JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF ELECTRICAL & COMPUTER ENGINEERING

TITLE: PERFORMANCE EVALUATION OF ADVANCED MODULATION TECHNIQUES WITH PD-NOMA FOR 5G APPLICATIONS

Jimma Institute of Technology, Faculty of Electrical & Computer Engineering in partial fulfillment of the requirements for the degree of master of science program in Communication Engineering

By

Kedir Ebrahim

December 23, 2022

Jimma, Oromia, Ethiopia

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Kedir Ebrahim

Main Advisor: Dr. Kinde Analay (Assoc. Prof.)

Co-Advisor: Mrs. Sofia Ali (M.Sc.)

December 23, 2022
Jimma, Oromia, Ethiopia

Declaration

I hereby declare that this thesis, with the title "Performance evaluation of advanced modulation techniques with PD-NOMA for 5G applications," is my own work, except where explicitly stated otherwise in the text, and I assure it with my signature. Research thesis submitted by:

Name	**Signature**	**Date**
(Student)		

As masters research advisors, we certify that we have read and evaluated this MSc thesis entitled as *"Performance evaluation of advanced modulation techniques with PD-NOMA for 5G applications"* is submitted by Kedir Ebrahim our supervisorship as main and co-advisors respectively.

Name	**Signature**	**Date**
(Main Advisor)		
(Co-Advisor)		

Approval

We, the undersigned members of board of examiners of the final report by **Kedir Ebrahim** have read and evaluated his thesis entitled Performance evaluation of advanced modulation techniques with PD-NOMA for 5G applications and examined the candidate. This is therefore to certify that the thesis has been accepted in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Communication Engineering Electrical& Computer Engineering.

Name	**Signature**	**Date**
(Advisor)		
(Co-Advisor)		
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(Internal Examiner)		

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Abstract

For many decades, the amount of wireless voice and data communications has grown at an exponential rate from one generation to other generation. Power domain non-orthogonal multiple access (NOMA) is one of the promising approaches for achieving high data rates, high energy efficiency, high spectral efficiency, very low bit error rate, good quality of services, and low latency, as well as serving a large number of users over a single resource and maximizing bandwidth utilization. Increased channel capacity represents an important point in order to get higher rates.The proposed system also reduces the number of unserved users in the given cluster. This study was conducted to explore the performance evaluation of advanced modulations based Power domain non-orthogonal multiple access (PD-NOMA) for 5G.

This thesis work specifically consists of three different 5G advanced modulations, such as orthogonal frequency division multiplexing (OFDM), filter bank multi carrier (FBMC), and universal filter multi carrier (UFMC), with the Power domain non-orthogonal multiple access techniques in order to increase the channel capacity and minimize interferences among different bands. The performance is compared interms of power spectral density(PSD), bit error rate (BER), spectral efficiency (SE), Capacity, interference, outage probability(OP) and computational complexity. The matlab simulation results show that, out of the three types of advanced modulation, filter bank multi carrier can achieve the highest channel capacity enhancement and better bit error rate compared to other waveforms. The combination of power domain, non-orthogonal multiple access, and filter bank multi carrier techniques combined with offset quadrature amplitude modulation allows a significant increase in throughput and a significant reduction in unserved users. Using the simulation, it has been observed that from the result the maximum capacity value obtained for FBMC/OQAM based PD-NOMA is greater than UFMC based PD-NOMA and OFDM based PD-NOMA in both cases of interfereces. Intems of system complexity orthogonal frequency division multiplexing (OFDM) is less complex than filter bank multi carrier (FBMC) polyphase network (PPN) and universal filter multi carrier (UFMC) is the third.

Key words: BER, FBMC, OFDM,PD-NOMA, SE and UFMC.

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Acronyms and Notation

1G	First Generation
2G	Second Generations
3G	Third Generations
4G	Fourth Generations
5G	Fifth Generations
ACLR	Adjacent Channel Leakage Ratio
AWGN	Additive White Gaussian Noise
CDMA	Code Division Multiple Access
CD-NOMA	Code Domain Non Orthogonal Multiple Access
CR	Cognitive Radio
CSIs	Channel State Informations
DL	Down Link
MRI	Energy Efficiency
eMBB	Enhanced Mobile Broadband
FBMC	Filter Bank Based Multicarrier
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GFDM	Generalized Frequency Division Multiplexing
ICI	Inter Carrier Interference
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference

LDS-CDMA	Low-Density Spreading CDMA
LDS-OFDM	Low-Density Spreading Based OFDM
mMIMO	Massive Multi Input Multi Output
mMTC	Massive Machine-Type Communications
MUD	Multi User Detection
NOMA	Non-Orthogonal Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OMA	Orthogonal multiple access
OOBE	Out- of- Band Emission
OOBL	Out-of-Band Leakage
OQAM	Offset Quadrature Amplitude Modulation
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PD-NOMA	Power Domain Non Orthogonal Multiple Access
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RA	Radio Access
RB	Resource Block
REs	Resource Elements
RF	Radio Frequency
SC	Superposition Coding
SCMA	Sparse Code Multiple Access
SE	Spectral Efficiency

SIC	Successive Interference Cancellation
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UEs	User Equipments
UFMC	Universal Filtered Multicarrier
UL	Uplink
URLLC	Ultra-Reliable Low-Latency Communications
a$_1$ and a_2	Power Coefficients
B$_w$	Band Width
B$_m ax$	Maximum Band Width
h	Channel Gain
P	Power
R$_b$	Acheivable Rate
n$_o$	Aditive White Gaussian Noise
T	Symbol Period
T$_x$	Transmitter
R$_x$	Receiver
α	Power Allocation Coefficient
ρ	Power Splitting Coefficient
η	Efficiency
τ_{max}	Delay
γ	Signal to Noise Ratio
σ^2	Variance

Chapter 1
Introduction

1.1 Background

Wireless communication technology has fundamentally changed the way we communicate. Cellular mobile communication is gaining popularity. For many decades, wireless voice and data communications have increased at an exponential rate from generation to generation [1, 2]. Wireless communication is based on radio, which means the electromagnetic waves are designed to carry information from a transmitter to one or more receivers. The cellular network is the one used for wireless communication. The remarkable success of cellular mobile radio and other wireless technology has fundamentally changed the way people communicate and conduct business [3]. This cellular network consists of a set of base stations (BSs) and a set of user equipment (UE). Each UE is connected to one of the BSs, which provides services to it [4].

In communication systems, the DL refers to the signals sent from the BSs to their respective UEs. Whereas the UL refers to transmission from the UEs to their respective BSs. OMA was the backbone for previous generations, but NOMA is the backbone for 5G, MA.NOMA is going to be one of the key enablers for cellular technologies. It provides high SE, user fairness, better connectivity, an enhanced data rate, and reduced latency for future RA. 5G is defined to have a maximum bandwidth of 100 MHz for frequency bands below 6 GHz [5]. Figure 1.1 depicts 5G spectrum considerations in terms of coverage and application areas.

5G is a wireless broadband technology based on the IEEE 802.11ac standard. In wireless networks, SE, EE, PSD, OOBE, BER, and throughput are the most important metrics in 5G networks. According to paper [6] one of the promising technologies for achieving broadband green communication is the improvement of 5G networks. Compared to OMA, the NOMA technique can further improve SE, EE, BER, PSD, and the achievable rate, but NOMA alone cannot fully satisfy the system's performance while advanced modulation-based PD-NOMA further improves the above metrics. NOMA techniques have been proposed recently as an emerging RA technology for 5G in order to achieve high SE, maximum EE, very low BER,

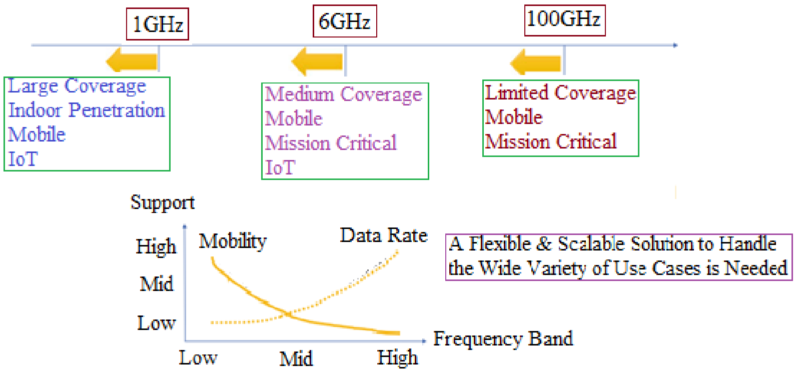


Figure 1.1: 5G Frequency band considerations [5].

good QoS, and low latency. This NOMA technique is used to serve multiple users at the same time, frequency, and code, but with different power levels in the case of PD. NOMA techniques have a significant SE gain over the traditional ones that were used in previous generations, i.e., OMA. There are different broad classifications of NOMA techniques. Those classifications are PD-NOMA and CD-NOMA [7]. From the above two classifications, this thesis work focuses on the combination of PD-NOMA with advanced modulation in terms of SE, maximum EE, OP, and low BER for 5G applications.

Because of their high EE, lower latency, and higher reliability, 5G technologies provide reliable connections anytime, anywhere and are applicable in areas such as M2M, D2D, IoT, the internet of things in vehicles, and mobile gaming [8, 9]. Also, 5G technology works in dense microcells, relay stations, a massive number of antennas per BS, and also in other devices, beam forming antennas, using mm waves, CR, spatial modulation, and NOMA [10]. Applying new multiplexing techniques for channel access is one way to improve high data rate and low latency communication in a 5G mobile cellular network.5G technology is envisioned to improve major key performance indicators (KPIs), such as peak data rate, SE, power consumption, complexity, connection density, latency, and mobility, significantly.

Some points to be considered in 5G are briefly explained below:
High SE: The modulation order, type of pulse shaping filter, and density of the lattice play an important role in determining the SE. The guard/CP units in time or frequency domains, as well as other extra overheads, reduce the SE, which is especially important for eMBB communication.

Low Latency: For URLLC applications, 5G aims for latency of less than 1 ms. This goal can be managed by shortening the transmission time interval or increasing the sub-carrier spacing [11].

High Reliability: The reliability is evaluated by the BER, or block error rate, and it is extremely important for mission-critical communications where errors are less tolerable. In addition, the re-transmissions due to errors cause an increase in latency, so high-reliability links are desirable to provide low latency as well.

Massive Asynchronous Transmission: For mMTC services, it is anticipated that a sizable number of nodes will communicate through the 5G network..

Low Device Complexity: Another crucial parameter for waveform design is computational complexity, which is based on the quantity of operations needed at the Tx or Rx. Additional windowing, filtering, and interference cancellation algorithms increase complexity substantially, and the system designer should consider them when designing cost- and energy-efficient transceivers.

High EE: Low computational complexity and low PAPR provide high EE. PAPR is a statistical metric that is evaluated by the complementary cumulative distributive function (CCDF) of the signal. Low PAPR is required to operate power amplifiers (PAs) efficiently, which are one of the most energy-hungry components in a transceiver.

Capacity enhancement is a major goal and target of 5G communications. This capacity enhancement can be obtained by using suitable NOMA, which is a strong for systems beyond 5G due to its capability of supporting massive communications. For 5G mobile communication, data speed and end to end latency are the major points to be considered. The main objective of the RA technique is to provide the mobile terminals with a connection to the core network.

Using a suitable MA technique is the most important point in improving the system capacity in terms of SE and EE. NOMA can utilize the BW more efficiently by accommodating multiple users over the same spectrum, time, and code. OMA and NOMA are the two most well-known MAs. There are different classes of OMA techniques: OFDMA, FDMA, TDMA, and CDMA. In the case of OFDMA, it allows multi-user communications through an OFDM mechanism in which sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other. While in TDMA, several users share the same frequency on a time-sharing basis. The main advantage of NOMA is that it allows multiple users to share a single frequency channel within the same cell at the same time, which was not possible in previous generations. The other benefits of NOMA are that it offers improved SE, higher cell edge throughput, relaxed channel feedback, and low transmission latency [12].

This thesis work focuses on the different parameters of advanced modulation techniques in order to identify which type of modulation meets the goal of PD-NOMA. One of the most important aspects of a cellular wireless system is mobility. The mobility of 5G mobile communication is achieved through the handover mechanism. This handover mechanism enables the UEs to move seamlessly within the coverage area of the network. The handover technique entails transferring control of an active session from one cell to another cell [13].

With the use of SC at the BS and SIC decoding techniques at the users, the NOMA scheme enables the simultaneous service of all users by utilising the entire BW to convey the data. In PD-NOMA multiple users are assigned to one RB through different power levels by utilizing SC and SIC [14]. The CD-NOMA maximizes user detection while minimizing symbol error rates by employing random Gaussian coding at the transmitters and compressive sensing at the receiver. The higher SE can be achieved by using efficient, advanced modulation-based PD-NOMA for 5G mobile communication. In 5G communication, reducing energy consumption has become of prime importance. For a given SE, each user's maximum EE performance can be achieved. This degree of efficiency can be adjusted by varying total power using power control schemes.

PD-NOMA allows the optimization of multi-user operation and allocates the same frequency resources to all the users in DL, where no spatial separation is needed. This can be achieved by using the SC technique. In the PD-NOMA, the users data is superimposed based on power level, while sharing the same frequency channel at the same time. At the receiver side, SIC is applied to retrieve a signal [15]. The figure 1.2 below shows the difference between traditional OMA and NOMA.

Properly selecting and using better advanced modulation techniques are essential for 5G applications. There are different advanced modulation waveforms for 5G applications; some

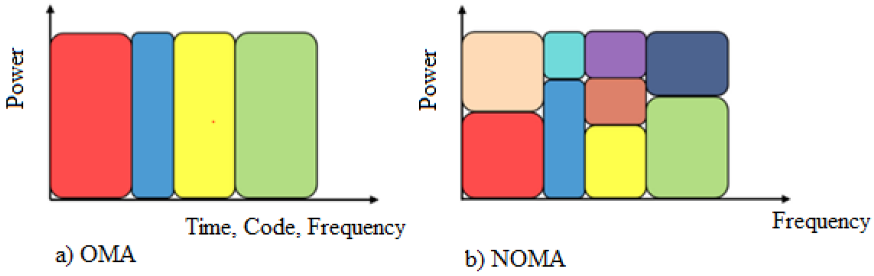


Figure 1.2: The difference between OMA and NOMA [16].

of them are GFDM, UFMC, FBMC, and OFDM; three of them analyzed with PD-NOMA in this research work. From different waveforms, this thesis work focuses on three of them, i.e., FBMC, UFMC, and OFDM. OFDM waveform has a high PAPR, which results in low efficiency of PA and increases battery consumption due to this reason it is not suitable for a large number of users in NOMA. GFDM is a block-oriented, non-orthogonal multi-carrier transmission scheme capable of spreading data across a two dimensional (time/frequency) block structure (multiple symbols per multi-carrier). The circular pulse shape of the individual sub-carriers in GFDM makes it possible for block-oriented transmission. But, in GFDM, the OOBE of the transmit signal is the problem, which is controlled by an adjustable pulse shaping filter that is applied to the individual sub-carriers [17].

Adding a pulse-shaping filter to individual sub-carriers leads to system complexity and increased cost. In order to get better diversity gain and SE, the FBMC modulation technique is combined with PD-NOMA. Using a guard band and CP, the OFDM system may prevent interference between symbols and carriers. Interference between sub-carriers and symbols brought about by synchronization issues, time and frequency variations on users' transmission channels, and other factors. The new waveforms such as FBMC, GFDM, and UFMC are proposed to solve the drawbacks of OFDM. GFDM-based NOMA systems were investigated in different research works and found to have lower PAPR as well as OOBR performance than OFDM-based NOMA systems [18]. But FBMC-based PD-NOMA is better than the others.In this thesis work, their performance in terms of SE, PSD, OP can be analyzed and evaluated. Under the conditions of equal SE, the complexity of the GFDM system is lower than that of the OFDM system.

The advanced modulation assisted NOMA technique is a critical future technology that will serve multiple users on the same frequency resource by utilizing NOMA principles, whether PD-NOMA or CD-NOMA. It gives a high SE, better cell edges, and reduces resource waste since communication resources are scarce. It allows allocating one frequency channel simultaneously to numerous users within the same cell. It serves multiple users at the receiver side by using multi user detection (MUD) algorithms, such as SIC, to detect the desired signals. In terms of network, NOMA is very crucial for 5G mobile communication. NOMA also has the innate ability to modify the transmission strategy in response to traffic and users' channel state information (CSIs) [19]. FBMC/OQAM based PD-NOMA is preferred for different reasons to meet the goals of 5G applications.

