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REDUCTION OF THE FREQUENCY OUT-OF-BAND EMISSIONS ON FILTER BANK MULTI-CARRIER 5G WAVEFORM

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Master's Thesis

Supervisor
Asst. Prof. Dr. Oguz KARAN

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The thesis titled REDUCTION OF THE FREQUENCY OUT-OF-BAND EMISSIONS ON FILTER BANK MULTI-CARRIER 5G WAVEFORM prepared by AHMED JUMAAH DHEYAB DHEYAB and submitted on 29 /12 /2023 has been **accepted unanimously** for the degree Master of Science in Electrical and Computer Engineering.

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I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Ahmed Jumaah Dheyab DHEYAB

Signature

PREFACE

I dedicate this work to supporting me in this life since my childhood, and to those whose.

eyes cried because to my chest tightness and were tired of think about me.

My father & My mother

And to who were the safety in my back and our warmth in time of need

My Brothers and Sisters

In this dedication, I thank my teacher and role model.

Asst. Prof. Dr. Oguz KARAN

for his keenness, patience, and guidance for me in this performance, which was and still is like a father. and to my friends and those who have rights over me

especially

Dr. Ahmed T. Hammoodi, Eng. Mustafa M. Hamdi, Eng. Saad R. Al_Dulaimy,

Eng. Alaa Ahmed.

Ahmed Jumaah Dheyab DHEYAB

Altınbaş -2023

ABSTRACT

REDUCTION OF THE FREQUENCY OUT-OF-BAND EMISSIONS ON FILTER BANK MULTI-CARRIER 5G WAVEFORM

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This research is dedicated to a comprehensive examination of multi-carrier digital modulation, particularly focusing on the widely used Orthogonal Frequency Division Multiplexing (OFDM) technique. The core aim of this investigation is to delve into the development of Filter Bank Multicarrier (FBMC) systems with the explicit objective of reducing undesirable emissions in the carrier wave within the context of 5G networks. Our primary motivation is the pressing need for more spectrally efficient and interference-resistant modulation techniques in the evolving landscape of wireless communications. A critical facet of our analysis is an extensive comparative study that systematically juxtaposes FBMC against alternative modulation methods. This comparative assessment offers a detailed and nuanced understanding of FBMC's relative advantages and limitations in comparison to its counterparts. To substantiate our findings and assess the practical viability of FBMC, we conducted real-world implementations leveraging the computational capabilities of MATLAB. These practical experiments involved signal enhancement measures aimed at achieving optimal performance. The results obtained through these empirical investigations are encouraging, indicating elevated efficiency levels and notable enhancements in transmission quality. These empirical outcomes lend credence to the potential of FBMC as a compelling solution in the realm of advanced wireless communication systems, particularly within the evolving paradigm of 5G networks.

Keywords: OFDM, FBMC, 5G Network, MATLAB, PAPR, BER, SNR, SDR, Modulation.

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ABBREVIATIONS

OFDM	:	Orthogonal Frequency Division Multiplexing
FBMC	:	Filter Bank Multi-Carrier
Li-Fi	:	Light fidelity
IoT	:	Internet of Things
AMPS	:	Advanced Mobile Phone System
TACS	:	Total Access Communication System
SMS	:	Short Message Service
MMS	:	Multimedia Messaging Service
RNS	:	Release Notification System
UE	:	User Equipment
IMT	:	International Mobile Telecommunications
IP	:	Internet Protocol
LTE	:	Long Term Evolution
ITU	:	International Telecommunication Union
GSM	:	Global System for Mobile Communication
AR/VR	:	Augmented / Virtual Reality
EM	:	Electromagnetic Waves
CMOS	:	Complementary metal-oxide Semiconductor
TDD	:	Time-Division Duplexing

MCM : Multi-Carrier Modulation

PHY : physical layer

FBME : Burst Maximum Exponent Frame

OOBE : Out-of-Band Emission

UFMC : Universal Filtered Multicarrier

GFDM : Generalized Frequency Division Multiplexing

F-OFDM : Filtered-Orthogonal Frequency Division Multiplexing

MIMO : Multiple-Input and Multiple-Output

URLLC : Ultra-Reliable and Low-Latency Communications

UF-OFDM : Universal Filtered Orthogonal Frequency Division Multiplexing

E-UTRAN : Evolved UMTS Terrestrial Radio Access Network

WLAN : Wireless Local Area Network

VoLTE : voice over Long-Term Evolution

GPRS : General Packet Radio Services

ISI : Inter-symbol Interference

ICI : Inter-carrier Interference

DVB-T : Digital Video Broadcasting – Terrestrial

PAPR : Peak-to-Average Power Ratio

GPS : Global Positioning System

BW : Bandwidth

ZF : Zero Forcing

MMSE	:	Minimum Mean Square Error
BER	:	Bit Error Rate
PSD	:	Power Spectral Density
SNR	:	Signal-to-Noise Ratio
WCDMA	:	Wideband Code Division Multiple Access
SINR	:	Signal-to-Interference plus Noise Ratio
RATs	:	Radio Access Technologies
OQAM	:	Offset Quadrature Amplitude Modulation
MATLAB	:	Matrix Laboratory
OMA	:	Orthogonal Multiple Access
NOMA	:	Non-Orthogonal Multiple Access

1. INTRODUCTION

When discussing the telecommunications field, the emphasis is commonly placed on contemporary technologies that facilitate secure communication among different devices, such as smartphones, computers, and modems, for wireless signal transmission. However, the term "telecommunication" technically refers to "distance communication." Despite the numerous methods of communication that humans have utilized throughout history, the term "telecommunication" has now become a specialized field in engineering. Field, the primary focus of this specialized field is to convert any form of information into an electrical signal and transmit it via a carrier to another location where a receiver can convert the signal back to its original form, thereby enabling the extraction of useful information.

Communication technology and engineering systems are continuously evolving, owing to their extensive association with various technical engineering fields. For instance, communication systems rely on numerous electronic components (such as active/ passive, linear/nonlinear, etc.) that form the fundamental infrastructure of transmitting and receiving devices. This indicates that the advancement and improvement of communication systems are closely connected to the development of electronic component quality and efficiency. It is also noteworthy to mention that one of the basic branches of science, mathematics, plays a significant role in this field. In the realm of remote communication technologies, we can observe the practical implementation of several mathematical operations, including differential equations, series, probability science, trigonometric relations, and many others. As a final note, the field of communications focuses on discovering alternative methods of traditional wired transmission and remote communication. These alternatives include wireless signals and soon-to-be-developed optical signal transmission technologies like Li-Fi. In the field of engineering, the information and signals exchanged through various communication systems are referred to as "signals." Therefore, before discussing the system itself, it is essential to consider the signal that will be transmitted through both ends. This is where mathematics plays a critical role in communication. Engineers represent signals transmitted through communication systems using mathematical relations. The design and construction of communication systems heavily rely on mathematical equations and operations to ensure the accuracy and efficiency of signal transmission. design and the construction of transmitting and receiving systems based on these mathematical relations is crucial to ensure the accurate transmission of the information carried within the signals. The discussion of communication systems and their components is vast and includes numerous challenges. One of the most significant challenges in this field is the successful transmission of signals from the transmitter to the receiver, especially as the distance between them increases. The greater the distance, the more complex the issues become, and engineers must find innovative solutions to overcome these technical challenges., As the process of transmitting electrical signals advances to 4G, 5G, and now, 6G, we are seeing greater improvements. When the 5G technology was introduced, it provided faster speeds and shorter transmission times. However, technical issues such as energy and signal loss over long distances have arisen. Our research focuses on studying the challenges associated with these signal losses in 5G technology, which we will examine through a series of tests. that we will provide.

1.1 THE HISTORY OF 5G WAVE

Wireless communication has become increasingly important over time, leading to the development of 5G technology. The evolution of wireless communication has been organized into stages and generations, with 1G being the first generation, followed by 2G, 3G, 4G, and most recently, 5G. Currently, the researchers are focusing on who the developing the next generation of wireless communication, including the promising advancements of 6G Advancements and developments in wireless communication systems have allowed for innovative and smart technologies, leading to the wide interconnectivity of objects through the Internet of Things (IoT). 5G technology is still undergoing significant development, providing high-speed data transfer that can adapts to modern technologies. It is a revolution in and of itself, offering unparalleled services with the potential to connect the world and society. We can now address the stages of the development of the Internet of wireless communications from the first generation to the fifth-generation technology.

1.1.1 First Generation (1G)

The inception of mobile networks can be traced back to first-generation technology (1G), which emerged in 1979. This initial system operated on an analog platform, utilizing a radio signal with a frequency of 150 MHz Its primary function was audio transmission, with a sequential exchange of communication between parties involved. Specifically, after one speaker concluded their message, the other party would respond accordingly. This technology facilitated communication in a unidirectional manner, unable to support simultaneous bidirectional transmission. However, the first generation, also known as 1G, exhibited several shortcomings and was deemed unreliable in terms of security [1]. It relied on the AMPS and TACS systems, offering a maximum speed of 2.4 Kbps [2].

1.1.2 Second Generation (2G)

The second generation (2G) represents a significant milestone in the evolution of mobile networks. Introduced in 1991, it marked a transition to digital technology, offering notable advancements such as improved voice call clarity and reduced communication errors through noise reduction techniques. Additionally, (2G) introduced various messaging capabilities, including text messages (SMS), picture messages, and later, voice and picture messages (MMS) on mobile phones [3]. The digital system replaced the analog signal, enabling more efficient and reliable transmission. Moreover, the introduction of General Packet Radio Service (GPRS) facilitated packet switching, making it suitable for internet connectivity. The data speeds achievable with 2G reached up to 64 Kbps [4]

1.1.3 Third Generation (3G)

Third generation (3G) technology was introduced in year "2000", revolutionizing the field of telecommunications. It leveraged an expanded transmission system that offered numerous benefits, including high-speed data transfer at rates reaching up to 2 Kbps. Notably, 3G technology excelled in terms of reliability, providing a robust and swift data transfer experience. It also implemented a multi-use framework aligned with the IMT 2000 standard [5].

Compared to its predecessor, (2G), (3G) technology boasted significant advancements. It featured a higher bandwidth and data transfer rate, catering to various web applications, voice, video, and IP address termination (e.g., Skype). With data rates reaching up to 100-300 Mbps, 3G delivered remarkable speed and performance [6].

Within the realm of 3G, three types of handovers were introduced:

a. Soft/Soft Handover: This type of handover allows seamless transition from one site to another without interruption. It ensures continuity for the user by maintaining simultaneous connections with both the source and target sites.

b. Inter-Frequency Handover: This handover involves switching from one frequency band to another. In 3G, the frequency range is typically 5MHz.

c. Inter-RAT Handover: This handover facilitates the transition between 3G and 2G networks, enabling seamless mobility between the two.

We can show the simple design of the 3G network Figure 1.1, which was designed by the software. for clarification

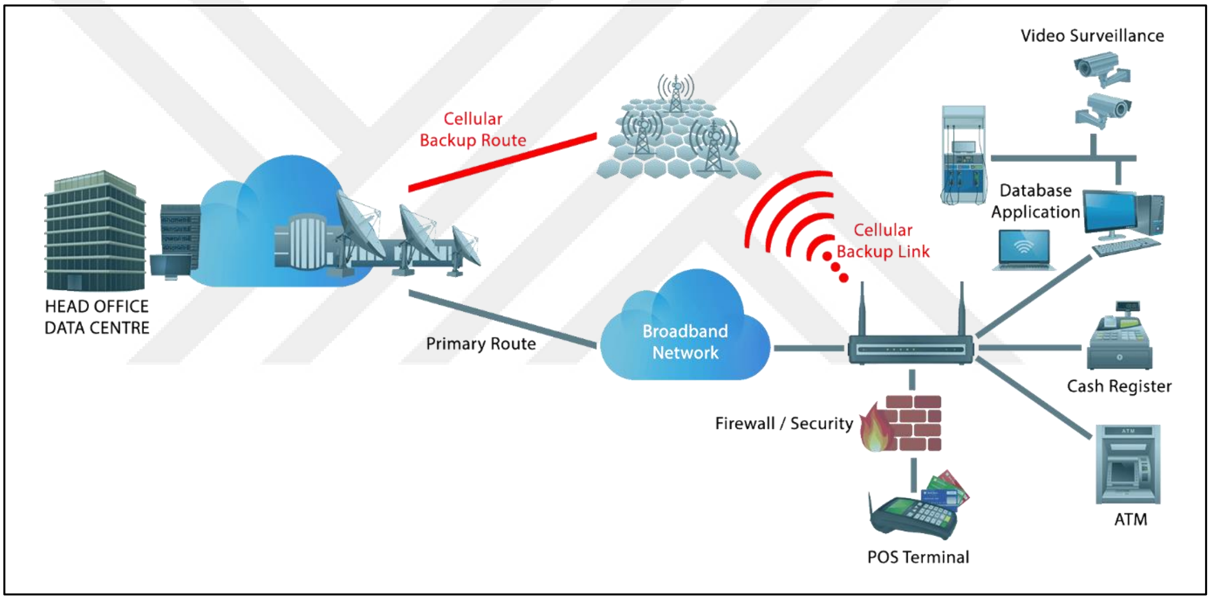


Figure 1.1: Simple Design for 3G Network [7].

