Original Research Article

Exploring Performance Metrics of OFDM, F-OFDM, FBMC, and UFMC Modulation Techniques for 5G Wireless Communication in Terms of PSD, BER, and SNR

ABSTRACT

Aim: The study explores the role of modulation techniques in 5G wireless communication systems to meet demands for higher data rates, lower latency, and improved connectivity. It focuses on optimizing power spectral density (PSD), enhancing data transmission reliability, and reducing bit error rates (BER) and interference.

Study Design: This study provides an overview of modulation concepts and their evolution from earlier generations to 5G. It examines primary modulation schemes used in 5G, offering a comparative analysis of their strengths and weaknesses.

Place and Duration of Study: The study was conducted in a research and development setting over six months, using MATLAB software for implementation**.**

Methodology: The study involved a literature review of modulation techniques in wireless communication, focusing on Orthogonal Frequency Division Multiplexing (OFDM), Filter-Orthogonal Frequency Division Multiplexing (F-OFDM), Filter Bank Multi-Carrier (FBMC), and Universal Filtered Multi-Carrier (UFMC). MATLAB software was used for simulation and analysis. The evaluation was based on performance in terms of PSD, BER, and signal-to-noise ratio (SNR).

Results: Orthogonal Frequency Division Multiplexing (OFDM) shows low BER at high SNR but degrades at lower SNRs, requiring high SNR to maintain low BER. Filter-Orthogonal Frequency Division Multiplexing (F-OFDM) improves BER over OFDM in noisy environments due to reduced out-of-band emissions and better spectral efficiency. Filter Bank Multi-Carrier (FBMC) has lower BER than OFDM, especially in multipath fading environments, and maintains lower BER at lower SNRs, offering superior spectral efficiency with higher complexity. Universal Filtered Multi-Carrier (UFMC) provides balanced performance with moderate BER across varying SNRs, offering a trade-off between simplicity and efficiency, with stable BER and enhanced spectral efficiency, and reduced latency compared to OFDM**.**

Conclusion: Advanced modulation techniques are crucial for 5G performance. Each scheme has strengths and weaknesses: OFDM is robust and widely used; F-OFDM, FBMC, and UFMC improve spectral efficiency, BER, and SNR management. Selecting the appropriate technique depends on network requirements. MATLAB simulation aids in optimizing 5G network performance.

Keywords: 5G wireless communication, Bit error rates (BER), Filter-Orthogonal Frequency Division Multiplexing (F-OFDM), Filter Bank Multi-Carrier (FBMC)Modulation techniques, Power spectral density (PSD),Universal Filtered Multi-Carrier (UFMC).

1. INTRODUCTION

The realm of wireless communication has undergone a transformative journey, reshaping our connectivity and interactions profoundly. From its inception to its omnipresent status today, wireless technology has facilitated seamless data transmission through the airwaves[1], transcending the confines of traditional wired networks. Its global reach, remote communication capabilities, and the proliferation of mobile devices have fundamentally altered how we engage with information and each other.

Modulation stands as the cornerstone of wireless communication, enabling the encoding of information onto carrier signals for transmission wirelessly. Through modulation, properties like amplitude, frequency, or phase of the carrier signal are manipulated, facilitating the efficient and reliable conveyance of data across the wireless medium. It's indispensable for encoding and decoding crucial information necessary for transmitting voice, video, and data wirelessly.

The journey from 1G to 4G wireless networks has witnessed remarkable progress in speed, capacity, and reliability. Each subsequent generation has brought enhancements in voice clarity, data rates, and network coverage, revolutionizing communication [2]. However, earlier generations grappled with limitations such as restricted coverage, slow data speeds, and susceptibility to interference, hindering their ability to meet escalating user demands and application requirements.

Modulation has been instrumental in shaping the capabilities and constraints of 1G to 4G wireless networks. Early 1G systems utilized basic modulation techniques like Amplitude Modulation (AM) and Frequency Modulation (FM) for transmitting analog voice signals, albeit with limited efficiency and quality. Advancing technology introduced digital modulation schemes such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) in 2G networks, enhancing data rates and spectral efficiency. Subsequent generations embraced sophisticated modulation techniques like Orthogonal Frequency Division Multiplexing (OFDM) and Code Division Multiple Access (CDMA), facilitating higher data throughput, enhanced spectral efficiency, and improved network performance.

The advent of 5G represents a monumental shift in connectivity, promising unparalleled speed, reliability, and scalability [3]. Engineered to support a diverse spectrum of applications including enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communications, 5G holds the potential to revolutionize industries and redefine our lifestyles. With its lightning-fast speeds, minimal latency, and extensive connectivity, 5G is poised to unleash innovations in healthcare, transportation, manufacturing, and entertainment. It fosters ground-breaking technologies like autonomous vehicles, remote surgery, smart cities, and immersive virtual experiences, ushering in an era of connectivity and digital transformation.

To harness the full capabilities of 5G networks, a variety of modulation techniques have been explored [4], each offering distinct advantages and trade-offs. Techniques like Orthogonal Frequency Division Multiplexing (OFDM), Filtered-OFDM (F-OFDM), Filter Bank Multicarrier (FBMC), and Universal Filtered Multicarrier (UFMC) have emerged as frontrunners, offering improved spectral efficiency, enhanced data rates, and increased resilience to interference [5]. This paper delves into the intricacies of these modulation schemes, conducting a comparative analysis to assess their performance metrics and suitability for the diverse demands of 5G communication networks. Through a nuanced understanding of modulation techniques, we aim to provide valuable insights for researchers, network designers, and industry stakeholders navigating the intricate landscape of next-generation wireless communication.

2. RELATED WORK

Muoghalu et al. [6] asserted that OFDM technology plays a pivotal role in modern wireless communication, effectively addressing inter-symbol interference (ISI) challenges. Studies investigating its Bit Error Rate (BER) performance highlight the effectiveness of various digital modulation techniques integrated into OFDM setups. Analysis often indicates that simpler modulation schemes like QPSK and 16-QAM outperform higher-order options in terms of BER. Additionally, simulations demonstrate how factors such as multipath fading profoundly influence OFDM's BER, underscoring the need for robust error correction mechanisms in real-world applications. In summary, comprehending BER dynamics within OFDM systems is essential for optimizing their design and resilience in practical communication settings.

Ali et al. [7] introduce Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) as a potential solution for enhancing Spectral Efficiency (SE) in 5G systems. By dividing the spectrum into smaller sub bands and employing tailored filters, F-OFDM reduces guard band requirements, leading to a 5%-6% increase in SE compared to OFDM. However, F-OFDM exhibits higher Bit Error Rate (BER) than OFDM. Real-time testing confirms its performance using USRP X310 at 2.45 GHz, highlighting its promise despite BER challenges.

