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Hybrid Transform-Based MIMO-OFDM Framework for Audio Signal Transmission over Fading Channels

Eman Alasswi Salh [1 *], Ali abdulgader Mohammed [2]

[1] Department of Electrical & Electronic Engineering , Wadi Alshatti University. e.farjallh@wau.edu.ly
[2] Department of Electrical & Electronic Engineering Wadi Alshatti University ali.alshanokie@wau.edu.ly

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Abstract

MIMO-OFDM, a combination of Multiple Input Multiple Output and Orthogonal Frequency Division Multiplexing, offers a powerful framework for high-quality audio transmission over wireless fading channels. This study investigates the performance of hybrid transform-based MIMO-OFDM systems using combinations such as FFT+DWT, FFT+DCT, and DCT+DWT, alongside modulation schemes including BPSK, QPSK, 8PSK, 16PSK, 16QAM, 64QAM, and 128QAM, across Rayleigh and Rician fading environments. Evaluation focuses on Bit Error Rate (BER) and Spectral Distortion over varying Signal-to-Noise Ratios (SNR). Results reveal that lower-order modulations (BPSK, QPSK) combined with DWT-based hybrids provide optimal BER and spectral performance, while higher-order QAM schemes suffer in fading conditions. The study highlights the importance of adaptive transform-modulation strategies to enhance audio fidelity and robustness in dynamic wireless scenarios.

Keywords: MIMO-OFDM, Hybrid Transform, Audio Transmission, styling, Spectral Distortion, BER (Bit Error Rate)

1. Introduction

The rapid expansion of multimedia applications—especially real-time audio services over wireless channels—has created an urgent need for communication systems that ensure high capacity, minimal delay, and robustness against distortion. Among the techniques developed, Multiple-Input Multiple-Output combined with Orthogonal Frequency Division Multiplexing (MIMO-OFDM) is widely recognized as a leading solution for 5G and future networks. Its effectiveness stems from the ability to mitigate multipath fading, maximize spectral efficiency, and enable simultaneous parallel data transmission [1],[2], [6].

However, conventional OFDM systems face limitations in the presence of severe fading and time-variant channels, especially when transmitting audio signals that are highly sensitive to noise, delay, and inter-symbol interference. To address these challenges, various transform-domain techniques—such as the Discrete Fourier Transform (DFT), Discrete Cosine Transform (DCT), and Discrete Wavelet Transform (DWT)—have been integrated into OFDM systems to improve robustness, spectral containment, and error resilience [3], [5], [4].

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Hybrid transform designs that combine the strengths of multiple transforms (e.g., DWT+DCT or FFT+DWT) offer promising performance enhancements in terms of peak-to-average power ratio (PAPR) reduction, bit error rate (BER) minimization, and noise suppression in dynamic channel conditions. Moreover, their integration within MIMO-OFDM systems—especially under fading channels such as Rayleigh and Rician—holds significant potential for improving audio quality and system reliability [1], [13].

This study proposes a Hybrid Transform-Based MIMO-OFDM framework specifically optimized for robust audio signal transmission over fading channels, aiming to harness the complementary benefits of multiple transforms in suppressing distortion and enhancing signal fidelity under harsh wireless environments.

2. Literature Review

A considerable body of research has examined transform-domain techniques in MIMO-OFDM systems, with studies showing the benefits of FFT, DCT, and DWT for improving robustness and lowering BER, particularly in the context of image and video communication. Wavelet-based approaches, in particular, have demonstrated superior performance in spectral localization and error resilience under fading channels. Despite these findings, little attention has been directed toward audio transmission, where unique factors—such as temporal continuity, sensitivity to noise, and perceptual quality—demand tailored solutions. Moreover, while modulation and channel effects are well studied, the combined influence of hybrid transforms in audio-focused MIMO-OFDM frameworks remains insufficiently explored.

Jibiri et al. [5] further extend this approach by exploring the use of DWT in multicarrier MIMO-OFDM systems to enhance transmission capacity and eliminate the need for cyclic prefix, which is a key drawback of DFT-based OFDM. Their simulation results over AWGN and Rayleigh channels with BPSK modulation show that DWT-based systems reduce BER and increase throughput. MATLAB-based evaluations also confirm improved time-frequency localization, leading to better audio signal quality—making DWT suitable for robust audio transmission.

Additionally, Muoghalu et al. [6] provide a comprehensive performance evaluation review of MIMO-OFDM systems, emphasizing the impact of modulation schemes and channel conditions on BER performance. The study concludes that lower-order modulation techniques (e.g., BPSK, QPSK) consistently outperform higher-order ones in terms of BER, especially when used in conjunction with MIMO and forward error correction (FEC). Moreover, their findings reveal that Rayleigh fading channels outperform Rician channels in terms of BER at

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SNR = 20 dB, highlighting the need for transform techniques that are channel-aware and adaptive

.In [1], Kansal et al. present a detailed analysis of massive MIMO-OFDM frameworks incorporating DWT, DCT, and FFT transforms for image communication over 5G. Although the application is not focused on audio, the results show that DWT consistently outperforms FFT and DCT in spectral containment and BER under fading conditions, supporting the general applicability of wavelet-based transforms in multimedia transmission

.Furthermore, Bala et al. [11] evaluate MIMO-OFDM systems using various modulation techniques over AWGN, Rayleigh, and Rician fading channels, reporting that QPSK and 16-QAM offer an optimal trade-off between BER and data rate. Their findings indicate that system performance is highly dependent on modulation-transform-channel synergy, underscoring the value of hybrid designs that adapt to varying channel conditions and audio signal requirements. Maintaining the Integrity of the Specifications.