1.1.4 Fourth Generation (4G)

The development of 4G technology commenced in Stockholm and later expanded to Oslo, Norway, in 2009. This breakthrough was achieved through the implementation of 4G Long Term Evolution (LTE) technology. Subsequently, it was introduced worldwide, offering users fast mobile internet connectivity and facilitating HD recording of games and conferences [8]. The advent of 4G technology brought about significant advancements, including wider bandwidth, enhanced security, and faster internet access. Notably, this generation of technology is compatible with LTE, as defined by the International

Telecommunication Union (ITU), with a specified speed of 100 Mbps [9]. Moreover, 4G technology supports broadband internet services, providing high capacity and speed at a relatively low cost per bit. as shown below in the Figure 1.2.

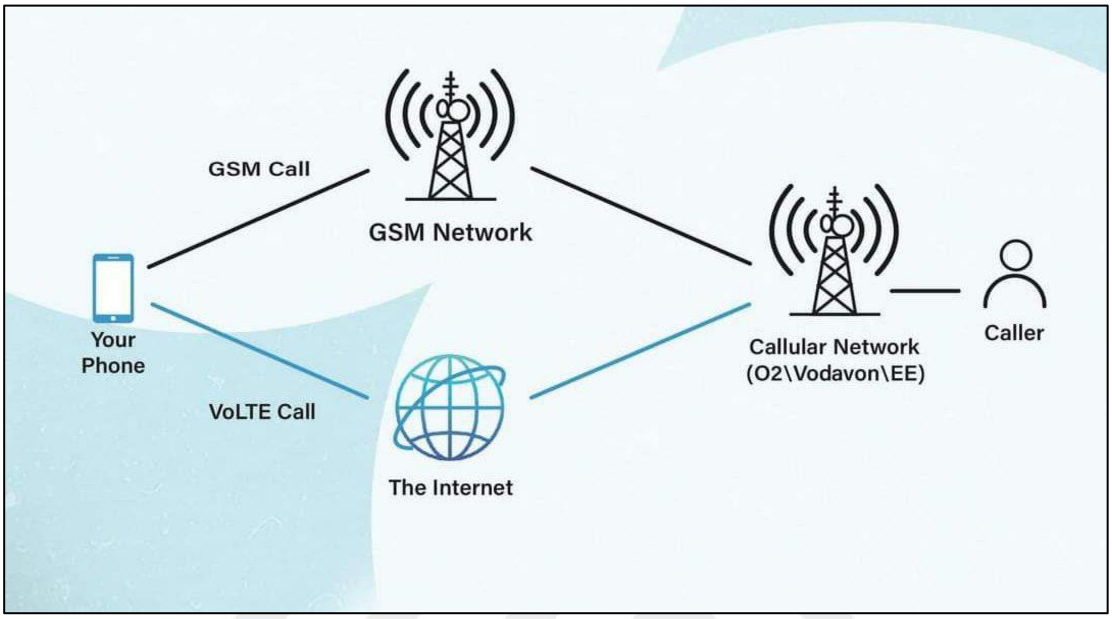


Figure 1.2: Simple Design for 4G Network [10].

1.1.5 Five Generation (5G)

5G networks represent the latest advancement in wireless cellular technology [11]. They encompass a set of modern technical standards that govern the functioning of cellular networks, including frequency usage and the interaction between network components such as computer processors, antennas, and data exchange mechanisms. The primary objective of 5G networks is to enhance the speed and responsiveness of wireless communications. Data transmission rates in 5G networks can reach up to 20 Gbps, and they provide a transmission latency of 1 ms or less, catering to applications requiring real-time feedback. Furthermore, 5G networks offer increased data capacity through wider bandwidth and advanced antenna technologies, enabling significant growth in wireless data transmission.

The future applications of the Internet of Things (IoT), such as mobile health, Internet of Vehicles, smart homes, industrial control, and environmental monitoring, will drive the exponential growth of IoT, with an estimated 20 billion connected devices by 2020 [12] [13]. In addition, 5G revolutionized various sectors of the economy in 2020, and it supports largescale data transmission in gigabits per second (Gbps). It also facilitates virtual private networks and provides connection speeds of 25 Mbps, with data bandwidth surpassing 1 Gbps. The upload and download speeds in 5G networks are exceptionally high [14]. We designed a virtual network using the program for clarification, in the below figure 1.3 simple design for 5G networks.

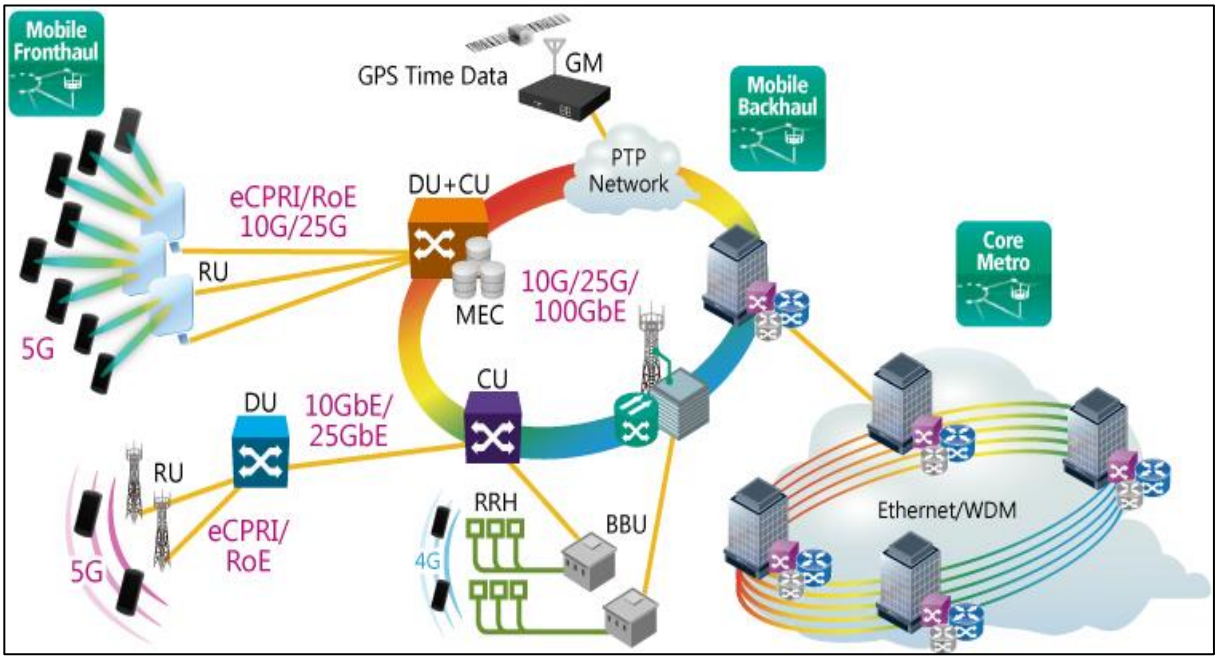


Figure 1.3: Simple Design for 5G network [15].

1.2 WHAT IS 5G WAVE?

5G represents the fifth generation of mobile networks and aims to accelerate activities reliant on internet connectivity. It is a new standard for wireless networks that builds upon the previous four generations. Implementing 5G in mmWave frequency bands offers several benefits [16], [17]. For consumer devices, 5G millimetre wave networks enhance user experiences by providing higher speeds and improved capacity. This opens possibilities for ultra-low latency augmented reality/virtual reality (AR/VR) gaming, 8K 3D video streaming at 100 frames per second, and more [18]. Another significant application area is the Internet of Things (IoT), enabling machine-to-machine communication without human intervention. This generates a vast amount of data, necessitating substantial bandwidth support [19]. Examples of massive machine-to-machine communication systems include smart power grids, integrated transportation systems, smart home devices, and industrial automation.

Additionally, 5G enables mission-critical control applications that require very low latency and high reliability, such as automated guided vehicles, telemedical procedures, drones, and remotely operated robots.

Designing semiconductor circuits for 5G at mmWave frequencies presents unique challenges. The propagation properties of electromagnetic waves at mmWave frequencies differ significantly from lower RF bands. The behaviour of active and passive CMOS components also varies at such high frequencies [20], [21], [22]. These challenges must be thoroughly understood when working with mmWave frequencies.

In terms of technology, the fifth-generation network relies on TDD (Time Division Duplex) technology. One notable issue with TDD is the time delay between the mobile core network and the end user. In the fourth generation, the lowest delay value was around 100 milliseconds, which posed a challenge for enabling Voice over LTE (VoLTE). Human hearing is sensitive to sound, and delays of 100-200 milliseconds become perceptible [23]. Therefore, the fifth generation 5G, network represents a great part of the revolution in development in the world of technology, which in turn contributed to achieving the speed of time.

1.3 WHAT IS MULTI-CARRIER MODULATION "MCM"?

In the response channel stage, multicarrier transmission is utilized, which is highly sensitive to the distance between the transmitter and the receiver. The proposed authentication scheme allows for comprehensive analysis and detection of all possible scenarios. Wireless security has gained increasing importance in various aspects of life due to the vulnerabilities and risks associated with wireless networks, including impersonation attacks and unauthorized hacking attempts. In the past, traditional cryptographic security mechanisms were employed to counter such attacks [24], [25]. However, it was recognized that additional efforts were necessary to prevent potential innovations as wireless technologies offer new avenues for interference. Several previous studies focused on authenticating the sender and receiver at the physical layer (PHY) using prior formats or secret shares, where the sender's authenticity is verified if the receiver can successfully demodulate and decode the transmitted signal. These works acknowledged that the physical characteristics of the wireless medium provide valuable domain-specific information that can complement and enhance traditional security mechanisms [26-27].

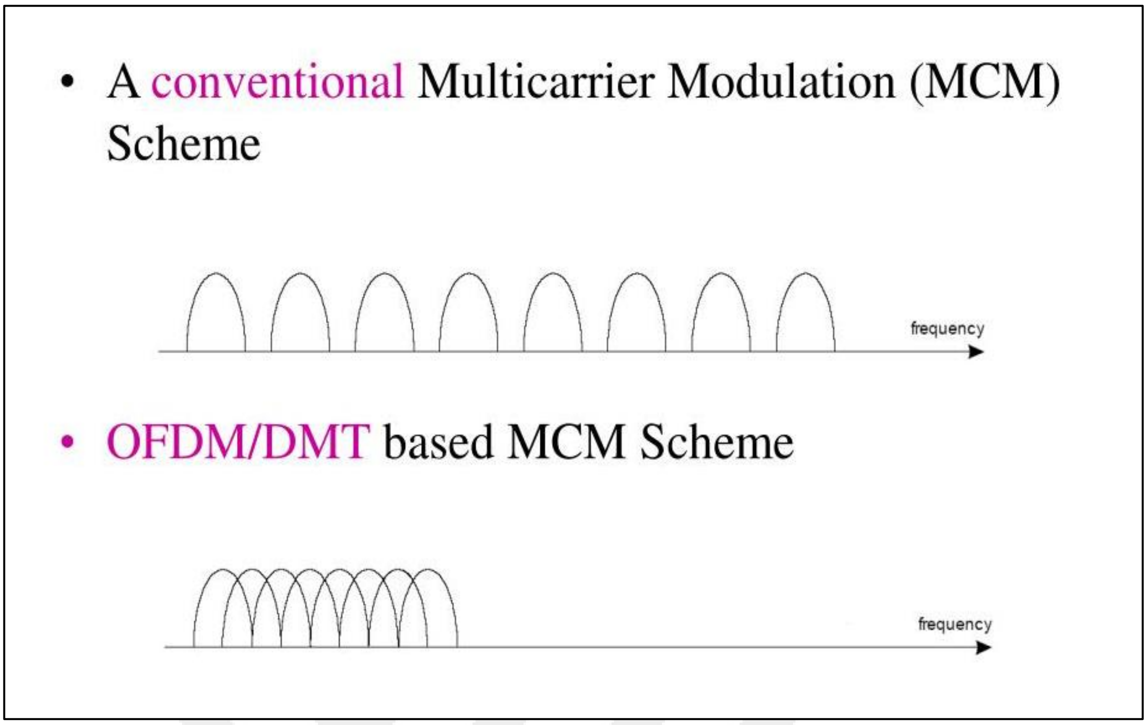
In this context, we assume a scenario with multiple transmissions that are sufficiently separated. In most Orthogonal Frequency Division Multiplexing (OFDM) systems, adjacent subcarriers are usually interconnected, but for our purposes, they need to be separate [28].

