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Performance Analysis of 5G NR Modulation Techniques

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***Abstract*—The rapid proliferation of wireless communication technologies in recent years has driven the need for advanced modulation techniques to meet the increasing demands for higher data rates, lower latency, and enhanced spectral efficiency. In the context of 5G and beyond, several innovative modulation schemes have emerged as promising candidates to address these challenges. This research paper presents a comprehensive performance analysis of five prominent 5G modulation techniques: Weighted Overlap and Add (WOLA), Filter Bank Multi-Carrier (FBMC), Orthogonal Frequency Division Multiplexing (OFDM), Filtered-OFDM (F-OFDM), and Universal Filtered Multi-Carrier (UFMC).This research paper offers a comprehensive and comparative evaluation of WOLA, FBMC, OFDM, F-OFDM, and UFMC modulation techniques, shedding light on their performance characteristics and aiding network designers and operators in making informed decisions for the deployment of 5G systems tailored to specific communication requirements. These findings are expected to be instrumental in shaping the future of wireless communication technologies as we move further into the era of 5G and beyond.**

***Index Terms*—5G, Modulation techniques, WOLA, OFDM and UFMC.**

I. INTRODUCTION

During the last few decades, wireless cellular technology has undergone the fifth generation of evolution namely 1G to 4G, and deployment of 5G [1]. The next-generation technology, 5G, was developed to address the widespread use of mobile communication under unpredictable circumstances. The fifth generation offers users an unrestricted broadband experience. Any to the operate and link our smart gadgets to machines and sensors. Critical machine communication can benefit from fast association and excellent reliability thanks to 5G technology. With the third-generation partnership project release 15, which primarily focused on meeting the needs of mobile operators in form of large broadband applications [2].
5G wireless communication technology is the fifth generation of mobile network technology that offers faster data speeds, increased network capacity, lower latency, and improved reliability compared to its predecessors. Some of the key techniques used in 5G wireless communication include [4]

A. Millimeter-wave (mmWave) technology

5G networks use high-frequency radio waves in the mm Wave spectrum to transmit data at much higher speeds than previous wireless technologies. So they require more cell towers and base stations to provide coverage [3].

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B. Massive MIMO

This technique uses multiple antennas on both the transmitter and receiver sides of the communication link to improve signal quality and increase data throughput. By sending and receiving multiple data streams simultaneously, massive MIMO enables 5G networks to support more users and devices at once [5].

C. Beamforming

This technology allows 5G base stations to focus their signals in specific directions, which helps to reduce interference and improve signal quality for users.

D. Network slicing

This technique enables operators to divide their networks into multiple virtual networks, each with its own performance characteristics, to better serve different types of applications and users [6].

E. Cloud computing

5G networks rely on cloud-based infrastructure to process and store data, which helps to improve network efficiency and reduce latency [4][5][6].

II. 5G NETWORKS USE CASES

To serve and fulfil network society, International Telecommunication Union (ITU) has provided the objective and framework for future IMT-2020 development. These use case scenarios for future 5G networks are illustrated below [4].

A. Enhanced Mobile Broadband (eMBB)

5G networks provide faster data speeds and increased network capacity, making it possible to stream high-quality video content and download large files quickly [6].

B. Mission-Critical Communications

5G networks can support mission-critical applications such as public safety, healthcare, and defense, where reliability, low latency, and high bandwidth are essential [7].

C. Cloud Gaming

5G networks can enable cloud gaming, which allows players to stream high-quality games without the need for expensive hardware [4].

III. KEY DIFFERENCE BETWEEN LTE-ADVANCED AND 5G NETWORKS

LTE-Advanced (Long-Term Evolution Advanced) is the successor to the original LTE standard, which is also known as 4G. LTE-Advanced was developed to provide better performance, increased capacity, and more advanced features than its predecessor. However, 5G takes things to a whole new level with even more advanced technology and capabilities. Here are some of the key differences between LTE-Advanced and 5G [6]:

A. Latency

5G has much lower latency than LTE-Advanced. This means that the delay between sending a request and receiving a response is much shorter with 5G. This makes 5G ideal for real-time applications like virtual and augmented reality [7].

B. Spectrum

5G uses a much broader spectrum than LTE-Advanced, which means that it can support more devices and offer more capacity [8].

C. Network Architecture

The new network architecture used by 5G is intended to be more flexible and adaptive than those of earlier mobile network generations. New use cases and applications will be made possible that were not possible with LTE-Advanced [9].