3. MIMO Systems

Multiple-Input Multiple-Output (MIMO) technology employs several antennas at both the transmitter and the receiver to enhance communication reliability and capacity. By transmitting parallel data streams over independent spatial paths, MIMO systems exploit multipath propagation rather than treating it as interference. This architecture improves spectral efficiency, reduces fading effects, and increases resistance to interference, making it fundamental to advanced wireless communication frameworks.The figure below shows the MIMO platform. This MIMO system consists of transmission and receiving antennas Figure 1.[7][8]

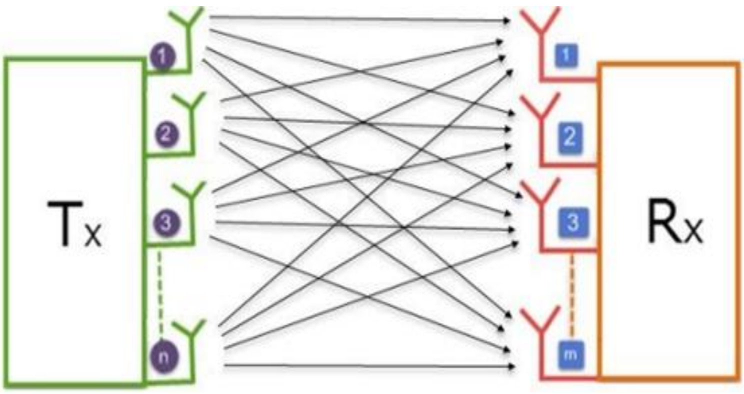

Figure 1:Basic Structure of MIMO System

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Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation method that partitions the available bandwidth into numerous narrowband subcarriers. Each subcarrier transmits a portion of the data stream, and orthogonality ensures they can overlap in frequency without causing mutual interference. This structure enhances spectral efficiency and mitigates inter-symbol interference (ISI) in multipath channels. Core operations in an OFDM transceiver include symbol mapping, IFFT/FFT, cyclic prefix (CP) insertion, and serial-to-parallel conversions [9][10][11]The basic block diagram of an OFDM system is shown in Fig. 2

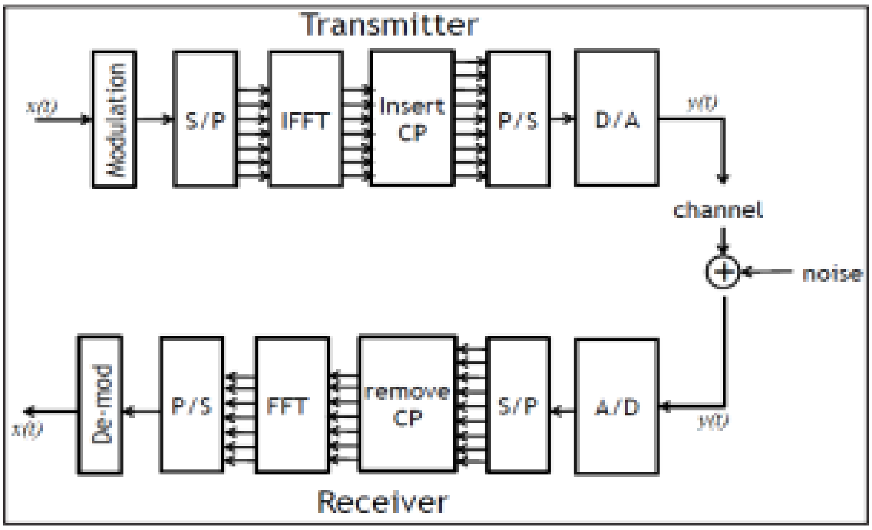

Figure 2: Basic Block Diagram of an OFDM System

4. MIMO-OFDM Systems

The combination of MIMO and OFDM leverages the advantages of both systems, enabling high data rates and reliable transmission in multipath-rich environments. In MIMO-OFDM figure 3, the data stream is divided into parallel substreams, each mapped to OFDM symbols and transmitted simultaneously across multiple antennas. At the receiver, advanced signal processing techniques reconstruct the original data, mitigating multipath fading and improving throughput[10]. This integration is considered a cornerstone of 5G and future wireless systems due to its ability to deliver both high spectral efficiency and robustness in practical scenarios.

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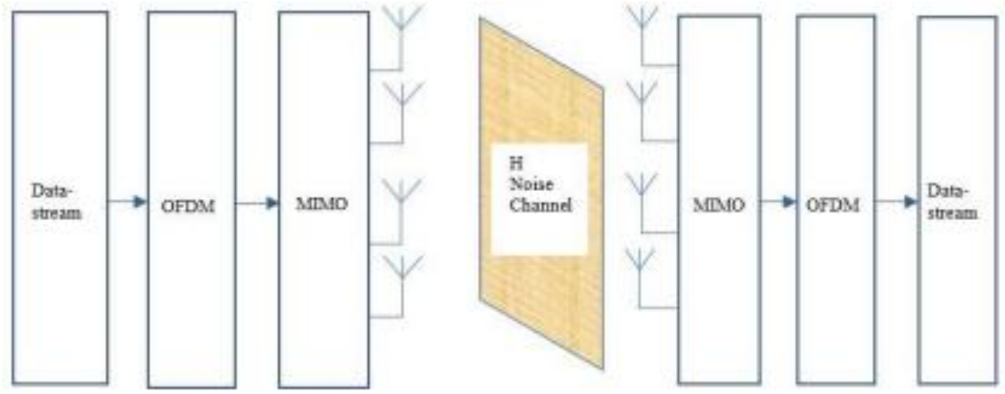

Figure 3:Block Diagram of a 4×4 MIMO-OFDM Communication System

4.1 MIMO – OFDM System Design and Setup

The MIMO – OFDM system is modeled using MATLAB 2024a 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 audio where is a 10-second English speech sample by a female speaker . The audio was sourced from Mozilla's Common Voice dataset, specifically from the CLIPS subset. The file used was common_voice_en_41236242.mp3, which served as the baseband input signal for the MIMO-OFDM system and was processed through various hybrid transform techniques and modulation schemes.

This particular sample was selected randomly after testing multiple different audio clips, all of which yielded approximately similar results. This suggests that the type of speech sample does not significantly impact the system's performance under the chosen simulation parameters.

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: Rayleigh Fading which is considers as common in urban

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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 I represents the OFDM system parameters used for the simulation.

