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# Performance Analysis of Combining Beamforming and ZF/ MMSE-SIC Equalization Techniques for MIMO DWPT-COFDM Systems

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**Abstract:** This study explores the enhancement of wireless communication through the integration of OFDM with MIMO and advanced techniques like COFDM, adaptive MIMO, and beamforming. It evaluates a 2×2 and 4×4 MIMO-DWPT-COFDM system, considering modulation (BPSK and QPSK) and equalization (ZF-SIC and MMSE-SIC) over a Rayleigh fading channel. MATLAB results reveal that more antennas, BPSK modulation, and MMSE-SIC equalization significantly improve BER performance. Specifically, for a BER of $10^{-4}$, the 2×2 MIMO system requires $E_b/N_0$ values of 10.4 (MMSE-SIC) and 11.4 (ZF-SIC), while the 4×4 MIMO system needs 5.5 (MMSE-SIC) and 5.9 (ZF-SIC). These findings emphasize the need for thoughtful system design and parameter optimization in achieving reliable and efficient wireless communication.

**Keywords:** MIMO-DWPT COFDM, adaptive modulation, equalization techniques, OFDM systems, Rayleigh fading channel.

## 1. Introduction

The rapid progress in communication is driven by the increasing number of users demanding high-speed data services, necessitating expanded bandwidth [1]. However, wireless communication faces challenges like Inter-Symbol Interference (ISI) and Multi-User Interference (MUI), particularly in high-density user environments [2], [3].

Simultaneously, Orthogonal Frequency Division Multiplexing (OFDM) and its variants like Coded OFDM (COFDM) have gained widespread adoption in wireless networks [4-8]. When coupled with Multiple Input Multiple Output (MIMO) spatial multiplexing, these systems deploy multiple antennas at each end, enhancing capacity and spectral efficiency [9-13]. They rely on the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) algorithms, which have drawbacks, including side-lobes due to a rectangular window and the need for a Cyclic Prefix (CP) to mitigate ISI, consuming 25% bandwidth [14-17].

An alternative approach utilizes the Inverse Discrete Wavelet Packet Transform (IDWPT) and DWPT algorithms, employing Wavelet Packets (WPs) as subcarriers instead of IFFT/FFT, overcoming issues like high Peak-to-Average Power Ratio (PAPR) and bandwidth wastage [18-20], with added improvements possible through antenna diversity techniques [21-23].

Equalization techniques in MIMO and MIMO-OFDM systems, including Zero-Forcing (ZF), Minimum Mean Square Error (MMSE), ZF-Successive Interference Cancellation (ZF-SIC), and MMSE-SIC, have been studied to mitigate ISI and enhance link reliability [24-31]. Spatial signal processing in multiple-antenna wireless devices, like ZF-Beamforming (ZF-BF) and MMSE-Beamforming (MMSE-BF), further enhances system performance [37].

This study focuses on implementing adaptive beamforming in a MIMO-DWPT-based COFDM system, introducing a novel algorithm to reduce ISI, enhance data reliability, and overall system performance through wireless physical layer network coding and ZF/MMSE-SIC equalization. An integrated approach optimizes beamforming weights and equalization filters to mitigate ISI effects from multipath propagation.

## 2. Proposed System Model

The general architecture of the proposed MIMO-DWPT-based COFDM system, incorporating an adaptive beamforming scheme at both the transmitter and receiver, is depicted in *Fig. 1*. This system transmits various signal variations (symbols) from $N_t$ transmitters to $N_r$ receiving antennas via distinct MIMO channels. To counter multi-path fading effects, known pilot symbols are periodically inserted among the transmitted encoded symbols. The OFDM system in this study employs two modulation techniques: Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK). COFDM symbols generated represent orthogonal sub-carrier frequencies, enabling simultaneous transmission of information symbols from different sub-carriers through the transmission channel, which can be flat fading or frequency-selective fading. During this journey, the signals encounter Additive White Gaussian Noise (AWGN) and undergo processing using an *n*-point IDWPT (Inverse Discrete