There are different phases to accomplishing this thesis successfully. The first step is a literature review. In this step, we review the articles that have been done before. The second step is data collection, method selection (an algorithm), and software selection, which are the most appropriate. The overall system design is the next step after algorithm selection. After overall system design, the next step is system implementation and software simulation (Matlab simulation). The next step is finding a suitable advanced modulation for PD-NOMA for 5G mobile communication following investigation of the results. The next stage is to prepare the draft report and then submit it after the results have been analyzed. The next step is final report preparation and final report submission. The thesis presentation follows.

1.2 Statement of the Problem

Nowadays, 5G networks are deployed in most part of the world. With this regard, 5G wireless networks has been deployed in capital city of Ethiopia and different countries. In 5G wireless communication networks, the system performance metrics like; overall capacity, throughput, system interference, SE, PSD, sum rate, and computational complexity are require if they optimal as compared to the previous 4G networks. Therefore, to fulfill such requirements, it requires maximizing SE, lowering OOBE, and reducing interference, lowering BER can be achieved with efficient advanced modulation. Thus, different 5G waveforms like; OFDM, UFMC and FBMC being used.

However, unlike FBMC, the OFDM has a much larger sideband spectrum which results in loss of the BW and there by overall system data rate is low. To use the limited resource in efficient way and then enhancing throughput and capacity, different NOMA techniques has been investigated. But, it does not clearly imply which type of NOMA with an advanced modulation technique is suitable for 5G applications. Therefore, the integrated waveforms with the NOMA techniques is highly required to enhance the system performance and way of utilizing the limited resources which are the requirements of 5G communication systems.

The advanced modulation techniques with PD-NOMA schemes are formulated for 5G applications to overcome the previous system drawbacks. Besides, interference is another a major impediment sense it has a negative impact on the system reliability, and efficiency and coverage are. However, there is a lack of a complete and fair comparison between advanced modulation and NOMA. Thus, to mitigate the above system limitation, in this thesis work, FBMC, UFMC, and OFDM techniques have been investigated with PD-NOMA to increase the number of connected users without increasing BS.

1.3 Objectives of the study

The study has the following general and specific objectives.

1.3.1 General Objective

The main objective of this thesis work is to evaluate the performance of PD-NOMA along with advanced modulation techniques for 5G wireless applications.

1.3.2 Specific Objectives

The specific objectives of this thesis work are the following:

- To review the different types of modulations techniques that can be used efficiently for PD-NOMA
- To analyze and identify advanced modulation techniques for PD-NOMA used 5G wireless systems
- To simulate the different types of modulations in MATLAB.
- To analyze PD-NOMA pe4rformance in terms of probability of BER, OOBE, PSD, achievable rate, SE, OP, Interference, and Capacity
- To evaluate the performance of PD-NOMA by combining it with the FBMC/OQAM, UFMC and OFDM techniques

1.4 Scope and Limitations of the Thesis

The scope of this thesis work is to study the three types of advanced modulation techniques with PD-NOMA for 5G applications. Finally, choose the sort of advanced modulation technology for PD-NOMA that is preferable for interference minimization and EE and SE utilization without power and bandwidth waste. The limitations of this thesis are limited to three advanced modulations with PD-NOMA and two user scenarios.

1.5 Significance of the Thesis

The significance of this thesis work is to investigate a particular type of advanced modulation techniques for PD-NOMA and as well as examine the potential effects of the different advanced modulation techniques will have on the 5G applications. This thesis work provides an overview of fundamental NOMA and advanced modulation technique properties, the performance characteristics of the particular advanced modulation based NOMA schemes. This information can be used to establish NOMA and advanced modulation techniques selection criteria for optimum system performance. This result will be an input for practical implementation of reliable and efficient advanced modulation with PD-NOMA for 5G application industries.

1.6 Contribution of the Thesis

In order to meet the demands in 5G systems we need better performance in SE, EE, Capacity, BER, OP and throughput in order to address the demands. To overcome such issues different types of advanced modulation for PD-NOMA, with their basic model, with their working principles, with their technical aspects, with their KPIs investigated. This thesis work contributes the analysis of three advanced modulation with PD-NOMA techniques in order to sight better SE, PSD, BER, OOBE, OP, and channel capacity. This thesis work also contributes which type of advanced modulation with PD-NOMA minimizes the interference. The hybrid structure that combines FBMC, OQAM and PD-NOMA has been developed for 5G applications.

1.7 Organization of the Thesis

This thesis work contains six chapters. The first chapter deals with the introduction part of 5G cellular networks and the multiple access techniques, motivational overview, statement of the problem, objectives, methodology, scope and the significance of this thesis work. The second chapter deals with theoretical background and literature review which includes OMA and NOMA. The third chapter discusses the advanced modulation methods used for 5G applications. In chapter four, various parameters, system modeling, and PD-NOMA are discussed. The simulation findings and discussions of various advanced modulations with PD-NOMA for 5G applications are covered in chapter five. A conclusion and recommendations can be found in the final chapter.

Chapter 2
Technical Background and Literature Review

2.1 Technical Background

Mobile communication has become an essential tool for modern society. In wireless communication, 5G is the standard for broadband cellular networks, which cellular phone companies began deploying worldwide in 2019, it provides connectivity to most current cellphones. As it was mentioned earlier, 5G cellular networks offer 1,000-fold gains in system capacity, peak data rates of up to 10 GB/s and 1 GB/s for low mobility and high mobility, respectively, and at least 100 billion device connections per km^2, whereas 4G only supports 4000 devices per km^2 and ultra-low power consumption with low latency [20, 21]. 5G technology creates never-before-seen opportunities for people and businesses.

5G replaces the 1G, 2G, 3G, and 4G networks as the most recent worldwide wireless standard. With the help of 5G, a brand-new sort of network can connect practically everyone and everything, including machines, objects, and gadgetry. The major goal of 5G is to provide faster peak data throughput of multiple gigabits per second (Gbps), extremely low latency, increased dependability, enormous network capacity, increased availability, etc. Improved efficiency and greater performance enable new user experiences and link new industries. For the next generation of cellular networks to be both EE and SE, the ever-growing number of mobile applications and user demands eventually led to new technological and architectural solutions.

In D2D communication, the cellular devices work as D2D users communicate with each other, bypassing the BS. The traditional technique of OMA-supported cellular mobile communication is expensive due to the limitations of the spectrum. 5G infrastructure is much more efficient when compared with other generations supported by OMA in terms of energy consumption, service creation, and hardware flexibility. Recent technologies, including 5G cellular communications, are characterized by numerous accesses to service multiple users with constrained BW resources.

Some examples of MA in OMA are FDMA, TDMA, CDMA, and OFDMA. Those types of MA were used in the history of mobile communications, from 1G to 4G. Here below the overview of mobile generations with their respective MA techniques. This section also discusses the distinctions between previous generations and 5G. The previous generations of mobile networks are 1G, 2G, 3G, and 4G, each of them discussed in the next section under OMA.

The NOMA approach is used in 5G cellular networks to give users access that is orthogonal to them in terms of time, frequency, code, or space. Each user of these techniques operates simultaneously in the same band, where their power levels serve as a means of differentiation. Using SC on the transmitter side, the NOMA approach enables the SIC receiver to identify between users in the UL and DL channels.

All of the previous generations 1G, 2G, 3G, and 4G led to 5G, which is intended to offer greater connection than has ever been possible. In order to support new deployment methods, empower next-generation user experiences, and provide new services, it has been developed with a larger capacity, high speeds, improved reliability, and minimal latency.

A 5G cellular network is designed to provide peak data rates of up to 20 GB/s, according to IMT-2020 specifications. In addition to offering faster peak data speeds, 5G is intended to increase network capacity by utilizing additional spectrum, such as mmWave. In addition to offering a more consistent user experience overall and a significant reduction in latency, 5G cellular networks can maintain high data rates even when users are moving about. Additionally, the new 5G New Radio (NR) mobile network is supported by a gigabit LTE coverage base, which can offer ubiquitous gigabit-class connections [22]. Use cases and requirements of 5G are hilighted in the figure below.

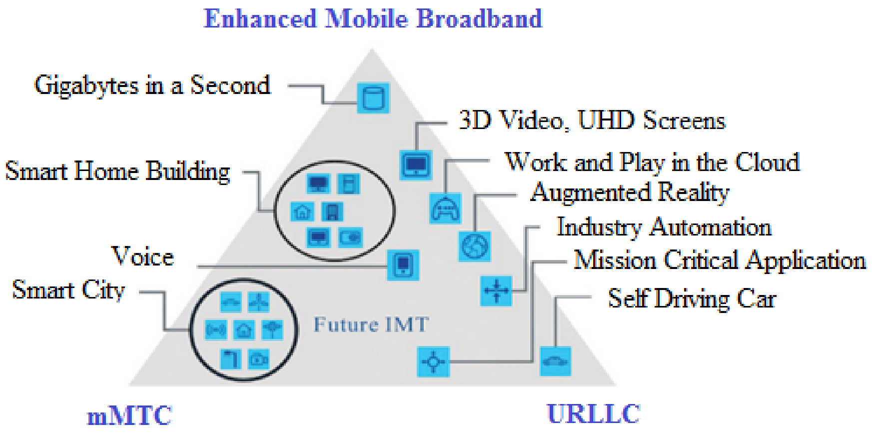


Figure 2.1: Usage Scenarios of IMT-2020 [22].

Figure 2.1 shows the usage scenarios of IMT-2020 for 5G applications in different areas . The concept of eMBB, mMTC and URLLC are explained in chapter one. How is 5G technology better than 4G technology? There are several reasons why 5G technology is better than 4G technology:

5G is significantly faster than 4G: It can be significantly faster than 4G, delivering up to 20 Gbps peak data rates and 100+ Mbps average data rates.

5G has more capacity than 4G: it is designed to support a 100x increase in traffic capacity and network efficiency.

5G has significantly lower latency than 4G: It features a 10x drop in end-to-end latency down to 1 ms, which enables it to give more rapid, real-time access.

5G is a unified platform: that is more capable than 4G. While 4G LTE concentrated on providing substantially faster mobile broadband services than 3G, 5G is intended to be a unified, more powerful platform that enables new services like mission-critical communications and the vast IoT, in addition to improving mobile broadband experiences. Additionally, all spectrum types (licensed, shared, and unlicensed), bands (low, mid, and high), and a variety of deployment strategies are natively supported by 5G.

5G uses spectrum better than 4G: In addition, 5G is intended to maximize spectrum utilization across a variety of spectrum regulatory regimes and bands, including low bands below 1 GHz, mid bands between 1 GHz and 6 GHz, and high bands known as mm wave.

Some of the basic requirements of 5G systems are [23]: High network speed in terms of Gbps (>=1Gbps) means the time required to download the video may be less than a second, it has low latency, it can handle a large number of devices simultaneously, it has a long battery life, and it has 100 percent connectivity in any place and anywhere.

But, the above requirement is not applicable in the case of 4G, 3G, 2G, and 1G cellular networks. The 4G, 3G, 2G, and 1G cellular network technologies are unable to handle the extreme and ever-increasing data rate and provide simultaneous connectivity to a large number of users because of the absence of NOMA in the previous generations. Because of OOBE and high PAPR, LTE systems, in particular, are unable to handle the rapid growth of data rates and connectivity.

In general, 5G networks fulfill several requirements, including the points below. A minimum peak data rate of 10 GB/s (100 times more than that in the 3GPP long-term LTE), a latency of 1 ms (ten times lower than that in 4G networks), and a connection density of 1,000,000 devices per km^2 (100 times more than 4G networks). All the points above drive the concept of NOMA.

2.2 Orthogonal Multiple Access Schemes

This type of MA is also applicable to wireless cellular networks. This type of MA resource block is orthogonally divided into time, frequency, and code domains. Using OMA MA has its own benefits and limitations. One of its benefits is that there is minimal interference among adjacent blocks, which makes signal detection relatively easy. Its drawback is that it can only support a limited number of users due to limitations in the number of orthogonal resource blocks, which limits the SE and the capacity of the cellular networks. Each of the OMA classes is discussed below:

2.2.1 Frequency Division Multiple Access

1G: It was introduced during the 1980s. This generation only delivers analog voice. In the case of FDMA, the frequency spectrum is divided into different slots. In this MA, there is wastage of BW. The FDMA assigns specific frequency channel to each available users out of the given BW. In the case of FDMA the given BW B is divided into frequency channels F which serves K users where in this case each user allocated its individual channel. But, it is not true in case of 5G cellular networks which uses the principles of NOMA.

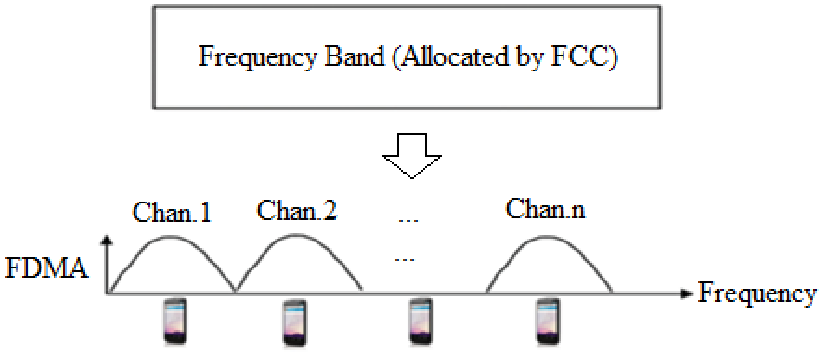


Figure 2.2: FDMA [24].

2.2.2 Time Division Multiple Access

2G: It was first introduced in the early 1990s. This generation introduced digital voice (e.g., CDMA). In TDMA, the information for each user is sent in non-overlapping time slots. In the case of TDMA, the device is assigned to different time slots. TDMA-based networks require accurate timing synchronization, which is challenging, especially in the uplink.

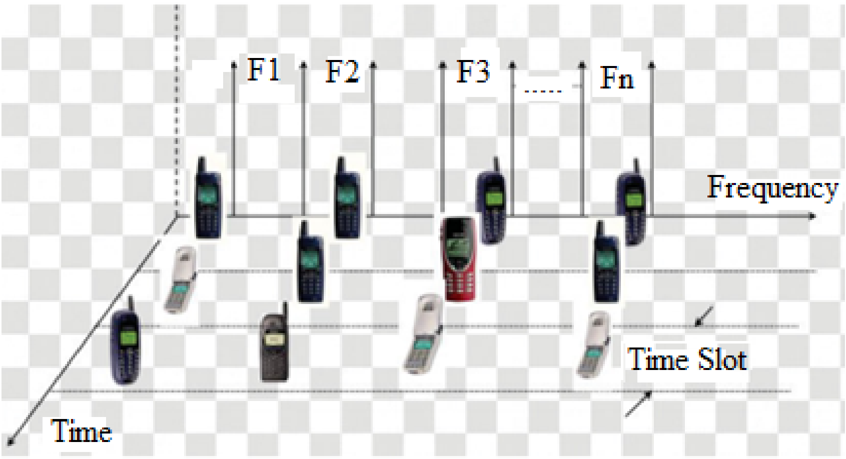


Figure 2.3: TDMA [24].

2.2.3 Code Division Multiple Access (CDMA)

3G: This technology was introduced in the early 2000s. This generation brought mobile data (e.g., CDMA 2000). There is a limitation in the case of FDMA and TDMA, so in order to overcome their limitation, CDMA was introduced. This multiple technique employs codes to separate users on the same channel.

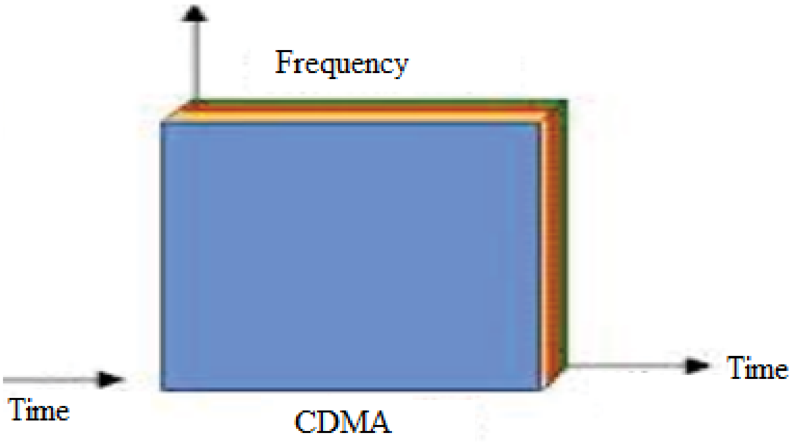


Figure 2.4: CDMA [24].

