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Performance Analysis of MIMO-OFDM Systems under Different Modulation Schemes and Channel Conditions Using Various Transform Techniques

Eman Alasswi [1,*], Ali abdulgader Mohammed [1], Ali Omar Al-Mathnani[1], Salem Alsaid [2]

[1] Electrical and Electronic Engineering Department, Faculty of Engineering, Wadi Alshatti University, Brack-Libya
[2] Communications and Computer Networks Department, Faculty of Information Technology, Sebha University, Sebha, Libya

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ABSTRACT

MIMO-OFDM, a combination of Multiple Input Multiple Output and Orthogonal Frequency Division Multiplexing, offers high data rates and improved spectral efficiency for wireless communications. This study evaluates MIMO-OFDM performance in digital image transmission using modulation schemes such as BPSK, QPSK, 16-QAM, 64-QAM, and 128-QAM under AWGN, Rayleigh, and Rician channels. Signal transforms including FFT, DWT, DCT, and DFT are applied to enhance robustness and reduce distortion. System performance is assessed based on Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR). Results show BPSK achieves lowest BER in all conditions, making it ideal for noisy environments, while higher-order QAM schemes yield higher throughput with increased BER at low SNR. DWT-based systems perform best in minimizing BER and preserving image quality. These results highlight the importance of selecting optimal modulation and transform techniques to balance data rate and reliability. Future work may explore adaptive modulation and hybrid transforms to improve performance in dynamic conditions.

تحليل أداء أنظمة MIMO-OFDM تحت تأثير تقنيات تعديل مختلفة وظروف قنوات متنوعة باستخدام تقنيات تحويل متعددة

إيمان العيساوي [1]،*، علي عبدالقادر محمد [1]، علي عمر المتناني [1]، سالم الصيد [2]

الكلمات المفتاحية:

نظام MIMO-OFDM
تقنيات التعديل
ظروف القناة
تقنية التحويل
معدل خطأ البتات (BER)

الملخص

يُعد نظام MIMO-OFDM، الذي يجمع بين تقنية الهوائي المتعدد (MIMO) وتقسيم التردد المتعامد (OFDM)، من الحلول الواعدة لتحقيق معدلات نقل بيانات عالية وكفاءة طيفية محسّنة في الاتصالات اللاسلكية. تهدف هذه الدراسة إلى تقييم أداء هذا النظام في نقل الصور الرقمية باستخدام أنماط تعديل مثل BPSK وQPSK وQAM-16 وQAM-64 و128-QAM، وذلك تحت ظروف قناة لاسلكية مختلفة تشمل AWGN، ورايلي، وريسيان. كما تم استخدام تحويلات إشارة مثل FFT وDWT وDCT وDFT لتحسين مقاومة الإشارة وتقليل التشوه. تم تقييم الأداء من خلال معدل الخطأ في البتات (BER) مقابل نسبة الإشارة إلى الضوضاء (SNR). أظهرت النتائج أن BPSK يحقق أقل BER في جميع الظروف، مما يجعله مناسبًا للبيئات المليئة بالضوضاء، بينما توفر أنظمة QAM عالية الترتيب معدل نقل أعلى على حساب BER مرتفع في الظروف ذات SNR المنخفض. وقد تفوق استخدام DWT في تقليل BER وتحسين جودة إعادة بناء الصورة. توضح النتائج أهمية اختيار التعديل والتحويل المناسب لتحقيق التوازن بين معدل البيانات وموثوقية الإرسال.

Introduction

In recent decades, wireless communication technology has experienced significant advancements to meet the growing demand for higher data rates and improved spectral efficiency. MIMO-OFDM systems have emerged as a promising solution, combining MIMO (Multiple Input Multiple Output) technology, which increases channel capacity by utilizing multiple antennas, and OFDM (Orthogonal Frequency Division Multiplexing), which mitigates inter-symbol interference and enhances spectral efficiency [1].

MIMO-OFDM systems are highly effective in addressing challenges posed by wireless channels, such as multipath fading and interference. Transform techniques like FFT, DWT, DCT, and DFT play a crucial role in improving system performance by enhancing signal processing and reducing the Bit Error Rate (BER) under various channel conditions, including AWGN, Rayleigh, and Rician [2].

In wireless communication, modulation schemes play a crucial role in determining the efficiency and robustness of the system. Despite the significant progress in MIMO-OFDM technology, further research is needed to understand the impact of different modulation schemes (BPSK, QPSK, and QAM) on system performance under different channel conditions. In addition, selecting the most appropriate conversion technique, modulation type, and appropriate

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*Corresponding author

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channel remains a challenge to achieve a balance between performance, data rate, spectral efficiency, and reliability.

This paper aims to analyze the performance of MIMO-OFDM systems under various modulation schemes (BPSK, QPSK, 16-QAM, 64-QAM) using different transform techniques, aiming to evaluate the impact of diverse channel conditions on system performance. The system performance will be evaluated by analyzing the BER as a function of different SNR levels, providing valuable insights for optimizing wireless communication system configurations.