Banelli et al. [8] identified the most suitable multicarrier modulation for 5G, analyzing the strengths and weaknesses of commonly used OFDM and evaluating waveform improvements. They assessed spectral efficiency, peak-to-average power ratio (PAPR), and power spectral density (PSD) of Universal Filtered Multicarrier (UFMC) and Filter Bank Multicarrier (FBMC) schemes. Recent examinations [9] highlighted the benefits of UFMC and FBMC schemes in 5G, emphasizing improvements in Out-of-Band (OOB) leakage and PAPR migration. Comparisons with Cyclic Prefix-OFDM (CP-OFDM) [10] revealed UFMC's advantages in reducing spectrum inefficiency and OOB emissions. Further studies [11] favoured UFMC over CP-OFDM due to reduced inter-carrier interference and side lobes. OFDM and UFMC structural analyses [12] provided insights into their transmitter and receiver designs.

FBMC modulation emerged as the preferred technique for meeting 5G requirements [13], with comparative analyses showing its superior performance over OFDM in packet delivery ratio, signal-to-noise ratio, and BER. These studies, while intricate for novice researchers, underline the significance of understanding new waveforms for 5G advancement. Hence, this review offers theoretical insights into OFDM while clarifying F-OFDM, UFMC, and FBMC waveforms, along with essential information on preceding mobile generations to grasp 5G influencing factors. Additionally, it ensures the adaptability of included simulation code for comprehensive understanding.

3. METHODOLOGY

The advancement of modulation techniques is crucial in influencing the performance and capabilities of wireless communication systems. Among the array of modulation schemes developed, Orthogonal Frequency Division Multiplexing (OFDM), Filtered-OFDM (F-OFDM), Filter Bank Multicarrier (FBMC), and Universal Filtered Multicarrier (UFMC) emerge as notable milestones in the pursuit of enhanced and dependable wireless connectivity.

3.1 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a highly effective modulation technique extensively utilized in modern wireless communication systems due to its capacity to handle frequency-selective fading and inter-symbol interference (ISI) [14]. By segmenting the available spectrum into numerous orthogonal subcarriers, each transmitting a portion of the overall data, OFDM improves spectral efficiency and minimizes interference. The block diagram of the OFDM transmitter and receiver is illustrated in Figure 1.

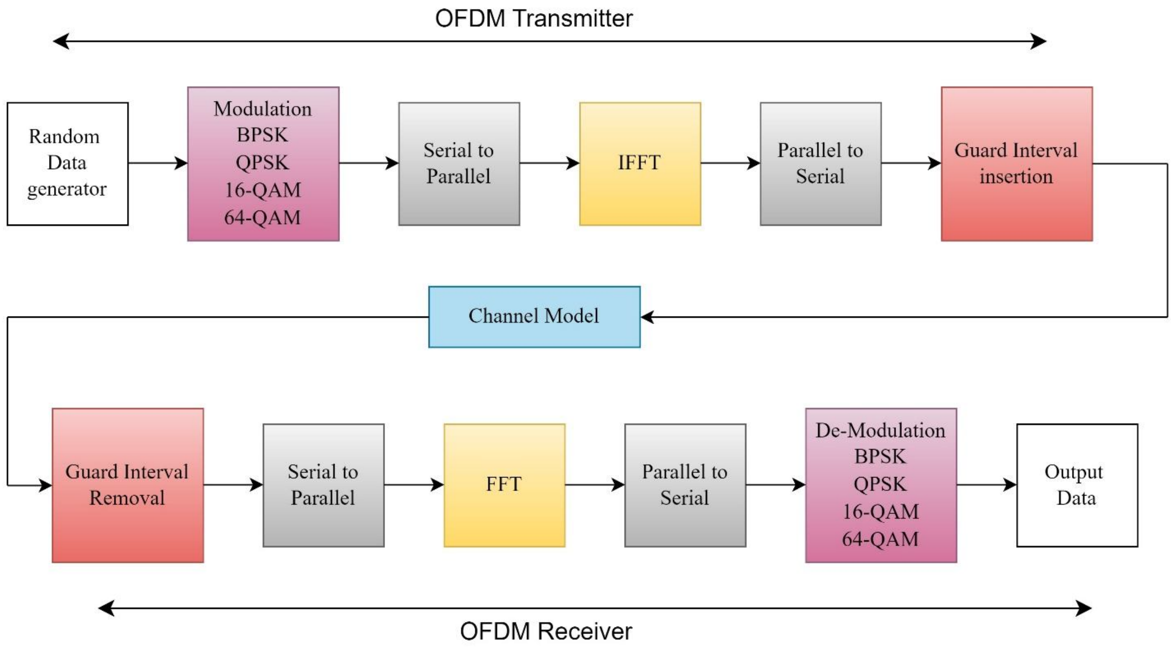

Figure 1: Functional Blocks of OFDM Transmitter and Receiver

In an OFDM transmitter, the input data stream is initially converted from a serial to a parallel format. These parallel data streams are then modulated using digital modulation schemes like QPSK or QAM. Following modulation, the data streams undergo an Inverse Fast Fourier Transform (IFFT), converting them from the frequency domain to the time domain. This process ensures the orthogonality of the subcarriers, allowing simultaneous transmission without mutual interference. To combat ISI, a cyclic prefix is added to each OFDM symbol, serving as a guard interval. The parallel data streams are subsequently reconverted to a serial format for transmission, and the digital signal is transformed into an analog signal for transmission over the wireless channel [15].

In an OFDM receiver, the received analog signal is first converted back to a digital format. This digital signal is then changed from a serial to parallel format, and the cyclic prefix is removed to mitigate ISI. A Fast Fourier Transform (FFT) is applied, converting the parallel data streams from the time domain back to the frequency domain, thereby recovering the original modulated data on each subcarrier. The frequency domain data is then demodulated to retrieve the initial data symbols, which are reconverted to a serial format to reconstruct the original data stream.

OFDM's primary advantages include its resilience to multipath fading, high spectral efficiency, reduced ISI, and scalability. By dividing the signal across many narrowband subcarriers, OFDM effectively mitigates the adverse effects of frequency-selective fading. The use of orthogonal subcarriers ensures efficient spectrum utilization, while the cyclic prefix helps reduce ISI, making OFDM suitable for environments with significant multipath propagation. Additionally, OFDM's adaptability to different bandwidths and data rates makes it versatile for various applications.

Due to its robustness, efficiency, and flexibility, OFDM has become a cornerstone of many contemporary communication standards, including Wi-Fi, LTE, and digital television broadcasting. Understanding the operations of its transmitter and receiver illustrates why OFDM is crucial in delivering high-quality wireless communication.

3.2 Filtered Orthogonal Frequency Division Multiplexing

Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is an enhanced modulation technique that builds on the traditional OFDM system by adding filtering processes. This improvement addresses issues such as spectral leakage and out-of-band emissions, resulting in better spectral efficiency and reduced interference. F-OFDM divides the spectrum into multiple narrowband orthogonal subcarriers grouped into sub-bands, each of which is precisely filtered [16]. This process significantly improves spectrum utilization, making F-OFDM particularly effective in environments where spectrum resources are scarce or costly.

In an F-OFDM transmitter as shown in Figure 2, the input data stream is divided into multiple subcarriers using an Inverse Fast Fourier Transform (IFFT). Unlike traditional OFDM, F-OFDM applies filtering to these subcarriers grouped into sub-bands. The filtering block is introduced after the IFFT stage, ensuring each sub-band is individually filtered to reduce out-of-band emissions and minimize interference with adjacent sub-bands. This filtering process maintains the orthogonality of the subcarriers and enhances the overall spectral efficiency of the transmission.