Wavelet Packet Transform) algorithm [22]. Notably, before this transformation, symbols are multiplied by distinct beamforming coefficients in the time domain, a crucial aspect of the adaptive beamforming scheme. The equivalent model of MIMO transmission is defined as:

$$S_m = \mathcal{Y}_m \cdot \mathcal{H}_m + n_m \qquad (1)$$

where m denotes the number of carriers, $\mathcal{Y}_m \in \mathrm{C}^{N_t \times 1}$ represents the transmitted vector, $\mathcal{H}_m \in \mathrm{C}^{N_r \times N_t}$ signifies the frequency matrix of the channel, $S_m \in \mathrm{C}^{N_r \times 1}$ the received vector and $n_m \in \mathrm{C}^{N_r \times 1}$ the AWGN noise. Since the weights are specific to each antenna and to each carrier, the transmitted signal can be written as:

$$\mathcal{Y}_m = \sum_{m=1,L} b_m \cdot \mathcal{X}_m \cdot g_m \cdot (2 \cdot n - m) \qquad (2)$$

where $b_m \in \mathrm{C}^{N_t \times 1}$ is the broadcast beamforming weight vector and $x_m$ is the complex symbol sent on the sub carrier *m*.

In the proposed system, a configuration of 64 sub-carriers is employed, with Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) modulation applied uniformly across all sub-carriers. This uniformity in constellation choice simplifies signal processing and ensures consistency. The communication channel is modelled as a Rayleigh fading channel, a common representation for wireless environments characterized by multipath propagation and random fading.

Now, let's focus on the receiver side, as depicted in *Fig. 1*. Here, a series of inverse operations is executed to reconstruct the transmitted data. Initially, the received signal is multiplied by the beamforming weights, which were calculated at the transmitter end. Pilot symbols, interspersed within the transmitted signal, are extracted at specific instances to estimate crucial channel parameters. This pilot-based estimation is essential for adapting the equalization and decoding processes to the prevailing channel conditions.

To further enhance signal recovery, the receiver employs an equalization approach, specifically the Minimum Mean Square Error with Successive Interference Cancellation (MMSE-SIC) or Zero-Forcing with Successive Interference Cancellation (ZF-SIC) technique. These methods are vital for mitigating the effects of interference, such as Inter-Symbol Interference (ISI), which is commonly encountered in wireless communication.

Additionally, the received signal undergoes processing using the Inverse Discrete Wavelet Packet Transform (IDWPT) algorithm. This step is instrumental in retrieving the data symbols from the received signal, effectively undoing the wavelet-based modulation applied at the transmitter. The recovered data symbols are subsequently subjected to demodulation and decoding processes to reconstruct the originally transmitted data.