The paper provides a review of related work, followed by a description of the mathematical model of the proposed system. After that, the simulation setup and results are discussed before concluding with the conclusions and recommendations for future research.

Related Work

The MIMO-OFDM systems has been extensively studied due to their significant advantages in wireless communication. Researchers have investigated various aspects of these systems, including modulation schemes, channel conditions, transform techniques, and performance optimization. This section reviews some of the key studies that have contributed to the development of MIMO-OFDM systems

For instance, Agboje et al. (2017) conducted a comparative analysis of MIMO-OFDM systems employing Discrete Wavelet Transform (DWT) versus the conventional Discrete Fourier Transform (DFT) for multicarrier modulation. The study evaluated system performance in terms of Bit Error Rate (BER) under Additive White Gaussian Noise (AWGN) and Rayleigh fading channels. Simulations were performed using modulation schemes such as 8-QAM and QPSK.

The results demonstrated that DWT-based MIMO-OFDM systems outperformed DFT-based counterparts by eliminating the need for a cyclic prefix, thereby enhancing spectral efficiency. Furthermore, the DWT-based system exhibited superior BER performance across various MIMO configurations, including 2×2 setups, highlighting its effectiveness in mitigating channel impairments while maintaining bandwidth efficiency [3].

Onebunne et al. developed a MIMO-OFDM system utilizing Discrete Wavelet Transform (DWT) for multicarrier modulation, contrasting its performance with the traditional Discrete Fourier Transform (DFT). The system's performance was evaluated in terms of Bit Error Rate (BER) under Additive Gaussian White Noise (AGWN) and Rayleigh flat fading channels using Binary Phase Shift Keying (BPSK). The results demonstrated that DWT-based systems achieved superior BER performance compared to DFT-based systems, eliminating the need for cyclic prefix and thereby enhancing spectral efficiency. Additionally, configurations such as 2×1, 2×2, and 2×3 MIMO systems were analyzed, revealing significant BER reductions in DWT-based schemes [4].

Waliullah et al. analyzed the BER performance of OFDM systems using modulation schemes such as BPSK, QPSK, 4-QAM, 8-QAM, and 16-QAM over AWGN, Rayleigh, and Rician channels. Their study demonstrated that the AWGN channel outperforms others with the lowest BER across all modulation techniques, with BPSK consistently showing superior performance. The research also explored image transmission via the AWGN channel and established that BPSK provides the best image quality due to its minimal BER. The simulations were performed using MATLAB, highlighting the effectiveness of AWGN and BPSK in OFDM systems for both data and image transmission [5].

MIMO-OFDM Technique

MIMO (Multiple Input Multiple Output) and OFDM (Orthogonal Frequency Division Multiplexing) are two powerful techniques widely used in modern wireless communication systems. Together, MIMO-OFDM provides enhanced capacity, robustness, and efficiency, especially in high-speed communication environments like 4G, 5G, and Wi-Fi.

MIMO (Multiple Input Multiple Output) System

The evolution of wireless communication technologies has driven advancements in antenna configurations to meet the growing demand for higher data rates and enhanced channel capacity. Traditional Single Input Single Output (SISO) systems have evolved into more complex setups like Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and, notably, Multiple Input Multiple Output (MIMO) systems. MIMO technology, utilizing multiple antennas at both the transmitter and receiver as illustrated in “Fig. 1”, leverages multipath propagation to improve signal robustness, increase data capacity, and enhance overall system performance.

MIMO systems implement spatial multiplexing, allowing signals to be transmitted across distinct spatial channels, thereby optimizing data throughput and hand-off processes. By combining transmit diversity and receive diversity, MIMO systems integrate the advantages of SIMO and MISO configurations, resulting in higher data rates and improved error performance. However, a critical trade-off exists between spatial multiplexing gain, which increases data rates, and diversity gain, essential for mitigating channel fading.

Diversity techniques in MIMO systems, such as spatial multiplexing, enhance reliability by transmitting the same information over multiple independent paths. This reduces the impact of fading and ensures robust signal reception. careful management of the diversity-multiplexing trade-off is essential to optimize hand-off processes for reliability and speed.[6,7]

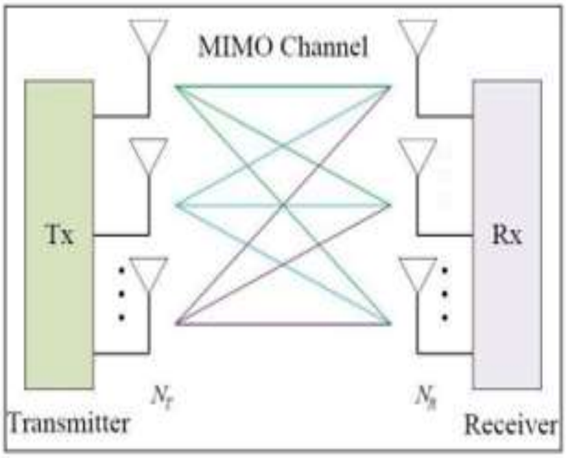

Fig. 1: $N_T \times N_R$ MIMO System Model

OFDM (Orthogonal Frequency Division Multiplexing)

