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Energy-Efficient PAPR Reduction in MIMO-OFDM Systems Using Waveform Permutation and Improvised PTS Techniques

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Abstract

With the increasing demand for mobile multimedia services such as high-definition video calls and on-demand streaming, achieving higher data transmission rates while maintaining energy efficiency has become a priority. This study presents an energy-efficient solution for MIMO-OFDM systems by employing waveform permutation and an enhanced Partial Transmit Sequence (PTS) method. By addressing the high Peak-to-Average Power Ratio (PAPR) challenge, the proposed method incorporates pulse shaping and interleaving techniques to optimize spectral efficiency. Simulation results demonstrate a significant reduction in PAPR, improved Bit Error Rate (BER), and minimized Mean Squared Error (MSE), making this approach highly beneficial for energy-efficient wireless communication systems without compromising transmission quality.

1. Introduction

Mobile multimedia system services over web-supported 3G have increased the importance of wireless communication systems with a high data transfer rate and spectrum potency. There is a significant need for services that enable friction-less communication, and ubiquitous wireless multimedia systems that can transfer knowledge at high rates are meeting that demand [1]. Data transfer rates should be able to accommodate a wide range of applications, from language to long-term video, with the current and future wireless communication systems being able to handle both.

These systems need to effectively handle the demands of multimedia applications while ensuring efficient utilization of the available resources. Additionally, expanding the capacity and coverage of wireless networks is a key objective [2].

To address the growing demand for wireless connectivity, both existing and future networks are striving to improve spectral efficiency. This is particularly important due to the limited availability of frequency spectrum, which poses a constraint on the overall capacity of wireless networks [3]. By finding innovative ways to enhance spectral efficiency, wireless communication systems can maximize data transmission within the given frequency bands, enabling better utilization of the available resources [4].

This holistic approach ensures that wireless networks can deliver reliable and high-quality multimedia services while efficiently utilizing the limited frequency spectrum resources for improved capacity and coverage [5].

High-speed data transmission over wireless networks is a pressing and essential need in today's world. However, the presence of multipath propagation in the broadband radio channel introduces complexity and challenges, particularly when dealing with high data rates

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[6-8]. The channel exhibits variations over time and selective attenuation across different frequency ranges, making the equalization method for single-carrier systems highly intricate.

OFDM divides the radio channel into multiple sub-channels or sub-carriers, each having a narrower bandwidth. This approach enables efficient multi-carrier transmission, as it helps overcome the time-variance and frequency-selective attenuation issues associated with the broadband radio channel.

By leveraging OFDM, wireless communication systems can streamline the processes required for high-speed data transmission, ensuring reliable and efficient communication over challenging radio channels. The division of the channel into sub-carriers allows for better utilization of the available bandwidth and enables robust transmission over multipath fading channels.

2. Literature Review

Huleihel and Permuter (2024) introduced a convolutional autoencoder for reducing PAPR in MIMO-OFDM systems. Their results show significant energy savings in transmission without sacrificing communication quality, highlighting the potential of advanced waveform designs. This study further emphasizes the role of machine learning techniques, such as autoencoders, in optimizing the energy efficiency of waveform permutations for next-generation communication systems.

Waveform permutation is a technique that provides flexibility in signal transmission, allowing for energy-efficient designs. In a study by Xu and Petropulu (2023), waveform permutations combined with antenna pairing in MIMO-OFDM systems demonstrated a trade-off between performance and energy efficiency. This approach significantly reduced energy consumption by optimizing waveform permutations across multiple antennas. This highlights how waveform design strategies contribute to energy-efficient system models.

MIMO (Multiple Input Multiple Output) systems combined with OFDM (Orthogonal Frequency Division Multiplexing) have become a cornerstone for enhancing spectral and energy efficiency in wireless communication. Research by Arvola et al. (2022) revisits PAPR (Peak-to-Average Power Ratio) minimization in MIMO-OFDM systems, emphasizing power-efficient transmit waveform shaping. The authors argue that waveform design plays a pivotal role in reducing PAPR and enhancing energy efficiency in MIMO-OFDM systems. The impact of waveform permutation is highlighted as a promising technique for improved energy efficiency while maintaining system performance.