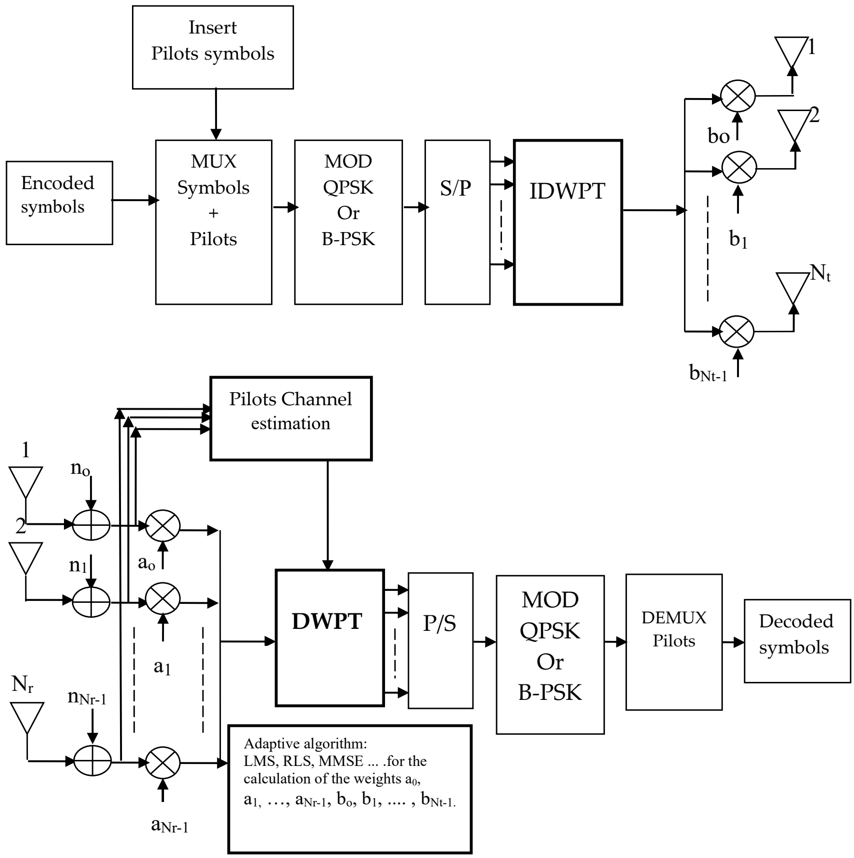


*Figure 1*: Block diagram of the proposed MIMO-DWPT COFDM system with beamforming and MMSE-SIC/ZF-SIC equalizer

By integrating these sophisticated techniques at the receiver, the proposed system is equipped to handle the challenges posed by the wireless channel, ensuring reliable and efficient communication even in the presence of fading and interference. In the upcoming sections, we will delve into the performance evaluation of this system, shedding light on its effectiveness in real-world scenarios.

For MIMO-DWPT COFDM system with adaptive beamforming and ZF-SIC, equalization:

$$SNR_1 = \frac{E\left[\left(\sum_{m=1}^{L-1} a_m^H \cdot b_m \cdot \mathcal{H}_m \cdot W_{ZF-SIC} \cdot \mathcal{X}_m \cdot g_m(0)\right)^2\right]}{E\left[\left(W_{ZF-SIC} \cdot a^H \cdot n\right)^2\right]} = \frac{E\left\{\left|\mathcal{X} \cdot g(0)\right|^2\right\}}{\sigma_n^2} = \frac{P \cdot \mathcal{X}}{\sigma_n^2} \cdot \left|g(0)\right|^2 \quad (3)$$

For MIMO-DWPT COFDM system with adaptive beamforming and MMSE-SIC equalization:

$$SNR_2 = \frac{E\left[\left(\sum_{m=1}^{L-1} a_m^H \cdot b_m \cdot \mathcal{H}_m \cdot W_{MMSE-SIC} \cdot \mathcal{X}_m \cdot g_m(0)\right)^2\right]}{E\left[\left(W_{MMSE-SIC} \cdot a^H \cdot n\right)^2\right]} = \frac{E\left\{\left|\mathcal{X} \cdot g(0)\right|^2\right\}}{\sigma_n^2} = \frac{P \cdot \mathcal{X}}{\sigma_n^2} \cdot \left|g(0)\right|^2 \quad (4)$$

## 3. Results and Discussions

In this section, the authors embark on a comprehensive performance analysis, primarily focusing on the Bit Error Rate (BER), to evaluate the effectiveness of two key equalization techniques: Zero-Forcing with Successive Interference Cancellation (ZF-SIC) and Minimum Mean Square Error with Successive Interference Cancellation (MMSE-SIC). These equalization methods are applied within the context of a MIMO-DWPT COFDM system with beamforming, utilizing Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) modulation schemes. The objective is to assess how these equalization techniques perform under various conditions, including the presence of Additive White Gaussian Noise (AWGN) and a multipath Rayleigh channel, both common challenges in real-world wireless communication scenarios.

To facilitate these performance evaluations, MATLAB simulations are employed, and the key simulation parameters are outlined in *Table 1*. These parameters serve as the foundation for the experiments and analysis, ensuring a consistent and standardized approach to the assessment of system performance.

