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OTFS with Multicarrier MIMO in Fading Scenarios

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Abstract - Recently, there has been increased awareness of the reliability of Orthogonal Time Frequency Space (OTFS) modulation as a method for wireless communication, especially in high-mobility and multipath situations. This work analyses the performance of OTFS under different fading conditions and investigates its integration with multicarrier Multiple-Input Multiple-Output (MIMO) systems. The study exhibits improved reliability and spectrum efficiency by utilising the advantages of multicarrier transmission and the resilience of OTFS, providing insights into its application for next-generation communication systems.

Keywords — OTFS, MIMO, multicarrier, fading scenarios

1. Introduction

Orthogonal Time Frequency Space (OTFS) modulation is gaining attention for its potential to significantly enhance wireless communication systems, especially in challenging environments characterized by high mobility and multipath fading. In contrast to conventional modulation schemes, OTFS maps data symbols in the delay-Doppler domain, which inherently offers improved resistance to the adverse effects of time and frequency dispersion. This unique approach makes OTFS particularly suitable for high-speed vehicular communication and other dynamic scenarios where maintaining reliable communication links is notoriously difficult.

In order to improve link stability and increase data capacity, Multiple-Input Multiple-Output (MIMO) technology has simultaneously revolutionised wireless communications by utilising multiple antennas at both the transmitter and reception ends. Multi-carrier transmission techniques such as Orthogonal Frequency Division Multiplexing (OFDM) can effectively mitigate inter-symbol interference and maximise spectral efficiency when used in conjunction with MIMO systems. By combining the advantages of both technologies, MIMO and OTFS integration offers notable performance gains.

This paper investigates the performance of OTFS modulation within the framework of multicarrier MIMO systems under various fading scenarios. We aim to explore how OTFS can be utilized to improve the robustness and efficiency of MIMO systems in scenarios where conventional methods might fall short. By examining the interplay between OTFS and MIMO, this study aims to provide a comprehensive analysis of their combined benefits and potential applications in next-generation communication systems.

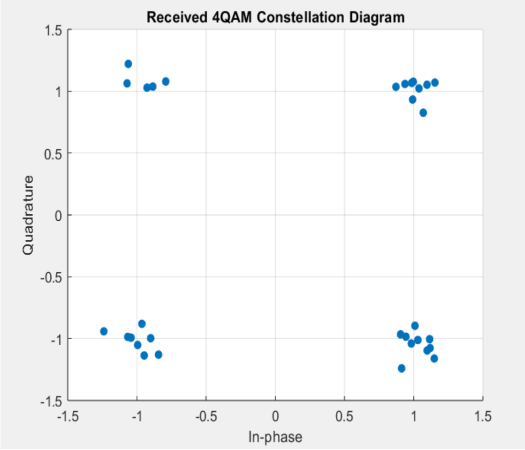


Fig.1 Constellation diagram for 4-QAM

2. Objectives

To generate an OFDM signal, we start by applying Quadrature Amplitude Modulation (QAM) to convert data bits into complex symbols. These symbols are then arranged into parallel subcarriers, followed by an Inverse Fast Fourier Transform (IFFT) to create the time-domain OFDM signal.

The performance of the generated OFDM signal is evaluated under Rayleigh and Rician fading conditions, which model different multipath environments. This analysis helps in understanding the signal's robustness and the impact of fading on bit error rates.

After introducing a cyclic prefix to mitigate inter-symbol interference, Additive White Gaussian Noise (AWGN) is added to the received OFDM signal. The impact of varying noise levels on signal quality is analyzed, focusing on error rates and signal-to-noise ratios.

Orthogonal Time Frequency Space (OTFS) modulation is integrated with the OFDM signal to enhance resilience against severe multipath fading. This combination leverages the strengths of both techniques, improving overall transmission reliability and spectral efficiency.

The designed OFDM and OTFS system is implemented on a National Instruments Universal Software Radio Peripheral (USRP) kit. This allows for real-time transmission and reception of signals, providing a practical platform for testing and experimentation in a laboratory setting.

An antenna suitable for 6G frequencies is designed, focusing on high-frequency operations and compact size. Key considerations include bandwidth, gain, and efficiency to ensure optimal performance in advanced wireless communication scenarios.

3. Methodology

The primary objective of this work is to assess the performance of OTFS-OFDM systems across different fading scenarios, including Rayleigh and Rician. By generating and combining OFDM signals with OTFS techniques, the research aims to enhance data throughput and reliability in challenging propagation environments.The study focusses on assessing important performance measures to provide insights into the optimisation of wireless communication systems for the future generation of applications, including Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and channel capacity.

