Performance Analysis and Comparison between F-OWDM (Filter Bank-based Orthogonal Wavelet Division Multiplex) and OFDM (Orthogonal Frequency Division Multiplex)

Project Report

Introduction

The rise of fifth generation (5G) and beyond wireless communication systems is driven by an increasing demand for high-data-rate transmissions, surge in device connectivity and the need for reliable, low-latency services across diverse applications. Unlike fourth generation (4G) long-term evolution/advanced (LTE/LTE-A) systems, 5G is designed to support advanced applications such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). This progression promises to significantly broaden the scope of current communication networks.

Traditional cyclic prefix-orthogonal frequency division multiplexing (CP-OFDM), which forms the backbone of 4G systems, effectively combats fading channels and maintains low complexity. But, its use of rectangular pulses increases susceptibility to frequency and time offsets, leading to significant out-of-band (OoB) leakage and performance degradation under dense user conditions. Consequently, researchers are exploring alternative waveforms to meet the requirements of future generations.

New waveforms like universal filtered multi-carrier (UFMC), filtered-OFDM (F-OFDM), generalized frequency division multiplexing (GFDM), and filter bank multi-carrier (FBMC) have been proposed to overcome these limitations.

The adaptation of wavelet-transform (WT) based OFDM is gaining traction as a robust alternative. Orthogonal wavelet division multiplexing (OWDM), which utilizes wavelet filter banks, enhances system resilience to noise and adjacent channel interference, while reducing inter-symbol interference (ISI) and inter-carrier interference (ICI). Comparative studies show that OWDM achieves superior spectrum efficiency and better performance in terms of peak-to-average power ratio (PAPR), bit error rate (BER) and power spectral density (PSD) compared to traditional discrete Fourier transform-OFDM (DFT-OFDM) and filtered DFT-OFDM (F-DFT-OFDM), highlighting its potential for enhancing F-OFDM systems.

Problem Statement

The high Peak-to-Average Power Ratio (PAPR) of Filtered-Orthogonal Frequency Division (F-OFDM) leads to inefficiencies and performance issues in 5G and beyond wireless systems, necessitating the exploration of alternative multicarrier modulation techniques.

Our reference studies propose the Filtered Orthogonal Wavelet Division Multiplexing (F-OWDM), utilizing wavelet transforms to replace Fourier transforms, aiming to eliminate the need for a cyclic prefix and to improve bandwidth efficiency while reducing PAPR, Bit Error Rate (BER) and Power Spectral Density (PSD) compared to conventional F-OFDM.

In this project, we aim to simulate and reproduce the OWDM system and report the results of its performance.

Current 5G Modulation Schemes

Quadrature Amplitude Modulation (QAM)

- QAM is a widely used modulation scheme in 5G for its efficiency in transmitting multiple bits per symbol.
- It modulates both the amplitude and phase of the carrier signal to represent digital data.
- Variants like 16-QAM, 64-QAM, and 256-QAM are commonly employed in 5G networks.

Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM is a fundamental modulation scheme in 5G, especially for downlink transmissions.
- It divides the available frequency spectrum into orthogonal subcarriers, allowing for efficient data transmission.

Generalized Frequency Division Multiplexing (GFDM)

- GFDM is a flexible approach to subcarrier multiplexing, which allows for lower Out-of-Band (OOB) radiation and reduced interference. It's considered for scenarios that require high spectral efficiency and low latency.

What is OFDM and OFDMA?

OFDM: Orthogonal frequency-division multiplexing is a method of data transmission where a single information stream is split among several closely spaced narrowband subchannel frequencies instead of a single Wideband channel frequency.

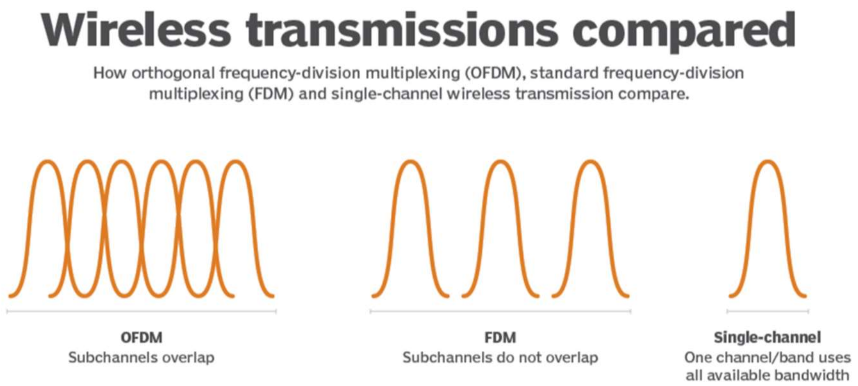

Figure 1: OFDM waveform source- https://www.techtarget.com/searchnetworking/definition/orthogonal-frequency-division-multiplexing