2.2.4 Orthogonal Frequency Division Multiple Access

4G LTE: This technology was introduced in the 2010s.This generation is used in the area of broadband. In OFDMA, the frequency allocation is basically at right angles. In this case, a number of users use the data at the same time. Information for each user is assigned to a subset of sub-carriers. The orthogonality avoids the need for separating the sub-carriers by means of a guard band that places empty frequency between adjacent sub-carriers [26].

The BW resource is saved by OFDMA. OFDMA has its own benefit, for instance, its robustness in the presence of multi-path fading. This technique has a high PAPR in the UL, which is taken as the limitation of using OFDMA for 5G applications. This high PAPR reduces power efficiency and imposes a power consumption burden on the UE; this effect reduces battery life on the UL side. However, because of the availability of power supplies at the BSs, this limitation is not as severe on the DL side.

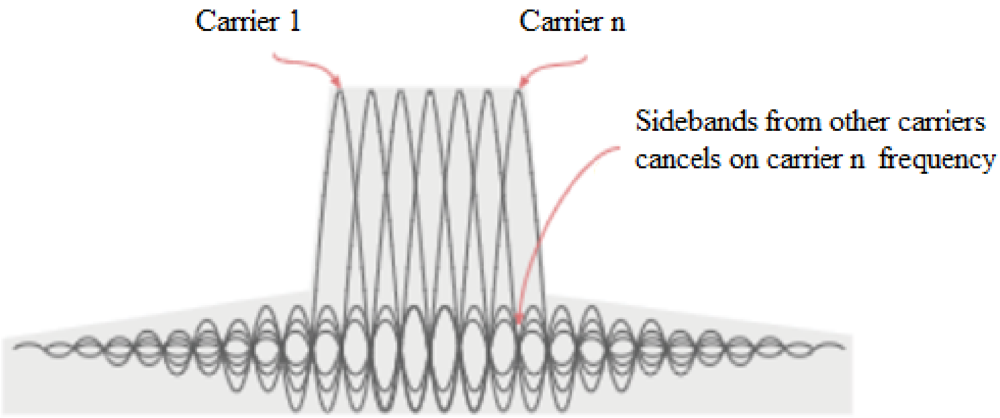


Figure 2.5: OFDMA [24].

As it is mentioned in the above paragraph above OFDMA is not suitable for UL. SC-FDMA (Single Carrier FDMA) is siutable for UL in LTE. from figure 2.6 below it is possible to observe the difference between OFDMA and SC-FDMA.

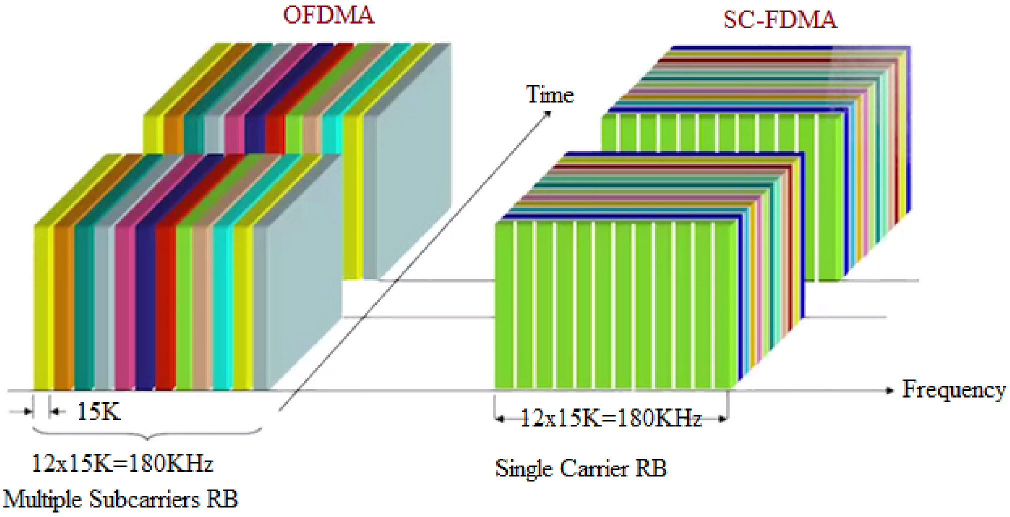


Figure 2.6: The difference between OFDMA and SC-FDMA [25].

2.3 Taxonomy of 5G PHY Layer Enhancement Techniques

According to the 5G New Radio 3GPP standard, the PHY layer modules are described in this 5G NR physical layer. From the figure below this thesis work focuses on 5G advanced waveform and PD-NOMA.

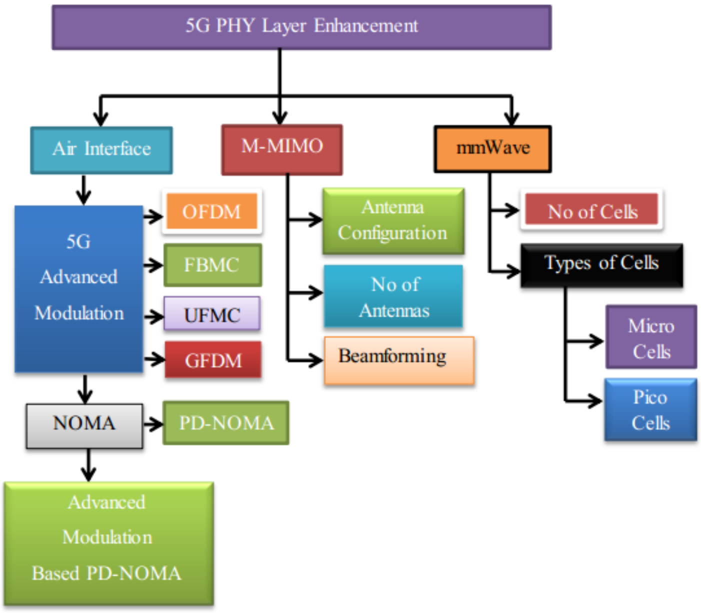


Figure 2.7: Taxonomy of 5G PHY layer enhancement techniques.

2.4 Literature Review

Different researchers have been worked on 5G modulations for different applications in [28] the comparison of UFMC, FBMC and F- OFDM with OFDM are dealt in terms of PSD, PAPR and constellation. But it is not dealt interms of SE, OP, and complexity. In [29] multidimensional index modulation for 5G application discussed in terms of different KIP's but, not dealt with the siutable type of NOMA whether it is CD-NOMA or PD-NOMA. Different studies on NOMA and modulation techniques, particularly PD-NOMA, have been conducted for the 5G requirements. Researchers works day and night to fulfill the demands of 5G during the past few years [19]. In different research, OFDM based NOMA was discussed in order to overcome the problems of capacity gain, PAPR, and DC power allocation [27, 30]. But, OFDM based NOMA has large PAPR which limits the capacity of the cystem. Various researchers have demonstrated that NOMA can be used effectively to meet both network-level and user-experienced data rate requirements for 5G. The design of a suitable MA technique is one of the most important aspects of improving the system's capacity. IM-modulation based OFDM-NOMA has been discussed in [39] but, it is discussed only interms of BER, not in terms of PSD, SE, OP, interference and OOBE. By its nature OFDM based NOMA has large PAPR which limits the system capacity.

Researchers all over the globe have started investigating NOMA as a promising MA scheme for RA. Also, the evolution of wireless networks to 5G poses new challenges for EE since the entire network will be ultra-dense. In [19] PD-NOMA attains multiplexing in PD, whereas CD-NOMA achieves multiplexing in CD. Also, CD-NOMA shares the entire set of available resources (time and frequency). In contrast, CD-NOMA utilizes user-specific spreading sequences that are either sparse sequences or non-orthogonal cross-correlation sequences of low correlation coefficient. But, they are not clearly explained with efficient modulation interms OOBE, PSD SE.

The SC and SIC, first proposed in [31], it is a technique in PD-NOMA for simultaneously communicating information to multiple receivers from a single source. This implies that the transmitter transmits multiple users information at the same time and at the same frequency. To decode the superimposed information at each receiver the SIC was used.

In [16] the concept of power allocation for two users rised, the NOMA scheme controls the throughput of each user by adjusting the power allocation ratio, P1/P2. But, which type of ower allocation is not discussed whether FPA or DPA for wireless networks. According to [32] the concept of cooperative communications has gained a great deal of attention due to its ability to offer spatial diversity to mitigate fading while resolving the difficulties of mounting multiple antennas on small communications terminals . NOMA for a multiple-antenna relay network has been studied in [33, 34]. These studies analyzed the outage behavior of mobile users and derived closed-form expressions for the exact OP.

According to [35] with a relatively large number of users, the combination of NOMA and MIMO can achieve a good throughput gain, but it does not rise to the concept of efficient modulation with PD-NOMA. According to several studies, it is advantageous to employ extreme low-density CD-NOMA in large systems where the number of resource elements and users increases without bounds while their load ratio remains constant [36]. Although PD-NOMA versus CD-NOMA has been studied, it has not been studied in terms of EE and SE for 5G mobile communication. Controllable interference among REs may be added to the CD with an appropriate complexity of receivers in order to resolve interference brought on by the absence of enough REs [36, 37].

In [19] the use of LDS-CDMA helps to limit the impact of interference on each chip of the basic CDMA systems, but, more or less, it was not studied in PD-NOMA. As stated in [19] SCMA provides low-complexity reception techniques and also offers improved performances. Most previous work on NOMA focuses on power allocation in order to improve the data rate [38]. But the data rate improvement is not only through power allocation; it also needs proper advanced modulation.

As it was studied in [40, 41] the appropriate power control mechanism for NOMA employing MMSE-based linear filtering to mitigate inter-cell interference can be ensured by employing PF-based multi-user scheduling. FBMC modulation technique was first proposed by Chang and Saltherg in the middle of the 1960s [42]. FBMC mainly has three kinds of modulation modes: cosine modulated multi-tone, filtered multi-tone, and OQAM-based OFDM (OQAM-OFDM). But, each of them are not compared with other type of modulation.

According to [43, 44], the GFDM and OQAM-FBMC both have a well-frequency-localized characteristic. Hence, it is suitable for high-mobility scenarios and provides more immunity to synchronization errors. Although GFDM provides flexibility in the waveform, the non-orthogonal transmission scheme but, it requires requires complex SIC algorithms at the receiver.

However, there is a lack of a complete and fair comparison between advanced modulation and NOMA. After the literature reviews, efficient advanced modulation with PD-NOMA has been identified for 5G communication by comparing different types of advanced modulation techniques for PD-NOMA schemes. Depending on this, three advanced modulations are analyzed and selected with PD-NOMA. Finally, FBMC, OQAM, and PD-NOMA are selected based on their high performances.

Chapte 3

Advanced Modulations Techniques for 5G Applications

3.1 Introduction

Modulation and waveforms are two of the key components of the physical layer that determine the system's throughput, reliability, and complexity. This research work deals with the most capable waveform contenders for 5G air interface.

The performance of an advanced modulation scheme is measured by different parameters, like:

Power efficiency: The power efficiency is defined as the required Eb/No (signal energy per bit to noise spectral density). This parameter describes the ability of advanced modulation techniques to preserve the BEP.

BW efficiency, or SE: It describes the ability of an advanced modulation scheme to accommodate data within a limited BW. As the data rate increases, the pulse width of the digital symbols decreases, and hence the BW increases [45].

$$\eta \mathrm{B} = \frac{\mathrm{Rb}}{\mathrm{Bw}} \mathrm{bps/Hz} \tag{3.1}$$

The system capacity of a digital mobile communication system is directly related to the BW efficiency of an advanced modulation scheme.

PSD: It specifies the power of various frequencies present in the signal and determines the range of power over which the signal frequencies are operated.

System complexity: It refers to the amount of circuits involved and the technical difficulty of the system.

Associated with this parameter of advanced modulation, the cost of manufacturing is the main concern in 5G applications. There are different advanced modulation techniques for 5G applications. Among those, a few of them are covered in the following:

3.1.1 Orthogonal Frequency Division Multiplexing

OFDM is an advanced modulation format used in modern wireless communication systems, including 5G cellular networks. OFDM is the most popular MCM scheme. OFDM combines the benefits of QAM and FDM to produce a high-data-rate communication system. The concept of OFDM was first proposed by R. W. Chang [46], recognizing that band-limited orthogonal signals can be combined with significant overlap while avoiding ICI. This type of modulation technique has been adopted as a major data transmission technique by many wireless communication standards, even if it does not fulfill the criteria of 5G requirements.

A key enabler for OFDM is the use of the IFFT to efficiently create the time-domain waveform from the array of modulated subcarriers. The 5G NR standard uses OFDM on both the UL and DL. The NR specification is designed with a high degree of flexibility to cover a diverse set of applications. The PAPR and degree of computational complexity are the primary determinants of the EE. Reliability is evaluated by BER; it is the capability of a network to carry out a preferred operation with very low error rates. 5G's maximum allowed latency for the URLLC is less than 1 ms. NOMA has become an indispensable technology for 5G wireless cellular networks. The main drawback of OFDM-based NOMA is that it has high PAPR and OOBE radiation [27].

In the case of PD-NOMA, power savings are required, so using efficient power is essential for lowering OOBE with efficient modulation. Mobile wireless systems employ OFDM in order to achieve high BW channels. LTE mobile uses OFDM for the DL (base station to mobile device), with a fixed subcarrier spacing of 15 kHz. The modulation on the subcarriers can be QPSK or 16QAM. The carrier spacing for 5G wireless is flexible (15, 30, 60, 120, 240, and 480 all in kHz) with up to 3300 subcarriers. For 5G, the subcarrier modulation can be QPSK, 16QAM, 64QAM, or 256QAM [47]. In the case of OFDM, a CP is used to remove ISI. On the receiver side, a one-tap equalizer is employed.

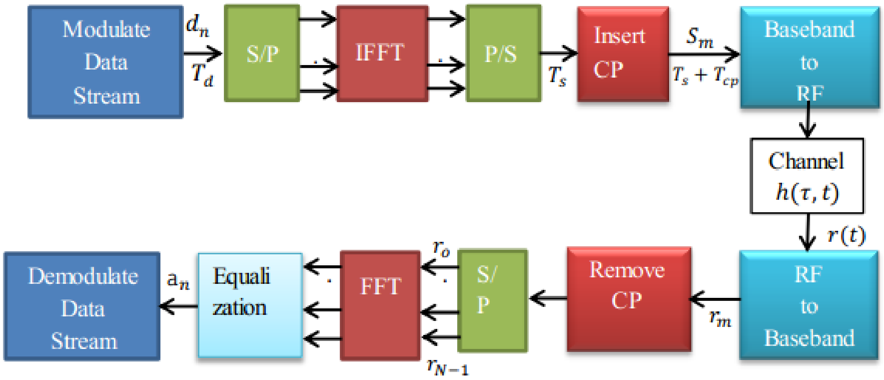


Figure 3.1: Physical layer block diagram of OFDM.