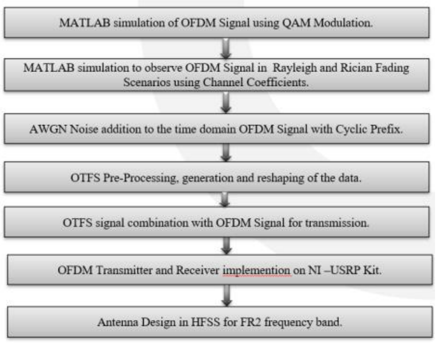


Fig.2:Complete flow of the work

First, the OFDM signal is created by modulating data symbols using quadrature amplitude modulation (QAM). Next, the time-domain representation is obtained from the frequency-domain using the Inverse Fast Fourier Transform (IFFT). To create the full OFDM signal, this entails generating a matrix of QAM symbols, running IFFT on each row, and merging the outputs.

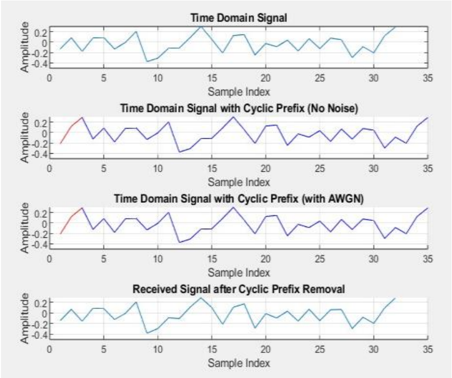
The second step is to Simulate the MATLAB code by applying Rayleigh and Rician fading models to the generated OFDM signal using channel coefficients to observe how these fading conditions affect the signal's performance. This involves convolving the OFDM signal with the fading channel impulse response and analyzing the impact on key metrics such as Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR).

The third step is to add Additive White Gaussian Noise (AWGN) to the OFDM signal in time domain, including the cyclic prefix, by generating noise with a specified power level and adding it to the signal. This step simulates the impact of noise on signal integrity and enables the evaluation of system performance under realistic conditions.

Combining the OTFS signal with the OFDM signal involves integrating the time-frequency domain representation of OTFS with the multicarrier structure of OFDM. This process leverages the robustness of OTFS against channel impairments and the spectral efficiency of OFDM, creating a hybrid signal that can enhance overall system performance in dynamic and multipath fading environments. The combined signal is then transmitted using a MIMO configuration to maximize data throughput and reliability., and implement this system using an NI (National Instruments) kit for practical validation.

4. Results

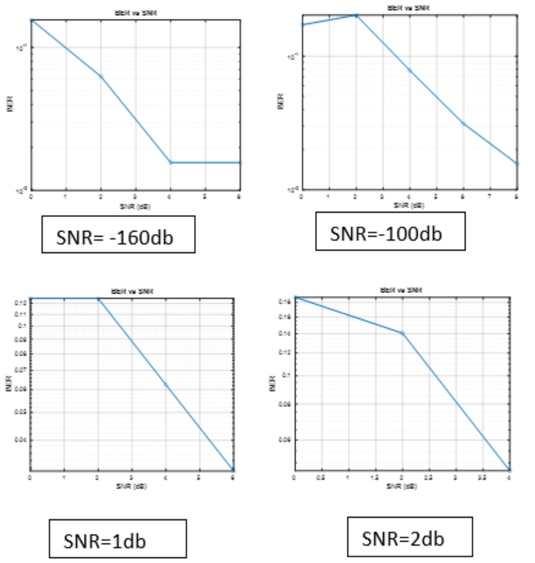
Fig.3: Plots of OFDM signal processing stages



1. **Time Domain Signal**: Shows the real part of the OFDM signal in the time domain before any modifications, representing the base signal generated by the IFFT.
2. **Time Domain Signal with Cyclic Prefix (No Noise)**: Displays the time domain signal with the cyclic prefix added, in blue, and the cyclic prefix itself, in red, without any noise, highlighting the prefix's role in mitigating inter-symbol interference.
3. **Time Domain Signal with Cyclic Prefix (with AWGN)**: Depicts the signal with the cyclic prefix after adding Additive White Gaussian Noise (AWGN). The noise is evident as random fluctuations superimposed on the signal, illustrating its impact on signal quality.
4. **Received Signal after Cyclic Prefix Removal**: Illustrates the signal after removing the cyclic prefix and processing through the channel. This plot shows the degraded signal quality due to noise and potential distortions introduced during transmission.

The figure 4 represents noise of -160db/hz, -100db/hz, -1db/hz, and 2db/hz added to the generated OFDM signal with a cyclic prefix with it.

In this simulation, we examine the effects of different noise levels on an OFDM signal transmitted through a 3x3 MIMO system. We apply varying levels of Additive White Gaussian Noise (AWGN) to the transmitted signal, simulating different Signal-to-Noise Ratios (SNRs). The plots illustrate the magnitude of the MIMO channel coefficients, the transmitted OFDM signal, the received signal with AWGN, and the detected OFDM signal using Zero-Forcing detection. These visualizations demonstrate the system's performance and the effectiveness of MIMO detection techniques under varying noise conditions.