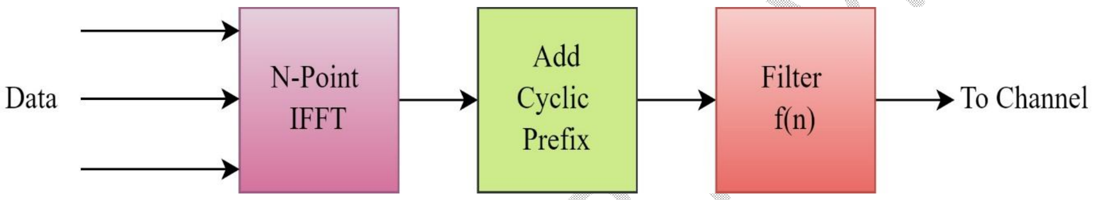

Figure 2: Functional Blocks of F-OFDM Transmitter

The F-OFDM receiver reverses the transmitter's process. The received signal is first converted from the time domain to the frequency domain using a Fast Fourier Transform (FFT). After the FFT stage, corresponding filters are applied to extract the desired sub-bands and reduce interference from adjacent bands. These filters isolate the sub-bands, allowing the receiver to accurately demodulate the transmitted data. By carefully filtering each sub-band, the F-OFDM receiver enhances the robustness of the communication system, especially in environments with high levels of interference or multipath propagation.The block diagram of F-OFDM receiver is as shown in Figure -3.

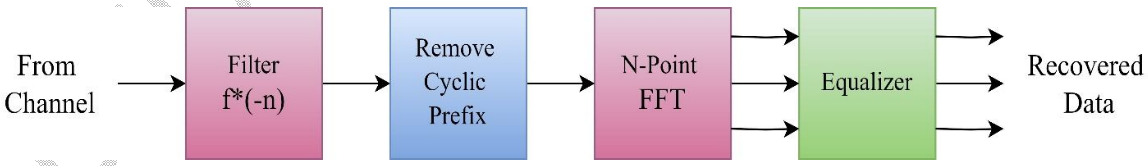

Figure 3: Functional Blocks of F-OFDM Receiver

F-OFDM is well-suited for various applications, particularly in modern wireless communication networks such as 5G [17]. Its ability to enhance spectral efficiency and reduce interference makes it ideal for enhanced mobile broadband (eMBB), which requires high data rates and reliable connectivity for applications like video streaming, online gaming, and virtual reality. F-OFDM is also beneficial for massive machine-type communications (MMTC), where many devices need to communicate simultaneously, such as in the Internet of Things (IoT) and smart city applications. Furthermore, the technique's low latency and high reliability make it suitable for ultra-reliable low-latency communications (URLLC), essential for critical applications like autonomous vehicles, industrial automation, and remote surgery. By offering flexibility and improved performance, F-OFDM supports the diverse and demanding requirements of next-generation wireless communication systems.

3.3 FBMC

Filter Bank Multicarrier (FBMC) modulation is an advanced technique utilized in wireless communication systems to improve spectral efficiency and minimize interference. Unlike traditional Orthogonal Frequency Division Multiplexing (OFDM), which employs a single prototype filter for all subcarriers, FBMC uses multiple filters that provide better frequency response control for each subcarrier. This makes FBMC particularly suitable for applications that require high data rates and robust performance in challenging environments [18].

In an FBMC transmitter as shown in Figure 4, the input data stream is split into several parallel substreams, each linked to a different subcarrier. These substreams are then processed through a set of synthesis filters designed to shape the frequency response of each subcarrier. After filtering, the substreams are combined and converted from the frequency domain to the time domain using an Inverse Fast Fourier Transform (IFFT). The resulting signal is then up-converted to the desired transmission frequency and transmitted.

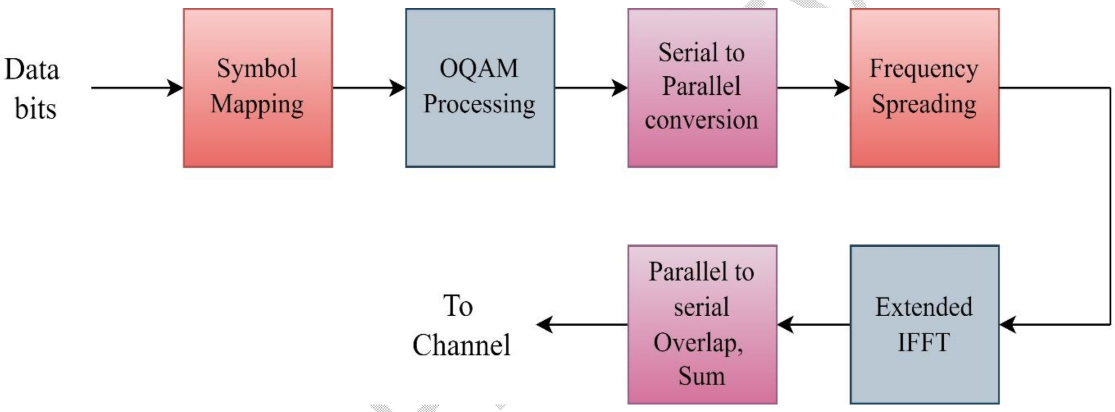

Figure 4: Functional Blocks of FBMC Transmitter

At the receiver, the incoming signal is first down-converted from the transmission frequency to baseband. It is then converted from the time domain back to the frequency domain using a Fast Fourier Transform (FFT). The frequency-domain signal is passed through a bank of analysis filters that isolate each subcarrier. These filters are carefully designed to match the synthesis filters used at the transmitter, ensuring accurate demodulation of the data carried by each subcarrier. Finally, the isolated subcarriers are combined to reconstruct the original data stream.The block diagram of FBMC receiver is as shown in Figure 5.