The discrete OFDM signal on baseband is expressed as the below equation [48]:

$$\mathrm{s_{OFDM}}\,[t] = \sum_{n=0}^{N-1} \mathrm{d}_n e^{j2\pi f_n t} \quad 0 \leq \mathrm{t} \leq T_s \tag{3.2}$$

In the above equation some symbols were used for instance d_n is the complex data symbol which modulate the n^{th} subcarrier, where T_s is time duration of OFDM symbol. The value of T_s can be found from $\mathrm{T}_s = \mathrm{NT_d}$ where $\mathrm{T_d}$ is the serial symbol duration. The value of f_n can be found from the below equation:

$$f_n = n/T_s, \quad \mathrm{n} = 0, 1, \ldots N_c - 1 \tag{3.3}$$

The CP in the case of OFDM is the cyclic extension of the symbol; this CP duration should be equal to the channel impulse response in samples minus one sample. The length of each guard interval in OFDM must be greater than the expected delay symbol, which is given by the equation below.

$$L_g \geq \frac{\tau_{\max} \times N_c}{T_s} \tag{3.4}$$

In the case of the OFDM block diagram above, the output from the IFFT is a CP extension of this sample result for the sampled sequence with cyclic extended guard interval, as shown in the equation below:

$$\mathrm{s_{OFDM}}\,[m] = \frac{1}{N_c} \sum_{n=0}^{N-1} \mathrm{d}_n e^{j2\pi nm/N_c} \quad \mathrm{m} = -L_g \ldots N_c - 1 \tag{3.5}$$

From the block diagram of OFDM, after the CP, the transmitted signal is up-converted and the RF signal is transmitted to the channel, then the channel output is down-converted. Finally, the received signal waveform is obtained from convolution with the channel impulse response and addition of the noise signal, which is given by equation 3.6:

$$r_{OFDM}(t) = \int_{-\infty}^{\infty} s(t-\tau)h(\tau, t)d\tau + n(t) \tag{3.6}$$

From the OFDM block diagram above, the output of FFT is the MC demodulated sequence consisting of N complex-valued symbols, which is represented by equation 3.7 below:

$$\hat{d}_n = \sum_{n=0}^{N-1} \mathrm{r}_m e^{-(j2\pi nm/N_c)}, \quad \mathrm{n} = 0, 1, \ldots N_c - 1 \tag{3.7}$$

Where the received symbol $\hat{d}_n$ can be obtained from the frequency domain representation of the equation 3.8 below:-

$$\hat{d}_n = H_n d_n + N_n, \quad \mathrm{n} = 0, 1, \dots N_c - 1 \tag{3.8}$$

H_n Stands for flat fading factor and N_n stands for the noise of the n^{th} sub channel. Finally, the $\mathrm{p/s}$ conversion of the output from FFT, the complex data symbols are given to the QAM demodulator, and the transmitted signal is estimated.

According to the paper [48, 49] some benefits and drawbacks of OFDM are listed.
OFDM has its own benefits: It is computationally efficient to implement the modulation and demodulation functions, resistant to frequency selective fading, mitigating ISI in frequency selective channels, allowing flexible spectrum adaptation for channel conditions, and eliminating the need for an equalizer.
OFDM has some drawbacks: MC signals with high PAPR require high linear amplifiers. Otherwise, performance degradation will occur and OOBE will be enhanced. Loss in SE due to the guard interval, sensitivity to the Doppler effect, sensitivity to frequency synchronization problems, large dynamic range amplitude, sensitivity to carrier frequency offset and timing offset, high PAPR, high OOBE, and BW inefficiency.

Generally, due to different reasons, OFDM is not suitable for 5G cellular networks. OFDM's drawbacks, such as the need for a high PAPR radio frequency power amplifier, as well as its sensitivity to carrier frequency offset and high OOBE, make it unsuitable for 5G cellular networks.
The following factors limit the use of OFDM in 5G applications:
CP overhead: In this type of waveform, the addition of the CP adds redundancy to the signal transmission since the same content is transmitted twice as the CP is a copy of the tail of the symbol placed at its beginning. The CP overhead can be expressed as a function of symbol duration and duration of the CP given in equation below [50, 51].

$$\beta_{\text{overhead}} = \frac{T_{CP}}{T_{CP} + T_{\text{symbol}}} \tag{3.9}$$

Sensitivity to frequency and timing offsets: The orthogonality in the case of OFDM is based on the assumption that the TX and RX are using the exact same reference frequency. In terms of frequency offsets, the orthogonality lost causes the sub carrier leakage known as inter-carrier interference (ICI).

High PAPR: One of the most difficult aspects of OFDM, resulting in a high crest factor. The high PAPR compared to a single carrier transmission technique occurs due to the summation of many individual sub carriers [51].

3.1.2 Generalized Frequency Division Multiplexing

GFDM is also a modulation technique for 5G wireless communication systems, with many advantages over conventional OFDM. The GFDM modulation scheme has been regarded as one of the most promising for 5G waveforms due to its properties, such as low latency, low OOBE, robustness against carrier frequency offset (CFO), and time offset (TO). The GFDM is also combined with mMIMO technology, which equips each BS with an array of many active antennas, which are used to spatially multiplex many UE to improve SE.

GFDM is a novel waveform concept in 5G modulation and demodulation; it is also made up of non-orthogonal sub carriers that distribute data in time and frequency dimensional blocks.

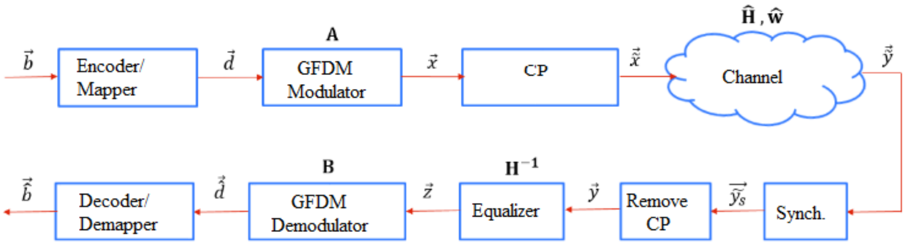


Figure 3.2: Functional block diagram of GFDM.

In this type of waveform, the filtering process is applied to sub carrier-wise, which improves OOBE but generates ISI, which can be removed by adding the CP when compared to OFDM. In order to enhance the SE, the tail-biting technique can be applied to reduce the CP length. The GFDM provides a low-latency signal because it uses circular filtering with prototype filters instead of the linear convolution that is used in the FBMC [52].

GFDM uses only one CP for one block, slightly less than a CP for every multicarrier symbol, which results in an enhancement for the system. The other point in the case of the GFDM waveform is that without CP, as the number of blocks increases, the OOBE radiation also increases. The use of RRC filter, allows the GFDM to be flexible, which would be difficult to achieve with other prototype filters.

GFDM has its own benefits: Low latency, low PAPR, low OOBE, low adjacent channel leakage ratio (ACLR), and relaxed requirements for time and frequency synchronization
Due to the above benefits, GFDM is applicable to a variety of scenarios, and its parameters can be adapted to meet the requirements of specific services.
In the case of the GFDM waveform, as the modulation order and the number of antennas increase, the complexity of the maximum likelihood (ML) detector and the MMSE detector causes an impediment for real-world applications. This research work focuses on the one with less complexity as the number of antennas increases.

3.1.3 Filter Bank Multi-Carrier

FBMC is an enabling technology for enhancing the fundamental SE because of the well-localized time and frequency traits adopted from a pulse shaping filter per subcarrier. As a result, the overhead of the guard band required to fit in the given spectrum BW is reduced.The main benefit of FBMC is achieved by expanding the prototype filter pulse and symbol duration over symbol intervals in the time domain, resulting in overlapping pulses with duration, where stands for the symbol intervals. In this waveform, by effectively increasing symbol duration, it is possible to handle the multi-path fading even without using CP overhead [52].

Filter-specific parameters are used in this type of modulation to allow for more sensitive adjustments and increased flexibility. FBMC does not require CP or guard time, unlike OFDM and GFDM. For this reason, the SE of FBMC is not degraded by such redundancy. Sub-carrier filtering is used in FBMC to solve the ISI problem. FBMC is applicable in CR in order to solve the problem in SE [42].
There are several types of FBMC, one of which is FBMC/OQAM.This type of FBMC is the most popular filter bank scheme, which results in high SE. The most fundamental parts of the FBMC/OQAM system are:

- Synthesis filter bank at the TX
- Analysis filter bank at the RX

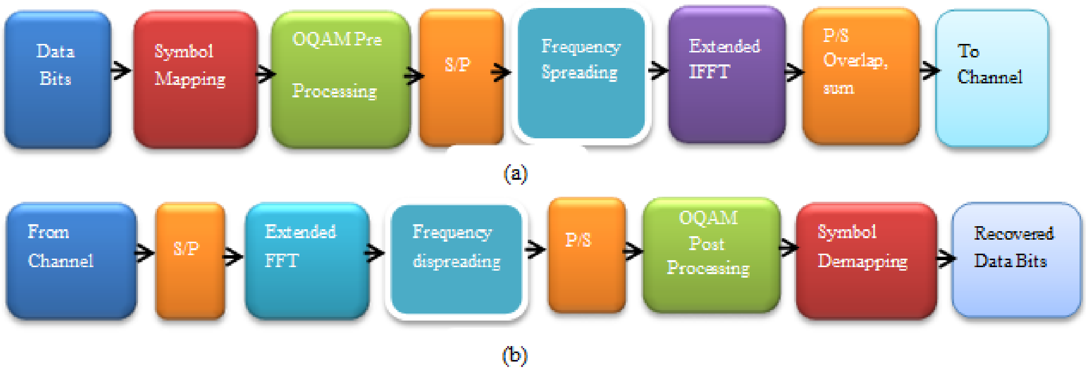


Figure 3.3: Transceiver of FBMC a) Transmitter b) Receiver [54].

The figure 3.4 shows that the filter bank used at the transmitter side is called a SFB, and the filter bank used at the receiver side is called an AFB.

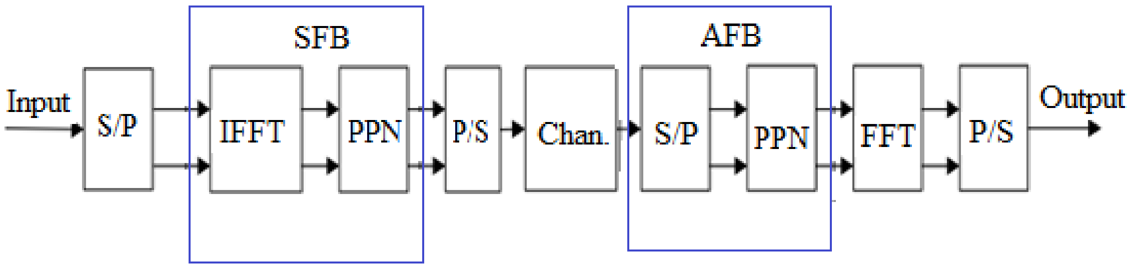


Figure 3.4: Shows the fundamental parts of FBMC [55].

The discrete-time base band signal at the o/p FBMC TX with OQAM modulation can be expressed as the equation below [56]:

$$y(m) = \sum_{K=0}^{M-1} \sum_{n=-\infty}^{\infty} x_k[n]\beta_k[n]p\left[m - \frac{nM}{2}\right] e^{j(\frac{2\pi}{M})km} \tag{3.10}$$

Where m is the sample index at SFB $\mathrm{o/p}$ and AFB $\mathrm{i/p}$, n is the sample index at OQAM preprocessing o/p and post-processing $\mathrm{i/p}$, M is the number of sub-carriers in the filter bank and $\beta_k[n]$ is given by the equation below: -

$$\beta_k[n] = (-1)^{kn} \exp\left(-j\frac{2\pi k}{M}\left(\frac{L_p - 1}{2}\right)\right) \tag{3.11}$$

$$x_k[n] = d_k[n]\theta_k[n] \tag{3.12}$$

$$\theta_k[n] = j^{k+n} \tag{3.13}$$

In order to maintain the orthogonality, the $d_k[n]$ is multiplied by $\theta_k[n]$ also in order to achieve high SE complex modulated filter banks are usually used, this means all sub-channel filters are frequency shifted versions of the prototype filter $P[m]$ [56]. Therefore, the k$^{\text{th}}$ synthesis filter $\mathrm{g_k}[\mathrm{m}]$ can be expressed as the below equation:

$$g_k[m] = p[m] \exp\left(j\frac{2\pi k}{M}\left(m - \frac{Lp-1}{2}\right)\right) \tag{3.14}$$

Where $\mathrm{m} = 0, 1 \ldots L_p - 1$

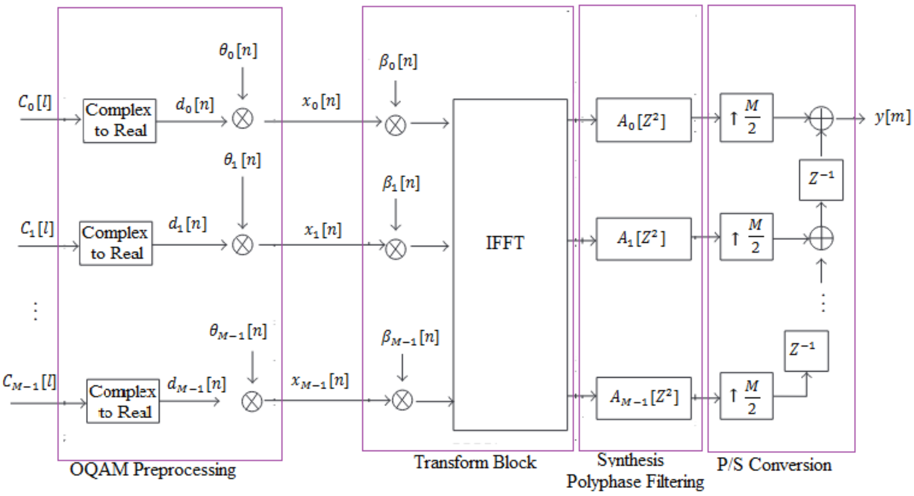


Figure 3.5: Block diagram of FBMC/OQAM TX [56].

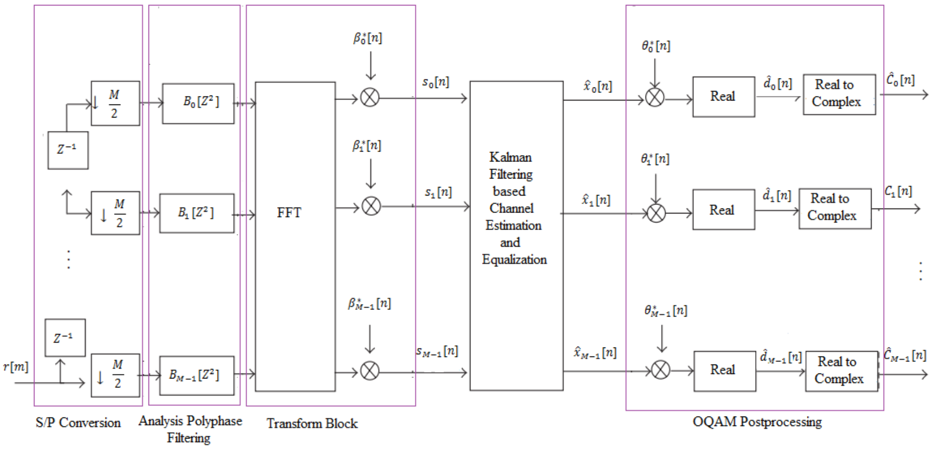


Figure 3.6: Block diagram of FBMC/OQAM RX [56].

3.1.4 Working Principles of FBMC-OQAM System

The FBMC-OQAM system is one of the most important systems for 5G mobile communication technologies. As FFT is used for fast implementation of OFDM, the FFT algorithm is also used for fast implementation of FBMC-OQAM. The FFT algorithm used for the fast implementation of FBMC-OQAM can be categorized into two commonly used types.

i. Frequency spreading FFT

ii. Polyphase network FFT

Filter Bank Multi-Carrier with Offset Quadrature Amplitude Modulation(FBMC/OQAM), the use of FBMC with appropriate filter PPN allows to obtain an almost negligible ISI and ICI, and provides a better spectral efficiency [61].

From the two classes, PPN-FFT is the most efficient due to the following reasons:

a. Having low computational complexity compared to the FS-FFT

b. It can effectively suppress ISI without frequency expansion and CP.

The figure 3.7 shows that the framework of the FBMC-OQAM is implemented using the PPN algorithm.

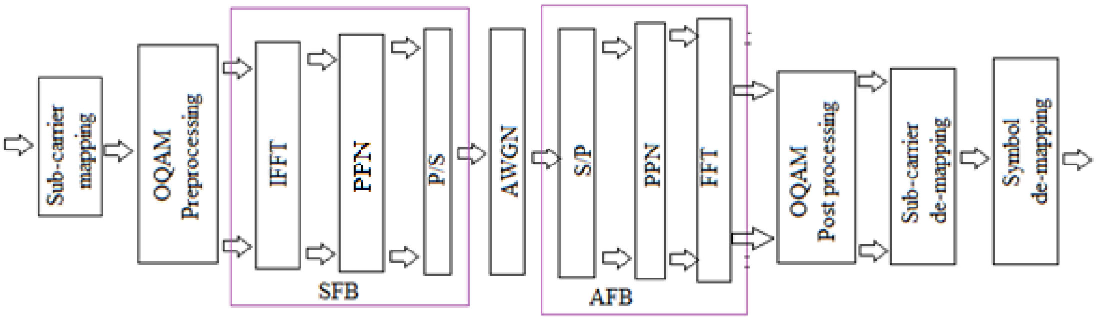


Figure 3.7: FBMC-OQAM PPN based [57].