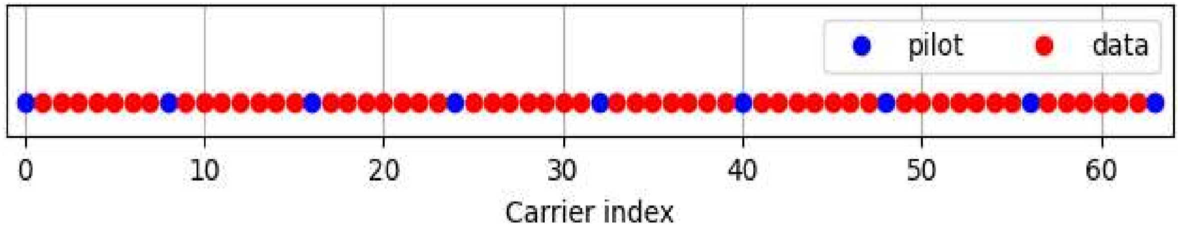

Figure 2 : OFDM signal pilot and user data.

OFDMA: OFDMA (orthogonal frequency-division multiple access), a technology in Wi-Fi 6, improves wireless network performance by establishing independently modulating subcarriers within frequencies. This approach allows simultaneous transmissions to and from multiple clients.

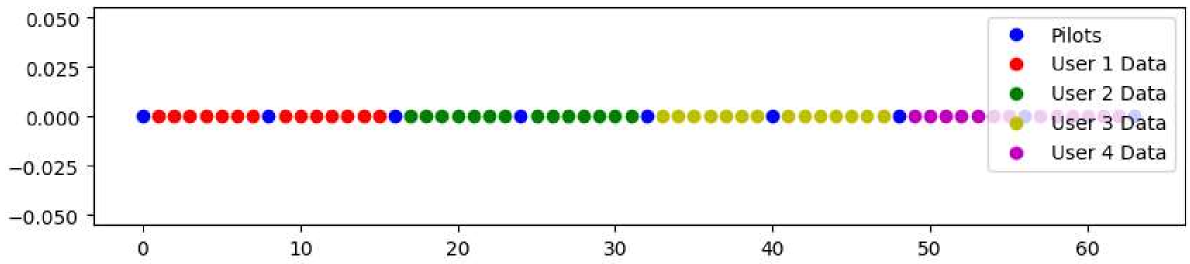

Figure 3: OFDMA pilots and user data

OFDM v/s OFDMA

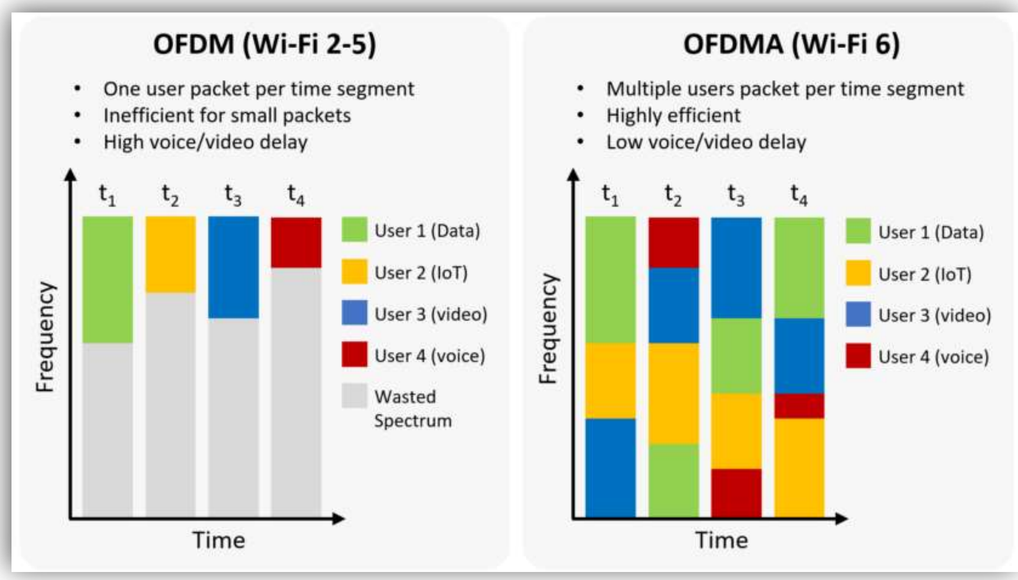

Figure 4: comparison between OFDM and OFDMA

OFDM

Some of the issues and shortcomings of the traditional OFDM are listed below-

1. **High Peak-to-Average Power Ratio (PAPR):** conventional OFDM suffers from high PAPR which causes the RF power amplifiers to operate in its nonlinear region, thus lowering its power efficiency.
2. **Sensitivity to Frequency Offset and Phase Noise:** Traditional OFDM's sensitivity to frequency offset and phase noise leads to inter-carrier interference (ICI) which leads to degradation of signal integrity. The wavelet-based approach in F-OWDM inherently reduces susceptibility to these issues due to overlapping property of the subcarriers enhancing the system's robustness against such problems.
3. **Need for Cyclic Prefix (CP):** In OFDM, the cyclic prefix is required to combat ISI and preserve orthogonality of the carriers over multipath channels. This reduces spectral efficiency and bandwidth. F-OWDM eliminates the need for a CP due to the overlapping properties of wavelets, which effectively handle ISI while improving bandwidth efficiency.
4. **Spectral Leakage:** OFDM uses the Fourier Transform, which causes spectral leakage due to the sinusoidal basis functions that extend infinitely. This issue is overcome by wavelet transforms in F-OWDM, which are better at confining energy within a finite duration.

Wavelet Transform

The wavelet transform is a powerful mathematical tool used for signal processing and analysis that can provide both time and frequency information simultaneously, offering a way to analyze different components of a signal at various scales.

Wavelet transforms work by breaking down a signal into a series of scaled and shifted versions of a waveform called the "mother wavelet." The process involves convolving the signal with a wavelet function (Haar, Daubechies, Biorthogonal, Symlet etc.) that vary in width, allowing detailed analysis of signal features at different scales. This feature is especially beneficial for analyzing non-stationary signals where the spectral properties change over time.