*Table 1*: Simulation Parameters

| Parameters | Specifications |
|---|---|
| Channel | Rayleigh |
| Beamforming Type | Adaptive |
| Signal Constellation | BPSK-QPSK |
| MIMO | 2×2, 4×4 |
| Convolutional coder | 1/2 |
| Number of sub-carriers | 64 |
| Wavelet package | Haar |

The simulations will provide valuable insights into the robustness and reliability of the proposed MIMO-DWPT COFDM system with adaptive beamforming, shedding light on its ability to maintain low BER rates in the presence of noise and channel impairments. The subsequent analysis of these results will contribute to a deeper understanding of the system's real-world applicability and its potential advantages in various wireless communication scenarios.

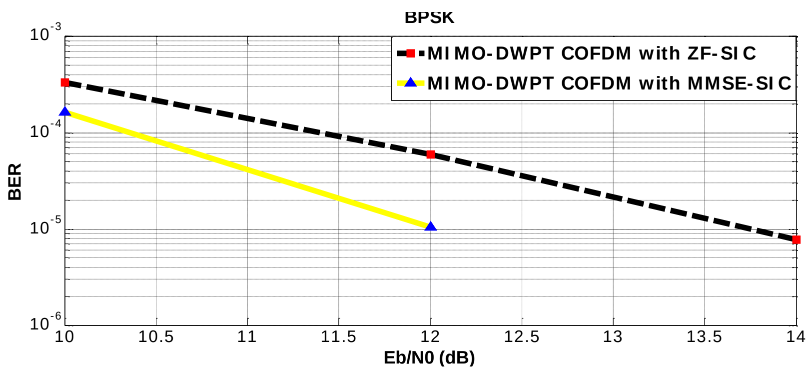


*Figure 2*: BER Performance comparison of ZF-SIC and MMSE-SIC equalization techniques for 2×2 MIMO-DWPT COFDM system with beamforming using BPSK modulation

*Fig. 2* presents the Bit Error Rate (BER) performance of a 2×2 MIMO-DWPT COFDM system with beamforming, utilizing both Zero-Forcing with Successive Interference Cancellation (ZF-SIC) and Minimum Mean Square Error with Successive Interference Cancellation (MMSE-SIC) equalizers. The modulation scheme employed in this evaluation is Binary Phase Shift Keying (BPSK).

The graph in *Fig. 2* offers valuable insights into how the system's BER performance varies under different equalization techniques. It provides a visual representation of how effectively ZF-SIC and MMSE-SIC mitigate interference and noise in the transmission, ultimately impacting the system's ability to maintain a low BER, which is critical for reliable data communication.

By analyzing the BER curves in *Fig. 2*, it is possible to discern which equalization technique performs better under the specific conditions and configurations of the 2×2 MIMO-DWPT COFDM system with beamforming. This information is instrumental in making informed decisions about the choice of equalization method in practical wireless communication applications, where achieving high data reliability is of utmost importance.

The observations from *Fig. 2* indeed underscore the importance of a higher signal-to-noise ratio ($E_b/N_0$) in achieving better Bit Error Rate (BER) performance. Additionally, the analysis reveals that the Minimum Mean Square Error with Successive Interference Cancellation (MMSE-SIC) equalizer consistently outperforms the Zero-Forcing with Successive Interference Cancellation (ZF-SIC) equalizer in terms of BER.

For instance, at an $E_b/N_0$ value of 12 dB, the MMSE-SIC-based system achieves an improved BER of approximately $10^{-5}$, while the ZF-SIC-based system lags slightly behind with a BER of approximately $5\times10^{-5}$. This distinction underscores the superiority of the MMSE-SIC equalization technique, particularly in scenarios where a higher $E_b/N_0$ is available.

To further illustrate the impact of varying the number of transmitting and receiving antennas on the BER performance of the proposed system using MMSE-SIC and ZF-SIC equalizers, *Fig. 3* is presented. This figure showcases the simulation results obtained as the number of antennas is increased from 2 to 4 at both the transmitter and receiver ends.