From figure 3.7, the main objective of OQAM pre-processing is to maintain orthogonality between the sub-carriers. On the TX side, the IFFT operation is carried out on the transmission symbols, and then the prototype filter banks with different offsets are filtered. At the RX side FFT operation is carried out. Therefore, the original signal is recovered by FFT and OQAM.

In comparison to OFDM, FBMC has the following fundamental distinctions:

i. Uses OQAM mapping in place of QAM mapping to reduce ICI using effective filtering.

ii. To minimize ISI and ICI, PPN filtering is used after the IFFT process to obtain enhanced frequency and time localization based on the shape and length of the prototype filter.

iii. It does not require CP because it uses frequency and temporal localization with filtering and QAM modulation. This can reduce side lobes to a minimum level.

iv. The low delay spread guarantees optimal performance with simple one-tap equalizers.

v. Suitable for a high-mobility environment with a fragmented spectrum for multi-point coordination.

Some important parameters for providing flexibility in FBMC modulation waveforms are filter length and filter localization in time or frequency.

FBMC has its own advantages that make it more efficient than others: Better spectrum shape, better spectrum usage, reduced sides lobe, less OOBE, the signal transmitted without CP, environmental robustness is high, and robustness to narrow band jammers and impulse noise are all desirable [58]. As well as having benefits, it also has some limitations: High latency, very narrow frequency, long filter length, and additional hardware are all required.

3.1.5 Universal Filtered Multi-Carrier

This is also a type of waveform that is used in 5G communication systems. It is a potential waveform for wireless communication. Sometimes it is called unified filtering OFDM (UF-OFDM). Some benefits of using the UFMC waveform are: High SE, support for short burst transmission, a smaller amount of side lobe level, low latency, and no CP addition. Figure 3.8 below deals with the PSD of UFMC, which outperforms OFDM.

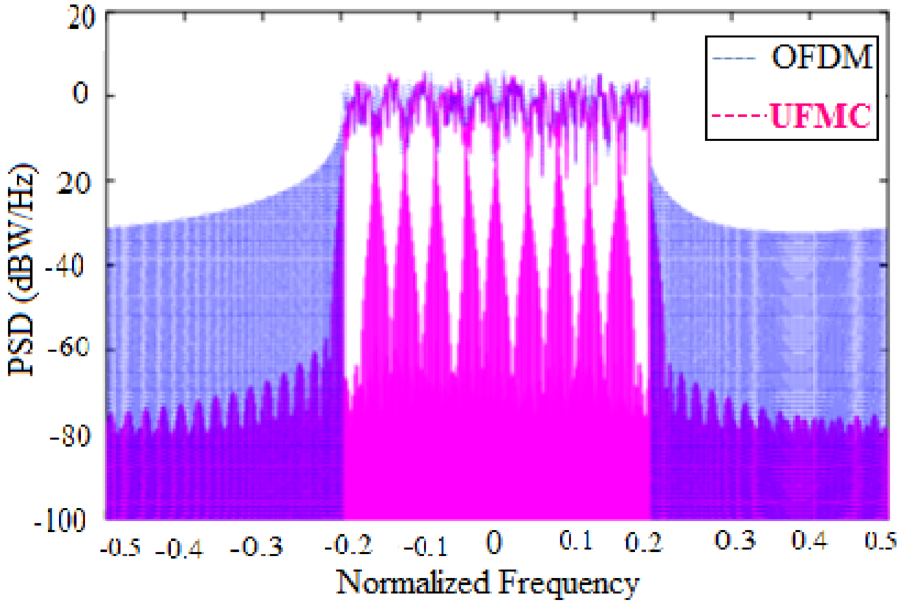


Figure 3.8: Comparison between OFDM and UFMC [59].

F-OFDM: With minor differences, this waveform is similar to UFMC.

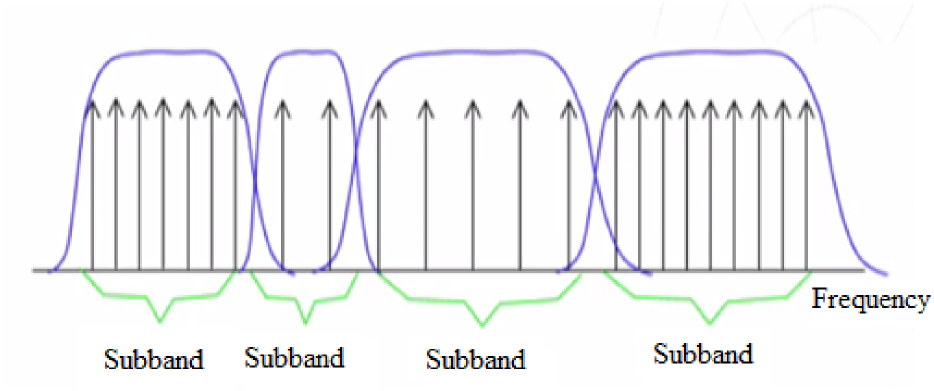


Figure 3.9: Sub band division in F-OFDM

In this type of waveform, the whole band is divided into multiple sub-bands, and each sub-band has a different BW according to the user's requirements. However, in UFMC, the sub-carrier spacing was the same for each sub-band, whereas in F-OFDM, the sub-carrier spacing is different in each sub-band to allow the user to use the spectrum efficiently. In this type of waveform, CP is added in each sub-band to avoid ISI, and the length of CP is added flexibly as required to avoid extra spectrum usage. Also, the IFFT is performed flexibly as required by each user [60].

From MCM discussed in [43], the FBMC-OQAM outperforms FBMC-QAM due to its capability to overcomes the problem of ISI. As the summary of waveforms shows, the filter-based waveforms have much better OOBE when compared to OFDM for 5G communication systems. FMBC has the best OOBE as compared to others, but it has higher computational complexity. FBMC has the best immunity to ICI and is the most vulnerable to ISI. UFMC and GFDM have better OOBE, but they have complexity and asynchronous transmission capability issues. While F-OFDM has a greater OOBE and a moderate level of complexity, it is a good contender for flexible and asynchronous transmission scenarios.

3.2 Comparison Between OFDM, FBMC, UFMC, and GFDM

The OFDM is used as a reference for others to compare in this section. Depending on these performance evaluations, others are compared in terms of PAPR, BER, PSD, and complexity.

3.2.1 Comparison of FBMC With OFDM

As previously stated, FBMC and OFDM each have their own set of advantages and disadvantages.Under this portion, FBMC and OFDM are compared. In order to overcome the limitation of the well-known waveform, which is OFDM, the FBMC is computed and compared. In the case of OFDM, as it is known, there is reduced SE and strict synchronization. CP results in a reduction of the SE in the case of OFDM. In the FBMC waveform, filters (usually low-pass filters) are uniformly spaced and have a higher selectivity to achieve minimum cross-talk. OFDM suffers from poor spectral selectivity compared to FBMC. The FBMC waveform overcomes the limitation of the OFDM waveform [21, 62].

In the FBMC, the prototype filter is the one used for zero-frequency carriers and is the basis for the other sub-carrier filters. The filter is characterized by the overlapping factor, which stands for the number of multi-carrier symbols that overlap in the time domain. The prototype filter order for FBMC is chosen for comparison and simulation purposes [63, 64, 65, 66]. In order to achieve full capacity in the case of FBMC, OQAM processing is used. In FBMC, the real and imaginary parts of the complex data symbol are not transmitted at the same time. The imaginary part is delayed by half the symbol duration. Figure 3.3 above deals with the Tx and Rx of FBMC with OQAM.

FBMC provides SE and is a more selective system; CP is not needed in the case of FBMC, and it provides robust narrow band jammers. The development of MIMO-based FBMC is very limited and not trivial. To design wider BW and higher dynamic range system will have more difficulty in achieving RF performance, and it is more complex compared to OFDM. Even in the presence of complexity, FBMC outperforms.

There are some application areas of FBMC: In CR communications, multiple access networks, access to television white space, power line communication, and MIMO communication. Compared to FBMC, OFDM is more sensitive to the CFO, while FBMC is less sensitive. Therefore, FBMC performs better with the increase in mobile consumers.

3.2.2 Comparison of UFMC With OFDM Waveform

Under this portion, UFMC and OFDM are compared in order to identify which one is suitable or efficient for 5G cellular networks. UFMC was one of the alternate waveforms to

OFDM in the 3GPP RAN study phase I during 3GPP Release 14. As well known, there is a loss of SE in the case of OFDM due to higher side lobes, as well as a strict synchronization requirement; however, when compared to UFMC, the UFMC overcomes some of the limitations of OFDM.

Here is a comparison between UFMC and OFDM with their corresponding parameters. In the case of UFMC, the filtering is used to reduce the OOBE. It is important to note that in this case, the entire band is filtered in filtered OFDM, whereas individual sub carriers are filtered in FBMC, and groups of sub carriers (sub-bands) are filtered in UFMC. The sub-carrier grouping in the case of UFMC allows the way to reduce the filter length (when compared with FBMC). In this case, a Chebyshev window with parameterized side-lobe attenuation is employed to filter the IFFT output per subband [67].

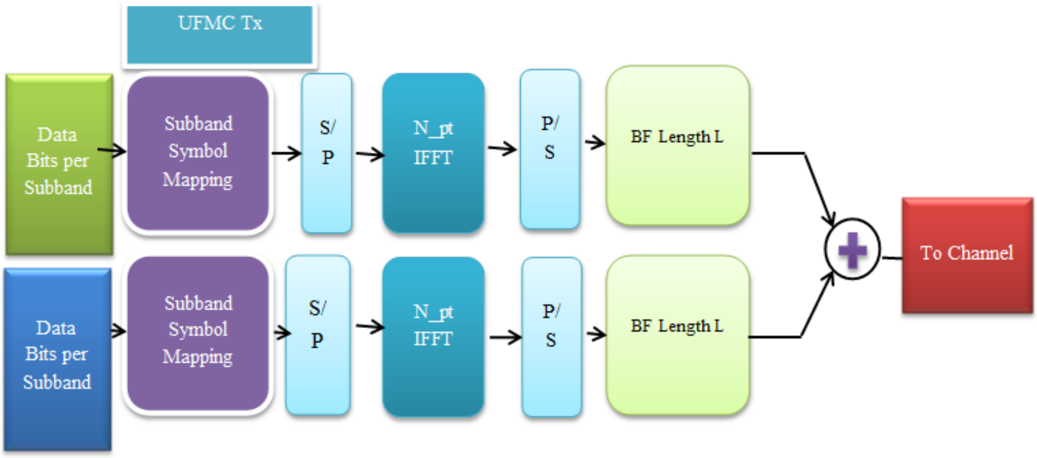


Figure 3.10: The transmit-end processing diagram of UFMC.

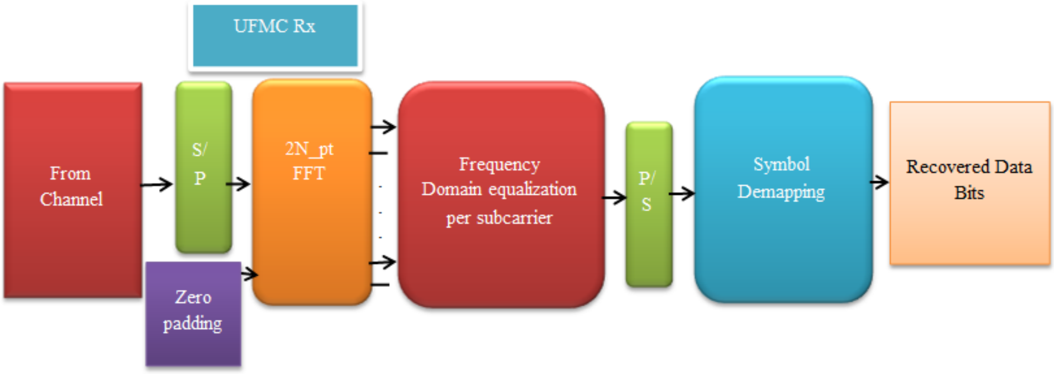


Figure 3.11: The receive-end processing diagram of UFMC.

3.2.3 Comparison of GFDM With OFDM Waveform

This type of waveform is a multi-carrier modulation scheme with sufficient flexibility to meet the requirements for 5G cellular networks. Unlike the OFDM waveform, the GFDM waveform transmits M symbols per sub-carrier and is oversampled by N, where N >= K and K stands for the number of sub-carriers. In this waveform, the pulse shaping filter is applied to each sub-carrier. Finally, the sub-carrier signals are added together in order to form the final waveform [68]. The mechanism for reducing OOBE in this type of waveform is to filter each sub-carrier using a pulse shaping process.

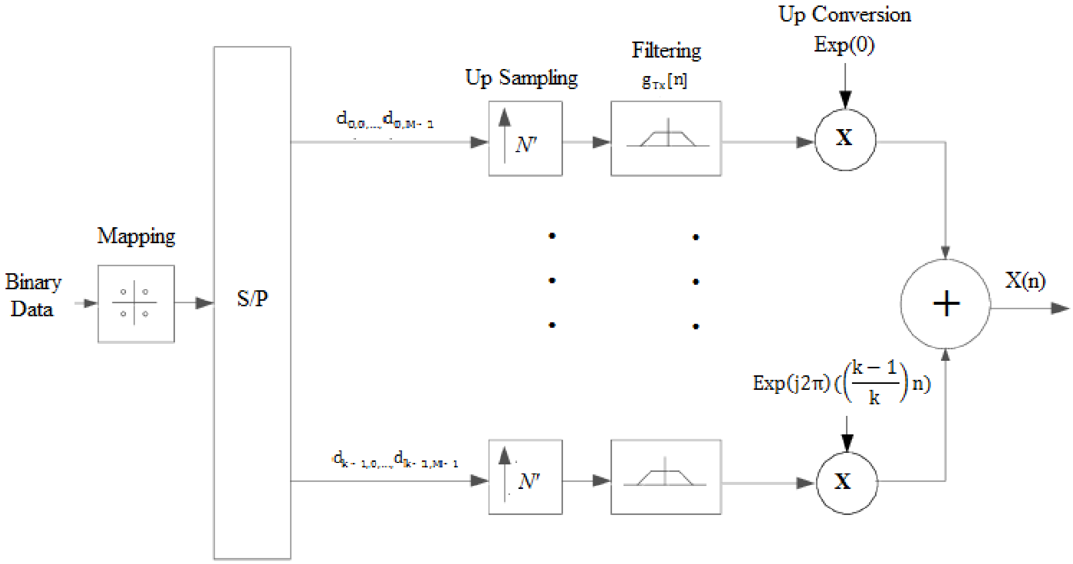


Figure 3.12: The basic structure of the GFDM transmitter diagram.

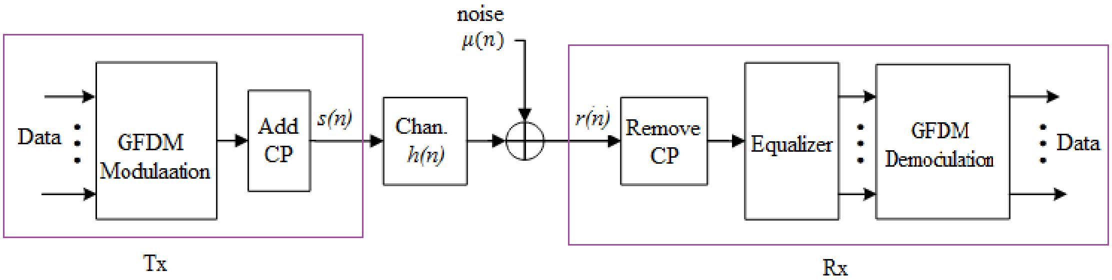


Figure 3.13: GFDM Tx and Rx [69].

According to [70], there is a comparison between OFDM, GFDM, and FBMC. In comparison, the FBMC is chosen as the more efficient advanced modulation. A list of parameters and comparison results are listed in the table 3.1

Table 3.1: Comparison between OFDM, GFDM and FBMC [70].

Parameters	OFDM	GFDM	FBMC
SE	Low	High	High
PSD	Low	Medium	High
PAPR	High	Medium	Low
Complexity	Low	High	Medium
ACLR(Adjacent channel leakage ratio)	Low	–	High

In general, the system capacity of a mobile communication system is directly related to the BW efficiency of the modulation scheme. A fundamental upper bound on achievable BW efficiency is stated by Shannons theorem. The theorem states: "For an arbitrarily small probability of error, the maximum possible BW efficiency is limited by the noise in the channel." This capacity is given by the equation below [45]:

$$\eta_{B\max} = \frac{C}{B} = \log_2\left(1 + \frac{S}{N}\right) \tag{3.15}$$

Where C is the channel capacity in bps, B is the RF BW and S/N is the signal to noise ratio.