The key concepts in wavelet transform include decomposition and reconstruction. Decomposition involves passing the signal through a series of Low Pass and High Pass filters (LPF & HPF) to analyze the signal at different frequencies and resolutions. The output consists of approximation coefficients, representing low-frequency components and detail coefficients, representing high-frequency components. Reconstruction, on the other hand, is the process of rebuilding the original signal from these coefficients, ensuring that no information is lost if the transform is reversible.

Fourier transforms when compared with wavelet transforms, decomposes a signal into sinusoids of different frequencies, providing a frequency spectrum that shows the entire duration of the signal. However, it lacks the ability to locate these frequencies in time. In contrast, wavelet transforms provide information about both frequency and location in time, making them highly effective for analyzing transient, high-frequency components. Moreover, wavelets are better suited for analyzing signals with sharp spikes and edges, as they adaptively match the scale of analysis to the frequency of interest, a capability not inherent in the Fourier approach. Thus, wavelet transforms offer a flexible and comprehensive framework for signal analysis, applicable across various domains including telecommunications, image processing, and beyond.

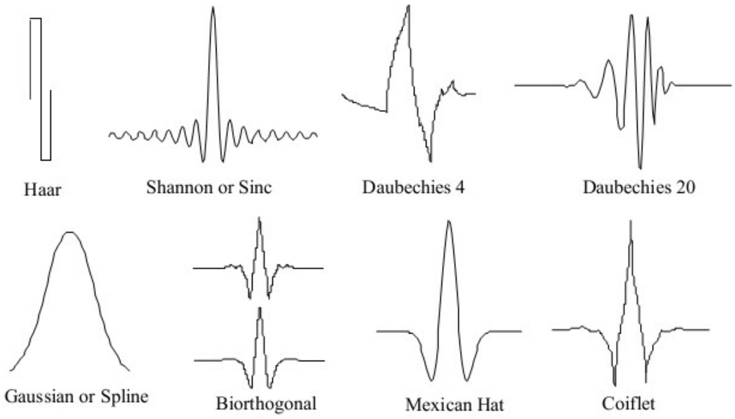

Figure 5: Types of Wavelet Functions (source: https://www.continuummechanics.org/wavelets.html)

HAAR WAVELET

The Haar wavelet function, referred to as "haar", was first identified by a Hungarian scientist. It is the oldest and simplest form of wavelet function. Known for its memory efficiency, the Haar wavelet effectively preserves the energy of the signal.

DAUBECHIES WAVELET

The Daubechies wavelets, which are both orthogonal and biorthogonal, are denoted by dbN, where N represents the order within the family. These wavelets are characterized by their lack of symmetry.

BIORTHOGONAL WAVELET

Biorthogonal wavelets are a type of wavelet known for their linear phase properties and biorthogonal nature. These wavelets enable precise signal reconstruction using FIR filters. As a generalization of orthogonal wavelet systems, biorthogonal wavelets offer greater flexibility and are easier to design.