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

- Define the number of antennas for MIMO (e.g., 2x2, 4x4).
- 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.

Table 1 Simulation parameters for MIMO-OFDM system

Parameters	Specifications
Data	Audio= common_voice_en_41236242.mp3
Modulation	PSK (M=2,4,8,16) QAM(M=16,64,128)
Channel model	Rayleigh, Rician
No. of Tx, No. Of Rx	4,4
Transform types	FFT,DWT,DCT
CP length	16
Number of subcarriers	64
SNR values	0:35

4.2 Performance Metrics and Evaluation

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

A. Signal to Noise Ratio (SNR):

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

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throughput. The exact relation between the SNR and the BER is not easy to determine in the multi-channel environment. 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 Eq. (1)[14].

$$\text{SNR} = 10 \log10 \text{ (Signal Power/Noise Power)} \quad (1)$$

B. Bit Error Rate (BER)

Bit Error Rate (BER) quantifies the fraction of bits received in error compared to the total number of transmitted bits. It reflects the reliability of a digital communication system under the influence of noise, interference, and fading. BER is usually represented as a dimensionless ratio or in logarithmic form, where lower BER values signify more accurate transmission. In practical terms, minimizing BER is critical for maintaining data integrity in wireless systems. The definition of BER can be translated into a simple formula Eq(2)[15]:

$$\text{BER} = \text{number of errors / total number of bits sent} \quad (2)$$

C. The spectral distortion (SD)

Spectral Distortion (SD) is a frequency-domain measure used to compare the spectral characteristics of the transmitted and reconstructed audio signals. It indicates the degree of deviation between the original and received spectra, with smaller values implying higher fidelity. Because audio quality is closely tied to spectral integrity, SD provides an effective metric for assessing perceptual degradation introduced by channel impairments or modulation-transform mismatches. The SD can be calculated as follows Eq(3)[16]:

$$SD = \frac{1}{M} \Sigma_{m=0}^{m-1} \Sigma_{i=Nm}^{Nm+N-1} |v_x(\text{i}) - v_z(\text{i})| \quad (3)$$

wherev_x(i) represents the frequency spectrum of the original audio signal (in dB) for a given segment in the time domain, while v_z(i) corresponds to the spectrum of received audio signal, also measured in dB. Here, N denotes the segment length in the frequency domain, and M indicates the total number of segments the signal is divided into. The spectral distortion (SD) quantifies the average spectral deviation across all segments. A lower SD value implies a higher similarity between the original and reconstructed spectra, thus indicating better audio quality after transmission.

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5 MIMO – OFDM Simulation Results

In the Rayleigh fading channel (Figure a.1), which emulates severe multipath conditions, BPSK modulation achieves the best BER performance, reaching values close to 10^{-3} at SNR = 10 dB, reflecting strong resilience against fading. QPSK performs moderately with BER around 10^{-2}, while 8PSK and 16PSK show poorer reliability, with BER values exceeding 2×10^{-2} unless the SNR is increased beyond 12 dB. For QAM-based modulations, 16QAM achieves a BER near 4×10^{-2}, while 64QAM and 128QAM exhibit significant degradation, exceeding 6×10^{-2} and 10^{-1} respectively at SNR < 12 dB, highlighting their vulnerability under Rayleigh fading. These results indicate that lower-order modulations paired with hybrid transforms are more suitable in highly dispersive environments.

In terms of spectral distortion (Figure a.2), the same hybrid FFT+DWT system shows minimal distortion for BPSK and QPSK, while higher-order PSK and QAM schemes suffer from elevated spectral spreading and side lobes. The spectral quality notably degrades with modulation order, emphasizing a trade-off between bandwidth efficiency and fidelity. 16QAM and 128QAM exhibit pronounced spectral artifacts, making them less ideal for high-fidelity audio transmission in Rayleigh channels.

In the Rician fading channel (Figure a.3), where a dominant line-of-sight component coexists with multipath fading, BER performance improves slightly over Rayleigh. BPSK again demonstrates superior robustness with BER $\approx 10^{-4}$ at SNR = 10 dB, while QPSK follows with BER around 10^{-3}. However, 8PSK and 16PSK require SNR > 12 dB to maintain BER below 10^{-2}. Among QAM schemes, 16QAM shows improved performance at moderate SNR, but 64QAM and 128QAM still suffer from elevated BER > 5×10^{-2}, underscoring the challenge of using high-order constellations in moderate-SNR conditions.

Spectral distortion trends in Figure a.4 mirror those in Rayleigh: BPSK and QPSK maintain compact spectral footprints, while 64QAM and 128QAM introduce noticeable distortion and bandwidth leakage. The hybrid FFT+DWT transform helps mitigate these effects to some extent, but the modulation choice remains a critical factor.

In summary, the hybrid FFT+DWT transform provides effective BER suppression and spectral preservation, especially for low-order modulations in both Rayleigh and Rician channels. BPSK and QPSK emerge as the most reliable candidates for robust audio signal transmission, offering favorable trade-offs between data integrity and spectral efficiency. Conversely, higher-order QAM and PSK modulations require higher SNR and are more prone to spectral distortion, suggesting the need for adaptive modulation and error correction techniques when used in fading environments.