3.3 Introduction to NOMA Techniques in Emerging Wireless Systems

NOMA technology focuses on the fundamental idea that more than one user can be served in each orthogonal resource block, for instance a time slot, a sub-carrier, a spreading code, etc. In this technique, multiple users share allocated resources through PD. MA is used to maximize the throughput based on path capacity enhancements, channel error reduction, mobility enhancement, and latency reduction using improved path switching control, and to minimize handover interruption using re-transmission timeout control and improved device/UE handover decisions.

In 5G, the benefits of optimization in cellular networks include boosting network performance, satisfying diverse QoS requirements, saving energy, and reducing capital expenditure

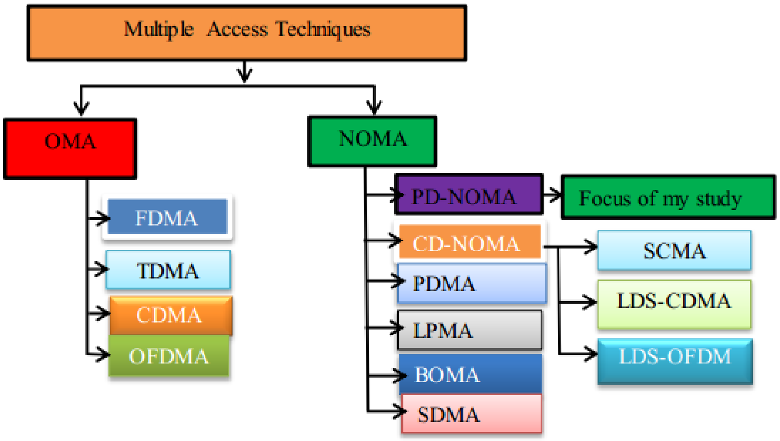


Figure 3.14: Classification of MA techniques

and operation expenditure.

Unlike OMA UEs, those in NOMA are allowed to simultaneously use the same sub-channel, as shown in figures 3.16 and 3.18. To address the diverse demands for low latency, high reliability, huge connections, increased fairness, and high throughput, NOMA is a key enabling technology for 5G wireless networks. The major role of NOMA is to serve multiple users in the same resource block, such as a time slot, sub-carrier, or spreading code. NOMA is also one of the potential for radio access to address the increasing demands of mobile traffic.

NOMA has its own protocols. Its protocol can increase cell capacity, making it a very promising MA technique among the different medium access control protocols for 5G mobile communication. In OMA, in order to avoid interference, each user uses orthogonal communication resources such as time slots, frequencies, or codes.

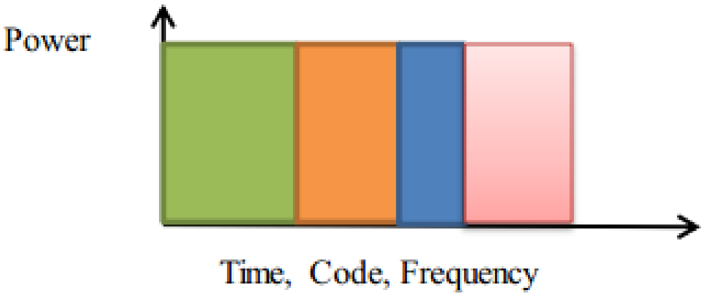


Figure 3.15: OMA resource distribution.

NOMA-based systems employ OFDM for MCM, which induces or produces a high PAPR. This high PAPR makes conventional modulation-based NOMA systems spectrally and energetically inefficient [71]. PD-NOMA and SIC are viable options with low-complexity receivers. NOMA is forecast to play an essential role in the next generation of cellular networks for both UL and DL transmission. In NOMA, the multiplexing of signals with disparate power levels allows for the efficient use of SIC and point-to-point capacity, achieving FEC codes. In many cases, NOMA can score significant performance gains over OFDMA (OMA) when the power levels are sufficiently disparate. NOMA has resurfaced to emphasize the importance of allocating more power to distant users in order for them to have acceptable QoS.

In the case of NOMA, far users should be allocated enough power to reliably recover their own messages directly by treating the other users' information as noise. On the other hand, the near user needs to first recover the message of the far user. Then it subtracts this message from the received signal to recover its own message. The feature of NOMA is not only to yield large throughput but also to ensure fairness for wireless communication networks. The major idea of NOMA is to serve multiple users using the same resource in terms of time, frequency, and space.

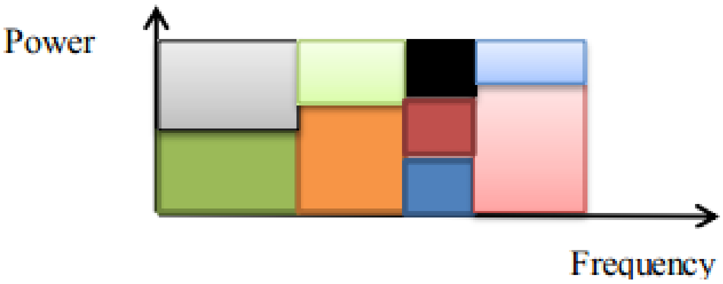


Figure 3.16: NOMA resource distribution.

Recent studies demonstrate that NOMA has the potential to be applied in various 5G communication scenarios, including M2M communications and the IoT. There is some existing evidence of performance improvement when NOMA is integrated with various effective wireless communication techniques, such as cooperative communications, MIMO, beamforming, space-time coding, network coding, FD, etc. In this thesis, NOMA integration with modulation waveforms is discussed. With NOMA, all signals are added and separated at the receivers by considering their different power levels.

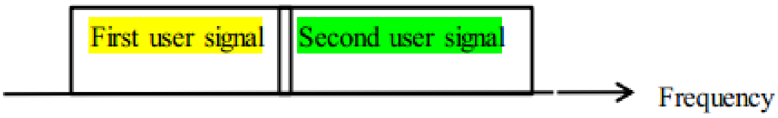


Figure 3.17: Shows how the given BW is used without the concept of NOMA.

The above figure 3.17 shows how the resources are allocated for the two users in FDMA. It uses different BW for different users. But, in NOMA, the given BW is shared by the two users with different power levels.

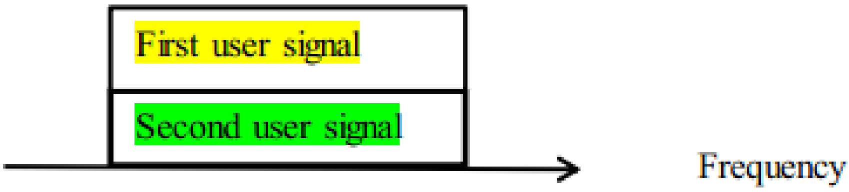


Figure 3.18: Shows that the frequency spectrum is utilized in case of NOMA.

In a NOMA system, the most crucial function at the transmitter is power allocation, followed by SC, and at the receiver end, SIC. The overall system throughput and performance depend on user clustering, the power allocation scheme, and the SIC at the receiver, which is expected to have minimal error. The main features of NOMA include its capability to support a large number of new mobile connections and its high SE.

Using SC on the TX side and SIC on the RX side makes the system to utilize the same spectrum for all users. At the transmitter side, all the individual information signals are superimposed into a single waveform, whereas at the receiver side, the SIC decodes the signals one by one until it finds the desired signal. For instance, figure 3.19 below illustrates how the three signals are superimposed at the TX and decoded at the receiver side.

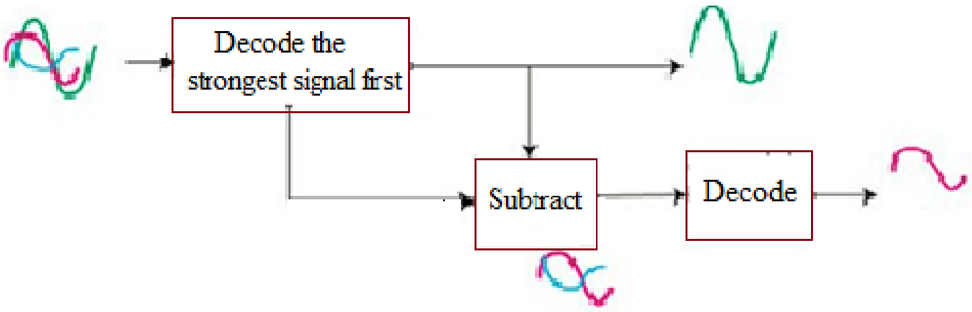


Figure 3.19: The SC at the Tx and SIC at the Rx in case of NOMA [72].

In this case, the strongest signal at the SIC is decoded first, with other signals treated as interference.The SIC iterates the process until it finds the desired signal. Simply put, SIC can be defined in three steps:It detects other users' text; it removes the other users text; and it detects its own text.

In this thesis, advanced modulation-based PD-NOMA is discussed with the principle of SCI. In SCI, the stronger interfering signals will be removed until the desired signal is obtained.

Chapter 4

PD-NOMA Based Advanced Modulation scheme

4.1 Introduction to PD-NOMA Based Advanced Modulation scheme for 5G Applications

The MA technique lies at the heart of cellular communication systems; it allows multiple users to share resources. In the NOMA-based system, two users can share the same spectral band, where each user has different power allocated to them. Beyond the multiplexing signals, there are different domains like PD, CD, and spatial domains, but in this thesis work, PD-NOMA with FBMC-OQAM is proposed in order to support massive connectivity for 5G applications.

The basic principle of PD-NOMA is that it can support multiple users in the same RB by identifying them with different power levels. Therefore, this PD-NOMA supports more connectivity and provides higher throughput with limited resources. PD-NOMA is the simplest type of NOMA, which assigns a different power level to each user. Fixed and dynamic power allocations (FPA and DPA) are two categories for power allocation in PD-NOMA. FPA is the simpler of the two divisions, but DPA is better suited to mobile environments than FPA [80].

PD-NOMA is very important in 5G cellular networks. In NOMA, the capacity region of DL is known, enabling us to find the optimum power allocation. NOMA can also improve user fairness in a smooth and optimal way through flexible power allocation. This type of NOMA serves several users with the same frequency and time resources, but with different power levels according to the channel conditions. In PD-NOMA, the proper power allocation among mobile users is another major problem in NOMA-based wireless networks. The basic operation of PD-NOMA includes the SC technique to combine the transmit signals and the SIC technique to separate the signals at the receiver.

The main attractive point of PD-NOMA is that it has a simple implementation. PD-NOMA is implemented on existing networks without modifying the network infrastructure. PD-NOMA does not need additional BW in order to improve SE, unlike CD-NOMA. The main advantages of PD-NOMA are that it has a high SE and is compatible with other techniques.

The PD-NOMA is considered as strong for use in 5G applications. PD-NOMA guarantees that several users are served with the same resources using SC methods at the transmitter and SIC at the receiver [81]. One of the attractions of using PD-NOMA is that it can be used in combination with the UL MU-MIMO scheme in order to further overload resources. At the BS, the UE with a much higher received power is decoded first by treating the other UEs as noise [82].

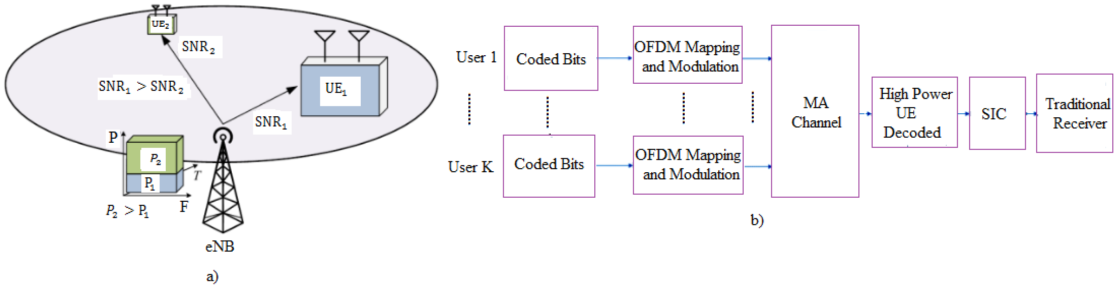


Figure 4.1: Principle and Block diagram of OFDM based PD-NOMA scheme for two users [82].

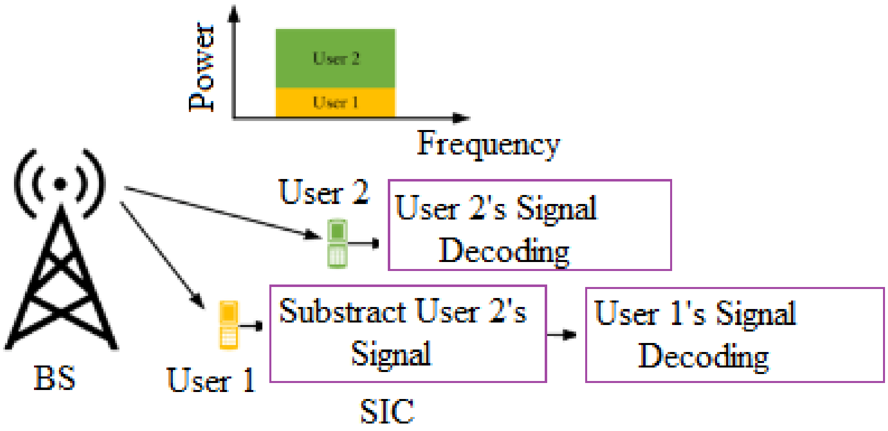


Figure 4.2: DL transmission of PD-NOMA [73].

4.2 Combination of Efficient Advanced Modulation With PD-NOMA

Under this section, efficient modulation waveform and PD-NOMA are combined in order to produce efficient power and spectrum as well as low PAPR, low OOBE, and low side lobe for 5G applications. FBMC is applicable in many application areas, like CR and others. The FBMC has negligible frequency spectrum leakage, which makes it robust to interference resulting from frequency offset.

The use of FBMC with CR can have a powerful effect on the ICI resulting from timing offset; this can maximize the total information rates and mitigate the interference constraint between PU and SU because of the low spectral leakage of its prototype filter. Also, using FBMC with PD-NOMA increases the system SE and reduces OOBE. The other thing is that FBMC is a type of multicarrier waveform that meets the NOMA performance requirements with a simple configuration. Its simple complexity makes it suitable for use with NOMA. It is also suitable for use when the efficiency of the cellular network is required. FBMC have lower spectral side lobes compared with the OFDM, UFMC due to the employment of pulse shaping filters, which means that the FBMC have ability to adjust parameters and asynchronous transmission.

After analyzing and comparing different types of waveforms, FBMC/OQAM is selected as an efficient waveform, and it is integrated with PD-NOMA. In the case of FBMC, the ISI problem due to the overlapping of time symbols is solved due to OQAM modulation. This thesis focuses on the enabling technology of 5G, which is the new air interface and specifically the efficient modulation scheme.

The GFDM waveform is non-orthogonal by nature [33], but system complexity matters for this waveform in 5G cellular networks. In this thesis, FBMC/OQAM is selected for its low latency, low PAPR, low OOBE, and low ACLR. This waveform also has a flexible transceiver design. The FBMC/OQAM waveform is useful in many application areas, such as FD radio and CR.

FBMC is one of the efficient waveform inorder to satisfy the demands of future cellular networks. This type of MCM uses a prototype filter with a lower side lobe and faster spectral decay, which enables it to have the advantages of reduced OOBE and higher SE. FBMC modulation with offset performs much better. Furthermore, FBMC and OQAM have the highest symbol density, which is defined as the time frequency spacing of TF = 1 for complex-valued symbols. While in OFDM-based schemes, symbol density is lower (TF > 1), additionally worsening the SE. FBMC also increases the throughput. FBMC performs much better and has the additional advantage of a maximum symbol density, TF=1 (complex).