The challenge signal is modulated by sinusoids in multiple vectors, and the verification process is carried out with the modification of the provided key in Equation (1) as

$$\kappa i \ \rightarrow \ \kappa i \, di \tag{1.1}$$

$$y = \sqrt{}Esej\theta 1 \cdot \ [\rho 1\kappa 1, \rho 2\kappa 2, \cdots, \rho M\kappa M] + w \tag{1.2}$$

Multi-Carrier Modulation (MCM) is a technology that involves transmitting data over multiple carriers that are typically spaced apart. This technique offers several advantages, making it a preferred choice for data transmission. One key benefit of MCM is its resilience against interference, which allows for more reliable and robust communication in the presence of external disturbances. MCM is also resistant to narrowband threading, meaning that it can effectively handle signals with varying bandwidth requirements without significant degradation in performance. Additionally, MCM can mitigate the effects of multipath propagation, which occurs when signals take multiple paths and arrive at the receiver with different delays, resulting in signal distortion. By distributing the data across multiple carriers, MCM can mitigate the impact of multipath and improve the overall quality of the received signal. Consequently, multi-carrier modulation techniques are widely utilized for data transmission due to their efficiency in utilizing the available spectrum and their ability to deliver reliable and resilient signal waveforms in real-world environments. We can show in the figure 1.4 below the shape of the MCM signal.



- A conventional Multicarrier Modulation (MCM) Scheme
- OFDM/DMT based MCM Scheme

Figure 1.4: Multi-Carrier Modulation MCM [29].

1.4 BACKGROUND STUDY

In this thesis, our main tool for carrying out the required mathematical operations will be the MATLAB program. We will focus on the modulation of the transmitted and received signals in the context of 5G technology. MATLAB is widely acknowledged for its capabilities in modelling and simulating engineering operations, making it an ideal choice for analysing problems and implementing effective solutions before real-world implementation. MATLAB is a versatile program that allows for the modelling and simulation of engineering operations across various branches. Its broad range of functionalities aids in analysing problems and finding effective solutions prior to their actual implementation. By utilizing MATLAB, we can identify potential issues and devise strategies to prevent or mitigate them, ensuring a more efficient and successful implementation of engineering projects.

1.5 RESEARCH PROBLEM

Out-of-range Emissions, often known as OOBE for short, are any emissions that a wireless communication system generates that are not inside the frequency range that was intended for use by the system. The issue statement relating to OOBE may be summed up as follows when it is considered in the light of 5G waveforms: Spectrum Contamination 5G networks operate in certain frequency bands that have been assigned by regulatory agencies. These bands are susceptible to interference from other 5G networks. It is possible for there to be interference with other wireless systems if there is enough OOBE present. These other wireless systems would be running in nearby frequency bands. Because of this interference, the performance of adjacent communication systems may suffer, which will have an effect on the overall spectral efficiency. Compliance with Regulatory Standards: In order to guarantee that there is equitable spectrum sharing and a minimal amount of interference, regulatory authorities put restrictions on the amounts of out-of-band emissions that are permitted. It is essential for operators of 5G systems to comply with these standards to fulfil the criteria set out by regulatory bodies and to ensure a peaceful coexistence with other services. Interference with Sensitive Receivers the OOBE that is emitted by 5G transmitters has the potential to cause interference with sensitive receivers. These receivers include those that are used in radio astronomy, satellite communication, and critical infrastructure systems. It is necessary, to safeguard the integrity and performance of these delicate applications, to make certain that the out-of-band emissions produced by 5G systems are maintained below acceptable ranges.

Filtering and Signal Processing Complexity: Additional filtering and signal processing methods may be necessary on the transmitter side to reduce out-of-band emissions. Because of this, 5G base stations and devices may become more complicated and expensive, and there is a possibility that they could experience signal distortion or delay as a result. Waveform design, power control mechanisms, improved filtering methods, and spectrum management tactics are required to solve the OOBE issue in 5G waveforms. The objective is to keep the spectral leakage to a minimum while also ensuring that the signal being broadcast remains within the frequency band that has been allotted to it. This will guarantee that regulatory requirements are met while also preventing negative interference with other systems.

1.6 IMPLEMENTATION OF PURPOSE

In every generation of the Internet of Things (IoT), transmission issues arise due to energy loss and difficulties in signal propagation. Specifically, the signal tends to weaken as it travels long distances, necessitating solutions to address these challenges. Researchers and scholars have been particularly focused on finding technical solutions since the advent of fifth generation (5G) technology in 2017, which offers high-speed data transfer capabilities. despite the advancements and benefits of 5G, technical problems still arise in data transfer and storage. The fifth generation boasts twice the data transfer speed of the fourth generation, ranging from 10 to 100 gigabytes per second, but it encounters challenges in signal transmission, leading to signal loss. In our research, we aim to mitigate these problems by reducing signal loss in 5G transmission through modulation techniques modelled using the MATLAB program.

1.7 OUTLINE

This research is divided into two chapters. The first chapter talks about the introduction, which contains an explanation of analogy wireless communications “from 1G to 5G” and simple previous studies on the title of this work. The second chapter contains the methodology, results, discussions, and conclusions.

2. LITERATURE REVIEW

Wireless communications have become an integral part of our daily lives and are considered the foundation of technological advancements. They have significantly contributed to accelerating collaborative operations that promote harmony and development across various sectors such as military, industrial, and education. Since its inception with the first-generation (1G) technology in the 1960s, wireless communications have continuously evolved. At each stage of development, human efforts have aimed to enhance data transmission speed and accuracy.

However, along with progress, wireless communications face several challenges. A study focused on improving the Filter Bank Multicarrier (FBMC) technique for cognitive radio spectrum sensing in future networks, J. K. Tugnait. et al. (2013) [30]. This study investigated the performance of aggregated FBMC signals by applying single or consecutive wavelength conversion, W. C. Jakes. et al. (1974) [31]. Another comparative study evaluated the Bit Error Rate (BER) and Power Spectral Density (PSD) of FBME and Orthogonal Frequency Division Multiplexing (OFDM), Sheikh, J. et al. (2020) [32]. An analytical framework proposed the use of out-of-band (OOB) assistance for the base station (BS) detection problem, analysing the statistical properties of the generalized logarithm probability ratio detector and its performance, Alkhlefat, Y. et al. (2020) [33]. The study concluded that the OOB scheme not only enhances detection performance but also reduces system burden.

In another study, a new method was proposed that utilized pulse modulation based on the Kaiser-Bessel filter instead of the standard Dolph-Chebyshev filter for waveform generation in Universal Filtered Multicarrier (UFMC) systems. The objective was to reduce spectral leakage to neighbouring sub-bands. The UFMC system was simulated using MATLAB software, and a comparative analysis of the Dolph-Chebyshev and Kaiser-Bessel filters demonstrated improved power spectral density and lower sidebands for UFMC with the Kaiser-based window, compared to UFMC with Dolph-Chebyshev filters and conventional OFDM, Akila, I. S. et al. (2022) [34].

2.1 THE OUT-OF-BAND EMISSION ON THE 5G WAVE

An out-of-band emission refers to the transmission of signals on frequencies that are outside the desired bandwidth, resulting from the modulation process. These emissions cannot be reduced without impacting the transmission of corresponding information. Strong out-of-band emissions can degrade receiver performance and potentially cause complete signal outage, preventing the receiver from receiving any signal, including the intended useful signal. Additionally, harmonics can be generated in both the receiver and transmitter.

Reducing out-of-band emissions (OOBE) is a crucial objective in 5G mobile communications and beyond, aimed at improving spectrum efficiency. Several techniques have been proposed to suppress OOBE, such as universal OFDM filtering (UF-OFDM) and enhanced UF-OFDM (eUF-OFDM) for downlink systems, and OFDM (UFDFTs-OFDM) and enhanced UFDFTs-OFDM (eUFDFTs-OFDM) for uplink systems. Xiu, Y. et al. (2019) [35-39]. These techniques effectively reduce out-of-band emissions but may require complex implementation due to time-domain convolution with many taps, especially in uplink systems.

Alternatively, low-complexity schemes like global time-domain OFDM (UTW-OFDM) and UTW-DFTs-OFDM have been proposed to achieve low out-of-band emissions. Y. Mizutani et al. (2017) [40-43]. UTW-DFTs-OFDM utilizes a new time-domain window function to address the implementation complexity of EUFDFTS-OFDM. Simulation results using LTE uplink parameters have shown that UTW-DFTs-OFDM with the proposed windowing function achieves similar transceiver characteristics to EUFDFTS-OFDM.

Out-of-band emission requirements are specified in various communication standards such as GSM, UTRAN, E-UTRAN, and Wireless Local Area Network (WLAN). These requirements aim to limit or reduce unwanted broadcasting caused by transmitters of user equipment (UE) or base stations (BS) outside the bandwidth of their respective channels, particularly due to non-linear component defects.

2.2 5G WAVES AND FEATURES

5G networks are cellular networks that divide the service area into small geographical areas known as cells. Within each cell, all 5G wireless devices connect to the internet and telephone network through radio waves transmitted and received by a local antenna. One of the key advantages of 5G networks is their higher download speeds, capable of reaching a maximum speed of 10 Gbps (Gb/s) when only one user is connected to the network. Y. Kodama, et al. (2017) [44]. Compared to 4G, 5G networks have a broader bandwidth, enabling faster speeds and the ability to connect a larger number of devices simultaneously. This improvement enhances the quality of internet services in densely populated or crowded areas. Hoffman, et al. (2019) [45].

The design of 5G radio networks is based on the expectation of accommodating a wider range of use cases and scenarios compared to 4G systems. The telecom industry has identified three main categories of 5G services: enhanced mobile broadband (EMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communications (MMTC). Each of these services comes with distinct requirements and presents new technical challenges for the 5G air interface. Given the diverse needs of these services, the OFDM (Orthogonal Frequency Division Multiplexing) family of technologies is considered the appropriate choice for 5G New Radio (5G-NR), spanning from EMBB and beyond. This means that 5G will not introduce a completely new waveform or multiple access technology; instead, it will build upon OFDM, which is currently used in LTE, WiMax, and Wi-Fi networks.

2.3 FILTER BANK MULTI-CARRIER MODULATION " MCM" FOR 5G

Multi-carrier modulation (MCM) is a method of transmitting data by dividing it into multiple components and transmitting each component over separate carrier signals. This technique is used in various communication systems, including wireless local area networks (WLANs) and technologies like orthogonal frequency division multiplexing (OFDM), frequency division multiplexing (FDM), and time division multiplexing (TDM).

With the rapid development of mobile terminal equipment and diversified data services, wireless communication technologies are evolving quickly. Modulation techniques, such as OFDM, have been extensively studied and applied, particularly in fourth generation (4G) mobile communication systems. OFDM offers advantages like high spectrum efficiency, resistance to frequency selective fading and narrowband interference, robustness against fading, interference resistance between signal waveforms, compatibility with multiple-antenna (MIMO) technology, and low transceiver complexity.

In the context of 5G networks, which support a wide range of service scenarios with diverse transmission technology requirements, new technologies have been developed to meet the evolving business needs. Several modulation techniques, including orthogonal frequency division multiplexing (OFDM), Filter Bank Multicarrier (FBMC), Universal Filtered Multicarrier (UFMC), and Filtered OFDM (F-OFDM), have been studied and compared in terms of performance characteristics and computational complexity. Duffy, C. et al. (2021) [46].

Research has shown that, except for OFDM, the other modulation techniques (FBMC, UFMC, GFDM, and F-OFDM) exhibit low out-of-band leakage. FBMC and UFMC, in particular, do not use cyclic prefix (CP), resulting in high temporal frequency efficiency but increased complexity. GFDM offers flexibility in its frame structure, lower complexity, and good applicability. F-OFDM, with its sub-band filtering, provides fast side-lobe attenuation and high spectral efficiency, effectively mitigating adjacent band interference and meeting the requirements of diverse service scenarios in 5G networks. Li zhiyong, et al. (2017) [47].