Orthogonal Frequency Division Multiplexing (OFDM) is a technique of coding digital signal data on many carrier frequencies which are all orthogonal to one another. Orthogonal means that all the signals in the sub-carriers are not related to each other In modern communication, there is a need for high-speed data transmission, not just for speech and control data but also for real-time images. To prevent inter-symbol interference (ISI), it is necessary for the symbol duration to surpass the delay time. Long symbol periods reduce the data rate, resulting in inefficient communication. Frequency Division Multiplexing (FDM) divides the available spectrum bandwidth into sub-bands. Closely spacing carriers increase the data rate. Inter-carrier interference results from insufficient carrier spacing. Guard bands must be placed between adjacent carriers to prevent data lowering inter-carrier interference (ICI). The basic idea behind these systems is to split the entire bandwidth into smaller sub-bands while maintaining orthogonally. Orthogonal Frequency Division Multiplexing (OFDM) divides a channel into many overlapping sub-channels as shown in Figure 2. No sub-channel guard band. OFDM has orthogonal sub-channels. This band split reduces Inter Symbol Interference (ISI) when using wide-band broadcasts in frequency selective channels [5,9,10].

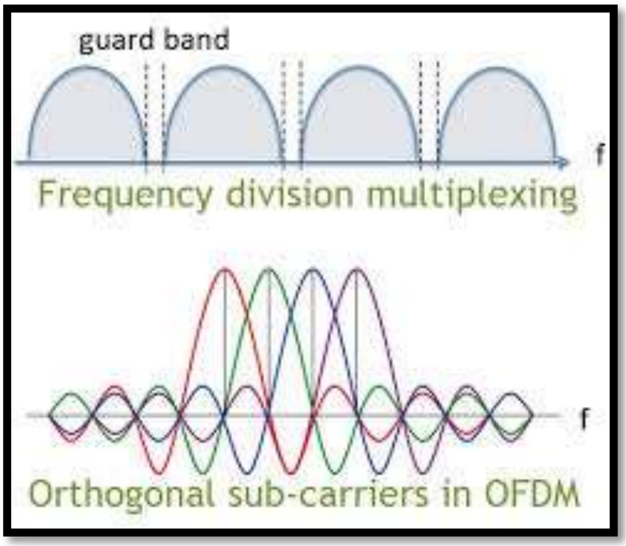

Fig 2: The spectrum of OFDM signals

OFDM is the best solution for 5G mobile communications. WiMAX, DAB, and DVB use it. OFDM provides several advantages, including enhanced data transmission speed, reduced vulnerability to selective fading, simplified channel equalization, and resilience against both co-channel interference and sudden bursts of noise. However, OFDM can be sensitive to co-channel interference and phase instability.

“Fig. 3” represents the block diagram of OFDM system, consist of transmitter and receiver. The data bits inserted are firstly mapped using different modulation techniques and it is converted from serial to parallel through convertor. Now N subcarriers are present and each sub-carrier consists of data symbol. These N subcarriers are generated by inverse fast Fourier transform (IFFT) block. The output of IFFT block is written as

$$f(n) = \sum_{k=0}^{N-1} f(k)\, exp(\frac{j2\pi kn}{N}) \qquad (1)$$

Cyclic Prefix (CP) is added to the output of the IFFT block in order to mitigate the Inter symbol interference. After adding CP, the signal is sent to parallel to serial convertor and then, this signal is sent to either Rayleigh channel or AWGN channel. At the receiver, the data is converted to parallel by using serial to parallel convertor and cyclic prefix is removed. After removing the CP, the received samples are sent to a Fast Fourier transform (FFT) block to demultiplex the multi-carrier signals. The output of FFT block is given as

$$f(n) = \sum_{k=0}^{N-1} f(n)\, exp(\frac{j2\pi kn}{N}) \qquad (2)$$

$$0 \le k \le N-1$$

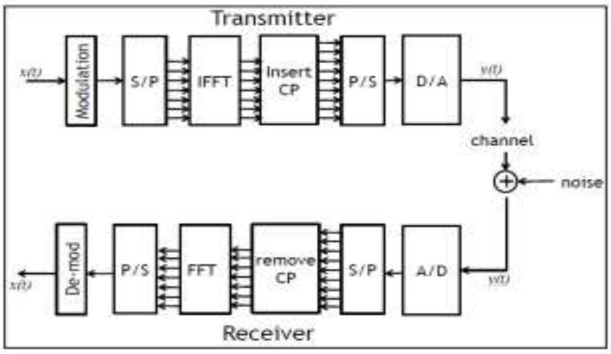

Fig 3: Basic Block Diagram of an OFDM System

MIMO – OFDM System

The combination of MIMO and OFDM is particularly powerful in modern wireless communication systems. MIMO enhances data throughput through spatial multiplexing, while OFDM ensures efficient spectrum use and combats channel impairments such as multipath fading.[5, 8]

The MIMO-OFDM systems can send multiple data streams in parallel over different spatial channels. Each subcarrier in the OFDM system can carry a portion of the data stream, and different antennas transmit the data simultaneously as shown in “Fig. 4”. MIMO offers diversity gain by utilizing multiple antenna paths to combat fading and interference. This is particularly useful in environments with high multipath propagation. By combining spatial diversity from MIMO with the orthogonality of OFDM, MIMO-OFDM systems can achieve high data rates with robust performance even in challenging channel conditions. In MIMO-OFDM systems, Channel State Information CSI is essential for optimal performance. The transmitter uses this information to adjust the transmission power and data rate according to the quality of the channel.