SYMLET WAVELET

Symlet wavelets, denoted as symN, are recognized as the least-asymmetric wavelets within the Daubechies family and feature the maximum number of vanishing moments. These wavelets are modifications of the dbN wavelets, altered by Daubechies to enhance their symmetry and simplicity.

COIFLET WAVELET

Coiflets, a type of discrete wavelet, were developed by Ingrid Daubechies following a request from Ronald Coifman. These wavelets are designed to feature scaling functions with vanishing moments, contributing to their near-symmetric nature.

WAVELET TRANSFORM IN OFDM

- **Higher Bandwidth Efficiency:** Due to wavelets' overlapping sub-carrier property in the time and frequency domains, the received signal always maintains orthogonality and hence does not require a cyclic prefix.

- **Lower PAPR value.**

Experimental Setup & Method

- In this setup we are using 64 OWDM subcarriers which includes 55 data carries to carry the data bits and 9 pilot carriers for channel estimation. For generating the data bits, we have used a binomial distribution. In practice, the pilot carrier values are known to both the transmitter and receiver and the receiver uses the received value of the pilot carriers to estimate the channel impulse response and ultimately reconstruct the data carriers.
- For modulation of the carriers, we have used 16QAM where the carriers are mapped into groups of 4 bits.

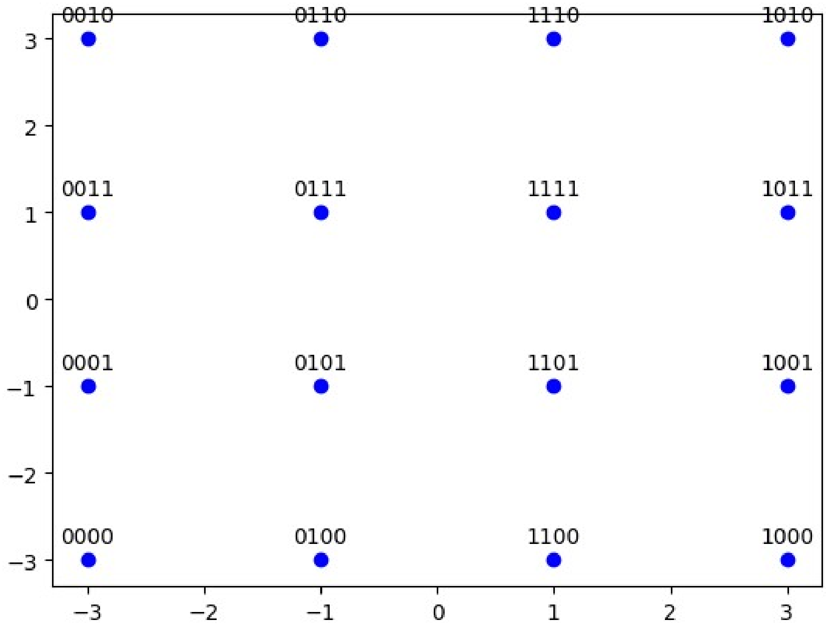

Figure 6: 16QAM using Gray Mapping

- The QAM modulated signal is then fed into the IDWT (Inverse Discrete Wavelet Transform Block). In this setup, we are using a level 3 reconstruction i.e. we perform IDWT three times by passing the QAM modulated as the approximation coefficients and a zero-padded signal as the detail coefficients. As per the proposed design, the convolution of step in IDWT is a circular type convolution which is set by setting the mode to 'periodic'. The IDWT and DWT steps are applied using the Pywavelets package in python. The approximate coefficients (signal) is up-sampled by a factor of 2 and fed into a LPF while the detail coefficients (zero-padded signal) is up-sampled and passed through the HPF. The outputs of the filters are combined and the process is repeated 2 more times to get the final output which is ready for transmission.