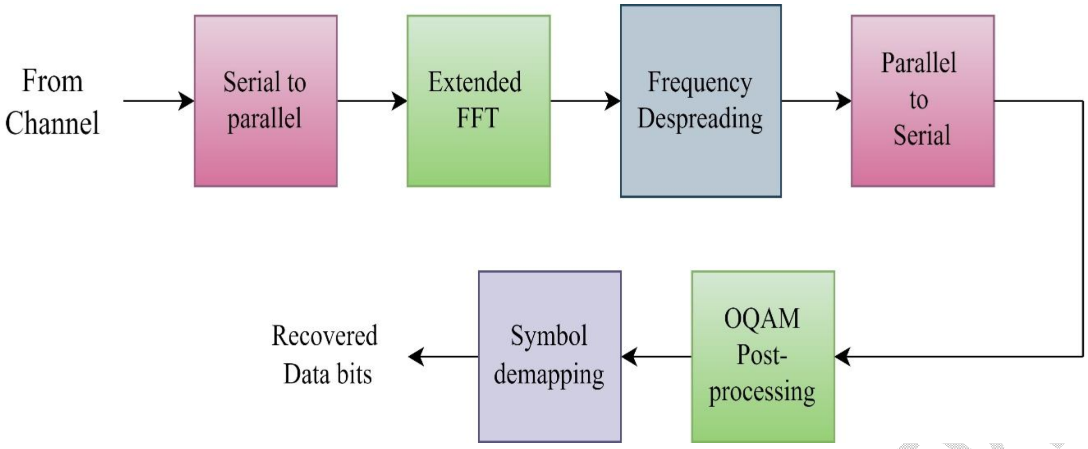

Figure 5: Functional Blocks of FBMC Receiver

FBMC modulation offers several benefits, including improved spectral efficiency and reduced inter-carrier interference, making it ideal for various applications. In broadband wireless access, FBMC can deliver high-speed internet in both urban and rural areas, supporting activities such as video streaming, online gaming, and large data transfers. Its efficient spectrum utilization makes it suitable for cognitive radio systems, where it can dynamically adapt to changing spectral environments. As part of next-generation wireless communication standards like 5G and beyond, FBMC is poised to meet demands for high data rates, low latency, and reliable communication. Additionally, the robustness of FBMC against interference and its efficient spectrum use make it ideal for satellite communication systems, which often operate in crowded frequency bands. Overall, FBMC modulation significantly enhances the performance and efficiency of wireless communication systems, making it a key technology for future communication networks.

3.4 UFMC

UFMC modulation is an innovative approach aimed at enhancing the efficiency and reliability of wireless communication systems. It combines elements from both Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier (FBMC) modulation techniques. UFMC's unique method of applying filters to groups of subcarriers offers a balanced solution, optimizing spectral efficiency while minimizing interference and out-of-band emissions [19]. This makes UFMC particularly suitable for next-generation communication systems like 5G.

In UFMC transmitters as shown in Figure 6, the input data stream is segmented into multiple groups of subcarriers, each representing a distinct sub-band. These sub-bands undergo an Inverse Fast Fourier Transform (IFFT) to convert the data into the time domain. Afterward, specific filters tailored to each sub-band are applied to refine the signal, focusing on reducing spectral leakage and enhancing spectral confinement. Once filtered, these sub-band signals are combined and prepared for transmission at the desired frequency.

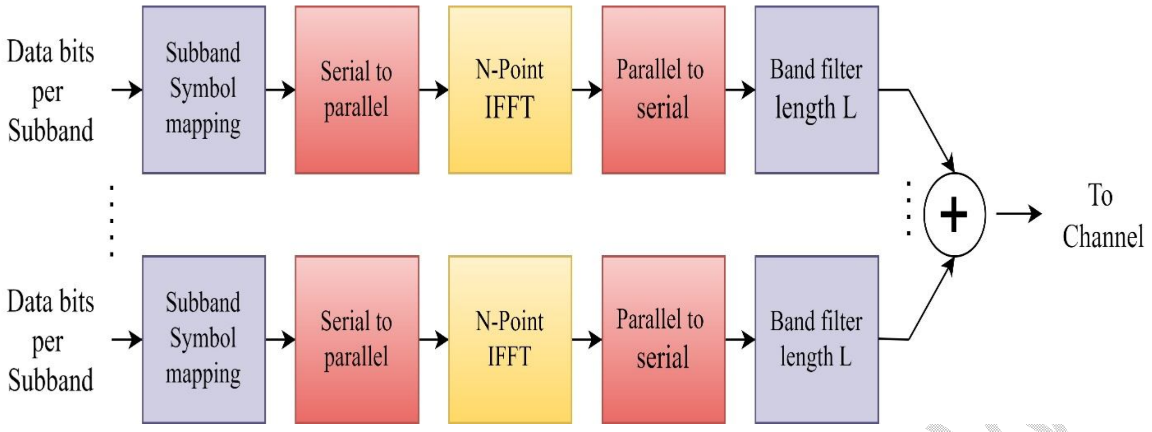

Figure 6: Functional Blocks of UFMC Transmitter

Upon reception, UFMC signals are down-converted to baseband and transformed back into the frequency domain using a Fast Fourier Transform (FFT) process. The signal is then segmented into sub-bands, mirroring the groups established during transmission. Each sub-band undergoes filtering to eliminate unwanted spectral elements and isolate the intended signals. Subsequently, the filtered sub-band signals are demodulated and merged to reconstruct the original data stream.The block diagram of UFMC receiver is as shown in Figure 7.

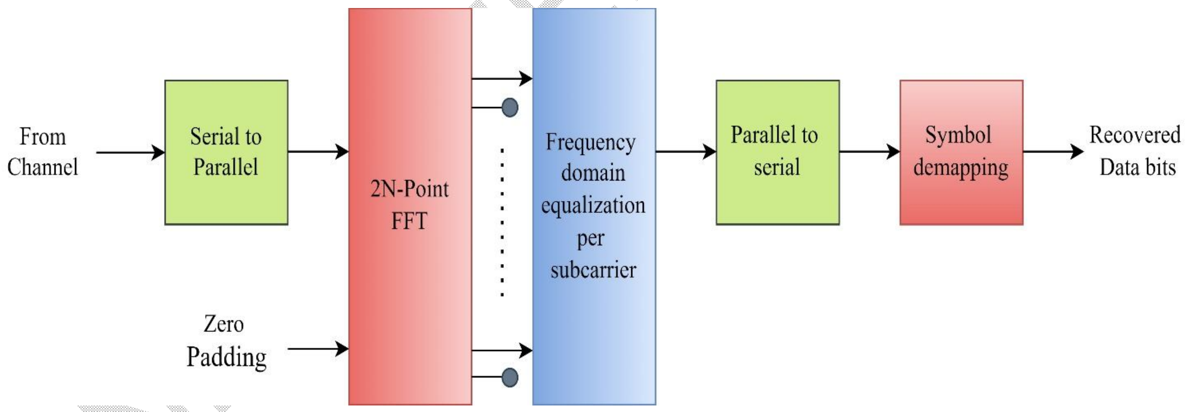

Figure 7: Functional Blocks of UFMC Receiver

UFMC modulation offers numerous advantages, making it suitable for various applications demanding high efficiency and resilience against interference. Its ability to curtail out-of-band emissions makes it ideal for scenarios with stringent spectral requirements, such as coexisting with older systems. UFMC finds ample use in 5G applications, supporting diverse needs like enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). Additionally, UFMC is valuable for vehicle-to-everything (V2X) communications in automotive contexts, ensuring reliable connectivity. It also finds relevance in cognitive radio systems, where adaptability and dynamic spectrum access are paramount. Overall, UFMC elevates the performance and adaptability of wireless communication networks, positioning it as a pivotal component in future communication technologies.

3.5 Evaluated Parameters

In the realm of 5G networks, modulation techniques serve as crucial elements in attaining the lofty goals of high data rates, minimal latency, and dependable connectivity essential for cutting-edge communication systems. Assessing the efficacy of OFDM, F-OFDM, FBMC, and UFMC entails analyzing essential performance metrics like Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and Power Spectral Density (PSD). These metrics offer a comprehensive evaluation of the modulation techniques, shedding light on their applicability across diverse 5G scenarios and applications.