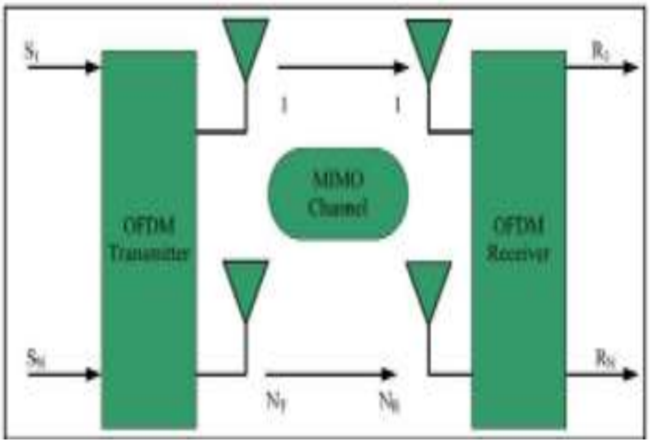

Fig 4: MIMO – OFDM System

Methodology

The methodology for conducting a comparative study of modulation schemes in MIMO-OFDM systems, under various transform techniques and channel conditions, can be broken down into several key steps. Each step focuses on a specific aspect of the study to ensure a thorough and systematic analysis.

MIMO – OFDM System Design and Setup

The MIMO – OFDM system is modeled using MATLAB and is shown in Fig. 4 the Simulation of the OFDM System is firstly done then the MIMO-OFDM System Setup is done by Define the number of antennas for MIMO (e.g., 2x2, 4x4, 8x8) . In the OFDM system the data to be transmitted on each carrier is the baseband signals are Generated for each modulation scheme (BPSK, QPSK, 16-QAM, 64-QAM) and map the data onto the subcarriers in the OFDM system. The serial data stream is formatted into the word size required for transmission and shifted into a parallel format. Zero padding has used in our system to increase sampling rates for better resolution of signals. Apply the IFFT (Inverse Fast Fourier Transform) to convert the data from frequency domain to time domain.in order to get the corresponding time waveform. then Insert cyclic prefix (CP) to mitigate inter-symbol interference (ISI) caused by multipath where the guard period is added to the start of each symbol. After the guard has been added, the symbols are then converted back to a serial time waveform. This is then the base band signal for the OFDM transmission.

A channel model is then applied to the transmitted signal. This research use different channel conditions, such as: AWGN (Additive White Gaussian Noise) which is considers as ideal for simulating a noise-free environment, and Rayleigh Fading which is considers as common in urban environments with multipath propagation and Rician Fading Models environments with a line-of-sight component along with scattered signals. The model allows for the signal to noise ratio (SNR). The SNR is set by adding a known amount of white noise to the transmitted signal.

The receiver basically does the reverse operation to the transmitter. In the receiving side, the model recovers the input data, and performs an analysis to determine the transmission error rate. Table 1 represents the OFDM system parameters used for the simulation.

Table 1 Simulation parameters for MIMO-OFDM system

Parameters	Specifications
Data	Image"baboon'png'
Modulation	PSK (M=2,4,8,16) QAM(M=16,64,128)
Channel model	Rayleigh, AWGN, Rician
No. of Tx, No. Of Rx	2,2
Transform types	FFT,DWT,DCT,DFT
CP length	16
Number of subcarriers	64
SNR values	0:20

In this research , the MIMO-OFDM System Setup will be as following:

- Define the number of antennas for MIMO (e.g., 2x2, 4x4).
- Then Specify the number of subcarriers in the OFDM system (e.g., 64, 128).
- Choose different modulation schemes for the comparison (BPSK, QPSK, 16-QAM, 64-QAM).
- Implement various transform techniques (FFT, DWT, DCT) to evaluate their effect on performance.
- Use different channel conditions, such as:AWGN, Rayleigh Fading and Rician Fading.