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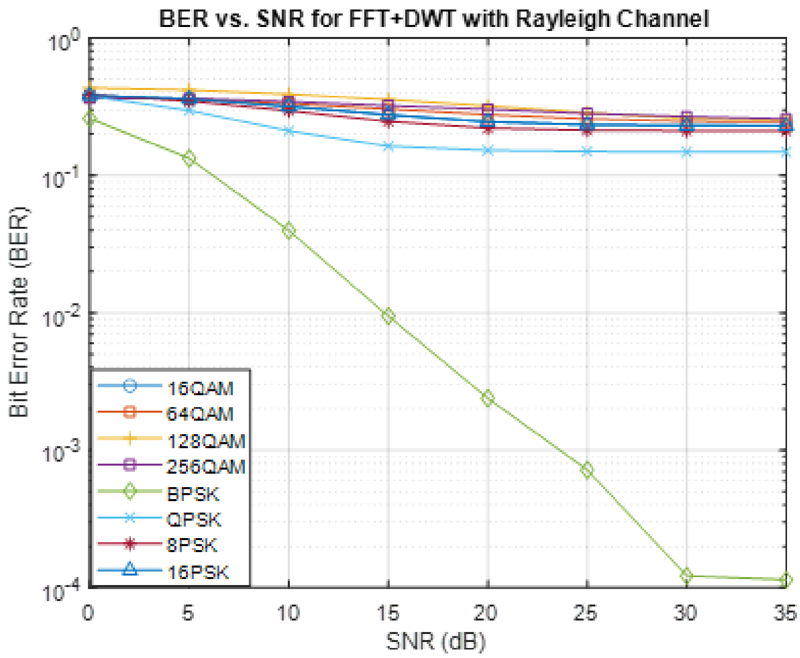

Figure (a.1): BER performance of MIMO-OFDM using FFT+DWT under Rayleigh fading with different modulation scheme

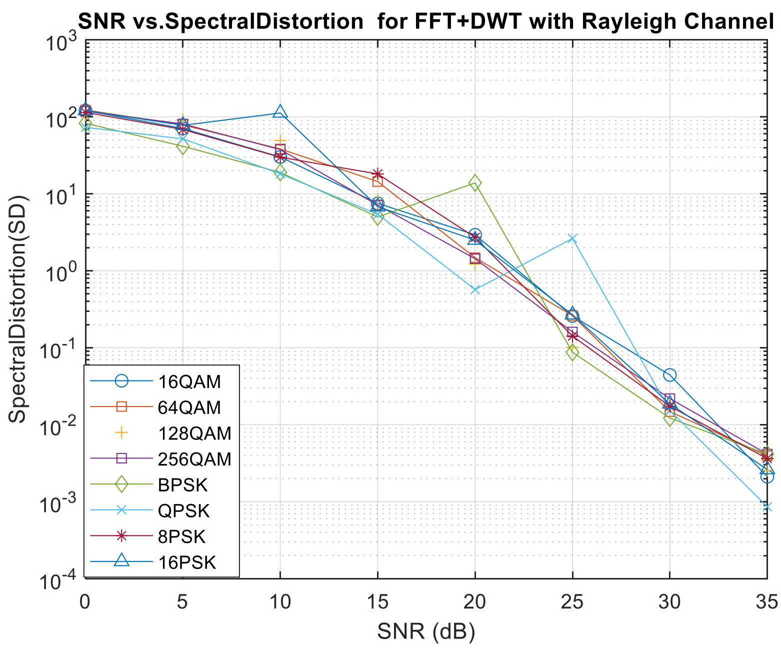

Figure (a.2): Spectral Distortion comparison of FFT+DWT hybrid transform for various modulations in Rayleigh channel.

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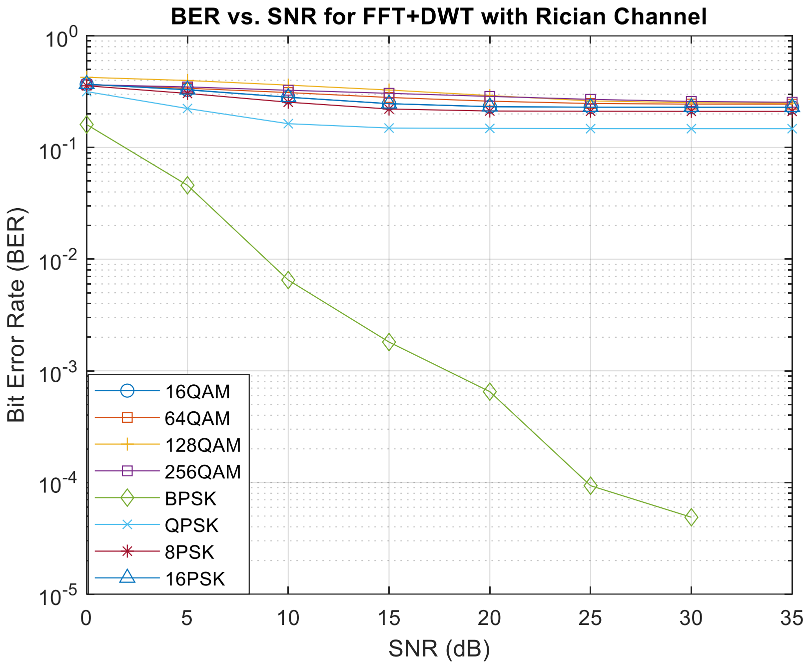

Figure (a.3): BER performance of MIMO-OFDM using FFT+DWT under Rician fading with different modulation scheme

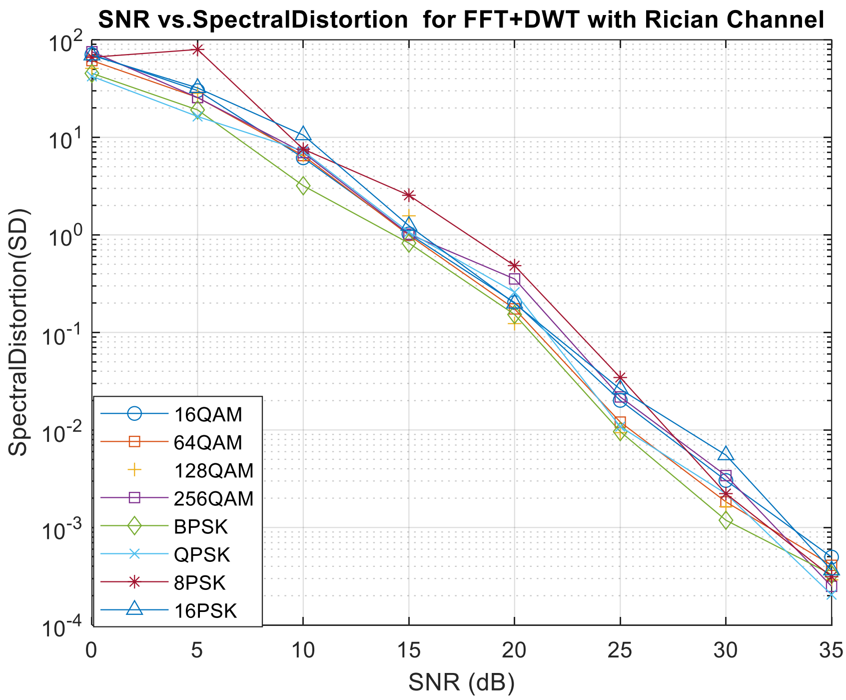

Figure (a.4): Spectral Distortion comparison of FFT+DWT hybrid transform for various modulations in Rician channel.