3. MATERIALS AND METHODS

3.1 INTRODUCTION

In this thesis, our main tool for carrying out the required mathematical operations will be the MATLAB program. We will focus on the modulation of the transmitted and received signals in the context of 5G technology. The MATLAB is widely acknowledged for its capabilities in modelling and simulating engineering operations, making it an ideal choice for analysing problems and implementing effective solutions before real-world implementation. MATLAB is a Diverse abilities program that allows for the modelling and simulation of engineering operations across various branches. Its broad range of functionalities aids in analysing problems and finding effective solutions prior to their actual implementation. By utilizing MATLAB, we can identify potential issues and devise strategies to prevent or mitigate them, ensuring a more efficient and successful implementation of engineering projects.

after this we will use simulation study utilizes MATLAB and high-frequency filters to model FBMC and OFDM systems. by choosing appropriate input parameters.

3.2 IMPLEMENTATION OF PURPOSE

Materials and methods are a section commonly found in research articles, scientific reports, or academic publications. It provides detailed information about the materials used and the methods employed in the study or experiment.

In this section, authors typically describe:

a. Materials: includes a list of all the materials, substances, or equipment used in the study. It may mention specific chemicals, reagents, instruments, or devices.
b. Experimental Design: Authors explain the overall experimental design, including the research question or objective, the hypothesis (if applicable), and the methodology used to conduct the study.
c. Procedures: This subsection describes the step-by-step procedures followed to carry out the experiment, data collection, and data analysis.
d. Data Collection: Details about how data were collected, including the measurements, observations, or experiments conducted.

e. Data Analysis: Authors explain the statistical or analytical methods used to analyse the collected data and draw conclusions.
f. Ethical Considerations: If applicable, researchers mention any ethical considerations considered during the study, such as obtaining informed consent or following ethical guidelines.

The "Materials and Methods" section serves as a crucial reference for other researchers to replicate the study and verify its findings. It ensures transparency and reproducibility in scientific research.

3.3 FILTER BANK OF MULTICARRIER

A Filter Bank of Multicarrier (FBMC) is a type of modulation scheme used in digital communication systems. It is comparable to Orthogonal Frequency Division Multiplexing (OFDM) but differs in how it processes the subcarriers. In FBMC, a set of filters are used to convert the data symbols into a parallel set of signals, each corresponding to a subcarrier. These subcarriers have overlapping frequency bands, which helps in achieving better spectral efficiency compared to OFDM, especially in scenarios with highly dispersive channels. The use of overlapping subcarriers allows FBMC to mitigate the effect of inter-symbol interference (ISI) and inter-carrier interference (ICI), which can be significant in OFDM systems. FBMC is being researched and considered for use in various wireless communication standards due to its potential advantages in certain scenarios. However, it's essential to consider various factors, such as implementation complexity and system performance, before adopting FBMC in practical applications, we can show Figure 3.1 Transmitter / Reciver Filter Bank

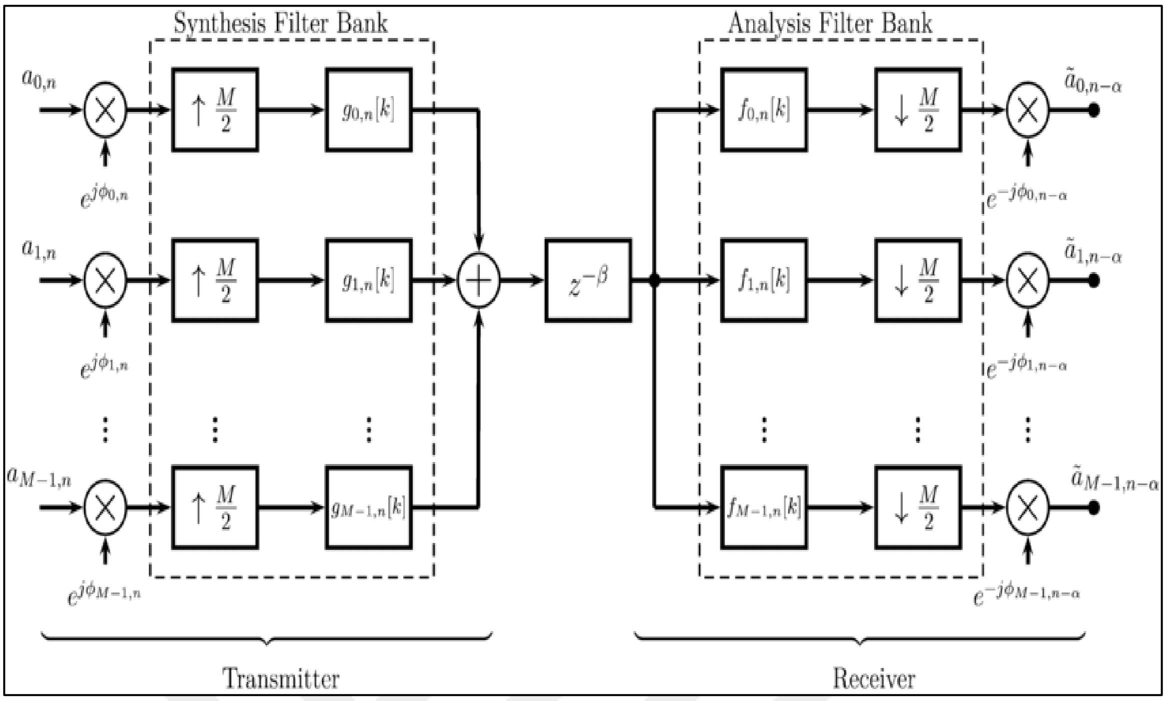


Figure 3.1: Transmitter / Reciver Filter Bank [48].

To provide a mathematical analysis of a frequency-domain equalization filter, let's consider the basic equations involved. A frequency-domain equalization filter aims to compensate for the effects of channel distortion and improve the overall performance of the communication system. Let's denote the received signal in the frequency domain as \(Y(f) \) and the transmitted signal as \(X(f) \). The received signal \(Y(f) \) can be represented as:

\[Y(f) = H(f) \cdot X(f) + N(f) \] (3.1)

Where:

\(H(f) \) represents the channel frequency response.
\(X(f) \) is the transmitted signal in the frequency domain.
\(N(f) \) denotes the additive noise in the frequency domain

The goal of the frequency-domain equalization filter is to design a filter response \(G(f) \) such that the equalized signal \(Z(f) \) is obtained as:

\[Z(f) = Y(f) \cdot G(f) \] (3.2)

By substituting the expression for \(Y(f) \):

$$Z(f) = [H(f) \cdot X(f) + N(f)] \cdot G(f) \tag{3.3}$$

Now, let's consider the ideal scenario where the equalization filter exactly compensates for the channel distortion, meaning $G(f)$ is the inverse of $H(f)$:

$$G(f) = \frac{1}{H(f)} \tag{3.4}$$

In this case, the equalized signal $Z(f)$ becomes:

$$Z(f) = [H(f) \cdot X(f) + N(f)] \cdot \frac{1}{H(f)} = X(f) + \frac{N(f)}{H(f)} \tag{3.5}$$

The equalized signal $Z(f)$ is now an improved version of the transmitted signal $X(f)$, where the noise term is divided by the channel frequency response. This division helps mitigate the effects of channel distortion and improve the overall signal quality.

Please note that this is a simplified analysis, and real-world implementations might involve more complexities, such as dealing with practical constraints, non-idealities, and different types of equalization techniques. The effectiveness of the frequency-domain equalization filter also depends on factors like the accuracy of channel estimation and the properties of the channel itself.

One of the main topologies used in fourth-generation systems is Orthogonal Frequency Division Multiplexing (OFDM). It has various commercial applications such as wireless networks (Wi-Fi 802.11), Multiple-Input Multiple-Output (MIMO) systems, cellular systems (LTE), and digital video broadcasting (DVB-T). In addition to this, the OFDM system has several advantages including the ability to operate in frequency-selective channels, resilience against multipath fading effects, easy implementation using fast Fourier transform algorithms, and low inter-symbol interference due to the favourable channel conditions for each subcarrier waveform. Due to these features, OFDM remains a candidate for 5G networks. However, OFDM has known issues that might hinder its use in 5G, such as sensitivity to frequency synchronization, high Peak-to-Average Power Ratio (PAPR) levels requiring high-power linear amplifiers to avoid signal saturation and distortion. Hence, advanced research efforts are necessary to propose alternatives meeting fifth-generation requirements. One alternative method for data transmission using multiple carriers, like OFDM, is Filter Bank Multi-Carrier (FBMC). In the FBMC scheme, multiple filters are used to transmit data in parallel, using one filter per carrier.

3.3.1 Out-Band Filter Bank

An Out-of-Band Filter Bank is a type of filter bank used in digital communication systems. designed to filter out-of-band signals, which are unwanted signals or interference that fall outside the desired frequency range of the communication system. In wireless communication, out-of-band signals can cause interference and degrade the system's performance. To address this issue, an out-of-band filter bank is used to eases or remove signals outside the designated frequency range, a guarantee that only the desired signals within the band of interest are passed through. Out-of-band filtering is crucial for managing spectral efficiency, reducing interference, and complying with regulatory requirements for radio frequency emissions. This type of filter bank can be an essential component in various wireless communication standards and applications to ensure reliable and efficient data transmission while maintaining signal integrity and minimizing interference.

3.4 OUT-BAND FILTER BANK ARCHITECTURE DESIGN FOR SPECTRUM SENSING

A Filter Bank design for Spectrum Sensing is a structure used in the process of electromagnetic spectrum sensing. This design aims to separate the signals within the desired frequency range from the signals outside the desired range. Spectrum Sensing is used to detect and identify the current usage or vacant frequency bands for wireless communication or other applications. When employing an Out-of-Band Filter Bank in this process, the desired signals (within the designated frequency range for sensing) are separated from the signals outside this range. The design of an Out-of-Band Filter Bank for Spectrum Sensing involves selecting and implementing the appropriate filters to filter and separate the sensed signals, passing them on to subsequent data processing or decision-making stages based on the results of spectrum sensing. The use of an Out-of-Band Filter Bank is crucial in spectrum sensing applications as it can enhance the accuracy and efficiency of spectrum sensing and ensure precise detection of desired frequency bands, Figure 3.2 It is clear out-of-band filter bank.

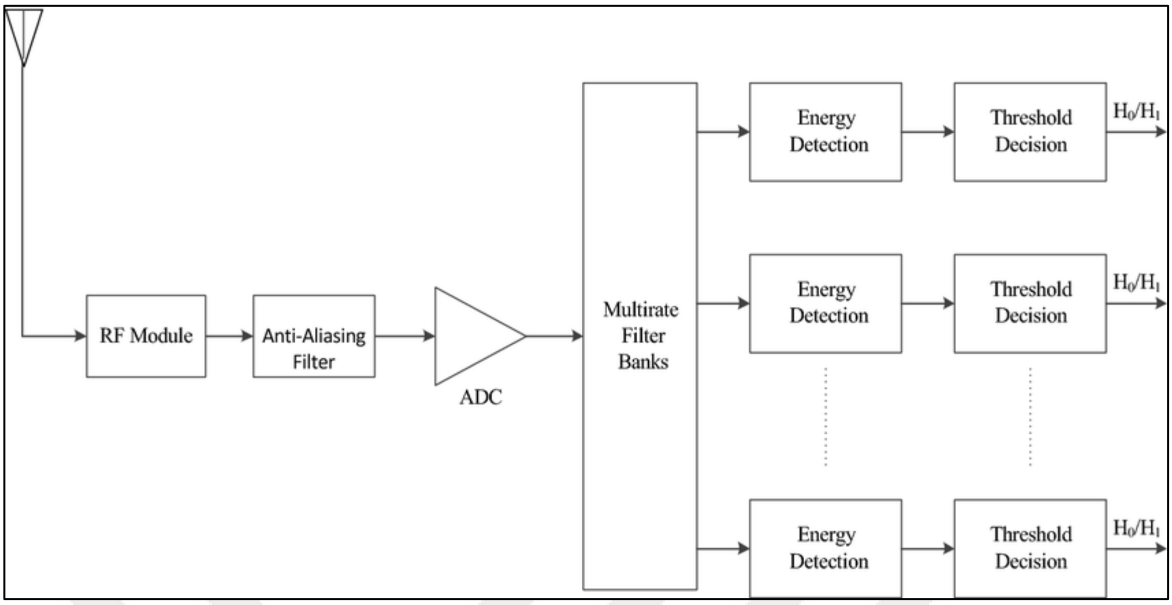


Figure 3.2: Out-of-Band Filter Bank [49].