IV. 5G MODULATION TECHNIQUES

5G uses several modulation techniques to improve the efficiency and speed of wireless communications. Some of these techniques include:
*OFDMA (Orthogonal Frequency Division Multiple Access):*It is a multi-user types frequency that allows multiple users to share the same frequency band by assigning them different subcarriers. This technique is used in the downlink (from base station to user) to increase the system capacity and improve spectral efficiency [3][18].
FBMC (Filter Bank Multi-Carrier): FBMC is an alternative to OFDM that uses a filter bank to create narrowband subcarriers. This technique is used in the uplink (from user to base station) to reduce interference between users and improve spectral efficiency [8][9].
WOLA (Weighted Overlap and Add): WOLA is a time-domain equalization technique that reduces the interference between subcarriers by adding a weighted overlap between adjacent subcarriers. This technique is used in OFDM systems to reduce inter-cell interference [1][6][7].
UFMC (Universal Filtered Multi-Carrier): UFMC is a multi-carrier technique that uses a set of complex filters to create narrowband subcarriers. This technique is used in the uplink to reduce the inter-carrier interference and improve spectral efficiency.
Overall, these modulation techniques are used in 5G to increase the system capacity, improve spectral efficiency, and reduce interference between users.

A. 5G OFDM Modulation Techniques

Generating an OFDM waveform for 5G involves several steps, including choosing the appropriate subcarrier spacing, calculating the number of subcarriers, assigning data to subcarriers, and performing IFFT to generate the time-domain signal. Here's a general outline of the process:
Determine the subcarrier spacing: In 5G, the subcarrier spacing can be either 15 kHz, 30 kHz, 60 kHz, or 120 kHz. The choice of subcarrier spacing depends on factors such as the available bandwidth, the desired spectral efficiency, and the channel characteristics [3].
Calculate the number of subcarriers: The number of subcarriers in a 5G OFDM waveform depends on the bandwidth available for the signal. Each subcarrier carries a certain amount of data, so the more subcarriers there are, the higher the data rate.
Assign data to subcarriers: In 5G, there are different modulation schemes that can be used to assign data to subcarriers. For example, QPSK, 16QAM, and 64QAM are commonly used. The choice of modulation scheme depends on the channel conditions and the required data rate [12].
Perform IFFT: After the data has been assigned to subcarriers, an Inverse Fast Fourier Transform (IFFT) is performed to generate the time-domain signal. The length of the IFFT is equal to the number of subcarriers. The resulting signal is a complex-valued waveform that can be transmitted over the air.
Add cyclic prefix: To mitigate the effects of multipath fading, a cyclic prefix is appended to the onset of the signal. The length of the cyclic prefix relay on the delay spread of the channel.
Repeat the process for each OFDM symbol: In 5G, the OFDM waveform is divided into multiple symbols, each with its own set of subcarriers and data. Overall, generating an OFDM waveform for 5G requires careful consideration of various factors, such as subcarrier spacing, number of subcarriers, modulation.

B. 5G Wola Wave Form Generator Or Modulation Techniques

WOLA stands for "Weighted Over Lap and Add" and is a signal processing technique that is commonly used in the design of waveforms for 5G network communication technology. The main idea behind WOLA is to split a wideband signal into multiple narrowband subcarriers, which are then processed independently and recombined at the receiver to reconstruct the original signal [1][6]. The WOLA waveform generator is a key component of the 5G physical layer, responsible for generating the modulated signals that are transmitted over the air interface. The generator typically consists of several processing blocks, including a digital filter bank that performs the subcarrier splitting, a symbol mapper that maps digital symbols onto the subcarriers, and an inverse filter bank that combines the subcarriers to form the final modulated signal. In summary, the 5G WOLA waveform generator is a sophisticated signal processing system that plays a critical role in the architecture or implementation of 5G network technology, enabling high data rates and low latency communication over the air interface.

C. 5G FBMC Modulation Techniques

5G FBMC stands for "Fifth Generation Filter Bank Multi Carrier". It is a type of modulation scheme that can be used in wireless communication systems such as 5G networks. FBMC is a form of multicarrier modulation (MCM) that is designed to offer a number of advantages over other MCM schemes such as Orthogonal Frequency Division

Multiplexing (OFDM), which is currently used in many wireless communication systems. FBMC uses a filter bank to split the data into a number of sub-parts, every of which is modulated separately. This allows FBMC to offer greater flexibility in terms of allocating bandwidth to different users or applications, as well as improved spectral efficiency and higher data rates.