*Bit Error Rate:*It quantifies the frequency of bit errors within a specific timeframe or as the ratio of erroneous bits to the total transmitted bits. In the context of 5G, where high-frequency and high-speed communication is prevalent, BER serves as a critical gauge for assessing system reliability. A lower BER signifies superior performance, indicating minimal errors in data transmission. This metric is pivotal in evaluating the resilience of modulation techniques across various signal environments and noise levels. Accurate BER assessment is vital for upholding data integrity, particularly in the dynamic and noisy settings characteristic of 5G networks. The BER is determined by the formula presented in Equation 1 as:

$$\text{BER} = \frac{\text{Number of bit errors}}{\text{Total number of transmitted bits}} \quad (1)$$

Signal-to-Noise Ratio: SNR is the ratio of the signal power to the noise power present in the system and is a key indicator of the quality of the received signal. A higher SNR typically signifies clearer and more distinguishable signals, leading to improved data transmission quality, which is crucial for the high data rates expected in 5G networks. Evaluating modulation techniques based on SNR helps in understanding their performance under various noise conditions and in different environments. In the context of 5G, SNR directly impacts the achievable data rates and the reliability of connections, particularly in dense urban areas and scenarios with significant interference.The SNR is derived from the formula indicated in Equation 2, and its value is typically expressed in decibels.

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \left(\frac{\text{P}_\text{s}}{\text{P}_\text{n}} \right) \quad (2)$$

Where,

P_s is average signal power

P_n is average noise power

Power Spectral Density: PSD signifies the power dispersion of a signal across different frequency components, playing a crucial role in assessing the bandwidth utilization efficiency of a modulation technique. In 5G networks, where spectrum efficiency is of utmost importance, a well-optimized PSD ensures effective distribution of the signal's power across the spectrum, thereby minimizing interference and enhancing spectral efficiency. PSD analysis is essential for the design and implementation of 5G systems to meet stringent requirements for bandwidth utilization and interference management. It offers valuable insights into the distribution of spectral energy over time, which is essential for long-term signal analysis and system optimization in 5G environments. The formula for PSD is given by Equation 3 as:

$$S\,(f\,) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) e^{-j2\pi f t} dt \right|^2 \quad (3)$$

Evaluating 5G modulation techniques based on BER, SNR, and PSD provides a thorough understanding of their performance characteristics. These parameters help identify the strengths and weaknesses of different modulation schemes, guiding their optimization for specific 5G applications. By focusing on these critical metrics, engineers and researchers can ensure efficient, reliable, and high-quality 5G wireless communication systems. Understanding the interplay between BER, SNR, and PSD is vital for designing robust 5G systems capable of operating effectively in diverse and challenging environments, meeting the high expectations set for next-generation networks.

4. RESULTS AND DISCUSSIONS

Modulation techniques are best assessed and understood through a Bit Error Rate versus Signal to Noise Ratio graph, a vital tool for evaluating the performance of communication systems. These graphs, evaluated using MATLAB, provide insights into how different modulation techniques perform under varying signal and noise conditions. The BER versus SNR graphs for the OFDM, F-OFDM, FBMC, and UFMC modulation techniques are depicted in Figures 8, 9, 10, and 11. These graphs plot BER on the y-axis and SNR on the x-axis, showing how BER changes as SNR varies.