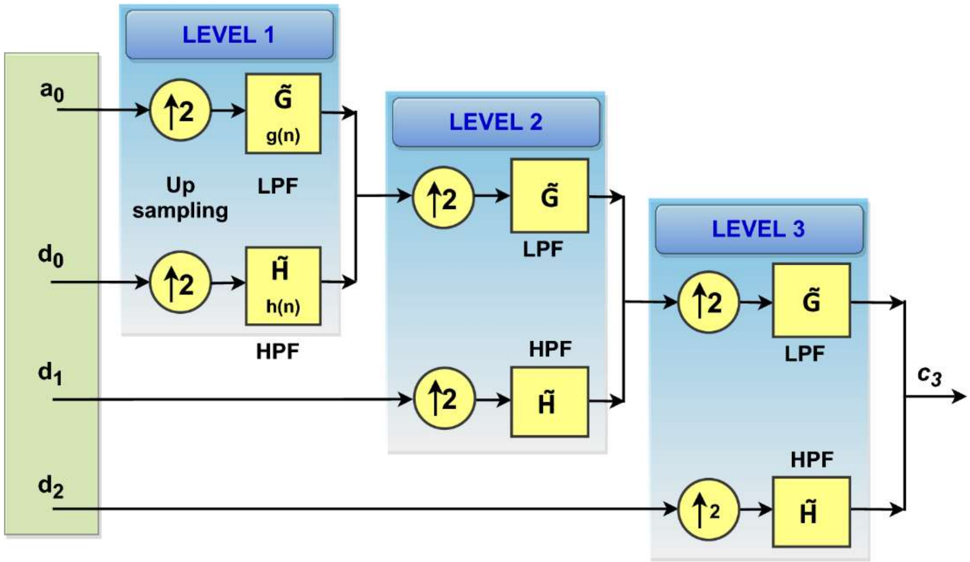

Figure 7: Three-level inverse discrete wavelet transform [1]

- The output of the IDWT block, the time series signal, is then fed into the channel to the receiver. The channel response is defined by -> $[1,\ 0\ ,\ 3+3j]$ + noise (as defined by SNR). When the signal is fed into the channel, the signal is essentially convolved with the channel's impulse response.
- Once the signal is received, level-3 DWT (decomposition) is performed to obtain the approximation and detail coefficients. Here, the process outlined in the IDWT block is performed in the reverse direction to retrieve the original signal. We retain the approximate coefficients and discard the detail coefficients since we only require the low frequency components.

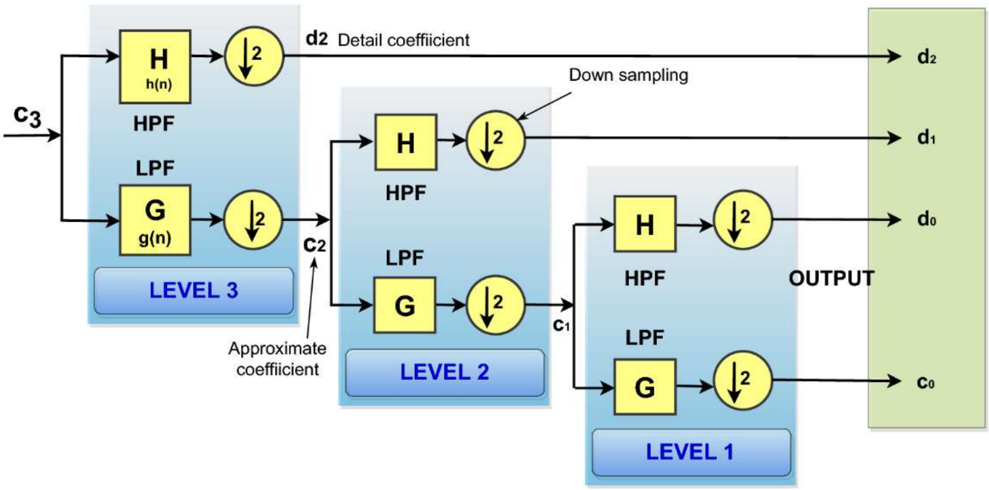

Figure 8: Three-level discrete wavelet transform [1]

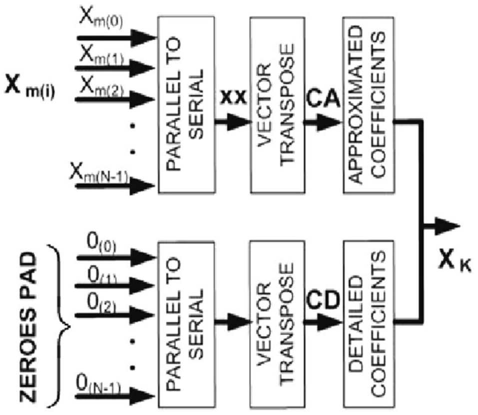

Figure 9: Transmitter IDWT Block [3]

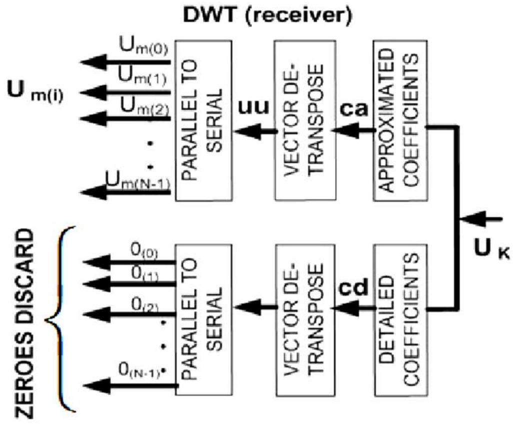

Figure 10: Receiver DWT Block [3]

- After decomposition, the pilot carriers are extracted and used for channel estimation and equalization of the data carriers. The data carriers are retrieved by de-mapping with the same QAM map.