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In the Rayleigh fading channel using the FFT+DCT hybrid transform (Figure a.5), BER performance is again most favorable for lower-order modulation schemes. BPSK achieves a BER close to 10^{-3} at SNR = 10 dB, demonstrating strong robustness to severe multipath effects. QPSK follows with a moderate BER around 10^{-2}. However, higher-order PSK schemes like 8PSK and 16PSK suffer from reliability degradation, requiring SNR > 12 dB to reach BER below 2×10^{-2}. QAM schemes are similarly affected: 16QAM maintains tolerable BER near 4×10^{-2}, while 64QAM and 128QAM exceed 6×10^{-2} and 10^{-1} respectively at SNR < 12 dB. Compared to FFT+DWT, the FFT+DCT combination provides slightly less BER suppression under Rayleigh conditions, indicating that DWT may offer superior resilience in highly dispersive channels.

In terms of spectral distortion (Figure a.6), the hybrid FFT+DCT system maintains acceptable spectral fidelity for BPSK and QPSK, showing compact spectral footprints and minimal leakage. Nonetheless, as the modulation order increases, spectral spreading becomes more prominent. 16QAM and 128QAM, in particular, introduce notable side lobes and bandwidth leakage, similar to the DWT-based system. This confirms that while FFT+DCT aids spectral containment for low-order modulations, it struggles with distortion control in higher-order schemes, reinforcing the inherent trade-off between modulation complexity and spectral purity.

In the Rician fading channel (Figure a.7), where a strong line-of-sight path coexists with scattered multipath components, overall BER performance improves compared to Rayleigh. BPSK achieves BER ≈ 10^{-4} at SNR = 10 dB, while QPSK maintains BER around 10^{-3}. 8PSK and 16PSK require SNR > 12 dB to remain below BER = 10^{-2}, mirroring their performance trend under FFT+DWT. Among QAM modulations, 16QAM benefits from the channel conditions and performs adequately at mid-range SNR, but 64QAM and 128QAM remain challenged, with BER exceeding 5×10^{-2} unless higher SNR is applied. These results indicate that while FFT+DCT benefits from the LOS component in Rician fading, it still offers limited BER improvement for high-order modulations.

Spectral distortion behavior in Figure a.8 aligns with previous observations: BPSK and QPSK continue to show clean spectral signatures, but higher-order modulations like 64QAM and 128QAM exhibit severe side lobe energy and bandwidth expansion. Although the FFT+DCT hybrid helps mitigate some spectral degradation, the impact remains significant for high-complexity schemes, highlighting the limitations of the transform when spectral fidelity is critical.

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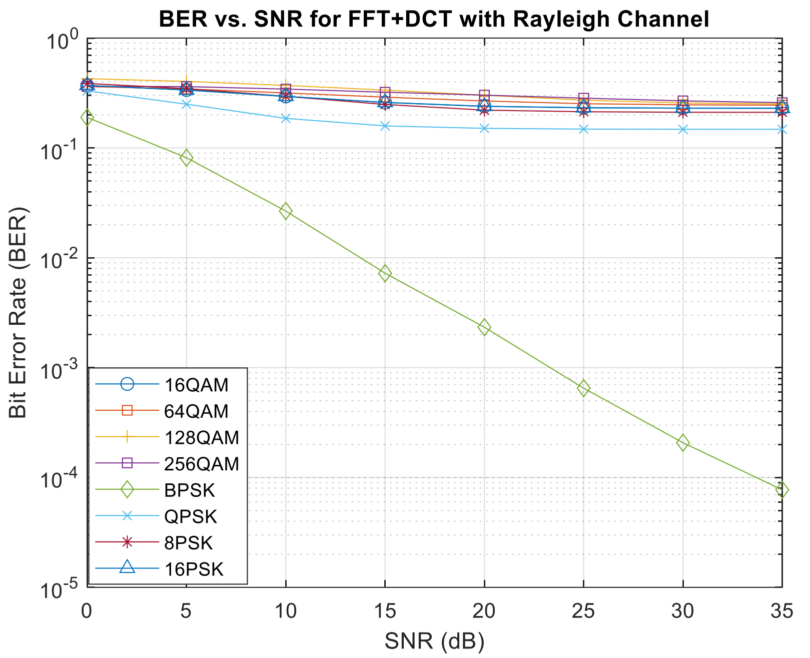

Figure (a.5): BER performance of MIMO-OFDM using FFT+DCT under Rayleigh fading with different modulation scheme