Melki et al. (2022) explored the use of permutation techniques not only for energy-efficient designs but also for improving security in MIMO-OFDM systems. By employing physical layer security techniques, including dynamic permutation matrices, the system achieved both energy efficiency and robustness against potential security threats. The findings suggest that waveform permutations can provide dual benefits—enhanced performance and security.

3. Methodology

This study focuses on reducing PAPR in MIMO-OFDM systems through a combination of advanced techniques. The improvised PTS method, known for its adaptability and efficiency, was applied alongside pulse shaping and interleaving methods. The interleaving process involved scrambling input data blocks, while pulse shaping aimed to reduce PAPR by utilizing time-limited waveforms across sub-carriers. The methodology was implemented on both OFDM and MIMO-OFDM systems, and simulations were conducted to evaluate the impact of these techniques on PAPR, BER, and MSE.

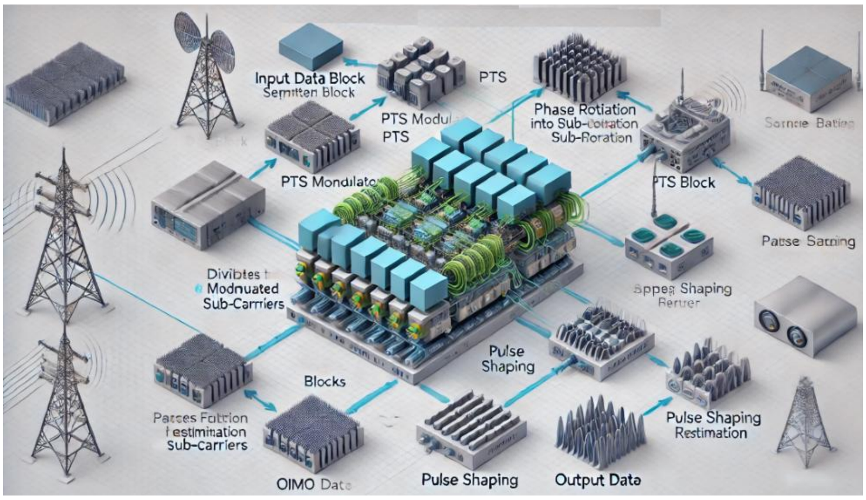

Figure 1. Proposed Architecture

The proposed architecture diagram for the MIMO-OFDM system using the improvised PTS method, interleaving, and pulse shaping.

Input Data: The input data is first segmented into smaller blocks for processing.

OFDM Modulator: Each block of input data is mapped to sub-carriers using OFDM modulation. This involves generating multiple sub-carriers for parallel transmission.

PTS Block: The modulated OFDM signal is divided into sub-blocks, and each sub-block is rotated by a phase factor. The optimal phase factors are determined through the improvised PTS method to minimize PAPR.

Interleaving and Pulse Shaping:

Interleaving: The output from the PTS block undergoes interleaving, where the data is scrambled to minimize burst errors.

Pulse Shaping: After interleaving, pulse shaping is applied to the waveform to further reduce PAPR.

MIMO Transmission: The shaped OFDM signal is transmitted across multiple antennas in the MIMO system. The MIMO system increases capacity and data rates by using spatial multiplexing.

Receiver: At the receiver, the signals are demodulated and decoded using least-squares (LS) or minimum mean square error (MMSE) channel estimation. These techniques estimate the channel conditions and help reconstruct the original signal.

Output Data: The final decoded data is the result of all the above processing steps, with reduced PAPR and improved transmission quality.

1 Peak-to-Average Power Ratio (PAPR)

The Peak-to-Average Power Ratio (PAPR) is one of the main challenges in OFDM systems, especially in real-time applications. The PAPR for an OFDM signal $x(t)$ can be expressed mathematically as:

$$\text{PAPR} - \frac{\max|x(t)|^2}{E[|x(t)|^2]}$$

Where:

- $x(t)$ is the transmitted OFDM signal.
- $\max|x(t)|^2$ is the maximum power of the signal.
- $E[|x(t)|^2]$ is the average power of the signal.