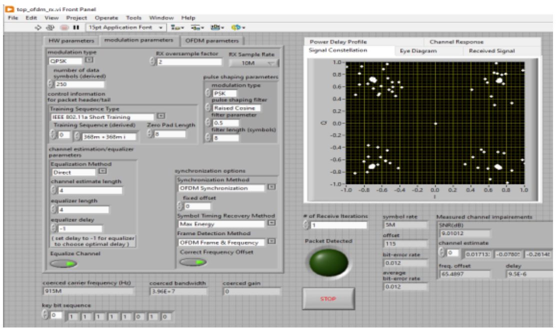
SNR= -160db

SNR=-100db

SNR=1db

SNR=2db

Fig.4: Different values of noise added to the OFDM signal



modulation type: QPSK
RX oversample factor: 2
RX Sample Rate: 10M
number of data symbols (derived): 250
control information for packet header/tail
Training Sequence Type: IEEE 802.11a Short Training
Training Sequence (derived): 0 | 368m +368m i
Zero Pad Length: 8
pulse shaping parameters
modulation type: PSK
pulse shaping filter: Raised Cosine
filter parameter: 0.5
filter length (symbols): 8
channel estimation/equalizer parameters
Equalization Method: Direct
channel estimate length: 4
equalizer length: 4
equalizer delay: -1
(set delay to -1 for equalizer to choose optimal delay)
Equalize Channel
synchronization options
Synchronization Method: OFDM Synchronization
fixed offset: 0
Symbol Timing Recovery Method: Max Energy
Frame Detection Method: OFDM Frame & Frequency
Correct Frequency Offset
# of Receive Iterations: 1
symbol rate: 5M
offset: 115
bit-error rate: 0.012
average bit-error rate: 0.012
Measured channel impairements
SNR(dB): 9.01012
channel estimate: 0 | 0.01713: | -0.0780! | -0.2614!
freq. offset: 65.4897
delay: 9.5E-6
coerced carrier frequency (Hz): 915M
coerced bandwidth: 3.96E+7
coerced gain: 0
key bit sequence: 0 | 1 1 1 1 1 0 1 0

Fig.5: Constellation Diagram of 4-QAM in LabVIEW

The Implementation of OFDM on an NI USRP kit yields the output of a 4-QAM signal which will be visualized in a constellation diagram as four distinct points arranged in a square pattern at coordinates (±A, ±A), where A represents the signal amplitude. Figure 5 represents the constellation output at the receiver end in LabVIEW Software Defined Radio.

Additionally, when analyzing an OFDM signal, a clear and open eye diagram indicates a clean, well-integrated signal with minimal distortion and interference, while a closed or overlapping eye suggests potential issues such as inter-symbol interference or synchronization problems. This is depicted in Figure 6.

The function otfs modulate, which applies Orthogonal Time Frequency Space (OTFS) modulation to the input data, is depicted in this graphic. It starts by restructuring the input data array into a N×MN \times MN×M matrix, where MMM stands for symbols and NNN for subcarriers. The data is subsequently reshaped and transformed using a 2D Inverse Symplectic Finite Fourier Transform (ISFFT) into the time-frequency domain. An Inverse Fast Fourier Transform (IFFT) is applied along the first dimension and a Fast Fourier Transform (FFT) along the second dimension, followed by scaling by N×MN \times MN×M, to transform the time-frequency domain signal into the delay-Doppler domain. The input data is modulated into an OTFS signal by this sequence of transformations, improving robustness against channel defects in high-mobility scenarios and multipath environments, and this 2D modulation is depicted in figure 7.