Performance Metrics and Evaluation

in order to evaluate the performance of the MIMO – OFDM system, the following evaluation criteria are used

Bit Error Rate (BER)

This criterion measures the error rate in terms of the number of incorrectly received bits. The BER can be translated into a simple formula:

BER = number of errors / total number of bits sent (3)

Signal to Noise Ratio (SNR)

The SNR is the ratio of the received signal strength over the noise strength in the frequency range of the operation. It is an important parameter of the physical layer of Local Area Wireless Network (LAWN). Noise strength, in general, can include the noise in the environment and other unwanted signals (interference). BER is inversely related to SNR, that is high BER causes low SNR. High BER causes increases packet loss, increase in delay and decreases throughput. The exact relation between the SNR and the BER is not easy to determine in the multi-channel environment[10]. Signal to noise ratio (SNR) is an indicator commonly used to evaluate the quality of a communication link and measured in decibels and represented by the formula:

$$\text{SNR} = 10\ log_{10}\ (\text{Signal Power/Noise Power}) \qquad (4)$$

MIMO-OFDM Simulation Results and Dissection

The simulation model accepts inputs as image data file. The channel simulation allows examination of common wireless multipath channel characteristics such AWGN ,Rayleigh fading and Rician Fading channel with various of the various transform techniques (FFT, DWT, DCT) and different modulation schemes (BPSK, QPSK, 16-QAM, 64-QAM) for the comparison.

In this section, the effect of changing modulation and transform techniques on data transmission in different channels will be tested and discusses as follows:

The analysis of “Fig. 5.a - 5.c” presents the Bit Error Rate (BER) performance of a MIMO-OFDM system under different modulation schemes across three channel conditions (AWGN, Rayleigh, and Rician Fading) using the FFT transform technique. The results indicate that BPSK and QPSK achieve the lowest BER across all Signal-to-Noise Ratio (SNR) values, demonstrating high robustness against noise interference, with BPSK being the most resilient due to its low power requirement. As the modulation order increases (8PSK, 16PSK, 16QAM, 64QAM, and 128QAM), BER performance degrades, requiring higher SNR to achieve the same level of reliability. Higher-order QAM schemes offer improved spectral efficiency but suffer from increased BER, particularly in low and moderate SNR regions, with 128QAM exhibiting the highest error rate due to its high sensitivity to noise. The AWGN channel “Fig. 5.a” provides the best performance, as it represents an ideal noise-limited scenario, whereas the Rayleigh fading channel “Fig. 5.b” introduces multipath fading effects, leading to increased BER, especially for higher-order modulations. In the Rician fading channel “Fig. 5.c”, the presence of a strong line-of-sight (LOS) component improves performance compared to Rayleigh fading, but higher-order modulations still exhibit a significant BER. Overall, BPSK and QPSK remain the most reliable across all conditions, while higher-order modulation schemes require higher SNR levels to achieve acceptable error performance.

The simulation results demonstrate that the Bit Error Rate (BER) is significantly influenced by the modulation scheme and the Signal-to-Noise Ratio (SNR) when using the DWT transform technique. In the AWGN channel “Fig. 6.a”, BPSK exhibits the lowest BER, highlighting its superior terms of noise robustness in OFDM systems. Similarly, in the Rayleigh channel “Fig. 6.b”, BPSK achieves the best performance with the lowest BER curve, followed by QPSK, while higher-order modulations such as 8PSK and 16PSK suffer from increased BER due to their tighter symbol spacing, making them more susceptible to interference. QAM-based modulations require a significantly higher SNR to achieve acceptable BER levels, with 128QAM performing the worst, followed by 64QAM and 16QAM. In the Rician channel “Fig. 6.c”, BPSK maintains strong performance even at low SNR levels (0–2 dB), while QPSK demonstrates a gradual BER improvement as SNR increases. Conversely, higher-order modulations like 16PSK and 128QAM demand an SNR above 15 dB to reach an acceptable BER, making them less efficient in noisy conditions. These findings emphasize the importance of selecting an appropriate modulation scheme based on the trade-off between noise resilience and data transmission rate, as higher-order modulations offer increased data rates but at the expense of higher BER in low-SNR environments.

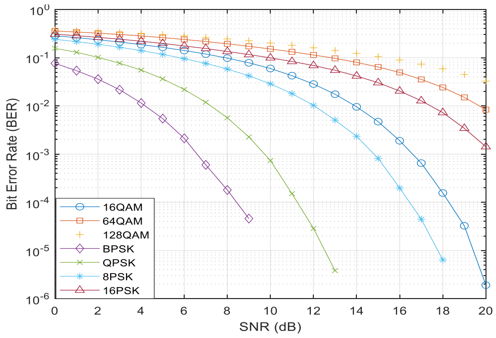

Fig. 5.a :BER Performance of MIMO-OFDM with Different Modulation Schemes in AWGN Channel Using FFT Transform

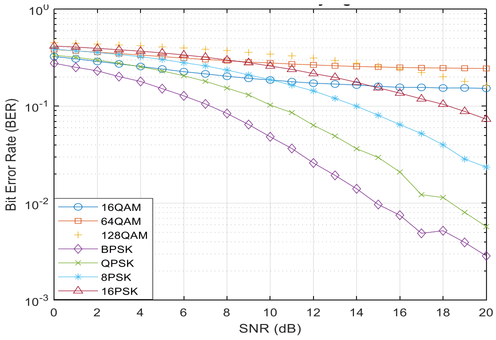

Fig.5.b: BER Performance of MIMO-OFDM with Different Modulation Schemes in Rayleigh Fading Channel Using FFT Transform