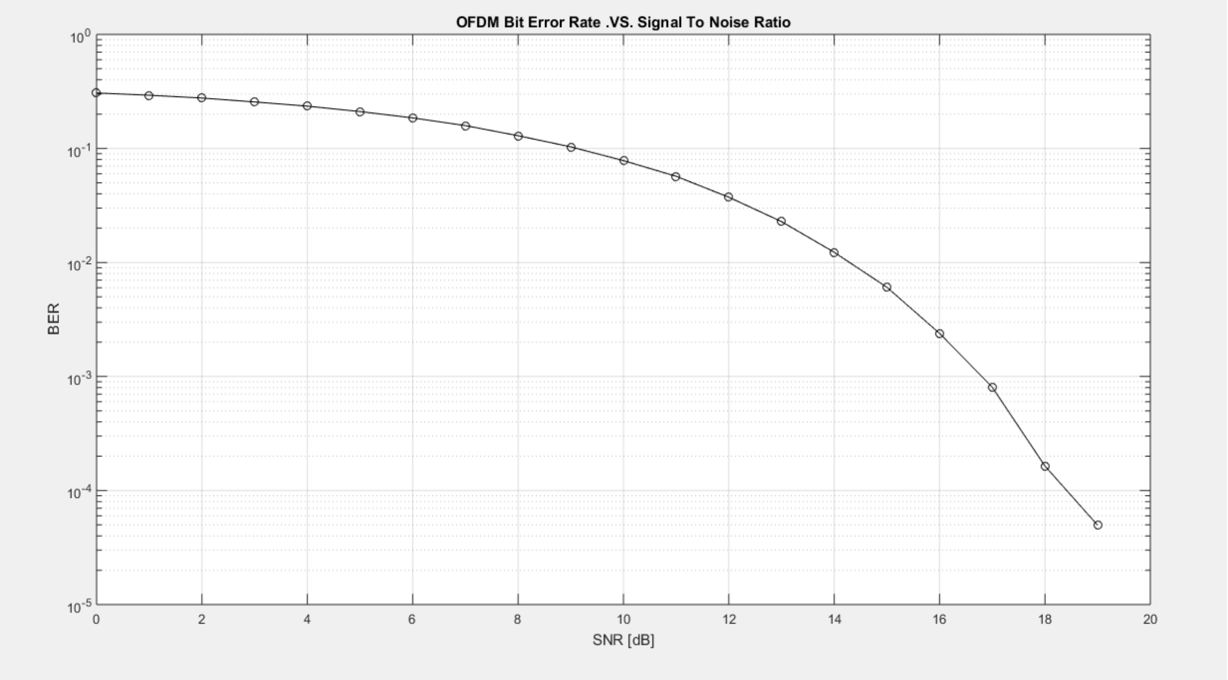

Figure 8: Analysis of BER vs. SNR for OFDM Modulation

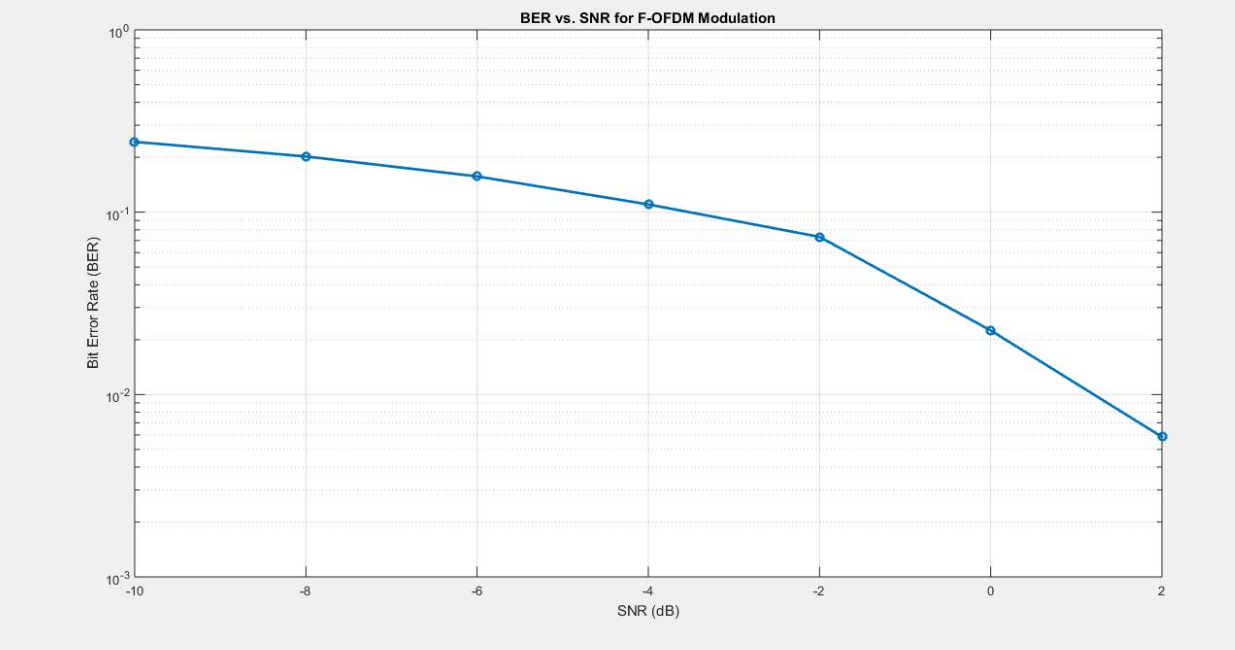

Figure 9: Analysis of BER vs. SNR for F-OFDM Modulation

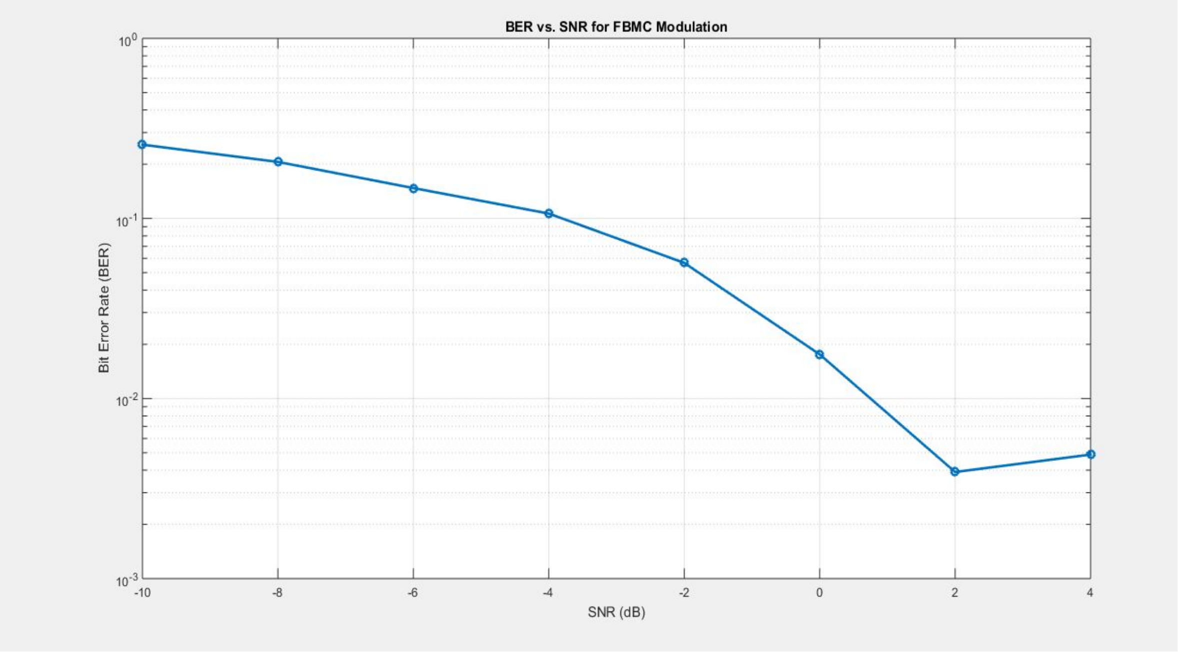

Figure 10: Analysis of BER vs. SNR for FBMC Modulation

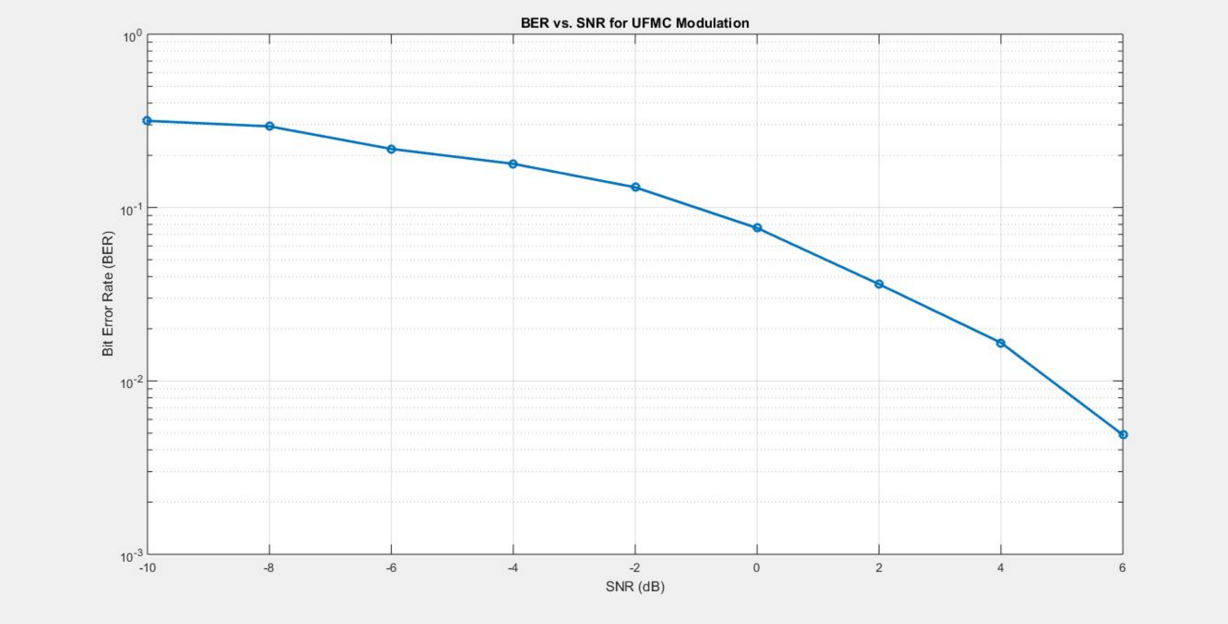

Figure 11: Analysis of BER vs. SNR for UFMC Modulation

The figures clearly demonstrate that at lower SNR values, the BER tends to be higher due to the noise power being comparable to or exceeding the signal power, leading to an increased error rate. Conversely, as the SNR increases, the BER decreases as the signal becomes more discernible from the noise. Typically, these graphs exhibit a downward trend, indicating improved performance, characterized by lower BER values, with higher SNR levels. Such graphical representations are vital for evaluating performance, facilitating comparisons among various modulation techniques, and showcasing how advanced schemes achieve superior performance at lower SNRs. Moreover, they aid in system design by guiding engineers in the selection of appropriate modulation techniques and signal processing methods tailored to meet specific performance requirements. Additionally, the BER and SNR values for OFDM, F-OFDM, FBMC, and UFMC are detailed in Table 1.