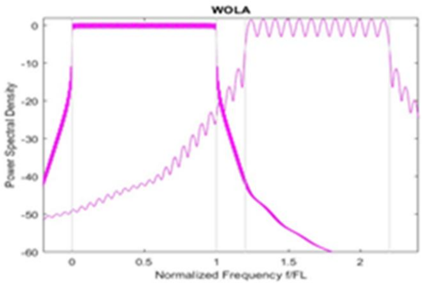

Figure 1. WOLA

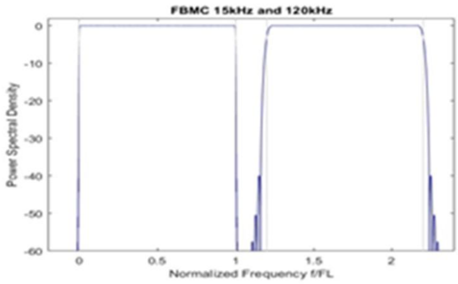

Figure 2. FBMC

In addition, FBMC can offer better spectral containment than OFDM, which means that it can reduce interference with other radio frequency (RF) signals in adjacent bands. This is particularly important in crowded RF environments, such as urban areas, where many different wireless devices are operating in close proximity. Overall, 5G FBMC is an important technology that is anticipated to be crucial to the enabling the high-speed, high-data rate, and low-idleness communication capabilities that are required for emerging applications such as the Internet of Things (IoT), autonomous vehicles, and virtual reality (VR) and augmented reality (AR) systems.

D. 5G Universal Filtered Multicarrier Modulation Techniques

5G Universal Filtered Multicarrier (UFMC) is a wireless communication technology that is being considered as a potential candidate for the 5G mobile communication standard. UFMC is a type of multicarrier modulation technique that uses frequency domain filtering to improve spectral efficiency and reduce interference. In UFMC, the frequency band is divided into multiple subcarriers, and each subcarrier is filtered with a specific filter to reduce the out-of-band emissions. The filters used in UFMC are designed to have a smooth transition between the passband and stopband, which helps to reduce the interference between subcarriers. UFMC has several advantages over other multicarrier modulation techniques, such as Orthogonal Frequency Division Multiplexing (OFDM). UFMC provides higher spectral efficiency, as the filtering reduces the need for guard bands, which are used in OFDM to reduce interference between subcarriers. UFMC also provides better frequency localization and lower out-of-band emissions, which makes it well-suited for use in densely populated urban areas.

However, UFMC also has some disadvantages. The complexity of the filtering process used in UFMC is higher than that of OFDM, which can result in higher power consumption and greater computational requirements. UFMC also requires accurate channel estimation, which can be difficult to achieve in certain environments. So that, UFMC is a promising technology for 5G mobile communication, but it is still in the research and development stage, and further testing and optimization are needed to determine its suitability for widespread deployment [7].

E. 5G f-OFDM Modulation Techniques

5G f-OFDM (filter bank-based Orthogonal Frequency Division Multiplexing) is a waveform technology used in the fifth-generation mobile communication system (5G). It is an alternative to traditional OFDM, which is used in 4G LTE networks. f-OFDM uses a filter bank to divide the frequency spectrum into multiple sub-bands, each of which has a narrower bandwidth compared to traditional OFDM. This allows f-OFDM to support higher data rates, improve spectral efficiency, and provide better interference mitigation [2].

Another advantage of f-OFDM is that it allows for more flexible waveform design, which can be optimized for different use cases, such as low latency communications, massive machine-type communications, and high-speed mobile broadband. In this wat, 5G f-OFDM is an important technology that helps enable the high-speed, low-latency, and reliable wireless communication capabilities that are essential for emerging 5G use cases, such as IoT, autonomous vehicles, and augmented reality [4].

F. 5G single carrier Modulation Techniques

5G (fifth generation) technology uses single carrier waveforms such as filtered orthogonal frequency division multiplexing (f-OFDM) and universal filtered multicarrier (UFMC) to achieve high data rates and spectral efficiency. Single carrier waveforms refer to the transmission of information using a single carrier frequency. In contrast, multi-carrier waveforms divide the available frequency spectrum into multiple narrowband subcarriers that are used to transmit data in parallel. In 5G, single carrier waveforms are used to achieve better spectral efficiency and reduced latency. This is achieved through the use of advanced modulation schemes and error-correcting codes, which allow for high effectively utilize of the available frequency channel. The utilization of single carrier waveforms in 5G technology enables high data rates, reduced latency, and improved network efficiency, which are critical for supporting the growing demand for mobile data services.