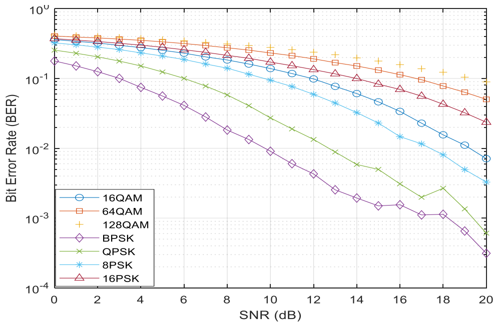

Fig.5.c : BER Performance of MIMO-OFDM with Different Modulation Schemes in Rician Fading Channel Using FFT Transform

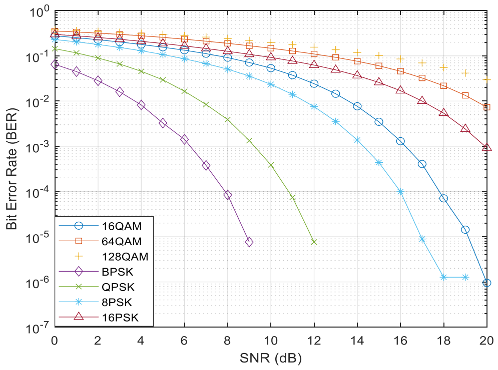

Fig. 6.a: BER Performance of Different MIMO-OFDM Modulation Schemes in AWGN Channel Using the DWT Transform Technique.

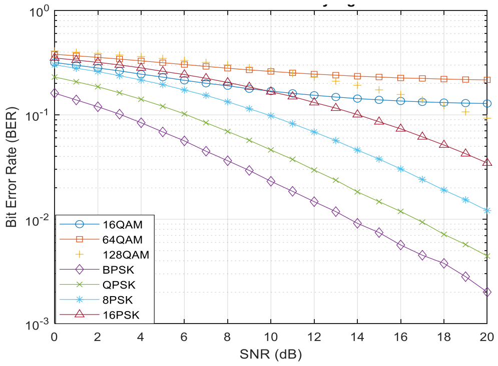

Fig. 6.b: BER Performance of Different MIMO-OFDM Modulation Schemes in Rayleigh Channel Using the DWT Transform Technique

The simulation results demonstrate that the Bit Error Rate (BER) is significantly affected by the modulation scheme and Signal-to-Noise Ratio (SNR) when using the DCT Transform Technique. In the AWGN channel “Fig.7.a”, BPSK achieves the lowest BER (~10^{-4} at SNR = 8 dB), demonstrating high noise resilience. QPSK follows with a BER of approximately 10^{-3} at the same SNR, while 8PSK and 16PSK show higher BER values around 10^{-2}, indicating lower resistance to noise. QAM-based modulations (16QAM, 64QAM, 128QAM) degrade in performance, with 128QAM exhibiting the worst BER (~10^{-1} at SNR = 8 dB), highlighting its high sensitivity to noise.

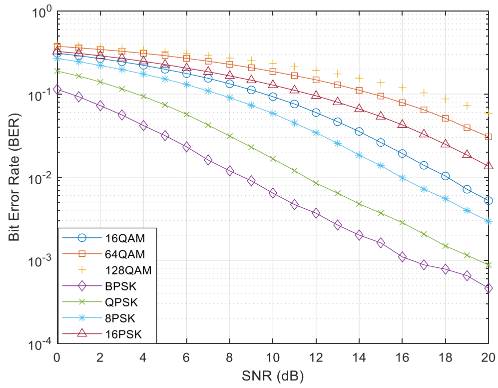

Fig. 6.c: BER Performance of Different MIMO-OFDM Modulation Schemes in Rician Channel Using the DWT Transform Technique.

In the Rayleigh channel “Fig.7.b”, BPSK maintains the lowest BER ($\sim10^{-3}$ at SNR = 10 dB), making it ideal for noise-prone environments. QPSK shows a slightly higher BER ($\sim10^{-2}$ at the same SNR), balancing data rate and noise tolerance. Higher-order modulations like 8PSK and 16PSK require an SNR of at least 12–15 dB to reach a BER below 10^{-2}, while 16QAM, 64QAM, and 128QAM exhibit even higher BER, with 128QAM exceeding 10^{-1} at SNR < 10 dB, indicating that these schemes require significantly higher SNR for reliable performance.

In the Rician channel “Fig.7.c”, BPSK again demonstrates superior performance, achieving a BER of $\sim10^{-4}$ at SNR = 10 dB, whereas QPSK achieves a BER of $\sim10^{-3}$ at the same SNR. Higher-order QAM schemes (16QAM, 64QAM, 128QAM) exhibit increased BER, with 128QAM requiring an SNR above 18 dB to achieve a BER of 10^{-3}. Similarly, 8PSK and 16PSK struggle with noise, maintaining a BER above 10^{-2} at SNR < 12 dB.

These results emphasize the critical trade-off between noise resilience and data transmission rate: lower-order modulations like BPSK and QPSK provide better BER at lower SNR, making them suitable for noisy environments, while higher-order modulations (QAM, PSK) enable higher data rates but demand significantly higher SNR to maintain acceptable error performance.

