFDM systems with these schemes results in high spectral efficiency (SE) and optimized performance regarding PAPR, BER, and Inter-Symbol Interference (ISI). MIMO antenna configurations, such as 4x1, operate with transmit power in the range of 100 mW to 150 mW per subcarrier and bulk carrier selection. Various configurations, including 2x2, 4x4, 2x1, 1x2, 4x1, and 4x2, are recommended to achieve high throughput, improved SE, and better error rate performance.

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