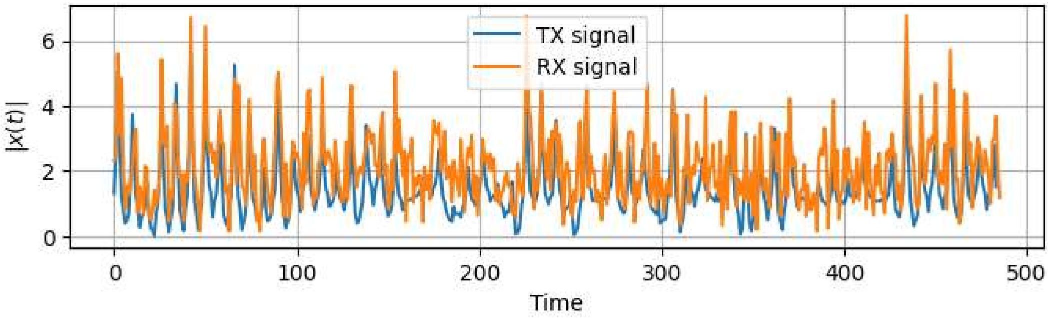

Figure 11: Wavelet: bior2.2; SNR: 5dB; Decomposition Level: 3

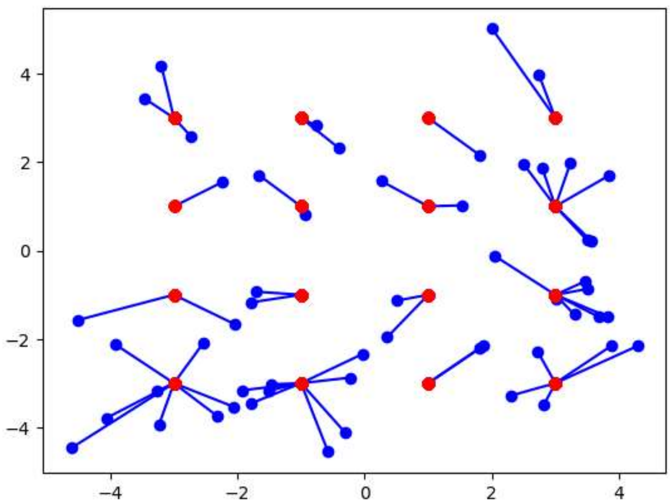

Figure 12: Received Constellation (Blue)

Result and Analysis

For a thorough performance evaluation of the F-OWDM system, the input data is modulated using the M-QAM technique. To analyze the effectiveness of the proposed system comprehensively, we examined various parameters including power spectral density (PSD), Peak-to-Average Power Ratio (PAPR), and Bit Error Rate (BER) performance.

In this study, we evaluated the performance of the F-OWDM system in both an AWGN environment and a multipath Rayleigh fading channel with 10 channel taps. We compared its performance with that of the F-OFDM system to assess the benefits of the F-OWDM system over the latter.

PSD

PSD serves as an important measure in evaluating the spectral efficiency of a specific waveform technique. Additionally, PSD represents the bandwidth efficiency of the proposed F-OWDM technique, and the adjacent channel interference caused by side lobe effects. In this section, we compare the PSD performance of the F-OWDM technique with that of the F-OFDM, C-OFDM, and OWDM techniques.