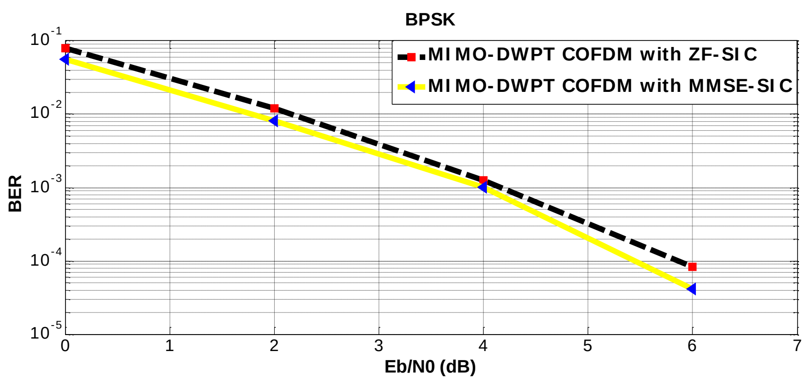


*Figure 3*: BER Performance comparison of ZF-SIC and MMSE-SIC equalization techniques for 4×4 MIMO-DWPT COFDM system with beamforming using BPSK modulation

*Fig. 3* provides a comprehensive view of how the BER performance evolves with changes in antenna configuration. The data gleaned from this analysis will offer valuable insights into the scalability and adaptability of the MIMO-DWPT COFDM system with beamforming when subjected to varying antenna configurations. These insights can guide the design and deployment of such systems in real-world communication scenarios, where the number of antennas may vary based on available resources and specific operational requirements.

The findings from *Fig. 3* affirm that the MMSE-SIC equalization technique outperforms the ZF-SIC equalization technique in terms of BER. Moreover, increasing the number of both transmit and receive antennas has a positive impact on system performance by reducing the bit error rate for both equalization methods. This improvement can be attributed to the ability of a higher number of antennas to mitigate noise, combat fading, reduce interference, and enhance both system throughput and capacity (the number of users the system can support).

Indeed, to achieve a BER of $10^{-4}$, the 2×2 MIMO system employing MMSE-SIC requires an $E_b / N_0$ of 10.4, while the ZF-SIC-based system necessitates an $E_b / N_0$ of 11.4. On the other hand, for the 4×4 MIMO system, the required $E_b / N_0$ values are 5.5 and 5.9 for MMSE-SIC and ZF-SIC, respectively. This comparison highlights the advantage of using a larger number of antennas, as it enables the system to achieve the desired BER performance with lower bit energy requirements. It also underscores the importance of efficiency and high throughput in systems with fewer antennas to support high-capacity applications.

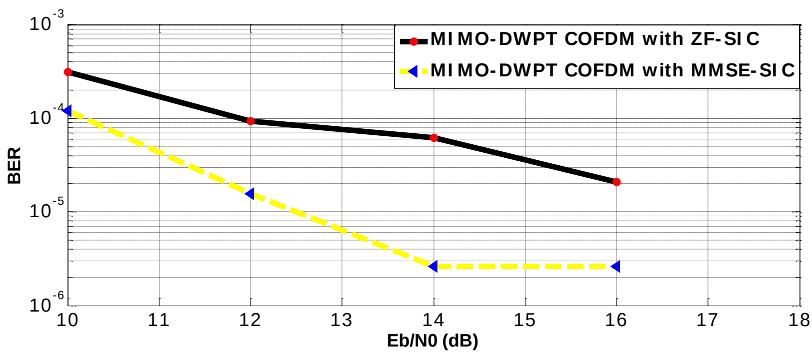


*Figure 4I* BER Performance comparison of ZF-SIC and MMSE-SIC equalization techniques for 2×2 MIMO-DWPT COFDM system with beamforming using QPSK modulation

To further analyze the BER performance of the proposed system, the authors investigated the impact of the modulation technique on system performance with both equalization techniques. *Fig. 4* presents a comparison of the BER performance for the 2×2 MIMO-DWPT COFDM system with beamforming, using QPSK modulation and both ZF-SIC and MMSE-SIC equalizers.

*Fig. 4* demonstrates that the MMSE-SIC equalization technique consistently outperforms the ZF-SIC equalizer, irrespective of the modulation scheme used. At an $E_b / N_0$ value of 12 dB, the system employing QPSK modulation achieves a BER of approximately $9\times10^{-5}$ with ZF-SIC, while the MMSE-SIC-based system boasts a significantly improved BER of approximately $1.6\times10^{-5}$. This outcome underscores the suitability of MMSE-SIC for maintaining low BER rates in wireless communication scenarios, even when more complex modulation schemes like QPSK are employed.