Table 1: BER and SNR Performance Metrics for Various Modulation Schemes

Signal to noise ratio (dB)	Bit error rate			
	OFDM	F-OFDM	FBMC	UFMC
-10	0.4184	0.2715	0.2657	0.3066
-8	0.4011	0.2168	0.2148	0.2822
-6	0.3815	0.1641	0.1567	0.2295
-4	0.3584	0.0986	0.1027	0.1943
-2	0.3356	0.0498	0.0543	0.1309
0	0.3075	0.0264	0.0231	0.0879
2	0.2758	0.0078	0.0059	0.0420
4	0.2356	9.7656e-04	9.4151e-04	0.0117
6	0.1843	0	4.0064e-05	0.0049
8	0.1302	0	0	0
10	0.0792	0	0	0
12	0.0372	0	0	0
14	0.0126	0	0	0
16	0.0023	0	0	0
18	1.9073e-04	0	0	0
20	0	0	0	0

The comparison of BER vs. SNR performance among OFDM, F-OFDM, FBMC, and UFMC modulation techniques highlights distinctive trends in their efficacy under varying noise conditions. At lower SNR levels, ranging from -10 dB to 0 dB, all techniques exhibit higher BER due to increased noise interference, with FBMC and UFMC showcasing marginally superior performance compared to OFDM and F-OFDM. However, as SNR rises, FBMC and UFMC consistently demonstrate lower BER values across the entire SNR range, suggesting their robustness in mitigating noise effects and maintaining reliable communication. Specifically, at higher SNR values, such as 10 dB and above, FBMC and UFMC exhibit significantly lower BER compared to OFDM and F-OFDM. These results suggest that FBMC and UFMC may be preferable choices for applications requiring enhanced noise resilience and improved BER performance across a wide range of SNR values.

Based on the simulated BER and SNR values, each modulation scheme presents unique advantages and drawbacks. OFDM is straightforward but performs poorly at low SNR levels. F-OFDM enhances spectral efficiency but introduces added complexity. FBMC delivers the best BER performance under challenging conditions but is the most complex to implement. UFMC strikes a good balance between performance and complexity but depends heavily on precise filter design. These factors should be carefully evaluated when selecting a modulation scheme for specific 5G applications.

The Power Spectral Density(PSD) versus Normalized Frequency graph offers valuable insights into how the power of a signal is distributed across various frequency components concerning the Nyquist frequency. With the PSD plotted on the y-axis and normalized frequency on the x-axis, this graph facilitates the analysis of the signal's spectral properties and its behaviour in the frequency domain. It serves as a crucial tool for evaluating spectral efficiency, bandwidth utilization, and interference characteristics, all of which are vital for the effective design and optimization of communication systems. Figure 12 presents the PSD versus Normalized Frequency graph for different modulation techniques, including OFDM, F-OFDM, FBMC, and UFMC.

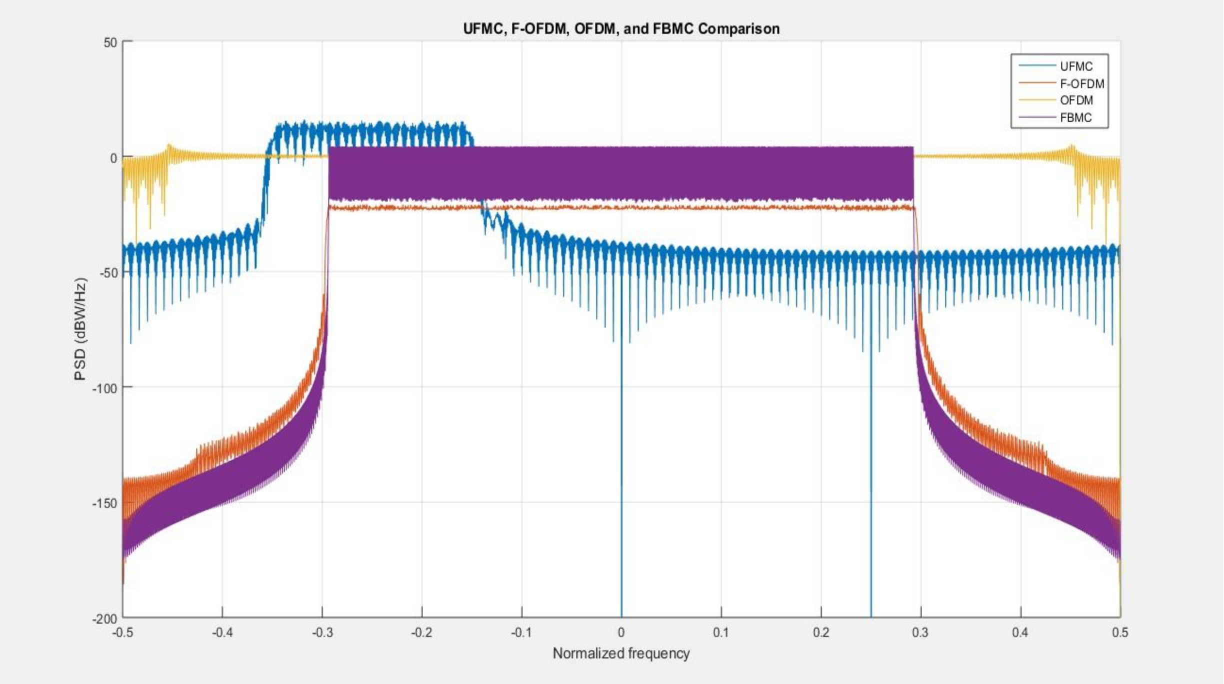

Figure 12: PSD Characteristics with Respect to Normalized Frequency for OFDM, F-OFDM, FBMC, and UFMC Modulation techniques

The figure clearly indicates that UFMC, OFDM, F-OFDM, and FBMC are distinct modulation techniques, each exhibiting unique Power Spectral Density (PSD) characteristics. The various parameters that can be concluded from Figure 12 are as follows:

Spectral Efficiency:

The analysis reveals that FBMC exhibits the highest spectral efficiency among the modulation techniques evaluated. Its spectrum appears compact with minimal out-of-band emissions, indicating efficient utilization of the available bandwidth. This characteristic renders FBMC particularly suitable for scenarios requiring high spectral efficiency and minimal interference with adjacent channels. Conversely, OFDM demonstrates broader out-of-band emissions compared to FBMC, suggesting lower spectral efficiency and a higher potential for interference. UFMC and F-OFDM also exhibit notable spectral efficiency but with slightly more out-of-band emissions than FBMC.