3.5 MODULATION SCHEMES

The process of signal modulation involves altering one of three parameters: amplitude, frequency, and phase angle. A similar technique is used during reception, referred to as demodulation. Due to the analog nature, binary digital information (0 and 1 bits) is transformed into analog signals in digital systems for transmission. This analog transmission occurs when sending digital information to a computer over a telephone line using a modem. Signal modulation is a crucial process in communication technology due to its ability to accommodate very high frequencies, leading to the development of new methods for information transmission, such as Funk, Microwave radio relay, and satellite transmission. Modulation techniques are employed in various systems like GSM, Bluetooth, television, GPS, and others, including:

a. Amplitude Modulation:

   In this technique, the carrier frequency signal's value is changed linearly based on the modulating (baseband) signal. It's easy to design and demodulate, but amplifying the amplitude makes the signal susceptible to noise and distortion if the transmitted signal isn't strong enough.

b. Phase Modulation:

In this type of modulation, the phase angle of the carrier frequency signal changes linearly with the modulating signal's value. Although this technique carries the advantages of frequency-domain modulation in a narrower bandwidth than its predecessor, the complexity lies in the devices' modulation and demodulation, limiting its applications.

Modulation also offers various benefits depending on the system used. In wireless communication systems, modulation contributes to increasing the transmitted or received signal's frequency, resulting in smaller antenna size (antenna). This is due to the inverse relationship between signal frequency and wavelength. Additionally, modulation enables the ability to combine signals and transmit them through a single medium.

3.5.1 OFDM-Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a technique for digital waveform modulation that utilizes multiple closely spaced subcarrier waveforms—previously modulated signals—each with its own frequency and higher bandwidth. Each of these subcarrier waveforms contains streams of data or parallel channels and is traditionally modulated at a low symbol rate; these are groups of related (though not identical) data bits with a total bit rate expressed in bits per second.

3.5.1.1 Ofdm Architecture Design

Orthogonal Frequency Division Multiplexing (OFDM) is a digital modulation scheme that extends the concept of subcarrier waveform shaping by employing multiple closely spaced subcarrier waveforms within the same individual channel. Instead of transmitting a high-speed data stream with a single subcarrier, OFDM uses a large number of closely spaced orthogonal subcarrier waveforms that are sent in parallel.

Each subcarrier waveform is modulated using a traditional digital modulation scheme, such as QPSK and 16QAM, at a low symbol rate. However, combining multiple subcarrier waveforms enables data rates like those achieved by traditional single-carrier waveform modulation schemes within equivalent bandwidths.

OFDM finds use in various modern broadband wireless systems with high data rates, including Wi-Fi and cellular communications. The utilization of numerous orthogonal subcarrier waveforms, each carrying data at a low bit rate, makes OFDM extremely flexible in mitigating effects of fading, interference, and selective fading, while also providing high spectral efficiency.

Early systems employing OFDM encountered relatively high signal processing requirements, but technological advancements have alleviated many of these concerns.

OFDM represents a form of multicarrier modulation where an OFDM signal consists of multiple closely spaced subcarrier waveforms, each shaped to carry different forms of data like audio and data. This modulation scheme spreads sidebands on both sides of a carrier, requiring the receiver to be capable of receiving the entire signal to successfully demodulate data.

Consequently, when sending signals close together, they must be sufficiently spaced apart to allow for separation at the receiver using filters, and a guard band is necessary between them. However, this is not the case with OFDM. Despite overlapping sidebands of each carrier, reception without expected interference is possible due to their orthogonal nature. This is achieved by making the subcarrier waveform spacing equal to the reciprocal of the symbol period.

Here are the mathematical equations related to OFDM architecture design:

i. Bandwidth (BW): Represents the total frequency bandwidth used in the OFDM system.

$$BW = (N\_subcarriers) \times (subcarrier\_spacing) \tag{3.6}$$

ii. Symbol Time (T_s): Represents the duration of each OFDM symbol (the time between the start of one symbol and the start of the next).

$$T\_s = 1 / (N\_subcarriers \times subcarrier\_spacing) \tag{3.7}$$

iii. Cyclic Prefix (CP) Length: Used to deal with channel delay and inter-symbol interference.

$$CP\_length = CP\_ratio \times T\_s \tag{3.8}$$

iv. Bit Rate (R): Represents the number of bits transmitted in each OFDM symbol.

$$R = (N\_data\_subcarriers - N\_pilots) / N\_subcarriers \tag{3.9}$$

v. Power Efficiency Factor (η): Indicates the system's efficiency in utilizing the transmitted power.

$$\eta = (N\_data\_subcarriers) \,/\, (N\_data\_subcarriers + N\_pilots) \tag{3.10}$$

vi. Net Bit Rate (R_net): Reflects the data transmission rate after considering interference, spectrum, and overhead.

$$R\_net = R \times \eta \tag{3.11}$$

These are just some examples of equations related to OFDM design. Equations can vary based on factors like the technology used, channel conditions, and other considerations.

Several techniques have been proposed to reconstruct a sparse signal from fewer samples than required by the Nyquist theory. In this research, a low-sampling-rate technique has been introduced, which enables the reconstruction of sparse information transmitted through Orthogonal Frequency Division Multiplexing (OFDM) modulation. We can show simple flowchart in Figure 3.3 for OFDM Design, below flowchart clear the system TX "Sender" and RX "Receiver."

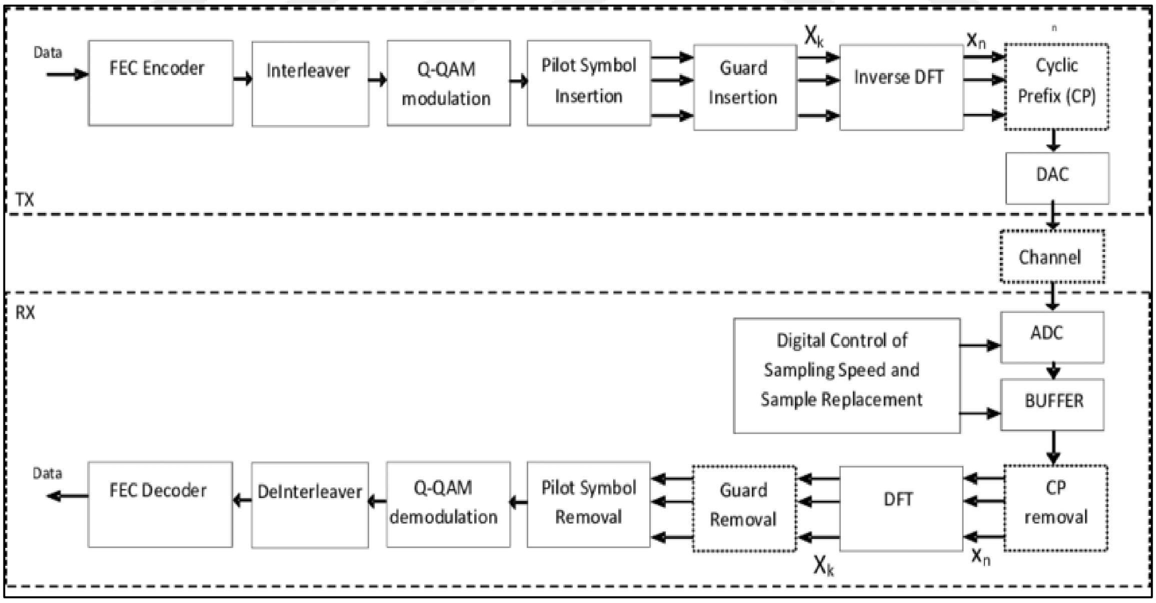


Figure 3.3: OFDM Design [50].

3.5.2 System Technologies for FBMC

The technology of Filter Bank Multicarrier (FBMC) transmission is a prominent contender for the upcoming wireless communication standard (5G). It is also considered an alternative to the well-known Orthogonal Frequency Division Multiplexing (OFDM) technique. To ensure interference-free communication, FBMC utilizes cyclic prefix (CP) alongside a rectangular pulse-shaping filter. This renders FBMC spectrally efficient when combined with large antenna arrays.

Here are the mathematical equations related to the Filter Bank Multi-carrier (FBMC) system design:

i. Bandwidth (BW): Represents the total frequency bandwidth used in the FBMC system.

$$BW = N\_subcarriers \times subcarrier\_spacing \tag{3.12}$$

ii. Symbol Time (T_s): Represents the duration of each FBMC symbol (the time between the start of one symbol and the start of the next).

$$T\_s = 1 \,/\, (N\_subcarriers \times subcarrier\_spacing) \tag{3.13}$$

iii. Bit Rate (R): Represents the number of bits transmitted in each FBMC symbol.

$$R = (N\_data\_subcarriers) \,/\, T\_s \tag{3.14}$$

iv. Filter Design: Represents the equations used to design the filters in FBMC to achieve low interference between adjacent subcarriers.

v. Power Efficiency Factor (η): Indicates the system's efficiency in utilizing the transmitted power.

$$\eta = (N\_data\_subcarriers) \,/\, (N\_data\_subcarriers + N\_guard\_subcarriers) \tag{3.15}$$

vi. Net Bit Rate (R_net): Reflects the data transmission rate after considering interference, spectrum, and overhead.

$$R\_net = R \times \eta \tag{3.16}$$

These are just some examples of equations related to FBMC system design. Equations can vary based on various factors, and it's important to consider specific conditions for applying the FBMC system. In a study in which the FBMC scheme was analyzed through computer simulation, the simulation showed that the FBMC system is superior to OFDM in terms of bit error rate (Ber) and PAPR [51]

FBMC can overcome this challenge by employing different modulation systems and specialized prototype filters. Linking FBMC with Multiple-Input Multiple-Output (MIMO) systems and varying antenna array sizes, starting from a 2x2 array and progressing to 8x8, 16x16, and 32x32 arrays, the system performance is evaluated. Metrics like Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) are used to assess each system's performance, and Bit Error Rate (BER) is measured against Signal-to-Noise Ratio (SNR) or Eb/No for each configuration.

Results indicate that FBMC with MIMO exhibits satisfactory improvements in performance. For a 2x2 MIMO system, MMSE outperforms ZF. Moreover, a substantial decrease in BER is observed with increasing array size. FBMC-SMT, a special case of FBMC, is evaluated using simulations. FBMC-CDMA, with 16 subcarriers, surpasses conventional Wideband Code Division Multiple Access (WCDMA) for more than five designated code channels. Signal-to-Interference plus Noise Ratio (SINR) analysis is also conducted for FBMC, aligning well with simulation results.

Hence, FBMC-SMT can act as a unified framework for flexible integration of multiple Radio Access Technologies (RATs), meeting variable requirements of 5G and heterogeneous wireless networks. It excels in cases like enhanced mobile broadband, massive machine-type communications, ultra-reliable low-latency communications, and future heterogeneous wireless networks, accommodating the surge in high-bandwidth multimedia data traffic and diverse application needs.

In light of this, the deployment of 5G in frequency bands below 6 GHz to support diverse use cases is emphasized. 5G will coexist with 2G, 3G, and 4G in the foreseeable future, leading to the necessity of dealing with multiple non-homogeneous base stations. Given the relatively independent standards of various radio access technologies, joint processing is crucial for resource optimization. Techniques like Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) are vital in these scenarios.

Furthermore, (OFDM) is expected to offer higher spectral efficiency and robustness against timing and frequency misalignments. FBMC, as one of the multi-carrier waveforms, has been widely adopted for 5G. It can serve as a complementary modulation scheme to cater to diverse use cases in heterogeneous wireless networks. Additionally, (OFDM) can be considered a special case of FBMC. As such, filter bank-based Frequency Division Multiple Access (FDMA) schemes can coexist with OFDMA, ensuring flexible integration with multiple access techniques.

FBMC filters each subcarrier modulated signal in a multicarrier system. The prototype filter is the one used for the zero-frequency carrier and is the basis for the other subcarrier filters. The filters are characterized by the overlapping factor, *K*, which is the number of multicarrier symbols that overlap in the time domain. The prototype filter order can be chosen as *2*K-1* where *K* = 2, 3, or 4 and is selected as per the PHYDYAS project. The current FBMC implementation uses frequency spreading. It uses an *N*K* length IFFT with symbols overlapped with a delay of *N/2*, where *N* is the number of subcarriers. This design choice makes it easy to analyze FBMC and compare it with other modulation methods. To achieve full capacity, offset quadrature amplitude modulation (OQAM) processing is employed. The real and imaginary parts of a complex data symbol are not transmitted simultaneously, as the imaginary part is delayed by half the symbol duration. These are just some examples of equations related to FBMC system design. Equations can vary based on various factors, and it's important to consider specific conditions for applying the FBMC [52]. The transmit-end processing is shown in the following Figure 3.4.