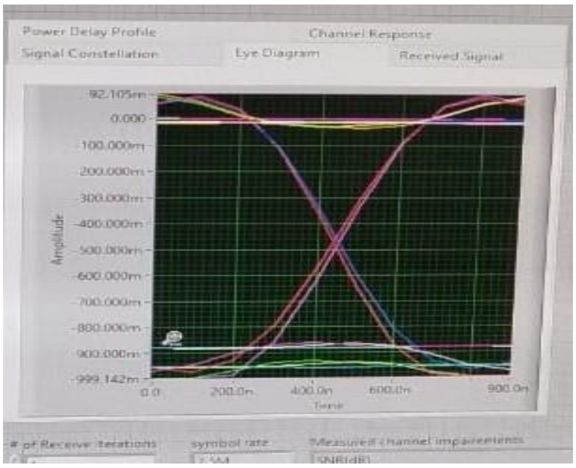


Fig.6: Receiver Eye Diagram

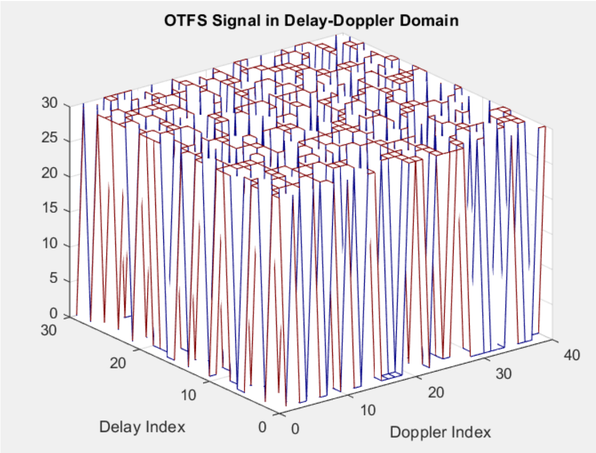


Fig.7: OTFS Output

The design of a 38 GHz antenna impacts OTFS with Multicarrier MIMO in fading scenarios by influencing beamforming capabilities, antenna array configurations, channel estimation accuracy, and overall system performance. A well-designed antenna can enhance the system's ability to manage fading, improve spatial multiplexing, and ensure robust communication in challenging environments depicted in figure 8.

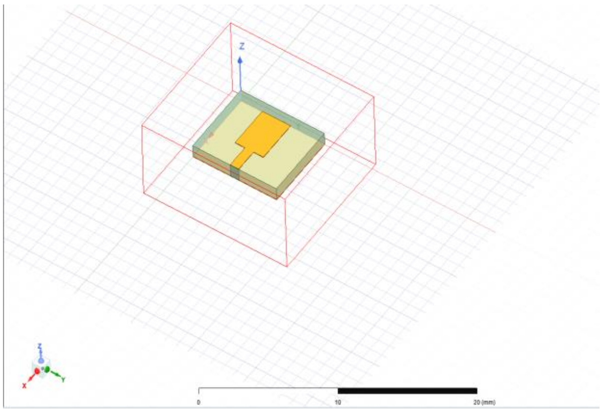


Fig.8: Antenna Design in HFSS

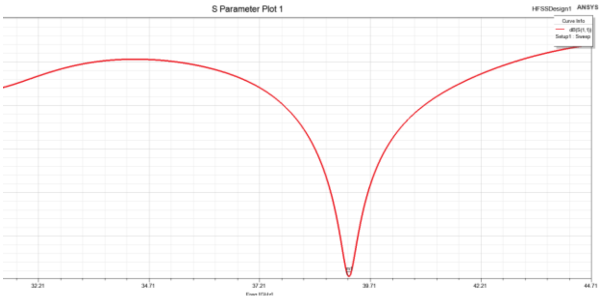


Fig.9: S Parameter Plot

The dip plot showing return loss (S11) versus frequency indicates that the antenna is resonant at approximately 38.5 GHz, achieving optimal efficiency for transmission and reception. A sharp and deep dip at this frequency reflects excellent impedance matching and a well-defined bandwidth, signifying minimized signal reflections and maximized power transfer. The low return loss at 38.5 GHz further confirms that the antenna is well-tuned for effective performance.X axis represents the reflection coefficient and Y axis is frequency.This is depicted in figure 9.

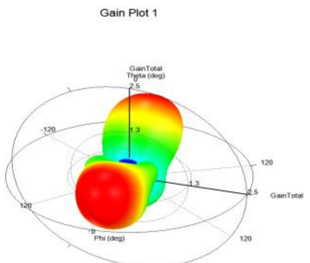


Fig.10: 3D Gain

The 3D polar plot of the antenna's radiation pattern shows its energy distribution, with the main lobe indicating primary radiation direction, higher intensity regions reflecting gain, and beamwidth revealing whether the antenna is high-gain and directional, essential for effective 6G communication.

5. Conclusion

This work has examined the integration of multicarrier Multiple-Input Multiple-Output (MIMO) systems under various fading situations with Orthogonal Time Frequency Space (OTFS) modulation. When coupled with MIMO technology's advantages in spatial diversity and multiplexing, OTFS's unique ability to map data symbols in the delay-Doppler domain holds great promise for enhancing wireless communication systems' performance. The OTFS-MIMO system provides enhanced robustness and spectrum efficiency, according to simulation studies, especially in high-mobility and multipath settings where traditional modulation techniques usually struggle.

The findings suggest that OTFS modulation can effectively mitigate the adverse effects of fading and Doppler shifts, making it a promising candidate for next-generation communication systems. Future research can build on this work by exploring advanced receiver algorithms, optimizing parameter settings, and conducting real-world experiments to further validate the benefits of OTFS in practical scenarios. By continuing to refine and expand the understanding of OTFS in multicarrier MIMO contexts, researchers can contribute to the development of more reliable and efficient wireless communication technologies.

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