Out-of-Band Emissions:

Examination of out-of-band emissions highlights significant differences between the modulation techniques. OFDM displays pronounced side lobes, indicating considerable out-of-band emissions that could lead to interference with neighboring channels. In contrast, FBMC shows the least out-of-band emissions, presenting a clean spectrum outside the main band. UFMC and F-OFDM fall between OFDM and FBMC in terms of out-of-band emissions, with better suppression compared to OFDM but not reaching the level of cleanliness achieved by FBMC.

PSD Characteristics:

Analysis of Power Spectral Density (PSD) characteristics reveals distinct profiles for each modulation technique. OFDM presents a relatively flat in-band PSD, but its high out-of-band emissions compromise spectral efficiency. FBMC maintains a flat in-band PSD with very sharp roll-off, effectively minimizing interference. UFMC and F-OFDM demonstrate a compromise between the two extremes, exhibiting better in-band and out-of-band characteristics compared to OFDM but falling short of FBMC's efficiency.

The analysis highlights FBMC as the superior modulation technique in terms of spectral efficiency and out-of-band emission suppression. UFMC and F-OFDM offer intermediate performance, while OFDM, despite its limitations, remains relevant due to its simplicity and widespread adoption.

5. CONCLUSION

The paper presents a comprehensive analysis of various modulation techniques, including OFDM, F-OFDM, FBMC, and UFMC, under different signal-to-noise ratio (SNR) conditions. Results demonstrate that while all techniques exhibit higher bit error rates (BER) at lower SNRs due to increased noise interference, FBMC and UFMC consistently outperform others, particularly at higher SNR levels, indicating their effectiveness in mitigating noise effects and maintaining reliable communication. Additionally, the analysis of Power Spectral Density (PSD) characteristics reveals FBMC's superiority in spectral efficiency and out-of-band emission suppression, making it well-suited for scenarios requiring high data rates and minimal interference. Furthermore, the paper discusses the unique advantages and drawbacks of each modulation scheme, with FBMC showing the best BER performance under challenging conditions, while UFMC strikes a balance between performance and complexity. In conclusion, the emphasis on FBMC as the superior modulation technique highlights its potential for specific 5G applications and provides valuable insights for selecting appropriate modulation schemes.

The suitability of each modulation technique for various applications emerges from the analysis. FBMC emerges as highly suitable for applications demanding high spectral efficiency and minimal interference, such as dense urban environments and high-data-rate scenarios. OFDM, despite its drawbacks in spectral efficiency and out-of-band emissions, might find preference in environments where interference is less of a concern or where simplicity and ease of implementation are paramount. UFMC and F-OFDM offer a middle ground, providing improvements over OFDM while being less complex than FBMC, making them suitable for applications requiring a balance between spectral efficiency and implementation complexity.

REFERNCES

1. A. Kumar and M. Gupta. A review on activities of fifth generation mobile communication system.Alexandria Engineering Journal. 2018; 57(2):1125-1135.

2. Das, Mangal & Kumar, Amitesh. Introduction to 5G Telecommunication Network. In book: CMOS Analog IC Design for 5G and Beyond. 2021; pp. 1-13. DOI: 10.1007/978-981-15-9865-4_1.

3. J. Navarro-Ortiz, P. Romero-Diaz, S. Sendra, P. Ameigeiras, J. J. Ramos-Munoz, and J. M. Lopez-Soler. A survey on 5G usage scenarios and traffic models. IEEE Communications Surveys and Tutorials. 2020; 22:905–929. DOI:10.1109/COMST.2020.2971781.

4. G. Shyam Kishore and H. Rallapalli. Towards 5G: A survey on waveform contenders. In Advances in Decision Sciences, Image Processing, Security and Computer Vision. ICETE, Springer, Cham, 2020;(4): 243–250. DOI:10.1007/978-3-030-24318-0_29.

5. Hazareena, Asiya & Mustafa, B. A Survey: On the Waveforms for 5G. Conference: 2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA). 2018; 64-67. DOI: 10.1109/ICECA.2018.8474641.

6. Muoghalu, Chidiebere & Achebe, Patience&Ferdinard, Aigbodioh. MIMO-OFDM Techniques for Wireless Communication System: Performance Evaluation Review. International Journal of Advanced Networking and Applications. 2023; 14(4):5572-5581. DOI:10.35444/IJANA.2023.14410.

7. Ali, Dia &Zuheir, Zahraa. An Experimental Study of F-OFDM Spectrum Efficiency for 5G Applications. International Journal of Microwave and Optical Technology.2022;17(1):1-9.

8. P. Banelli, G. Colavolpe, L. Rugini, and A. Ugolini. Post-OFDM modulations for 5G and beyond. University of Perugia, University of Parma. 2019. Available: https://research.unipg.it/handle/11391/1497664.

9. Z. E. Ankaralı, B. Peköz, and H. Arslan. Enhanced OFDM for 5G RAN. ZTE Communications.2020;15(S1):11–20.

10. S. Thiyagarajan and S. Veerappan. Performance analysis of UFMC and its comparison with CP-OFDM. International Journal of Engineering and Technology. 2018; 4(2):776–780. DOI:10.29126/23951303/IJET-V4I2P121.

11. N. S. Sathiyapriya. Implementation and study of universal filtered multi carrier under carrier frequency offset for 5G. International Journal of Electronics and Communications. 2015; 4(4): 1–5.

12. G. Kongara, C. He, L. Yang, and J. Armstrong. A comparison of CP-OFDM, PCC-OFDM and UFMC for 5G uplink communications. IEEE Access. 2019;7:157574–157594. DOI:10.1109/ACCESS.2019.2949792.

13. A. N. Ibrahim and M. F. L. Abdullah. The potential of FBMC over OFDM for the future 5G mobile communication technology. AIP Conference. Proceedings. 2017;1833(1): 020001. DOI:10.1063/1.5002019

14. H. Dun, C. C. J. M. Tiberius, and G. J. M. Janssen. Positioning in a multipath channel using OFDM signals with carrier phase tracking. IEEE Access. 2020;8:13011–13028.DOI:10.1109/ACCESS.2020.2966070

15. Farhang Boroujeny, B.; Moradi, H. OFDM inspired waveforms for 5G. IEEE Transactions on . Communications Surveys and Tutorials. 2016; 18:2474–2492.

16. L. Zhang, A. Ijaz, P. Xiao, M. M. Molu, and R.Tafazolli. Filtered OFDM systems, algorithms, and Performance analysis for 5G and beyond. IEEE Transactions on Communications. 2018;66(3):1205–1218.

17. M. A. Taher, H. S. Radhi, and A. K. Jameil. EnhancedF-OFDM candidate for5Gapplications. Journal ofAmbient Intelligence and Humanized Computing. January 2020; 12:635–652.

18. Yang, Xianzhen& Yan, Siyuan & Li, Xiao & Li, Fu. A Unified Spectrum Formulation for OFDM, FBMC, and F-OFDM. Electronics. 2020; 9:1285. DOI:10.3390/electronics9081285.

19. Al-qudami, Dheya Alhaq&Redadaa, Salah & Siham, Aissani &Ikni, Samir. Windowing for UFMC technique for 5G applications. Conference: The First National Conference on Advances in Telecommunications, Electronics and Computer Engineering (ATECE’24). May 07, 2024.