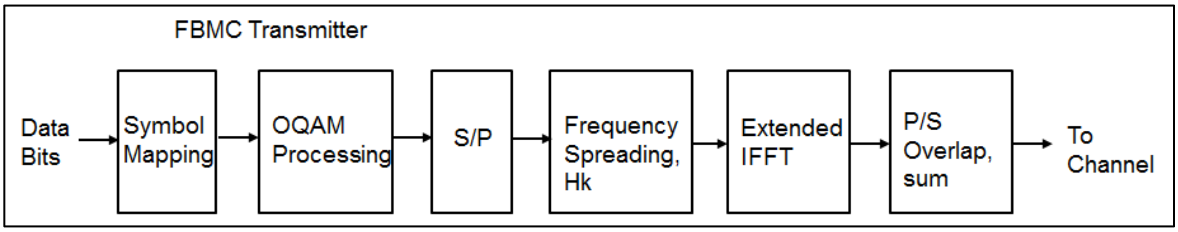


Figure 3.4: The Transmit-end Processing [50].

These are just some examples of equations related to FBMC system design. Equations can vary based on various factors, and it's important to consider specific conditions for applying the FBMC system [53].

It can be applied to a single input, single output (SISO) system [54] In a recent study, a deep neural network (DNN) based approach was proposed to deal with virtual interference, enabling the application of MIMO technology with FBMC/OQAM. It is shown from simulations that it provides good performance in conditions of bit error rate (BER) [55]. A machine learning-based CS channel estimation (CE) method for wireless communications is discussed, which plays an important role in industrial Internet of Things (IIoT) applications [56].

3.5.2.1 Fbmc Architecture Design

The FBMC (Filter Bank Multicarrier) architecture is a modulation scheme used in digital communication systems. It is designed to transmit data over multiple subcarriers with the help of a filter bank.

The FBMC architecture involves several key components:

a. Subcarrier Generation: Data symbols are mapped onto subcarriers to carry information. These subcarriers are generated using a filter bank, where each subcarrier corresponds to a specific frequency band.

b. Filter Bank: The filter bank plays a important role in FBMC. It is responsible for filtering the data symbols into parallel subcarriers with overlapping frequency bands. This overlapping nature helps in achieving better spectral efficiency and reducing inter-carrier interference.

c. Pulse Shaping: the Pulse shaping filters are used to shape the subcarrier signals, ensuring a smooth spectrum and reducing the out-of-band emissions.

d. Modulation: one from the subcarriers are generated and shaped, they undergo modulation, where the symbols are modulated onto each subcarrier using various modulation techniques.

e. Inverse Filtering and Demodulation: At the receiver side, the inverse filtering and demodulation processes are performed to extract the original data symbols from the received subcarriers.

FBMC architecture is known for its advantages over OFDM in scenarios with highly dispersive channels and in systems where spectral efficiency is crucial. It helps mitigate inter-symbol and inter-carrier interference, which can be significant in OFDM systems.

The design of FBMC involves careful consideration of the filter bank characteristics, pulse shaping filters, modulation schemes, and signal processing techniques to achieve optimal performance and efficient data transmission.

You have provided an accurate description of the design of Filter Bank Multicarrier (FBMC), which is indeed a modulation system used in digital communication systems for transmitting data across a set of subcarriers using a filter bank. The main components of FBMC design include subcarrier generation, where data symbols are assigned to subcarriers for information transmission. These subcarriers are generated using a filter bank, with each subcarrier aligned to a specific frequency range. The filter bank plays a crucial role in FBMC design, filtering the data symbols into parallel subcarriers with frequency-domain overlap. This overlap helps achieve better spectral efficiency and reduce interference among subcarriers. Pulse shaping filters are used to shape the subcarrier signals, ensuring a smooth spectrum, and minimizing undesired spectral emissions. Once the subcarriers are generated and shaped, they undergo modulation, where the symbols on each subcarrier are modulated using various modulation techniques. On the receiving end, reverse filtering and demodulation operations are performed to extract the original data symbols from the received subcarriers. FBMC design is known for its advantages over OFDM in scenarios with severe channel dispersion. It's essential to understand the well-designed filter bank, pulse shaping filters, modulation techniques, and signal processing to achieve optimal performance and efficient data transmission across various communication systems. The power spectral density of the FBMC transmit signal is plotted to highlight the low out-of-band leakage. The FBMC (filter bank multi-carrier) architecture involves several key components, each contributing to its operation. Here's a general overview along with some mathematical equations:

i. Subcarrier Frequencies: FBMC divides the total bandwidth into subcarriers. The subcarrier frequencies are determined by their index and the subcarrier spacing.

$$Subcarrier\_frequency\ [n] = n * subcarrier\_spacing, where\ n\ is\ the\ subcarrier\ index. \quad (3.17)$$

ii. Time-Domain Filtering: Each subcarrier is filtered by a prototype filter to shape its spectrum. The time-domain signal after filtering is given by the convolution of the input signal and the filter impulse response.

$$x_{filtered(t)} = \int \quad x(t - \tau) * h(\tau) d\tau \qquad (3.18)$$

Where:

x(t) is the input signal.

h(τ) is the prototype filter's impulse response.

* is the Represents convolution.

iii. Polyphase Structure: FBMC employs a polyphase structure to implement parallel filter banks for subcarriers. Each subcarrier's signal is divided into multiple phases, and each phase is filtered separately.

$$x\_phase[k][n] = x\_filtered(n * T\_s + k * T\_phi) \qquad (3.19)$$

Where:

T_s is the symbol time.

T_phi is the phase time.

k is the phase index.

iv. Frequency-Domain Equalization: In FBMC, frequency-selective fading can be mitigated by performing equalization in the frequency domain. This involves dividing the received frequency-domain signal by the frequency response of the channel.

$$Y\_equalized[k][n] = Y\_received[k][n] \,/\, H\_channel[k][n] \qquad (3.20)$$

Where:

$Y\_received[k][n]$ is the received frequency-domain signal.

$H\_channel[k][n]$ is the frequency response of the channel.

v. Guard Intervals: Similar to CP in OFDM, FBMC can use guard intervals to mitigate inter-symbol interference. The length of the guard interval depends on the channel delay spread.

$$Guard\_interval\_length = \alpha * T\_s \tag{3.21}$$

Where:

α is a constant determining the guard interval length.

These components collectively define the FBMC architecture and its mathematical foundations. The actual equations and implementations may vary based on specific FBMC variants and design considerations. We can show the below Figure 3.5 Normalized Frequency for FBMC.

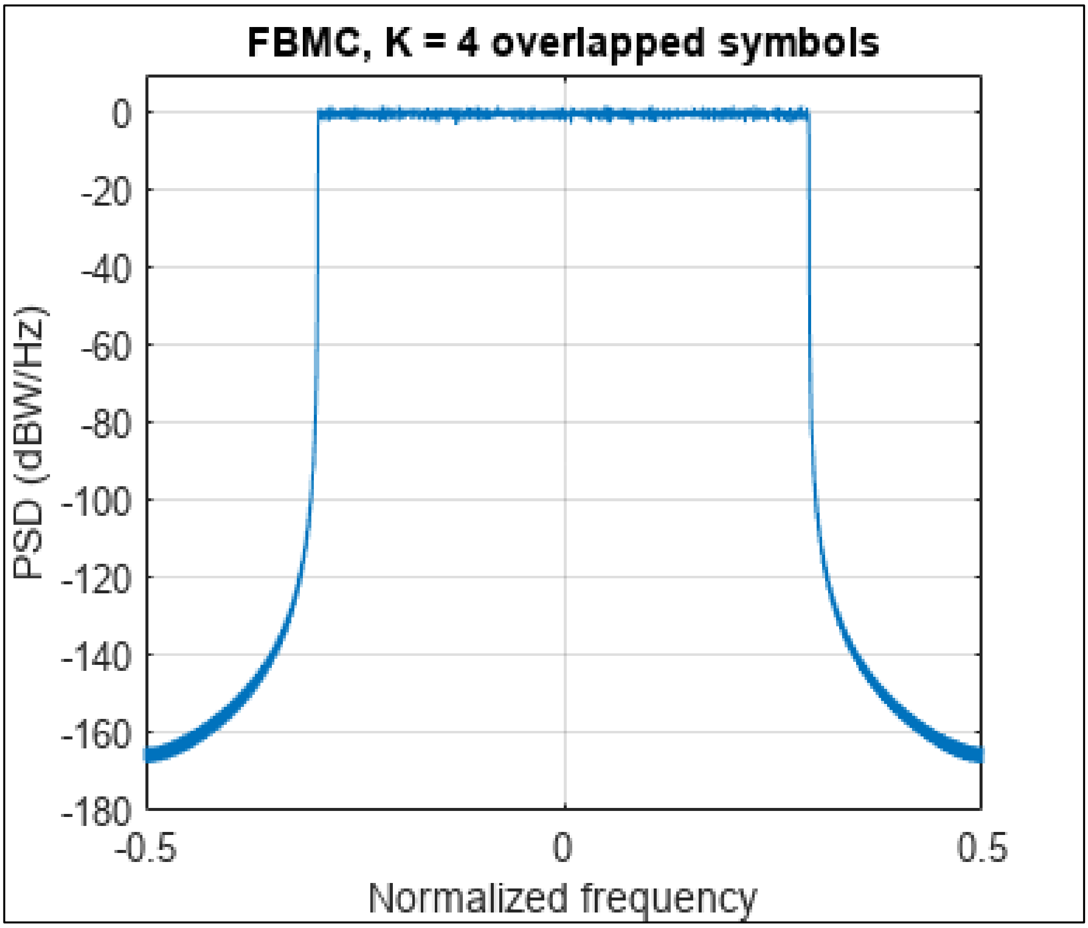


Figure 3.5: Normalized Frequency for FBMC [50].

The power spectral density of the FBMC transmit signal is plotted to highlight the low out-of-band leakage, highlighting equal 0 and low equal between -160 , and -180. Where K=4 overlapped symbols

4. RESULTS

In summary, this simulation study utilizes MATLAB and high-frequency filters to model FBMC and OFDM systems. The input parameters outlined in the respective tables are carefully chosen to represent the system's characteristics accurately. Furthermore, the filter length, as determined by the specified ratios, plays a critical role in defining the spectral behaviour of the communication signals in these systems, making it a key parameter to optimize for efficient and reliable wireless communication.

Simulation of Filter Bank Multicarrier (FBMC) and Orthogonal Frequency Division Multiplexing (OFDM) systems is a fundamental aspect of studying and analyzing wireless communication technologies. In this study, MATLAB software was employed as the simulation tool, allowing for precise control and modelling of these complex systems. High-frequency filters play a crucial role in shaping the transmitted signals in both FBMC and OFDM systems.

These filters are responsible for the Confinement the signal energy within specific frequency ranges and mitigating interference, which is vital in modern wireless communication systems.

To perform these simulations effectively, various input parameters were carefully selected and configured. These parameters are documented in Table 4.1 for FBMC and Table 4.2 for OFDM. Table 4.1 includes input coefficients specifically tailored for FBMC, while Table 4.2 provides the corresponding input parameters for OFDM. One critical aspect to consider is the filter length, which directly impacts the system's performance.

The filter length is intricately linked to two important factors: the ratio of the number of subcarrier waves to the number of subcarrier ranges and the ratio of the peak to trough of the filter within a single subcarrier range. These ratios influence the spectral characteristics of the transmitted signal and are essential in achieving the desired system performance and spectral efficiency.

In summary, this simulation study used MATLAB and high-frequency filters to model FBMC and OFDM systems. The input parameters outlined in the respective tables are carefully chosen to represent the system's characteristics accurately.

Furthermore, the filter length, as determined by the specified ratios, plays a critical role in defining the spectral behaviour of the communication signals in these systems, making it a key parameter to optimize for efficient and reliable wireless communication.

Table 4.1: FBMC Parameters**.**

FBMC Parameters	**Value**
FBMC_Number of Subcarriers	24
FBMC_Number of Symbols in Time	30
FBMC_Prototype Filter	Hermite-OQAM
FBMC_Subcarrier Spacing	15e3
FBMC_Over lapping Factor	4

The selection of these parameter values was informed by a vast review of previous research, providing a solid foundation for our investigation. Our primary objective was to enhance the performance of the carrier wave, a central component in wireless communication, within the framework of fifth generation (5G) technology. 5G technology represents a significant leap in wireless networks, promising advantages such as increased data rates, reduced latency, and improved connectivity.

To achieve this reinforcement, we strategically employed a high-frequency filter to shape the spectral characteristics of the carrier wave. High-frequency filters are pivotal in mitigating signal interference and optimizing spectral efficiency, aligning with the demanding requirements of 5G networks. This research focused on two key modulation schemes: Filter Bank Multicarrier (FBMC) and Orthogonal Frequency Division Multiplexing (OFDM). For FBMC, we selected parameter values derived from prior research to enhance its performance within the 5G context. Additionally, we integrated input coefficients for the OFDM system, as delineated in Table 4.2, recognizing OFDM's significance as a widely adopted modulation technique in contemporary wireless communication.