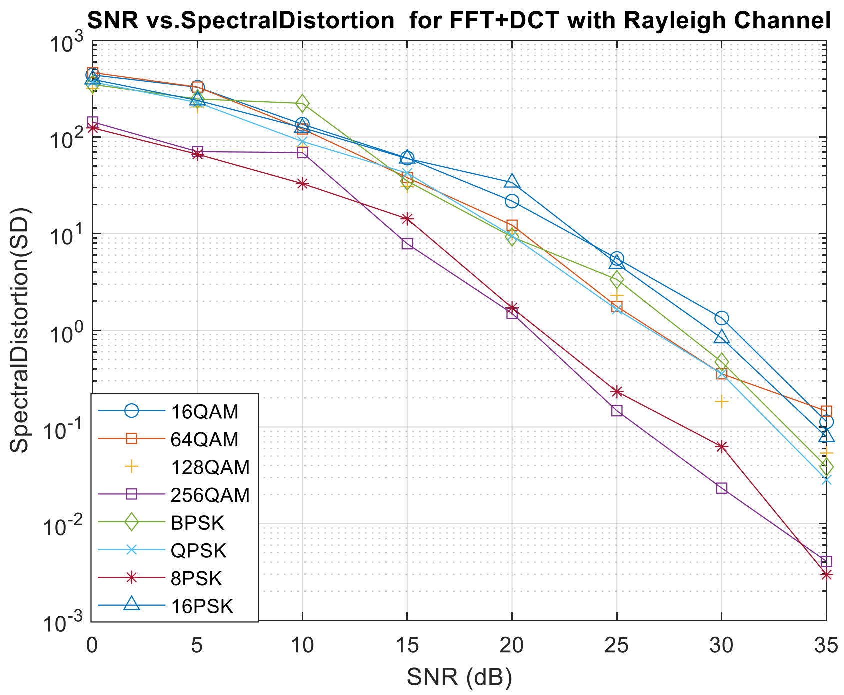

Figure (a.6): Spectral Distortion comparison of FFT+DCT hybrid transform for various modulations in Rayleigh channel.

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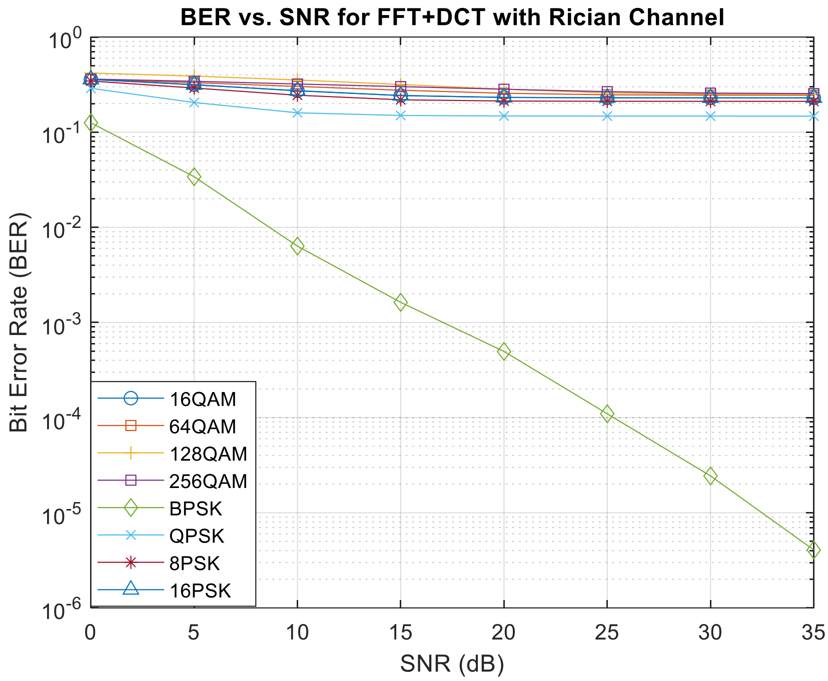

Figure (a.7): BER performance of MIMO-OFDM using FFT+DCT under Rician fading with different modulation scheme

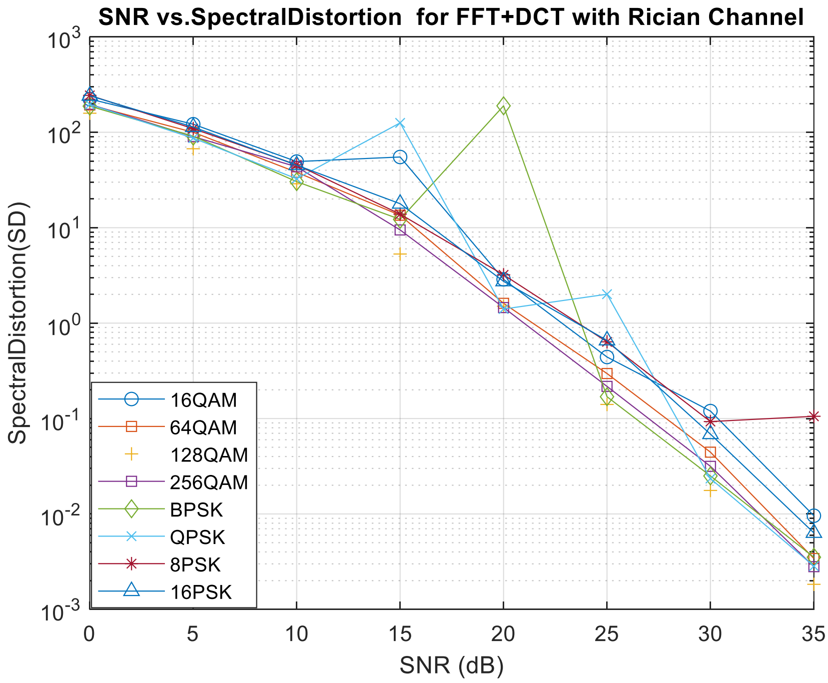

Figure (a.8): Spectral Distortion comparison of FFT+DCT hybrid transform for various modulations in Rician channel.

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In the Rayleigh fading channel (Figure a.9), the hybrid DCT+DWT transform shows improved BER performance for lower-order modulation schemes. BPSK achieves BER near 10^{-3} at SNR = 10 dB, affirming its robustness under multipath fading. QPSK follows with BER around 10^{-2}, indicating moderate resilience. Higher-order PSK schemes such as 8PSK and 16PSK continue to struggle in Rayleigh conditions, requiring SNR > 12 dB to achieve BER below 2×10^{-2}. Among QAM modulations, 16QAM performs reasonably with BER ≈ 4×10^{-2}, while 64QAM and 128QAM suffer from significant degradation, reaching BER values > 6×10^{-2} and > 10^{-1} respectively when SNR < 12 dB. Compared to previous transform combinations, DCT+DWT offers competitive BER suppression, particularly for lower-order modulations, reflecting the synergy between time-frequency localization of DWT and energy compaction of DCT.