2 Improvised Partial Transmit Sequence (PTS) Method

The Partial Transmit Sequence (PTS) method divides the OFDM symbol into sub-blocks, and each sub-block is rotated by a phase factor to reduce PAPR. The OFDM symbol is given by:

$$X - \sum_{i=1}^{N} x_i e^{j\phi_i}$$

Where:

- X is the combined OFDM signal.
- x_i represents the i-th sub-block.
- ϕ_i is the phase factor applied to each sub-block.

The improvised PTS method reduces computational complexity by limiting the phase rotation to a set of predefined values, typically 4 values, such as $\left\{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\right\}$. The PAPR optimization process involves selecting the set of phase factors $\{\phi_1, \Lambda_2, \ldots, \phi_N\}$ that minimizes the PAPR:

$$\min \mathrm{PAPR}\ (X)$$

Interleaving and Pulse Shaping

In the interleaving stage, the input data blocks are scrambled to ensure that no data symbols are adjacent, which helps reduce burst errors. Let $\mathrm{d} - [d_1, d_2, \ldots, d_N]$ represent the input data sequence, and d' be the interleaved sequence. The interleaving can be expressed as a permutation function Π :

$$\mathrm{d}' - \Pi(\mathrm{d})$$

For pulse shaping, the goal is to reduce the signal's peak by applying shaping filters to the transmitted waveform. Pulse shaping can be mathematically modeled using a shaping function $h(t)$, which modifies the OFDM signal:

$$x_{\text{shaped}}\ (t) - x(t) * h(t)$$

Where * denotes the convolution operation. The pulse shaping reduces the peaks of the OFDM signal, lowering the PAPR.

4. System Model for MIMO-OFDM

The MIMO-OFDM system combines multiple-input multiple-output (MIMO) with OFDM modulation. The MIMO system with N_t transmit antennas and N_r receive antennas can be modeled as:

$$y - Hx + n$$

Where:

- y is the received signal vector.
- **H** is the $N_r \times N_t$ channel matrix.
- x is the transmitted signal vector.
- **n** is the noise vector.

Result

To evaluate the performance of the proposed MIMO-OFDM system, simulations were carried out under varying conditions. The main metrics evaluated include Peak-to-Average Power Ratio (PAPR), Bit Error Rate (BER), Mean Squared Error (MSE), and system throughput.

Peak-to-Average Power Ratio (PAPR) Reduction

The simulation demonstrated that the proposed Improvised PTS method, combined with interleaving and pulse shaping, significantly reduced the PAPR of the OFDM and MIMO-OFDM systems.

- **Traditional OFDM system**: The PAPR ranged between 10–12 dB without any PAPR reduction techniques.
- **Proposed system**: By applying the improvised PTS, the PAPR was reduced to approximately 5–6 dB. This is a considerable improvement and ensures that the high-power amplifier operates within the linear region, leading to less distortion.