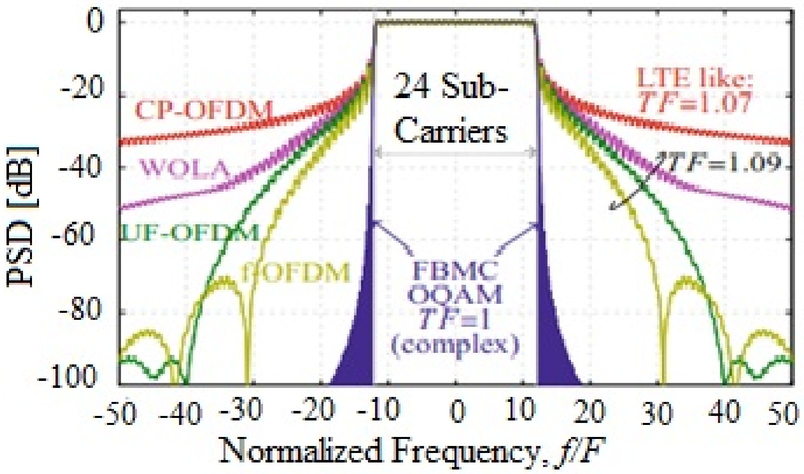


Figure 4.3: PSD of different modulations [5].

In terms of throughput, FBMC has a higher throughput than OFDM at 14 MHz. For high signal-to-noise ratio (SNR) values, the throughput of FBMC is approximately 30 percent higher than that of OFDM.

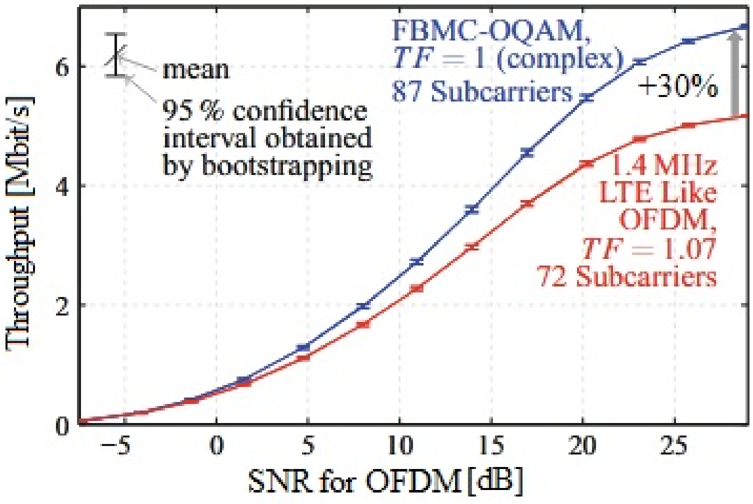


Figure 4.4: Comparison of throughput between FBMC and OFDM [5].

This type of MCM can also avoid ICI and ISI terms without the use of CP due to the use of per-subcarrier filtering (prototype filtering). The use of well-localized prototype filters enables the FBMC/OQAM system to have a lower OOBE when compared with other types of MCM. It uses multicarrier techniques that are immune to fading caused by transmission of more than one path at a time and also immune to ISI, besides being able to function compared to OFDM [83].

4.3 System Model

Under this portion the modeling of the system discussed for efficient modulation based PD-NOMA. The received signal of m^{th} user at k^{th} subcarrier given that the transmitted symbol of Sm,k. Under the modeling of a DL NOMA two users served in the single cell by single BS antenna. This single BS can serve two users UE1 and UE2 using the same resource block with different power levels. The BS transmits a combined signal X after superposition coding to both users. It can be modeled as below:

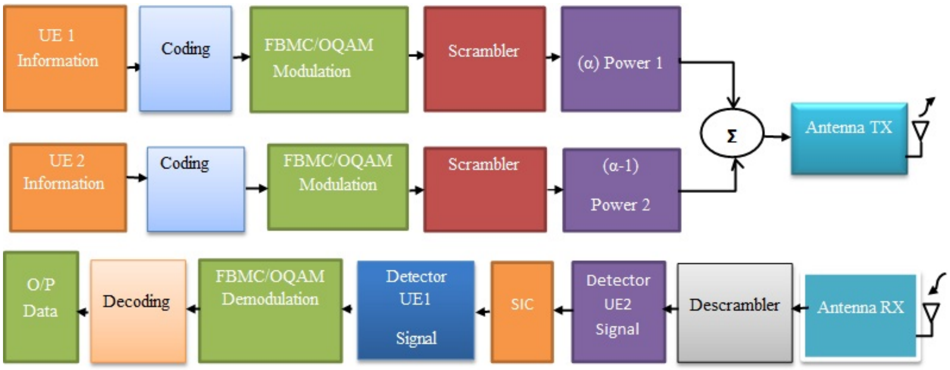


Figure 4.5: Modeling of advanced modulation-based PD-NOMA for DL cellular networks.

This proposed model of FBMC-OQAM replaces the complex orthogonality condition with the less orthogonality condition.

$\mathrm{R}\{\langle gl_1, k_1(t), gl_2, k_2(t)\rangle\} = \delta_{(l_2-l_1),(k_2-k_1)}$ and works in the principle of listed below:

Design a prototype filter with p(t) = p(-t) which is orthogonal for a time spacing of T = To and a frequency spacing of F = 2/To, leading to TF = 2. Reduce the time frequency spacing by a factor of two each, that is T = To/2 and F = 1/To, leading to TF = 0.5. The induced interference is shifted to the purely imaginary domain by the phase shift

$\theta_{l,k} = \pi/2(l + k)$

The big advantage of FBMC when compared with other non-orthogonal schemes is that the imaginary interference can easily be canceled simplify by taking the real part after equalization.

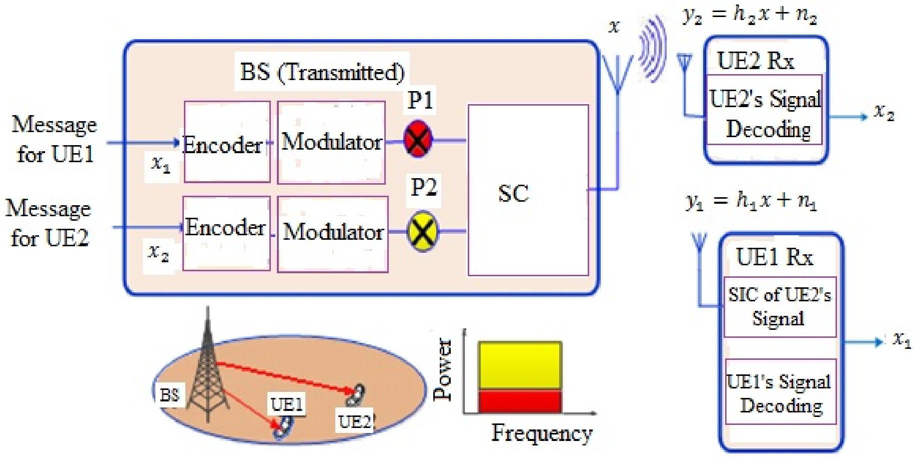


Figure 4.6: Relationship between the user and the channel gains.

In the above model X at the transmitter is the combination of both message of UE_1 and UE_2 which is represented as below equation [84].

$$X = x_1 + x_2 \tag{4.1}$$

Where

$$X_i = \sqrt{P_i} S_i, (i = 1, 2) \tag{4.2}$$

Both signals at the transmitter identified by the power allocated to them.

$$X_1 = \sqrt{P_1} S_1, X_2 = \sqrt{P_2} S_2 \tag{4.3}$$

From the figure: 4.6 UE_1 is nearest to the BS compared to the UE_2. For this case UE_1 has strong signal with better channel conditions. For this reason large power is assigned to UE_2 and small power is assigned to UE_1. At the receiver side UE_1 receives Y_1 which is represented by the below equation:

$$Y_1 = h_1 (x_1 + x_2) + n_1 \tag{4.4}$$

and UE_2 receives Y_2 which is represented as the equation below.

$$Y_2 = h_2 (x_1 + x_2) + n_2 \tag{4.5}$$

The system model at the receiver side is represented by the below equation:

$$\begin{pmatrix} y_1 \\ \\ y_2 \end{pmatrix} = \begin{pmatrix} h_{n,1} \\ \\ h_{n,2} \end{pmatrix} \cdot \left(\sqrt{P_1}S_1 + \sqrt{P_2}S_2\right) + \begin{pmatrix} n_{n,1} \\ \\ n_{n,2} \end{pmatrix} \tag{4.6}$$

$[h_{n,1}h_{n,2}]^{\mathrm{T}}$ stands for channel path gains corresponding to each reflected path in case of multi path channels. And $[n_{n,1}n_{n,2}]^{\mathrm{T}}$ stands for $AWGN$ corresponding to each receiver side.

$$y_{m,k} = H_{m,k}^{H}\sqrt{P_n}s_{m,k} + H_{m,k}^{H}\sqrt{P_n}s_{m,k} + n_k \tag{4.7}$$

The above equation indicates the general overall received signal of m^{th} user at k^{th} sub-carrier with the given transmitted symbol of $s_{m,k}$. The term $H_{m,k}^{H}\sqrt{p_m}s_{m,k}$ is the desired symbol while the term $H_{n,k}^{H}\sqrt{P_n}s_{n,k}$ is interference from another user.

FBMC Based PD-NOMA Downlink

In case of two users the base station creates a superposed signal containing data of both users

$$x_s = \sqrt{a_1\rho_s}x_1 + \sqrt{a_2\rho_s}x_2 \tag{4.8}$$

Where a_1, a_2 are function of total power given to user 1 and user 2 . In order to satisfy power constraint in PD-NOMA the below equations holds:

$$a_1 + a_2 = 1 \tag{4.9}$$

$$\rho_s = P_s/\sigma^2 \tag{4.10}$$

Where P_s is total transmit power and σ^2 is the variance. While the received signal at user i is given as the below equation:

$$y_i = h_i x_s + n_i \; where \; n_i \sim \mathcal{N}(0,1) \tag{4.11}$$

At user 1 the received signal is given by the equation below:

$$y_1 = h_1\left(\sqrt{a_1\rho_s}x_1 + \sqrt{a_2\rho_s}x_2\right) + n_1 \tag{4.12}$$

The SINR for decoding x_1 at u_1 is given by the below equation

$$\Upsilon_{(u_1)}^{(x_1)} = \frac{(a_1\rho_s|h_1|^2)}{(a_2\rho_s|h_1|^2+1)} = \frac{(a_1\rho_s\beta_1)}{(a_2\rho_s\beta_1+1)} \tag{4.13}$$

Where $\beta_1 = |h_1|^2$ and the pdf of β_1 is given as

$$f_{\beta_1}(\beta_1) = \frac{1}{\sigma_1^2} e^{-\frac{\beta_1}{\sigma_1^2}}, \; \beta_1 \geq 0 \tag{4.14}$$

At user 2

$$y_2 = h_2 \left(\sqrt{a_1 \rho_s} x_1 + \sqrt{a_2 \rho_s} x_2 \right) + n_2 \tag{4.15}$$

The SINR for decoding x_1 at u_2 is given by the below equation

$$\Upsilon_{(u_2)}^{(x_1)} = \frac{(a_1 \rho_s |h_2|^2)}{(a_2 \rho_s |h_2|^2 + 1)} = \frac{(a_1 \rho_s \beta_2)}{(a_2 \rho_s \beta_2 + 1)} \tag{4.16}$$

After decoding the first user and cancelling interference

$$y_2 = h_2 \sqrt{a_2 \rho_s} x_2 + n_2 \tag{4.17}$$

The SINR for decoding x_2 at u$_2$ is given by the below equation

$$\Upsilon_{(u_2)}^{(x_2)} = a_2 \rho_s |h_2|^2 = a_2 \rho_s \beta_2 \tag{4.18}$$

Where $\beta_2 = |h_2|^2$ and the pdf of β_2 is given as

$$f_{\beta_2}(\beta_2) = \frac{1}{\sigma_2^2} e^{-\frac{\beta_2}{\sigma_2^2}}, \; \beta_2 \geq 0 \tag{4.19}$$

In the case of PD-NOMA users with better channel conditions get less power. In the PD-NOMA, power allocation strategies play an important role in the capacity enhancement of the 5G mobile communication systems. Using efficient interference management is used to improve the cellular network's capacity. SIC, the most promising IC technique in wireless cellular networks, is one of the efficient methods of interference management. According to this principle, the signal with the strongest signal is decoded first.

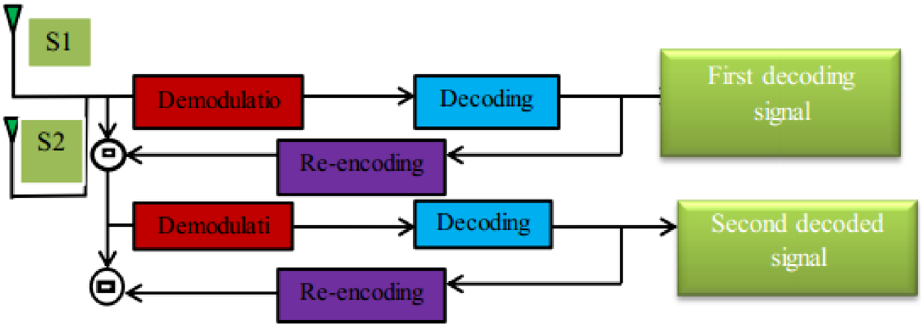


Figure 4.7: SIC [73].

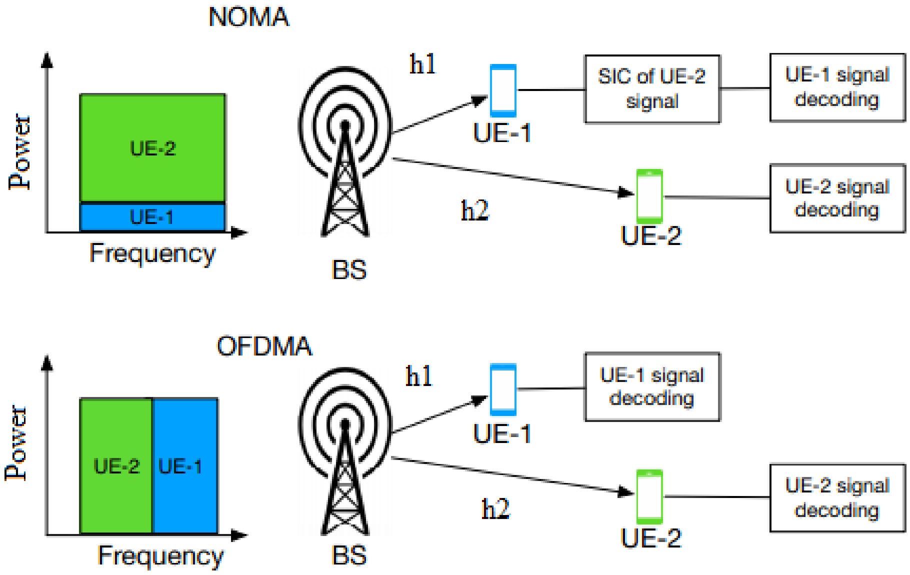


Figure 4.8: Multi-access schemes for two user scenario NOMA and OMA (OFDMA) [75].

In the above figure 4.8 single cell DL scenario considered with a single BS, and N users $\mathrm{U_i}$, with $\mathrm{i} \in N = \{1, 2\}$, and all terminals are equipped with a single antenna. The channels in this scenario are sorted as the equation below [19]:

$$|\mathrm{h}_1|^2 > |\mathrm{h}_2|^2 \tag{4.20}$$

Equation 4.20 implies that user $\mathrm{U_i}$ always holds the i^{th} weakest instantaneous channel.