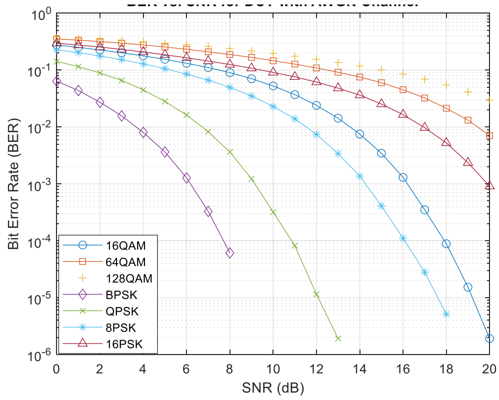

Fig.7.a: BER Performance of MIMO-OFDM with Different Modulation Schemes in AWGN Channel Using DCT Transform

The simulation results illustrate the impact of different modulation schemes on the Bit Error Rate (BER) under varying channel conditions using the DFT Transform Technique. In the AWGN channel “Fig.8.a”, BPSK achieves the lowest BER ($\sim10^{-4}$ at SNR = 8 dB), confirming its robustness against noise. QPSK follows with a BER of approximately 10^{-3}, while 8PSK and 16PSK show BER values around 10^{-2}, indicating lower resistance to noise. Higher-order QAM modulations (16QAM, 64QAM, 128QAM) exhibit increased BER, with 128QAM showing the worst performance ($\sim10^{-1}$ at SNR = 8 dB), highlighting its high sensitivity to noise.

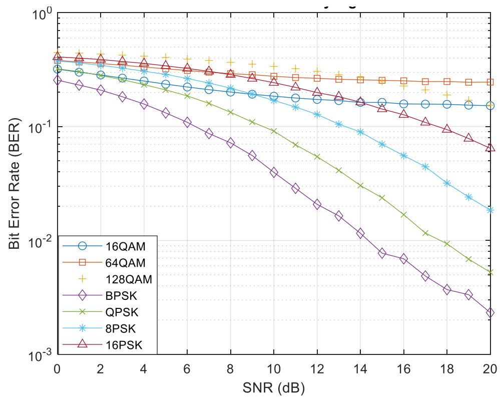

Fig.7.b: BER Performance of MIMO-OFDM with Different Modulation Schemes in Rayleigh Fading Channel Using DCT Transform

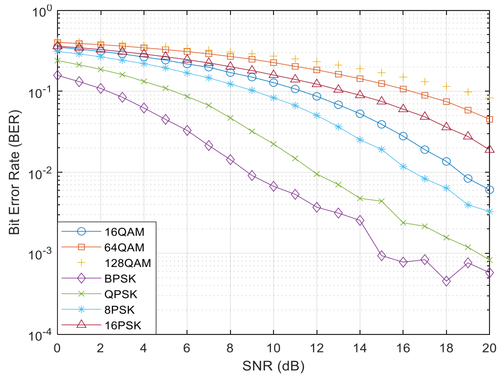

Fig.7.c: BER Performance of MIMO-OFDM with Different Modulation Schemes in Rician Fading Channel Using DCT Transform

In the Rayleigh channel “Fig.8.b”, BPSK maintains superior performance with a BER of $\sim10^{-3}$ at SNR = 8 dB, making it highly suitable for noise-prone environments. QPSK exhibits a slightly higher BER ($\sim10^{-2}$), while 8PSK and 16PSK maintain values above 10^{-2}, reflecting their reduced noise resilience. QAM-based modulations (16QAM, 64QAM, 128QAM) perform significantly worse, with 128QAM exceeding 10^{-1} at SNR = 8 dB, demonstrating the increased SNR requirements for reliable communication.

In the Rician channel “Fig.8.c”, BPSK again achieves the lowest BER ($\sim10^{-4}$ at SNR = 8 dB), followed by QPSK with a BER of approximately 10^{-3}. Higher-order modulations like 8PSK and 16PSK show BER values above 10^{-2}, indicating their increased susceptibility to noise in such conditions. For QAM schemes, 16QAM performs better than 64QAM and 128QAM, but 128QAM still exhibits a BER above 10^{-1}, confirming its inefficiency in low-SNR environments.

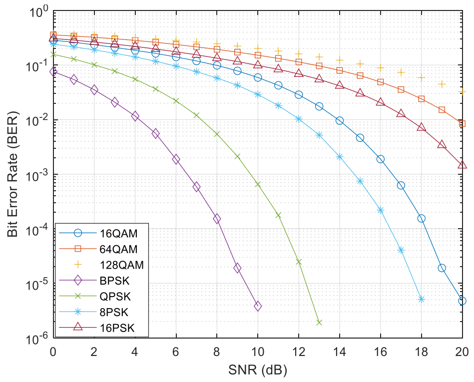

Fig.8.a: BER Performance of MIMO-OFDM with Different Modulation Schemes in AWGN Channel Using DFT Transform