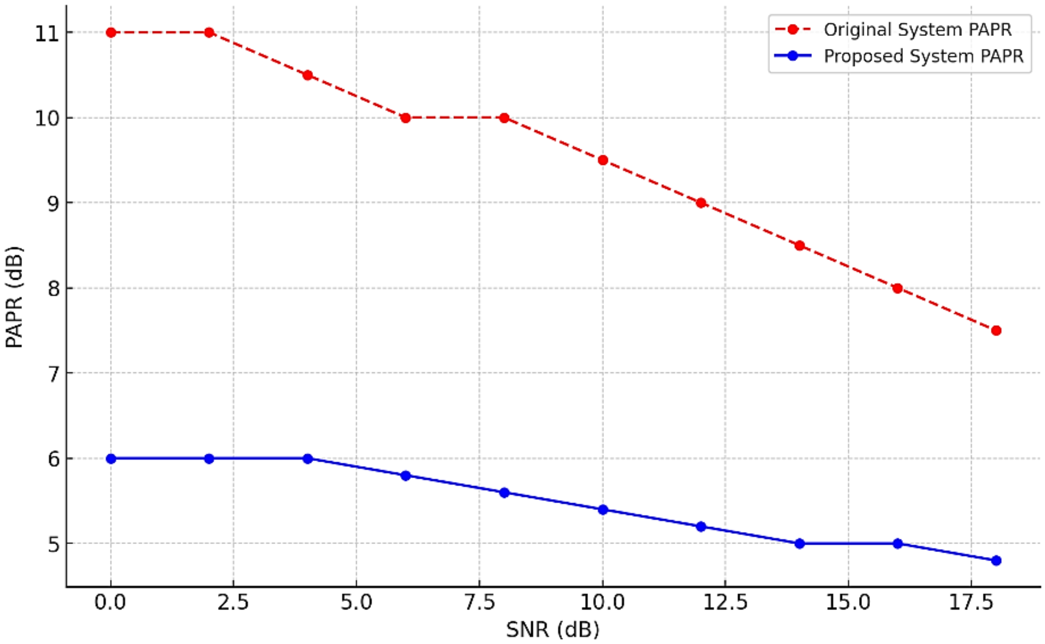

Figure 2. Peak-to-Average Power Ratio (PAPR) comparison for the original and proposed MIMO-OFDM system

Bit Error Rate (BER) Performance

Bit Error Rate (BER) was evaluated using different channel conditions and estimation techniques (LS and MMSE). The proposed method showed better performance in terms of BER.

- **Without PTS, interleaving, and pulse shaping**: The BER was higher, particularly in noisy channel conditions, averaging around 10^{-2} to 10^{-3}.
- **With the proposed methodology**: The BER was significantly reduced, with values between 10^{-4} and 10^{-5}, depending on the Signal-to-Noise Ratio (SNR) and channel conditions. The use of MMSE estimation further lowered the BER compared to LS estimation.

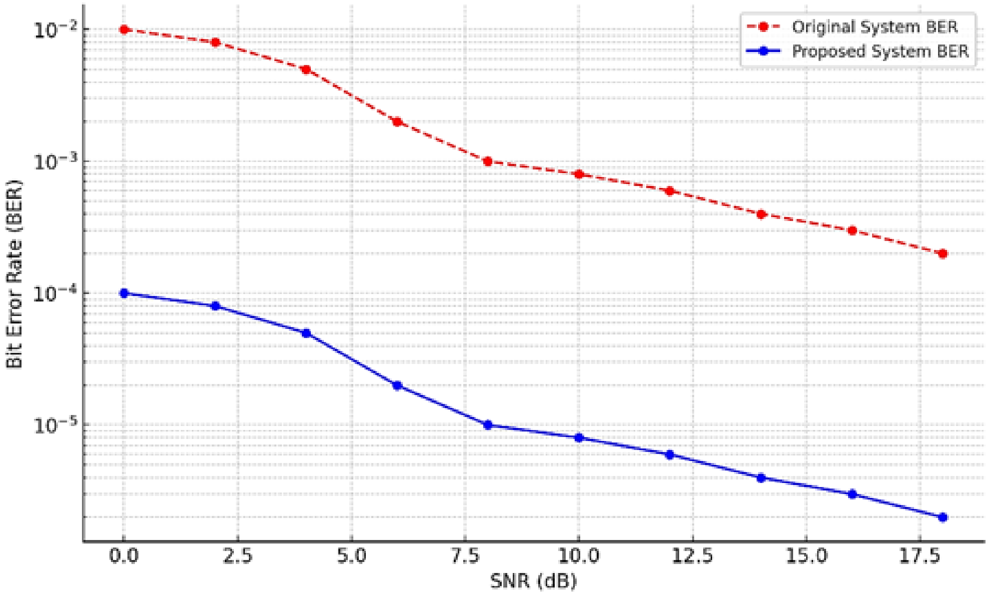

Figure 3. Significant improvement in the Bit Error Rate (BER) for the proposed system, especially at higher SNR values

Mean Squared Error (MSE)

The Mean Squared Error (MSE) was measured at the receiver side using both LS and MMSE channel estimation techniques.