In summary, our research aims to advance 5G technology by drawing from existing research findings and judiciously chosen parameters. These parameters play a pivotal role in optimizing carrier wave characteristics for both FBMC and OFDM systems, aligning with the evolving demands of 5G networks and facilitating the development of more efficient and resilient wireless communication solutions.

Table 4.2: OFDM Parameters**.**

OFDM Parameters	**Value**
OFDM_Number of Subcarriers	24
OFDM_Number of Symbols in Time	24
OFDM_Subcarrier Spacing	15e3
OFDM_Cyclic Prefix Length	1/(14*OFDM_Subcarrier Spacing)

Upon the application of these values to both FBMC and OFDM systems, an intriguing pattern emerged. All parameters, without exception, maintained a constant value. In essence, when a specific parameter value was employed within the FBMC framework, its corresponding parameter in the OFDM system exhibited adjustments, demonstrating a remarkable interrelation. A notable instance of this phenomenon was evident in parameters such as (the number of symbols in time and cyclic prefix length). These parameters consistently adhered to a fixed ratio of 1/(14*OFDM). This finding highlights a fundamental aspect of our investigation: the dynamic interplay and mutual adaptation of parameter values between FBMC and OFDM systems. This dynamic behaviour is inherently motivated by the shared goal of optimizing the carrier wave, a crucial component in wireless communication systems.

Within this context, the specified parameter values were meticulously integrated into the simulation environment via the MATLAB platform. The resulting outcomes are thoughtfully portrayed in the subsequent graphical representations, offering a comprehensive visual depiction of the research findings. The initial figure conspicuously displays a remarkable consistency in the outcomes observed for both the FBMC and OFDM systems.

This uniformity is reflected in a Power Spectral Density (PSD) in Figure 4.1, indicating a fundamental similarity in their spectral characteristics.

Upon closer examination, however, these results unravel substantial disparities between the two systems. In the case of the OFDM system, the PSD initiation at zero and its gradual ascent toward maximum values, ranging from -50 dB to -100 dB, depict its characteristic behaviour. In stark contrast, the FBMC system demonstrates a unique trajectory. It initiates from a baseline of zero and attains peak PSD values that span a wide range, from 200 dB to 350 dB. Notably, these PSD values are delineated concerning the frequency unit of MHz=5.

These findings extend beyond mere numerical values; they offer profound insights into the spectral attributes and power distribution characteristics of both FBMC and OFDM systems. They illuminate the distinct behaviours and spectral efficiency inherent to each system within the constraints of the specified simulation scenario. We can observe the result in Figure 4.1 which we obtained by applying in MATLAB for OFDM and FBMC.

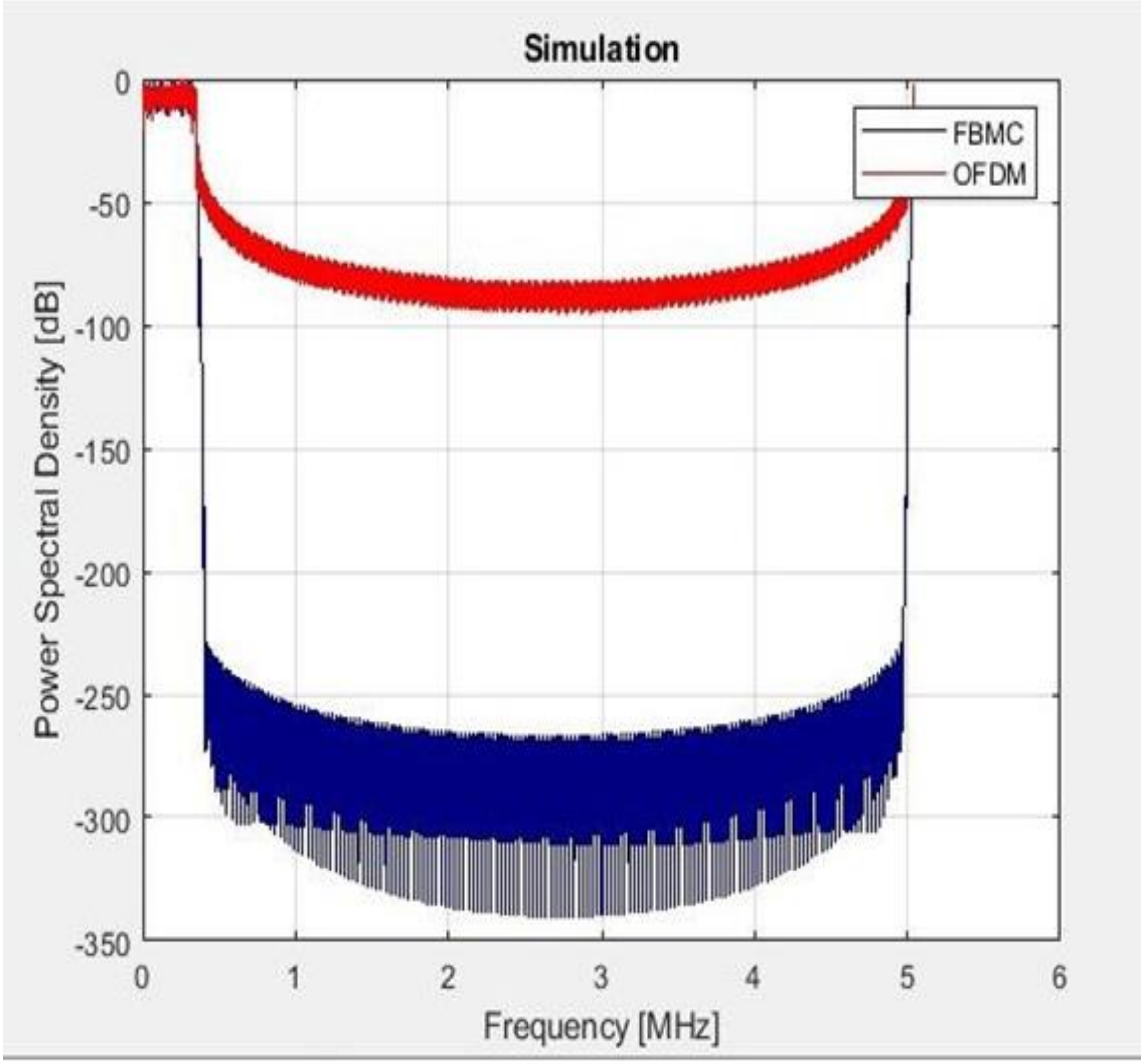


Figure 4.1: OFDM & FBMC Result.

Regarding signal degradation, specifically the signal-to-noise ratio (SNR) for OFDM (dB), noteworthy improvements have been implemented, and the outcomes are visually represented in Figure 4.2. In this graphical representation, the solid line corresponds to the theoretical carrier signal (OFDM), while the red circles graphically portray the Bit Error Ratio (BER) for the OFDM system. Concurrently, the 'x'-shaped markers symbolize the BER for the FBMC system. A thorough analysis of the figure reveals a progressive reduction in the noise ratio over time. Initially, the SNR exhibited values between 10^0 and 10^{-1}. Throughout approximately 20 to 25 seconds, Time is not fixed, but changes with the call, the SNR experienced a substantial decline, reaching the level of 10^{-4}. This substantial reduction holds significant implications as it significantly enhances the performance and integrity of the carrier signal.

This observed trend underscores the dynamic nature of signal quality within the OFDM system, showcasing its capacity to adapt and respond effectively to fluctuating noise conditions. Such adaptability is pivotal in bolstering signal robustness and reliability, which are fundamental attributes for the optimization of wireless communication systems. The graphical representation not only provides a visual understanding of these changes but also serves as a valuable tool for comprehending the behaviour of the carrier signal as it interacts with varying noise levels. This insight is crucial for refining and fine-tuning wireless communication systems, ultimately ensuring their efficiency and effectiveness in real-world scenarios. Below figure 4.2 represent the SNR for OFDM (dB)

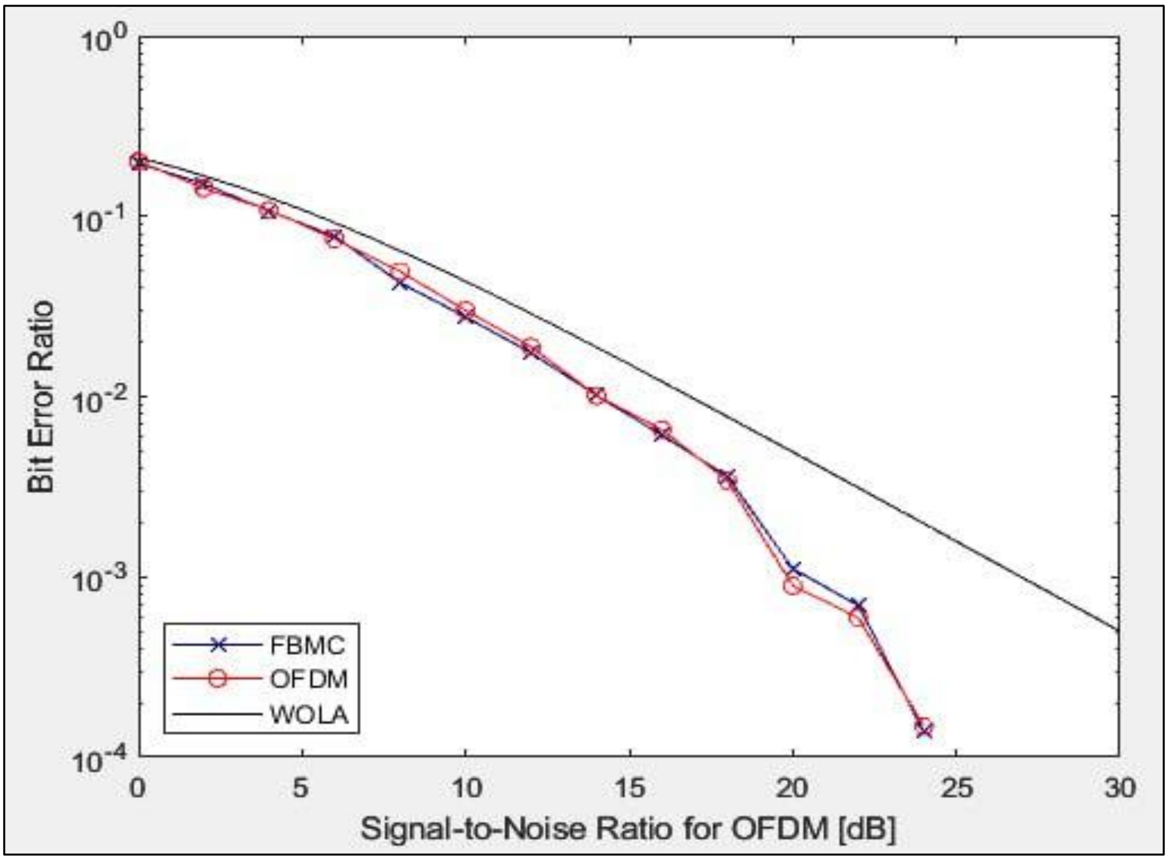


Figure 4.2: Signal-to-Noise Ratio for OFDM (dB).

5. DISCUSSION AND CONCLUSION

This research study delves into the fundamental transmit and receive characteristics of the FBMC modulation scheme, aiming to provide a comprehensive understanding of its performance. To explores this example further, it can experiment with various parameters, such as altering the number of overlapping symbols, adjusting protect band lengths, and varying Signal-to-Noise Ratio (SNR) values. It's worth noting that FBMC stands out as an advantageous modulation scheme when compared to OFDM, primarily due to its ability to achieve higher spectral efficiency. This advantage can be attributed to the per-subcarrier filtering technique employed in (FBMC). Unlike (OFDM), which relies on a uniform distribution of subcarriers across the entire bandwidth, FBMC applies filtering at each subcarrier. This selective filtering decrease interference and enhances spectral efficiency, making FBMC an attractive choice for advanced communication systems. By exploring the characteristics and parameters of FBMC, researchers can gain valuable ideas into its capabilities and limitations. This knowledge is essential for optimizing wireless communication systems and harnessing the benefits of FBMC's spectral efficiency in various real-world applications. Additionally, it contributes to the broader understanding of modulation schemes and their roles in modern communication technologies. In the future work, we suggest for this study may include:

i. Carrying out comprehensive field experiments to confirm the effectiveness of the FBMC modulation scheme in practical, ever-changing wireless settings, while evaluating its flexibility and resilience.
ii. Investigating the feasibility of incorporating artificial intelligence algorithms to autonomously fine-tune FBMC parameters, thereby facilitating self-improving and adaptive communication systems.

REFERENCES

[1] A. M. Abdulazeez and S. R. Zeebaree. 2018 "*Design and Implementation of Electronic Learning. System for Duhok Polytechnic University,*" Acad. J. Nawroz Univ., vol. 7, no. 3, pp. 249–258.