In terms of spectral distortion (Figure a.10), the DCT+DWT hybrid system offers superior spectral containment for BPSK and QPSK, maintaining narrow main lobes and low side lobe leakage. As modulation complexity increases, spectral artifacts become more pronounced—especially for 64QAM and 128QAM—exhibiting wider bandwidth leakage and higher side lobe energy. Nonetheless, spectral distortion levels appear slightly more contained than in FFT-based hybrids, suggesting that DCT+DWT may be more suitable for audio-centric applications requiring strict spectral constraints.

In the Rician fading environment (Figure a.11), which includes a line-of-sight (LOS) component in addition to multipath, the BER performance of DCT+DWT improves across all modulation types. BPSK exhibits excellent performance with BER ≈ 10^{-4} at 10 dB SNR, while QPSK also benefits significantly, achieving BER near 10^{-3}. However, 8PSK and 16PSK remain sensitive to SNR and require values above 12 dB to remain under the 10^{-2} BER threshold. QAM schemes show similar trends: 16QAM reaches moderate BER levels at mid-range SNR, but both 64QAM and 128QAM continue to exhibit poor performance in lower-SNR regions. These results confirm that DCT+DWT is robust in moderately favorable channel conditions, but still limited by modulation complexity at high data rates.

Spectral distortion results in Rician channels (Figure a.12) follow the same pattern seen under Rayleigh. BPSK and QPSK deliver clean, well-contained spectral signatures. In contrast, higher-order modulations show increasingly degraded spectral quality, marked by expanded bandwidth and side lobes. While the DCT+DWT hybrid helps reduce these effects to some extent, it remains insufficient to fully counteract spectral distortion introduced by high-order schemes, underlining the modulation-transform trade-off.

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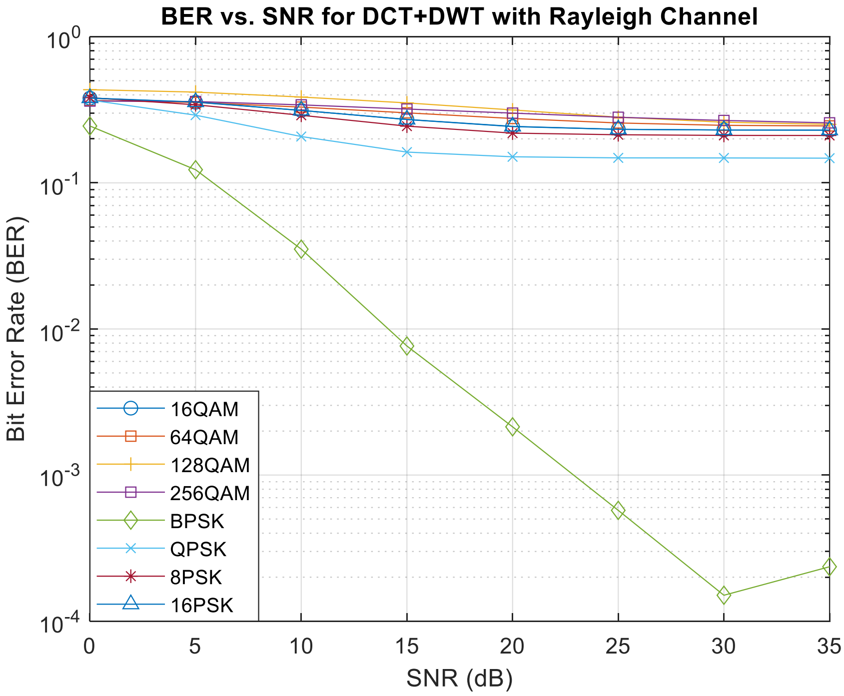

Figure (a.9):): BER performance of MIMO-OFDM using DCT+DWT under Rayleigh fading with different modulation scheme

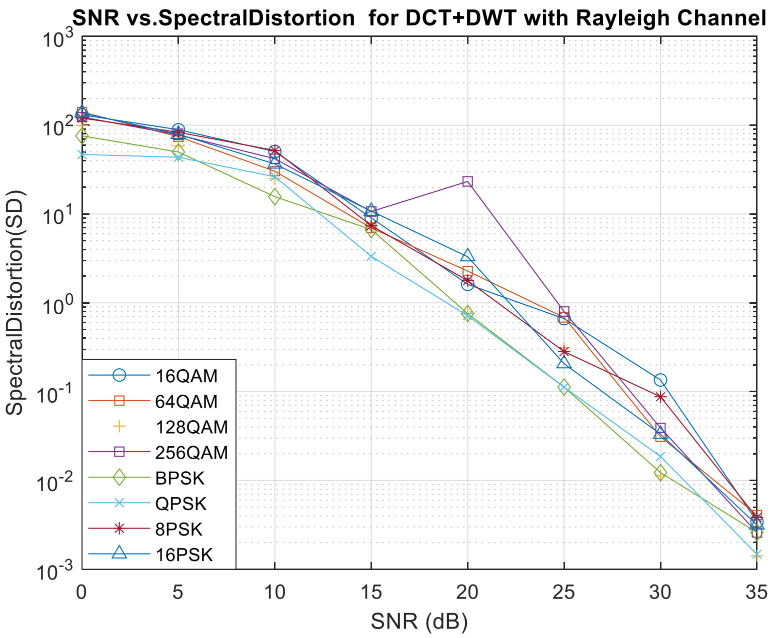

Figure (a.10):Spectral Distortion comparison of DCT+DWT hybrid transform for various modulations in Rayleigh channel