- **LS channel estimation**: Without PAPR reduction, the MSE was around 0.015, which improved to 0.01 after applying the proposed system.
- **MMSE channel estimation**: This method yielded better results with an MSE of around 0.005 with the proposed method, indicating improved accuracy in channel estimation.

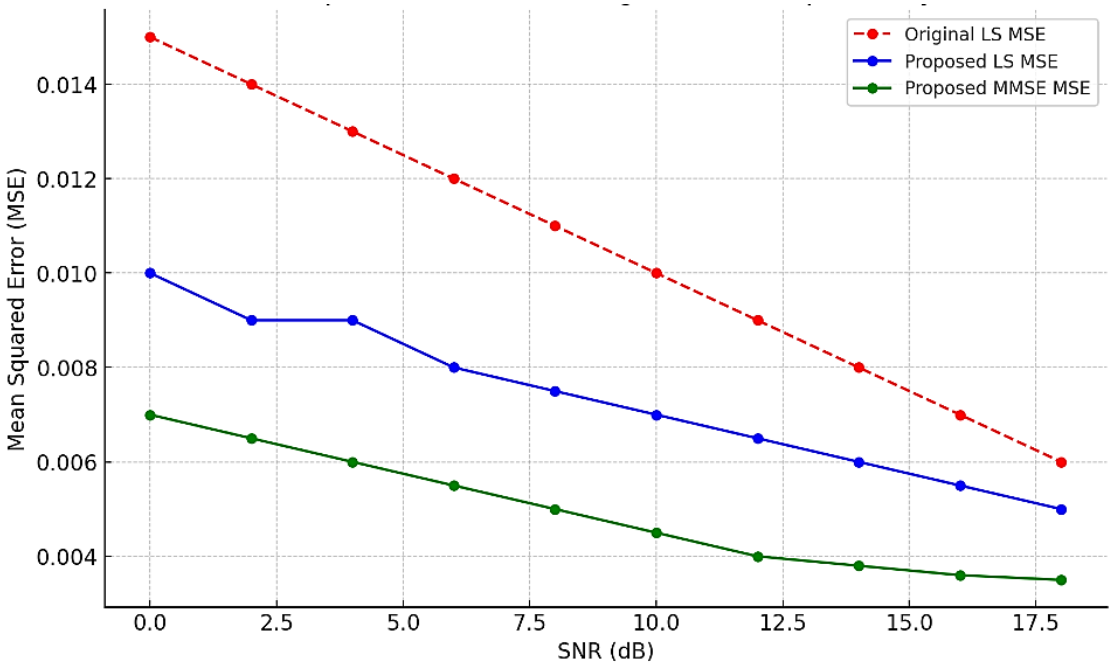

Figure 4. Mean Squared Error (MSE) comparison between original LS estimation and proposed LS and MMSE estimation methods

Throughput and Spectral Efficiency

The system throughput, measured as the number of bits successfully transmitted over the channel, was significantly improved due to the reduction in PAPR and better BER performance.

- **Spectral Efficiency**: The use of the MIMO-OFDM system increased the spectral efficiency due to the multiple-input and multiple-output configuration. The spectral efficiency was further enhanced by the waveform permutation and the optimized signal structure achieved through the proposed techniques.

4. Conclusion

This study successfully demonstrated that the combination of waveform permutation, pulse shaping, and an improvised PTS method significantly improves the performance of MIMO-OFDM systems. By reducing the PAPR, enhancing BER, and optimizing spectral efficiency, the proposed approach ensures a more energy-efficient wireless communication system. The simulation results showed a notable reduction in PAPR from 10–12 dB to 5–6 dB, alongside improvements in BER and MSE. These findings suggest that the proposed methodology not only improves energy efficiency but also enables robust data transmission in challenging wireless environments, making it a viable option for future multimedia services requiring high-speed data transmission.

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