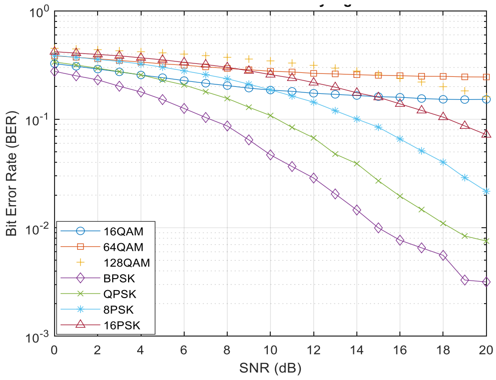

Fig.8.b: BER Performance of MIMO-OFDM with Different Modulation Schemes in Rayleigh Fading Channel Using DfT Transform

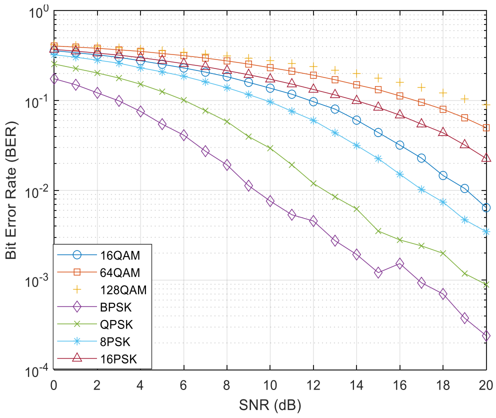

Fig.8.c: BER Performance of MIMO-OFDM with Different Modulation Schemes in Rician Fading Channel Using DFT Transform

These results emphasize the trade-off between noise resilience and data rate efficiency. Lower-order modulations (BPSK, QPSK) are ideal for noisy environments, as they maintain low BER even at lower SNR values. In contrast, higher-order modulations (QAM, PSK) require significantly higher SNR to achieve acceptable BER, making them more suitable for scenarios where maximizing data rate is a priority and the channel conditions are favorable.

The efficiency of digital image transmission over MIMO-OFDM systems is highly influenced by the transform technique used, modulation scheme, and wireless channel conditions. The results indicate that the choice of transform technique, whether DWT, DCT, or DFT, directly affects the Bit Error Rate (BER) performance and noise resistance.

Impact of Transform Techniques

- DWT (Discrete Wavelet Transform) has proven to be the most effective in reducing BER and enhancing noise resilience, as it minimizes inter-symbol interference and preserves signal quality during image transmission.
- DCT (Discrete Cosine Transform) provides moderate performance with lower computational complexity, but it requires higher SNR to achieve the same BER performance as DWT.
- DFT (Discrete Fourier Transform) is widely used in traditional OFDM systems but suffers from inter-carrier interference (ICI) at low SNR, leading to a higher BER compared to DWT.

Impact of Modulation Schemes on BER Performance

- Lower-order modulations like BPSK and QPSK deliver the lowest BER, making them ideal for low-SNR environments where noise resilience is critical.
- Higher-order modulations such as 8PSK and 16PSK provide higher data rates but require increased SNR to reduce BER, making them less efficient in noisy channels.
- QAM-based modulations (16QAM, 64QAM, 128QAM) offer higher transmission speeds but are highly susceptible to noise, with 128QAM showing the highest BER in all channels at low SNR levels.

Impact of Channel Conditions on Modulation Performance

- In the AWGN channel, where noise is evenly distributed, all modulation schemes improve with increasing SNR. BPSK achieves the lowest BER (~10^{-4} at SNR = 8 dB), while 128QAM exhibits the highest BER (~10^{-1} at the same SNR), indicating its sensitivity to noise.
- In the Rayleigh channel, where random fading significantly impacts signal quality, BPSK maintains the lowest BER (~10^{-3} at SNR = 8 dB), whereas higher-order modulations like 128QAM exceed 10^{-1} at the same SNR, requiring a much higher SNR for reliable performance.
- In the Rician channel, which includes a strong line-of-sight component, modulation schemes perform better than in the Rayleigh channel. However, BPSK still achieves the lowest BER (~10^{-4} at SNR = 8 dB), followed by QPSK (~10^{-3}), while 128QAM requires an SNR above 18 dB to reach a BER of 10^{-3}.

Conclusion

This study examined the impact of transform techniques, modulation schemes, and wireless channels on BER performance in MIMO-OFDM systems for digital image transmission. The results showed that DWT outperforms DCT and DFT, offering better noise resilience. BPSK and QPSK demonstrated the lowest BER, making them ideal for low-SNR environments, while higher-order modulations (e.g., 128QAM) required high SNR but enabled higher data rates.

Channel conditions significantly influenced BER, with AWGN providing stable performance, while Rayleigh and Rician channels introduced severe BER degradation. BPSK remained the most robust across all channels, whereas higher-order modulations struggled in fading conditions.

Future research could explore adaptive modulation, hybrid transform techniques, and error correction methods to further optimize performance. In conclusion, DWT with low-order modulations (BPSK, QPSK) is ideal for noisy environments, while high-order modulations are more suitable for high-SNR scenarios requiring higher data throughput. These insights contribute to enhancing MIMO-OFDM systems for efficient digital image transmission.

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