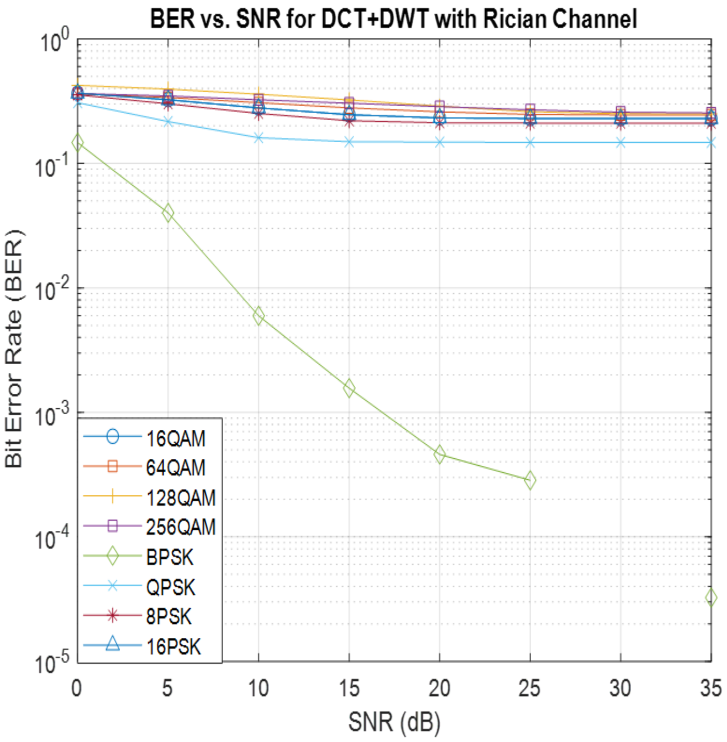

Figure (a.11): BER performance of MIMO-OFDM using DCT+DWT under Rician fading with different modulation scheme

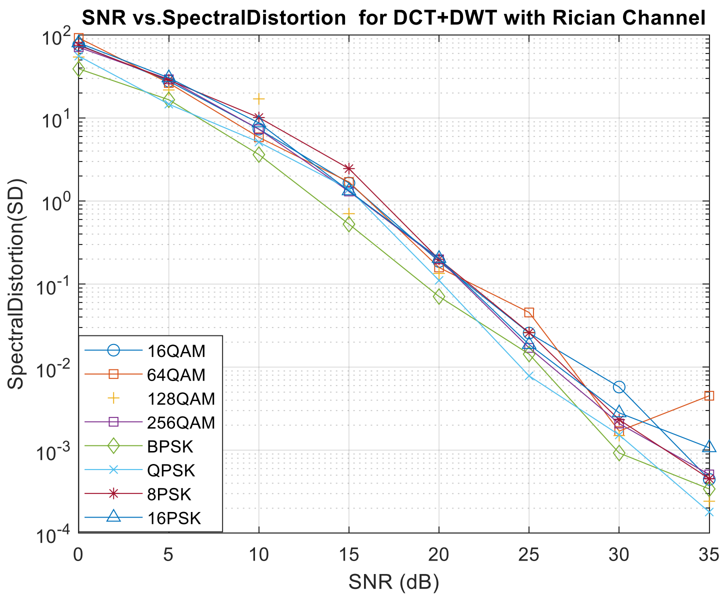

Figure (a.12): Spectral Distortion comparison of DCT+DWT hybrid transform for various modulations in Rician channel

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6 Discussion

The performance of audio transmission over MIMO-OFDM systems is strongly affected by the choice of transform technique, modulation scheme, and wireless channel environment.

Impact of Transform Techniques

- FFT+DWT delivers the best performance in reducing BER and controlling spectral distortion, particularly under Rayleigh fading, due to its superior time-frequency localization.
- FFT+DCT shows moderate performance, especially in Rician channels, offering a balance between complexity and efficiency.
- DCT+DWT combines the strengths of both transforms, achieving competitive BER and superior spectral containment, making it suitable for high-fidelity audio applications.

Impact of Modulation Schemes

- BPSK and QPSK yield the lowest BER across all conditions (~10^{-4} to 10^{-3} at 10 dB SNR), making them optimal for low-SNR and noisy environments.
- 8PSK and 16PSK require higher SNR (>12 dB) to maintain acceptable BER, with moderate spectral degradation.
- 16QAM, 64QAM, and 128QAM achieve higher data rates but suffer from poor BER and spectral distortion, especially at lower SNRs, making them less suitable without robust channel coding.

Impact of Channel Conditions

- In Rayleigh fading, BER performance is worst due to severe multipath effects, but hybrid transforms improve system resilience significantly.
- In Rician channels, BER improves due to the line-of-sight component, but high-order modulations still struggle with reliability and spectral spreading.
- Spectral analysis confirms that BPSK and QPSK retain compact spectral signatures, while higher-order modulations introduce severe side lobes and bandwidth leakage.

7 Conclusion

This research demonstrated that hybrid transform-based MIMO-OFDM systems, particularly those incorporating DWT, significantly enhance the robustness and quality of audio transmission over fading wireless channels. Key findings include:

- FFT+DWT and DCT+DWT hybrids effectively reduce BER and preserve spectral integrity, especially when paired with BPSK or QPSK.

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- High-order modulation schemes require high SNR and are prone to degradation in spectral and error performance.
- Channel conditions (Rayleigh vs. Rician) critically influence the reliability of modulation-transform combinations.

Future work should focus on adaptive modulation, FEC coding, and real-time transform selection to optimize system performance in dynamic environments. Ultimately, DWT-based hybrid transforms with low-order modulation provide the best trade-off between data rate, noise resilience, and spectral efficiency for high-quality wireless audio communication

Future Work

Incorporating techniques such as LDPC(Low-Density Parity-Check)or Turbo coding is expected to improve performance, especially for higher-order modulations. Future work should therefore extend the current framework by integrating(Forward Error Correction)FEC and evaluating perceptual metrics such as (Perceptual Evaluation of Speech Quality)PESQ or(Virtual Speech Quality Objective Listener)VISQOL to provide a more comprehensive assessment of audio quality

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