[2] G. S. Nitesh and A. Kakkar. 2016 *"Generations of mobile communication,"* Int. J. Adv. Res. Comput. Sci. Softw. Eng., vol. 6, no. 3.

[3] K. Jacksi, S. R. Zeebaree, and N. Dimililer. 2018 *"LOD Explorer: Presenting the Web of Data,"* Intl J. Adv. Comput. Sci. Appl., vol. 9, no. 1, pp. 45–51.

[4] S. Yadav and S. Singh. 2018 *"Review Paper on Development of Mobile Wireless Technologies (1G to 5G),"* Int J Comput Sci Mob Comput, vol. 7, pp. 94–100.

[5] M. Ramzan and J. A. Shaheen. 2017 *"Comparison: 3G Wireless Networks with 4G Wireless Networks Technology Wise,"* Int. J. Adv. Sci. Technol., vol. 108, pp. 1–10.

[6] E. Ezhilarasan and M. Dinakaran. 2017 *"A Review on mobile technologies: 3G, 4G and 5G,"* in 2017 second international conference on recent trends and challenges in computational models (ICRTCCM), pp. 369–373.

[7] Graham Warren, COO, Eurovision Media Services 2018 , www.signalhorn.com / Hybrid-Network-Solutions that can be easily integrated into existing corporate telecommunications networks .

[8] G. S. Nitesh and A. Kakkar. 2016 *"Generations of mobile communication,"* Int. J. Adv. Res. Comput. Sci. Softw. Eng., vol. 6, no. 3.

[9] A. M. AHMED, S. A. HASAN, and S. A. MAJEED. 2019 *"5G MOBILE SYSTEMS, CHALLENGES AND TECHNOLOGIES: A SURVEY,"* J. Theor. Appl. Inf. Technol., vol. 97, no.11.

[10] Kenneth Finch 2021 , address:2626 Nancy Street Durham NC 2770, https://reusellcvs.life New Attack Lets Hackers Decrypt VoLTE Encryption to Spy on Phone Calls.

[11] Nakazato, G. 2020 *"Development of Mobile Technology (3G, 4G, 5G)"*,Telecomm_unications Policies of Japan, 91-110.

[12] A. Morgado, K. M. S. Huq, S. Mumtaz, and J. Rodriguez. 2018 *“A survey of 5G technologies:regulatory, standardization and industrial perspectives,”* Digit. Commun. Netw., vol. 4, no. 2, pp.87–97.

[13] L. Zheng. 2018 “*5G Mobile Communication Development Trend and Several Key Technologies,”* in MATEC Web of Conferences, vol. 246, p. 03034.

[14] Salih, A. A., Zeebaree, S. R., Abdulraheem, A. S., Zebari, R. R., Sadeeq, M. A., & Ahmed, O. M. 2020 *"Evolution of mobile wireless communication to 5G revolution"* Technology Reports of Kansai University, 62(5), 2139-2151.

[15] Frigo, G., Morato, A., Fedullo, T., & Tramarin, F. (2023, May).https://images.app.goo.gl/Y9gxGpcgA3dAbY7T9. IEC 61850 on 5G Communication Infrastructure: Feasibility Analysis and Practical Considerations. In 2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) (pp. 1-6). IEEE.

[16] S. Ohmori, Y. Yamao, N. Nakajima. 2000 *"the future generations of mobile communications based on broadband access technologies IEEE Commun"*, Mag., 38 (12), pp. 134-142.

[17] M. Xiao, S. Mumtaz, Y. Huang, et al. 2017 *"Millimeter wave communications for future mobile networks IEEE"*, J. Sel. Areas Commun., 35 (9), pp. 1909-1935.

[18] Huang, M., Law, K. M., & Xu, C. 2021 *"The Mobile Technologies in the ‘Informative 'Society. Managing IoT and Mobile Technologies with Innovation"*, Trust, and Sustainable Computing, 35-59.

[19] M. Agiwal, N. Saxena, A. 2019 *"Roy Towards connected living: 5G enabled internet of things (IoT) IETE Techn"*, Rev., 36 (2), pp. 190-202.

[20] M. A. Niknejad, H. Hashemi. 2008 *"MM-Wave Silicon Technology: 60 GHz and Beyond"*, Springer Science & Business Media.

[21] B. Razavi. 2005 *"A 60-GHz direct conversion CMOS receiver"*, in Proc, IEEE Solid-State Circuits Conference, San Francisco, USA.

[22] J. Curtis, Z. Hongyu, A. Farshid. 2016 *"A fully integrated Ka-band front end for 5G transceiver"*, in Proc. IEEE MTT-S International Microwave Symposium (IMS), San Francisco, USA, 1-3.

[23] K. Lee, Y. Park, M. Na, H. Wang and D. Hong. 2017 *"Aligned Reverse Frame Structure for Interference Mitigation in Dynamic TDD Systems,"* IEEE Transactions on Wireless Communications, vol. 16, no. 10, pp. 6967 - 6978, Oct.

[24] A. Mishra, M. Shin, and W. A. Arbaugh. 2002 *"Your 802.11 network has no clothes,"* IEEE Commun. Mag., vol. 9, no. 6, pp. 44–51, Dec.

[25] M. Shin, J. Ma, A. Mishra, and W. Arbaugh. 2006 *"Wireless network security and interworking,"* Proc. IEEE, vol. 94, no. 2, pp. 455–466, Feb.

[26] L. Xiao, L. Greenstein, N. Mandayam, and W. Trappe. 2008 *"Using the physical layer for wireless authentication in time-variant channels,"* IEEE Trans. Wireless Commun., vol. 7, no. 7, pp. 2571–2579, Jul.

[27] D. Shan, K. Zeng, W. Xiang, P. Richardson, and Y. Dong. 2013 *"PHY-CRAM: Physical layer challenge-response authentication mechanism for wireless networks,"* IEEE J. Sel. Areas Commun., vol. 31, no. 9, pp. 1817–1827, Sep.

[28] P. L. Yu, J. S. Baras, and B. M. Sadler. 2008 *"Physical-layer authentication,"* IEEE Trans. Inf. Forensics Security, vol. 3, no. 1, pp. 38–51, Mar.

[29] Boppudi, B. S., Ambati, R. L., Beeram, S. G. S., Raghavan, S. V., & Anumala, V. S. (2023, June).https://images.app.goo.gl/U4KLuKxsmyGdUSi98. Performance Evaluation of Rake Receiver using Rayleigh Fading Channel in Terms of Bit Error Rate. In 2023 8th International Conference on Communication and Electronics Systems (ICCES) (pp. 460-464). IEEE.

[30] J. K. Tugnait. 2013 *"Wireless user authentication via comparison of power spectral densities,"* IEEE J. Sel. Areas Commun., vol. 31, no. 9, pp. 1791– 1802, Sep.

[31] W. C. Jakes. 1974 "Microwave Mobile Communications" New York, NY, USA: Wiley.

[32] Sheikh, J. A., Mir, Z. I., Mufti, M. U. A., Parah, S. A., & Bhat, G. M. 2020 *"A new Filter Bank Multicarrier (FBMC) based cognitive radio for 5g networks using optimization techniques"* Wireless Personal Communications, 112, 1265-1280.

[33] Alkhlefat, Y., Ragheb, A. M., Esmail, M. A., Alshebeili, S. A., & Seleem, H. E. 2020 *"Millimeter wave switching for single carrier and aggregated filter bank multi-carrier signals in radio over fiber networks"* Optical Fiber Technology, 60, 102335.

[34] Akila, I. S., Elakkiya, C., Mohana Priya, M., Nivedha, B., & Yadhaarshini, S. 2022 *"Performance analysis of filter bank multicarrier system for 5G networks. In Inventive Communication and Computational Technologies Proceedings of ICICCT 202"*, 1 (pp. 393-406). Springer Singapore.

[35] Xiu, Y., Wu, J., Xiu, C., & Zhang, Z. 2019 *"Millimeter wave cell discovery based on out-of-band information and design of beamforming"*, IEEE Access, 7, 23076-23088.

[36] Yarrabothu, R. S., & Nelakuditi, U. R. 2019 *"Optimization of out-of-band emission using kaiser-bessel filter for UFMC in 5G cellular communications"*, China Communications, 16(8), 15-23.

[37] A. Farhang, N. Marchetti, F. Figueiredo, and J. P. Miranda. 2014 *“Massive MIMO and Waveform Design for 5th Generation Wireless Communication Systems,”* Proc. Int. Conf. on 5G for Ubiq. Connectivity, pp. 70–75, Nov.

[38] V. Vakilian, T. Wild, F. Schaich, S. Brink, and J. F. Frigon. 2013 *“Universalfiltered Multi-carrier Technique for Wireless Systems Beyond LTE,”* Proc. 2013 GC Wkshps, pp. 223–228, Dec.

[39] F. Schaich, T. Wild, and Y. Chen. 2014 *“Waveform Contenders for 5G – suitability for Short Packet and Low Latency Transmissions,”* Proc. IEEE VTC2014-Spring, pp. 1–5, May.

[40] Y. Mizutani et al. 2017 *“Enhanced Universal Filtered-DFTs-OFDM for Longdelay Multi-path Environment,”* Proc. IEEE PIMRC2017, pp. 1–5. Oct.

[41] K. Mizutani, T. Matsumura, and H. Harada. 2017 *“A Comprehensive Study of Universal Time-domain Windowed OFDM-based LTE Downlink System,”* Proc. WPMC 2017, pp. 28–34, Dec.

[42] K. Mizutani, Z. Lan, and H. Harada. 2014 *“Time-domain Windowing Design for IEEE 802.11af based TVWS-WLAN Systems to Suppress Out-of-band Emission,”* IEICE Trans. Commun., E97-B, no. 4, pp. 875–885, Apr.

[43] K. Mizutani and H. Harada. 2016 *“Universal time-domain windowed OFDM,”* Proc. IEEE VTC2016-Fall, pp. 1-5, Sep.

[44] Y. Kodama, K. Mizutani, T. Matsumura, and H. Harada. *2017 “LTE Uplink System Based on Universal Time-domain Windowed DFTs-OFDM,”* Proc. WPMC 2017, pp. 35–40, Dec.

[45] Hoffman, Chris. January 7, 2019 "What is 5G, and how fast will it be?". How-To Geek website. How-To Geek LLC. Archived from the original on January 24, 2019. Retrieved January 23.

[46] Duffy, C. 2021 "5G explained: What it is, who has 5G, and how much faster is it really?". Cnn. com.

[47] Li zhiyong, zhu jiang. 2017 *"Comparison of spectrum efficiency between UFMC and OFDM technologies for 5G"* [J]. Information communications, (06):26-28.

[48] Guerra, D. W. M., & Abrão, T. (2019).https://images.app.goo.gl/UnrDSR4vC2tBPrA46. Efficient multitap equalization for FBMC-OQAM systems. Transactions on Emerging Telecommunications Technologies, 30(12), e3775.

[49] Sheikh, J. A., Mir, Z. I., Mufti, M. U. A., Parah, S. A., & Bhat, G. M. (2020).https://www.researchgate.net/figure/Filter-bank-architecture-for-spectrum sensing_fig1_338786685. A new Filter Bank Multicarrier (FBMC) based cognitive radio for 5g networks using optimization techniques. Wireless Personal Communications, 112, 1265-1280.

[50] Petrellis, N. (2014).https://images.app.goo.gl/2fQphmmemfzY1AcR6. Undersampling in orthogonal frequency division multiplexing telecommunication systems. Applied Sciences, 4(1), 79-98.

[51] Ning yongqiang. 2018 Research on key technologies of 5G new multi-carrier FBMC[D]. Beijing jiaotong university.

[52] Bedoui, A., & Et-tolba, M. (2017, November). A comparative analysis of filter bank multicarrier (FBMC) as 5G multiplexing technique. In 2017 International Conference on Wireless Networks and Mobile Communications (WINCOM) (pp. 1-7). IEEE.

[53] FBMC vs. OFDM Modulation - MATLAB & Simulink (mathworks.com)

[54] Raslan, W. A., Mohamed, M. A., & Abdel-Atty, H. M. 2022 *"Deep-BiGRU based channel estimation scheme for MIMO–FBMC systems",* Physical Communication, 51, 101592.

[55] Bedoui, A., & Et-tolba, M. 2021 *"A deep neural network-based interference mitigation for MIMO-FBMC/OQAM systems"* Frontiers in Communications and Networks, 2, 728982.

[56] Wang, H., Memon, F. H., Wang, X., Li, X., Zhao, N., & Dev, K. 2023 *"Machine learning-enabled MIMO-FBMC communication channel parameter estimation in IIoT",* A distributed CS approach. Digital Communications and Networks, 9(2), 306-312.