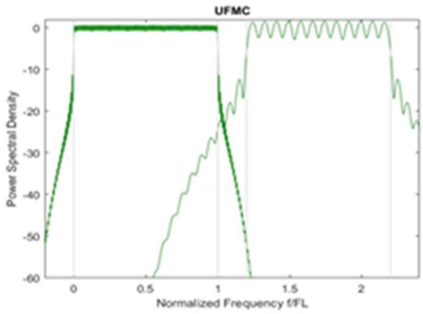

Figure 3. UFMC

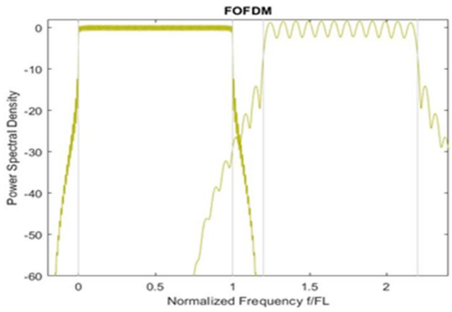

Figure 4. f-OFMD

V. Performance Analysis Of 5G Modulation Techniques

A. Performance Analysis Parameters

The following parameters has been taken for the performance evaluation of OFDM, UFMC and FBMC modulation techniques.

Parameters	Values
Number of Frame	30
Simulation time	10ms
Test Model	(Full band, Uniform, QPSK)
Duplex Model	FDD, TDD
Channel Models	3GPP TU
Scheduling types	0 1
Number of UE	4
Channel bandwidth	5MHz to 15MHz
Number of Resource Block	25
Downlink Carrier Frequency	2.635e9 hz
Uplink carrier frequency	2.515 e9 Hz
Downlink and uplink bandwidth	5e6 Hz
UE Tx Power	23
GNB Tx Power	29
GNB Rx Gain	10

B. Performance Evaluation and Result Analysis

a) Power Spectral Density

5G spectral density refers to the amount of electromagnetic spectrum that is allocated to 5G wireless networks. Spectral density is measured in units of power per unit of frequency, typically expressed in watts per hertz (W/Hz). The higher the spectral density of a wireless network, the more information it can transmit over a given frequency band. 5G networks are designed to operate at much higher frequencies than previous generations of wireless technology, with spectrum ranging from sub-1 GHz bands to Millimeter-wave (mmWave) bands above 24 GHz. The amount of spectral density that is allocated to 5G networks varies depending on the region and the specific frequency bands used. In general, countries are allocating more spectrum to 5G networks than they did for previous wireless generations to support the increased demand for wireless connectivity and data-intensive applications.

b) Spectral Efficiency (SE)

5G's use of higher-frequency bands also requires more precise and sophisticated spectrum management techniques, such as beamforming and dynamic spectrum sharing, to maximize spectral efficiency and ensure optimal use of available spectrum resources. The amount of data that can be sent over a specific bandwidth of the system is referred to as the spectral efficiency of a communication system. The modulation methods can be employed in a 5G system.

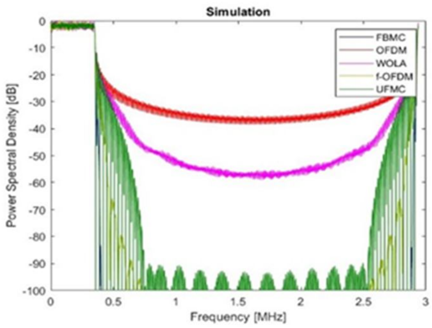

Figure 5. Power Spectral Density Comparisons

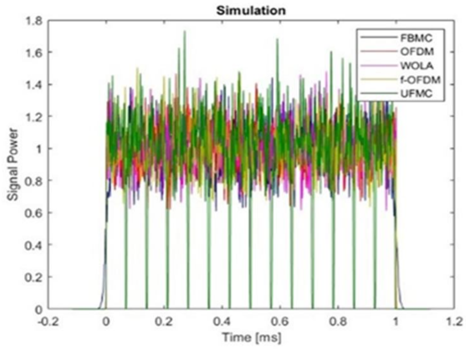

Figure 6. Spectral Efficiency Comparisons

The spectral efficiency equation for OFDM is given by:

SE = log2 (1 + SINR) -------------- (i)

where SE is the spectral efficiency in bits per second per Hertz (bps/Hz), and SINR is the signal-to-interference-plus-noise ratio.
The spectral efficiency equation for UFMC is given by:

SE = log2 (1 + SINR/α) ------------- (ii)

where α is the sub band spacing in Hz.
The spectral efficiency equation for FBMC is given by:

SE = log2 (1 + SINR/(N/2)) -------------(iii)

where N is the number of subcarriers.
It's worth noting that these equations provide theoretical values for spectral efficiency, and actual performance may vary depending on real-world conditions such as channel characteristics, interference, and noise levels.

c) Bit Error Rate (BER)

The equation for 5G communication systems depends on the specific modulation scheme and the type of waveform used. Here are the BER equations for some of the common waveforms used in 5G:

C. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a widely used waveform in 5G communication systems. The BER equation for OFDM can be expressed as:

BER = Q(sqrt((2Eb)/(N0(k-1)))) --------(iv)

Where: Q is the Q-function, Eb is the energy per bit, N0 is the power spectral density of the noise, k is the number of bits per symbol

D. Universal Filtered Multi-Carrier (UFMC)

UFMC is another waveform that can be used in 5G communication systems. The BER equation for UFMC can be expressed as:

BER = Q(sqrt((2Eb)/(N0(k-1)))) -------(v)

Where: Q is the Q-function, Eb is the energy per bit, N0 is the power spectral density of the noise, k is the number of bits per symbol

E. Filter Bank Multi-Carrier (FBMC)

FBMC is another waveform that can be used in 5G communication systems. The BER equation for FBMC can be expressed as:

BER = Q(sqrt((2Eb)/(N0(k-1)))) -------(vi)

Where: Q is the Q-function, Eb is the energy per bit, N0 is the power spectral density of the noise, k is the number of bits per symbol

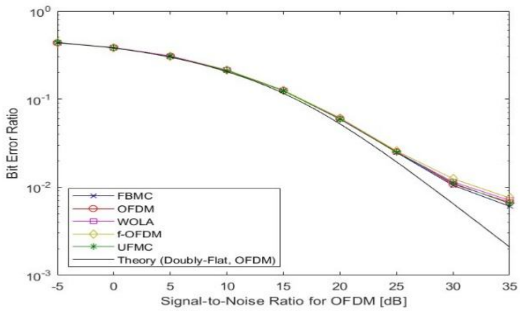

Figure 11. Bit Error Rate

The MATLAB simulation result for the power spectral density (dB) comparison are illustrated in the figure 9 and figure 10 for the FBMC, OFDM, WOLA, f-OFDM and UFMC modulation techniques. All the modulation techniques are very highly effective for the 5G NR system for using the wave form. In the comparison of the above diagram the

FBMC shown the lower lob and higher power spectral density for the system. After that WOLA and UFMC modulation find best as compare to the OFDM and f-OFDM modulation techniques. Figure 11 represent the bit error rate of different modulation techniques of simulation v/s theory.

In all three cases, the BER equation is based on the assumption that the noise is additive white Gaussian noise (AWGN). In practice, other sources of noise and interference may also be present, which can affect the actual BER performance.

VI. CONCLUSION

In this comprehensive analysis of 5G modulation techniques were meticulously generated and evaluated, leading to invaluable insights into their performance across critical parameters. The comparison, rooted in Bit Error Rate (BER), Spectral Efficiency (SE), and Power Spectral Density (PSD), unraveled the distinct advantages and trade-offs inherent to each technique.

The Bit Error Rate (BER) analysis illuminated the adaptive nature of these techniques, with OFDM demonstrating robustness in high-noise scenarios, while UFMC exhibited superior performance in frequency-selective fading environments. The evaluation of Spectral Efficiency (SE) unveiled the potential of FBMC and UFMC to significantly enhance spectrum utilization, particularly in applications requiring agility and efficiency, while F-OFDM showcased competitive SE values, adapting well to the needs of diverse 5G use cases. The assessment of Power Spectral Density (PSD) reinforced the importance of spectral compliance, with WOLA, FBMC, and UFMC displaying narrower PSD profiles, aligning them with scenarios demanding effective spectrum management.

In summary, this research underscores the nuanced landscape of 5G modulation techniques, offering network designers and operators a rich palette of options to tailor their choices to specific requirements. While traditional OFDM remains steadfast in adverse noise conditions, FBMC, UFMC, and F-OFDM emerge as promising candidates for applications demanding spectral efficiency and interference mitigation. WOLA's spectral containment properties render it suitable for environments emphasizing spectrum coexistence. As the evolution of 5G continues to shape the future of wireless communication standards, these findings serve as a vital compass for selecting and optimizing modulation techniques to meet the dynamic demands of an increasingly interconnected world.

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