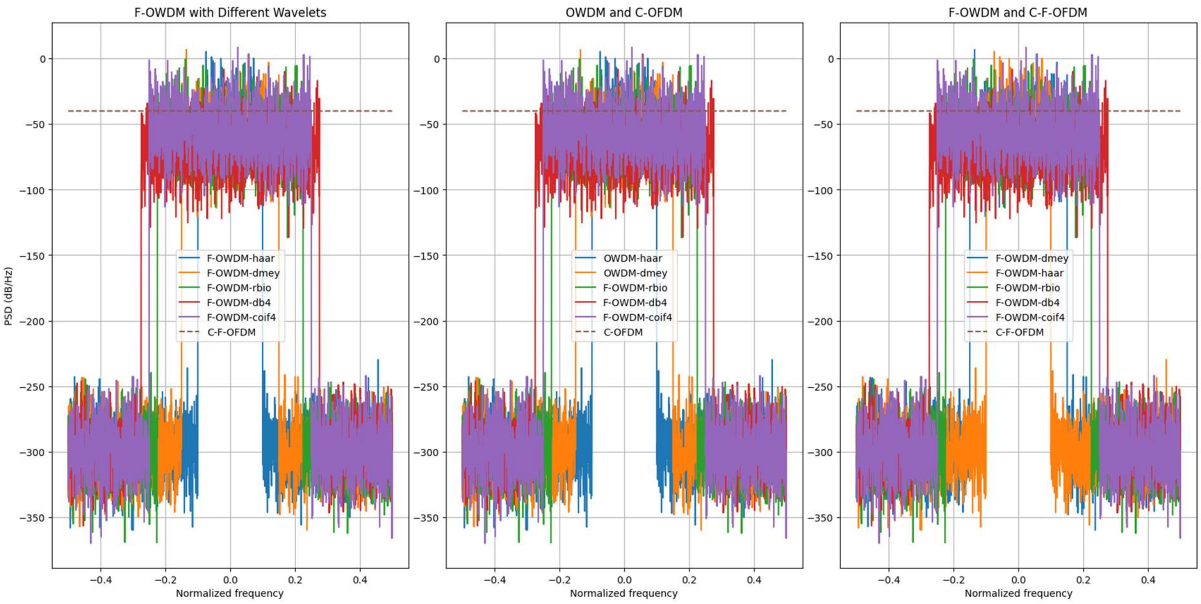

Figure 13: PSD Comparison with different wavelets

PAPR

PAPR is a key performance indicator (KPI) for wireless communication systems because it significantly influences the design and cost of power amplifiers through its impact on linearity levels. PAPR is assessed by calculating the complementary cumulative distribution function (CCDF) of the waveform, considering factors such as the number of subcarriers and the order of the constellation.

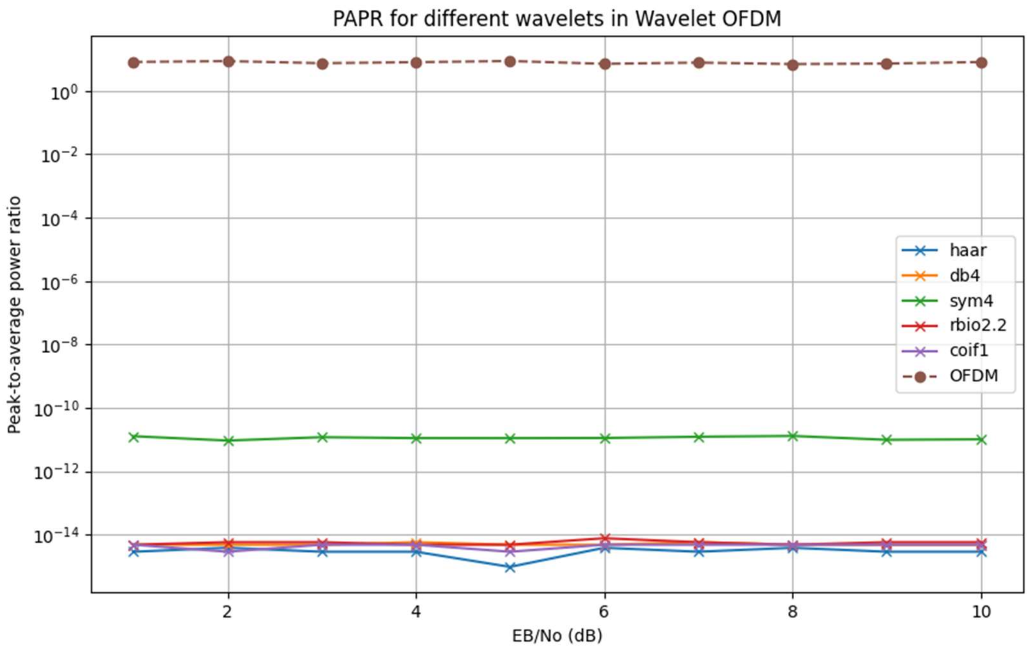

Figure 14: PAPR Comparison with different wavelets

BER

The simulation results for the Bit Error Rate (BER) characteristics of the F-OWDM system were evaluated in comparison with the F-OFDM system to assess the performance improvements of the proposed system. This analysis involved comparing the BER performance at various Signal-to-Noise Ratio (SNR) levels for both the F-OWDM and F-OFDM systems using 4-QAM and 16-QAM modulation techniques.