*Fig. 5* provides a detailed view of the impact of increasing the number of antennas on the Bit Error Rate (BER) performance of a MIMO-DWPT COFDM system with beamforming, utilizing both Zero-Forcing with Successive Interference Cancellation (ZF-SIC) and Minimum Mean Square Error with Successive Interference Cancellation (MMSE-SIC) equalization techniques. The modulation technique employed in this analysis is Quadrature Phase Shift Keying (QPSK).

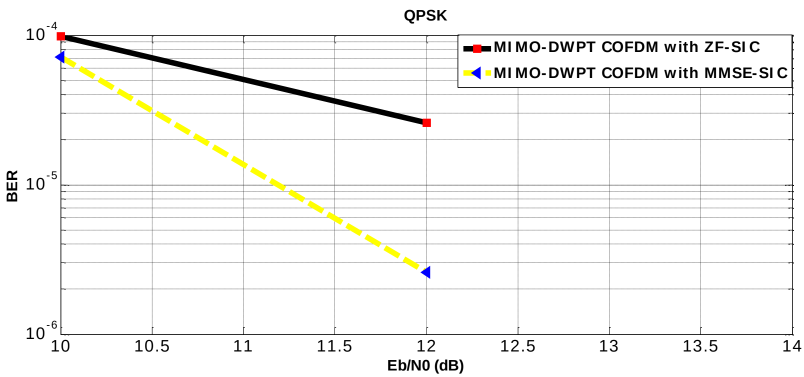


*Figure 5:* BER Performance comparison of ZF-SIC and MMSE-SIC equalization techniques for 4×4 MIMO-DWPT COFDM system with beamforming using QPSK modulation

The findings from *Fig. 5* highlight several key observations:

**1. Antenna Configuration Effect:** Increasing the number of antennas, especially in 4×4 MIMO systems, significantly impacts system performance. MMSE-SIC consistently outperforms ZF-SIC, particularly in configurations with more antennas.

**2. BER Performance at Low** $E_b / N_0$: Both ZF-SIC and MMSE-SIC perform similarly at low $E_b/N_0$ values, with BER curves converging.

**3. Increasing Gap at Higher** $E_b / N_0$: As $E_b / N_0$ increases, MMSE-SIC maintains a substantial performance advantage over ZF-SIC, especially in high signal-to-noise ratio conditions.

At $E_b / N_0$ of 10 dB, ZF-SIC achieves a BER of approximately $9.8\times10^{-5}$, while MMSE-SIC achieves a lower BER of about $7\times10^{-5}$. This performance gap persists at higher $E_b / N_0$ levels, such as 12 dB, where ZF-SIC reaches a BER of roughly $2.6\times10^{-5}$, and MMSE-SIC excels with a BER of approximately $2.6\times10^{-6}$. This indicates a significant 62.4% improvement in BER when transitioning from ZF-SIC to MMSE-SIC.

These results consistently highlight the superiority of MMSE-SIC over ZF-SIC across all scenarios, emphasizing the benefits of higher antenna configurations. Additionally, the study suggests that Binary Phase Shift Keying (BPSK) outperforms Quadrature Phase Shift Keying (QPSK) for both equalization techniques. This insight is valuable for optimizing MIMO-DWPT COFDM systems with beamforming. In summary, these findings offer practical guidance for enhancing wireless communication system performance, considering equalization techniques, antenna configurations, and modulation schemes.

## 4. Conclusion

This study conducted a thorough performance analysis of a MIMO-DWPT COFDM system with adaptive beamforming, considering various modulation schemes and equalization techniques in a Rayleigh fading channel. Key findings include the importance of increased antennas for improved SNR and a BER of $10^{-4}$. BPSK modulation with MMSE-SIC detector proved superior, achieving lower BER at an $E_b / N_0$ of 12 dB. These results highlight the significance of antenna configuration and modulation scheme selection in designing robust MIMO-DWPT COFDM systems for wireless communication.

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