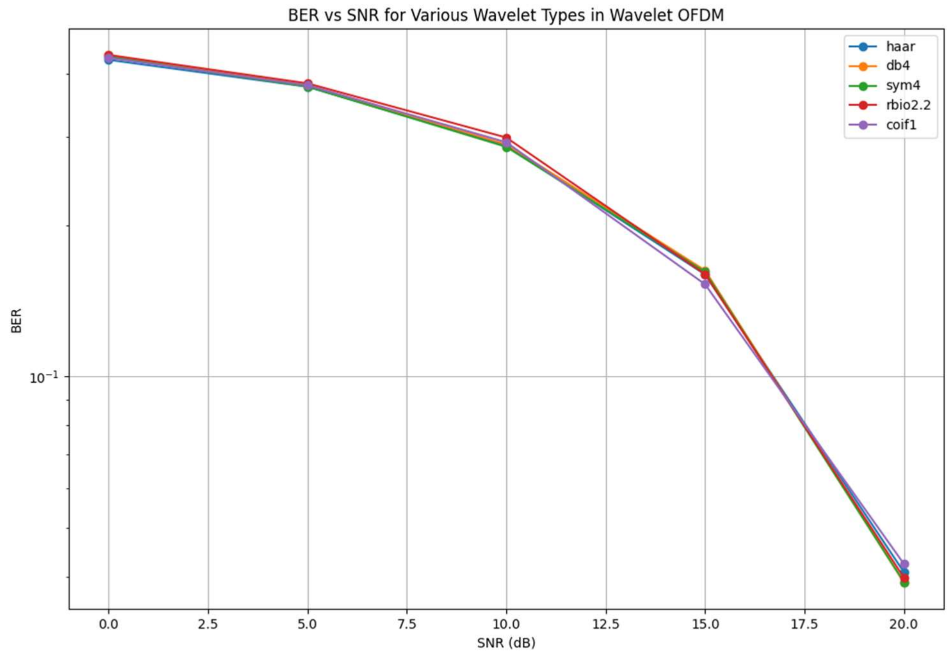

Figure 15: BER Comparison with different wavelets

Conclusion & Future Work

Our project successfully implemented and analysed the performance of Filter Bank-based Orthogonal Wavelet Division Multiplexing (F-OWDM) and Orthogonal Frequency Division Multiplexing (OFDM) systems using Python. Through this implementation, we were able to reproduce most of the theoretical results (as reported in [1]) and perform a comparative analysis, providing insights into the capabilities and limitations of each technique.

Our experiments show that OWDM offers advantages over traditional OFDM, particularly in terms of reducing inter-symbol interference (ISI) and inter-carrier interference (ICI), which enhances the robustness and efficiency. OWDM's use of wavelet-based filtering techniques also resulted in improved spectral efficiency (removal of CP), Bit Error Rate (BER) and a better peak-to-average power ratio (PAPR), making it a compelling choice for modern communication systems that require higher data rates and spectrum, like 5G.

Some of the challenges associated with OWDM are the computational complexity introduced by the wavelet transforms and the need for more sophisticated hardware to support real-time processing. Despite these challenges, the benefits of OWDM, particularly its efficiency in bandwidth utilization and its robustness against signal degradation, present a strong case for its adoption in 5G systems.

As a future work, exploring the use of Short Time Wavelet Transform could potentially yield better performance, as it is robust against phase changes. Additionally, reimplementing the system in MATLAB might provide a more accurate simulation output, capturing finer design aspects of the OWDM system that our Python implementation may have overlooked. Furthermore, experimenting with various low-pass and high-pass filters to find those better tuned for modulation signals could enhance system performance.

Overall, this project not only deepened our understanding of these two multiplexing techniques and the signal processing behind the scenes, but also demonstrated the simulated implementation of these systems.

Project Code: https://github.com/farishr/EECE7364-Mobile-Wireless-Networking-Project

References

[1] Almutairi, A.F., Krishna, A. Filtered-orthogonal wavelet division multiplexing (F-OWDM) technique for 5G and beyond communication systems. *Sci Rep* **12**, 4607 (2022). https://doi.org/10.1038/s41598-022-08248-3

[2] Mordecai F. Raji, JianPing Li, Amin Ul Haq, Victor Ejianya, Jalaluddin Khan, Asif Khan, Mudassir Khalil, Amjad Ali, Ghufran A. khan, Mohammad Shahid, Bilal Ahamad, Amit Yadav, Imran Memon, "A New Approach for Enhancing the Services of the 5G Mobile Network and IOT-Related Communication Devices Using Wavelet-OFDM and Its Applications in Healthcare", *Scientific Programming*, vol. 2020, Article ID 3204695, 13 pages, 2020. https://doi.org/10.1155/2020/3204695

[3] K. Abdullah and Z. M. Hussain, “Simulation of models and BER performances of DWT-OFDM versus FFT-OFDM,” *Discrete Wavelet Transforms*, IntechOpen, London, UK, 2011

[4] Python Implementation of OFDM - https://dspillustrations.com/pages/posts/misc/python-ofdm-example.html