4.4 Achievable Sum Rate and Power Allocation

4.4.1 Achievable Sum Rate

The throughput and achievable sum rate capacity of MA schemes could be efficiently maximized by using advanced modulation with PD-NOMA, which is the key parameter for the fifth generations of cellular communications. Interference in NOMA is controllable by non-orthogonal resource allocation [76]. The principle for NOMA with SIC is that user 2 first performs SIC to decode the signal for user 1, since the channel gain of user 2 is greater than that of user 1, because of the near user and far user. The decoded signal is then subtracted from the received signal of user 2. This resultant signal is eventually used to encode the signal for user 2. For user 1 SIC is not executed and user 1 is directly decoded. For NOMA users, the achievable data rate for users 1 and 2 is given by the below equations [19]:

$$\mathrm{R}_1 = \log_2\left(1 + \frac{\mathrm{P}_1 \,|\, \mathrm{h}_1|^2}{\mathrm{P}_2 \,|\, \mathrm{h}_1|^2 + \sigma_n^2}\right) \tag{4.21}$$

$$\mathrm{R}_2 = \log_2\left(1 + \frac{\mathrm{P}_2 \,|\, \mathrm{h}_2|^2}{\sigma_{\mathrm{n}}^2}\right) \tag{4.22}$$

Where for OMA, the achievable data rate is given by the equations below:-

$$\mathrm{R}_1 = \alpha \log_2\left(1 + \frac{\mathrm{P}_1 \,|\, \mathrm{h}_1|^2}{\sigma_{\mathrm{n}}^2}\right) \tag{4.23}$$

$$\mathrm{R}_2 = (1 - \alpha) \log_2\left(1 + \frac{\mathrm{P}_2 \,|\, \mathrm{h}_2|^2}{\sigma_{\mathrm{n}}^2}\right) \tag{4.24}$$

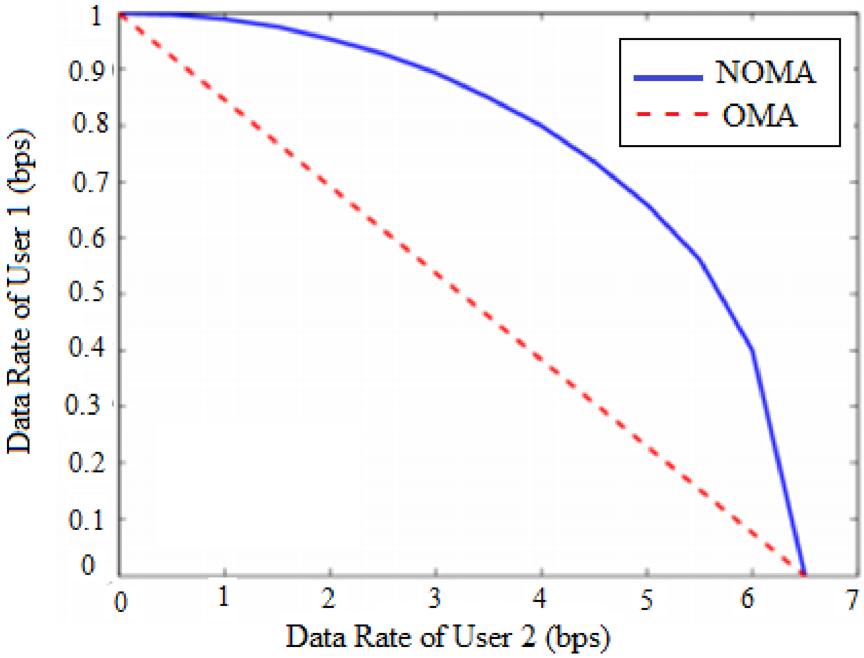


Figure 4.9: Capacity regions of NOMA and OMA for downlink [19].

The NOMA cellular system components are:

i. Multi-user grouping means deciding which users should be grouped together to deploy NOMA.

ii. Recourse allocation (it may be power, code, etc.); for instance, in the PD-NOMA case, users with large power differences are favorable.

iii. SIC or MUD interference cancellation techniques to remove the controlled NOMA additions.

Some of the possible benefits of using NOMA are:

Massive connectivity exists while OMA is limited by the number of orthogonal resources, but NOMA is not. NOMA supports an unlimited number of users. In terms of latency, OMA waits for available resource blocks to transmit, which is accomplished by waiting for an access grant, whereas NOMA can support flexible scheduling and grant free transmission. Therefore, NOMA has lower latency than OMA. In terms of improved SE (bps/Hz), every NOMA user can utilize the entire BW, whereas an OMA user can utilize a limited amount. The data rates of properly grouped users can be increased when compared to OMA [5].

4.4.2 Power Allocation

Multiple access technology in 5G cellular networks, especially PD-NOMA, is expected to significantly improve system performance. NOMA uses power in order to serve its users. Power is also a focal point in this thesis.

4.4.3 Proposed Algorithm for Resource Allocation

For this thesis work, an appropriate algorithm is proposed that maximizes the throughput and minimizes the number of blocked or unserved users. The combined resource allocation algorithm is known as positioning, clustering, and resource allocation (PCRA). This algorithm follows four different steps: (1) It determines the position of all UEs; (2) It clusters the UEs based on geographical distribution into near and far UEs. (3) it associates user pairing, and (4) it distributes resources. The algorithm below introduces the steps listed above.

Algorithm: PCRA algorithm

Step 1: Initialize: $\mathrm{RU} = 0$, is the index of the last RB used,
$\mathrm{US} = 0$, is the number of served users,
$\mathrm{UB} = 0$, is the number of unserved users,
$\dot{\mathrm{R}} = 0$, is the overall system throughput,
Step 2: Positioning:
2a: Receive the requests from all covered users,
2b: Calculate the position of each user $u\,(x_u, y_u)$ where,

$$x_u = x_\alpha \pm d_{u,\alpha}\cos(\varphi), y_u = y_\alpha \pm \sqrt{d_{u,\alpha}^2 - (x_\alpha - x_u)^2 - h^2}$$

Step 3: Clustering & Association:
3a: Split the users into two groups (near, far) according to their positions away from the transmitter.
3b: Sort each group members in ascending order based on their position.
3c: Construct the NOMA pair by selecting one user from each cluster that has the same order

3d: Calculate the distance between each pair d_{up},

$$d_{up}=\sqrt{\left(x_n-x_f\right)^2+\left(y_n-y_f\right)^2} \geq d_{\min}$$

3e: If $(d_{up}<d_{min})$ then, 3e1: Remove one user from a cluster alternately, 3e2: return to Step 3b

3f. Register highest required rate in each pair R_{um}.

3g calculate the required resource blocks for each pair,

$$\left(R_{\text{up}}=\left[\frac{R_{\text{utt}}}{R_y}\right]\right).$$

3h: Distribute the power between the pair users

$$(\text{near, far })=(\beta,(1-\beta)) P_s R_p$$

3i Calculate SINR for each user

$$\begin{aligned} & R^l=S+B_s \log_2\left(1+SINR^1\right), \\ & R^h=S * B_s \log_2\left(1+\operatorname{SIN} R^h\right),\end{aligned}$$

3j: NOMA will serve the weers with SINR ≥ 14 dB, and the others will be served individually.

3k : UP $=$ mumber of pair users.

3k: Case select

(1) Minimizing unserved users go to step 4

(2) Maximizing throughput go to step 5

Step 4: Resource allocation (minimize unserved users):

4a: Sort the pair users in ascending order based on the required data rate.

4b: WHILE $(RU \leq S$ && $US \leq UP)$

4b1: serve the pair users that required lowest R_{up}.

4b2: Update $RU=RU+R_{\text{up}}$.

4b3: Update $US=US+1$.

```
4b4: Remove the served users of the list.
4c: Calculate $UB = UP - US$.
4d: Calculate $\mathrm{R} = \sum$ Actual rate of served users.
Step5: Resource allocation (Maximize Throughput):
5a: Sort the pair users in descending order based on the required data rate.
5b: WHILE $(RU \leq S$ && $US \leq UP)$
5b1: Serve the pair users that required highest $R_{\text{up}}$
5b2: Update $RU = RU + R_{\mu p}$.
5b3: Update $US = US + 1$.
5b4: Remove the served users of the list.
5c: Calculate $UB = UP - US$.
5d: Cakulate $\mathrm{R} = \sum$ Actual rate of served users.
END
```

The above algorithm can be summarized as below:

Positioning: It is used to determine the location of mobile user with in the coverage area of the access point. The UE position (x_u, y_u) can be given by the figure 4.10 below:

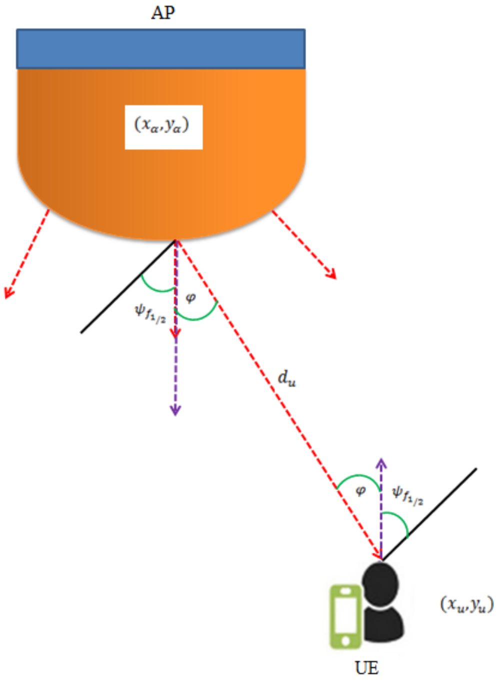


Figure 4.10: The schematic diagram of positioning system.

$$x_u = x_\alpha \pm d_{u,\alpha} \cos(\varphi) \tag{4.25}$$

$$y_u = y_\alpha \pm \sqrt{d_{u,\alpha}^2 - (x_\alpha - x_u)^2 - h^2} \tag{4.26}$$

Where x_α and y_α are coordinate of $AP_\alpha, d_{u,\alpha}$ the distance between AP_α and $UE_{u,\varphi}$ is the incident angle to PD, and h is the vertical distance between AP and UE

Clustering and Association: In case of multi user PD-NOMA user clustering or user pairing is an important power allocation algorithm among the users [85]. For multi users after allocating the position of all UEs they are sorted in ascending order based on their distance from the BS or AP then divided them in to two clusters (near, far). Clustered PD-NOMA increases capacity and throughput [86].

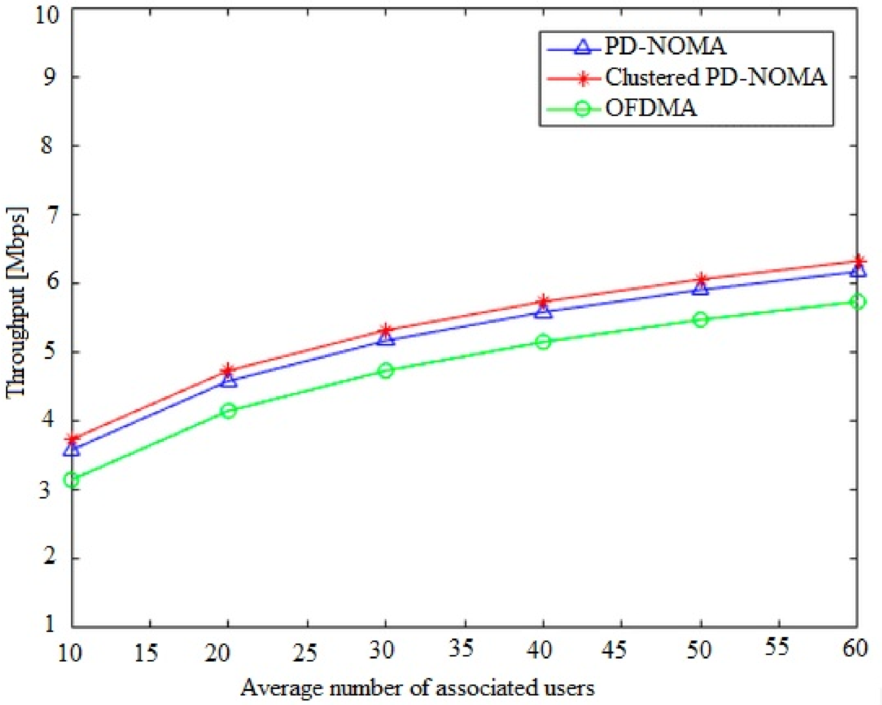


Figure 4.11: Number of associated users with BS vs. max throughput [86].

The distance between pair users in the two clusters can be calculated as the equation below:

$$d_{up} = \sqrt{(x_n - x_f)^2 + (y_n - y_f)^2} \geq d_{min} \tag{4.27}$$

Where x_n, y_n are the coordinates of near users, and x_f, y_f are the coordinates of far users.

The system capacity and performance of FBMC based PD-NOMA system can be greatly improved by using the proper user clustering strategy. The absence of user clustering in

PD-NOMA system increases the system overhead for error propagation. In order to avoid such overhead user clustering can be utilised to improve the capacity and efficiency of PD-NOMA.

Through user clustering the power distribution among users becomes an easy assignment. In clustering the total number of clusters (C) equals or less than half of the total number of users $(C \leq N/2)$. Each PD-NOMA cluster can have a minimum of two users and a maximum of N /2 users. Different steps in order to distribute users among clusters:
(1) Make C clusters with $C \leq N/2$
(2) Select a minimum number of users in each cluster to reduce intra-cell interference
(3) Each group must contain users with a maximum distance separation
Resource Allocation:- In PD-NOMA the resource allocation technique should satisfy the QoS under the constraints of power and bandwidth which maximizes the frequency reuse in PD-NOMA.

4.5 SE and EE Manipulations of PD -NOMA

The SE of an encoding or decoding scheme is the average number of bits of information per complex-valued sample that it can reliably transmit over the channel under consideration. It is the optimal use of spectrum or BW so that the maximum amount of data can be transmitted with the fewest transmission errors. In cellular networks, SE equates to the maximum number of users per cell that can provide an acceptable QoS. It is measured in bits per hertz (Hz) per cell.

4.5.1 Evaluation of FBMC-Based PD-NOMA Interms of EE

The EE of a cellular network can be defined by its performance divided by its energy consumption, where the definition of performance depends on the network entity it applies to. For a unit of energy consumed by the cellular network, the higher its performance is, the higher its EE is. It demonstrates the efficiency of advanced modulation-based PD-NOMA for 5G cellular networks. From the PD, radio components (RCs), for instance, power amplifiers and radio frequency components in BSs and UEs, dominate the power consumption. Considering the EE as the performance metric of interest, it can be defined as the ratio between throughput in bits per second per cell and the total power consumption in watts per cell as below [77]:

$$EE = \frac{Throughput(bit/s/cell)}{Powerconsumption(w/cell)} = \frac{R}{\Upsilon} \tag{4.28}$$

Υ Consists of the effective transmitted power $\mathrm{ET}_{\text{power}}$ and the circuit power consumption $\mathrm{C}_{\text{power}}$. The ET power takes the efficiency of power amplifier [ξ in consideration, such that

$$\gamma = \mathrm{ET}_{\text{power}} + \mathrm{C}_{\text{power}} \tag{4.29}$$

$$\mathrm{ET}_{\text{power}} = \frac{1}{\xi}\Sigma_{\mathrm{u=1}}^{\mathrm{U}}\mathrm{q}_{u} \tag{4.30}$$

Where q_{u} is the BS transmitted power to user U. The circuit power consumption $\mathrm{C}_{\text{power}}$ is the sum of different components according to [77]. Also $\mathrm{C}_{p\,\text{power}}$ represents encoding and decoding $p_{\text{cod/dec}}$ power consumed by the signaling of back haul bh and power consumed by digital signal processing p_{sp}.

$$\mathrm{C}_{\text{power}} = \mathrm{P}_{\text{fix}} + \mathrm{P}_{\text{tc}} + \mathrm{P}_{\text{ce}} + \mathrm{P}_{\text{cod}}/\mathrm{dec} + \mathrm{P}_{\text{bh}} + \mathrm{P}_{\text{sp}} \tag{4.31}$$

Where P_{fix} is the load independent power of infrastructure and power of control signaling, P_{tc} is the power consumed by transceiver chains which is given by the equation below:

$$\mathrm{P}_{\mathrm{tc}} = A\mathrm{P}_{\mathrm{BS}} + \mathrm{P}_{\mathrm{lo}} + \mathrm{UP}_{\mathrm{UE}} \tag{4.32}$$

Where P_{BS} is the power to operate the circuit components of the Bs, P_{lo} is the power consumed by local oscillator.P_{UE} is, the user equipment power. While P_{cod} / dec is the power required to encode and decode throughput.

$$\frac{P_{cod}}{p_{dec}} = (P_{cod} + P_{dec})\,R \tag{4.33}$$

Or in terms of bit/joule the energy efficiency can be defined as the below equation [78]:

$$\mathrm{EE}\,(\mathrm{bit/joule}) = \frac{\mathrm{Datarate}\,(\mathrm{bit/s})}{\mathrm{Energy\,consumption}\,(\mathrm{joule/s})} \tag{4.34}$$

The SINR is also the primary parameter used to assess how effectively the signal arrived at the receiver. It is defined as follows:

$$\mathrm{SINR} = \frac{P_R}{\sum_i P_i + P_z} \tag{4.35}$$

P_R is the received power, $\sum_i P_i$ is the sum of the interfering signals, and P_z is the noise power.

*PAPR:*The peak factor is a measurement characteristic of a signal. It is usually correlated with Peak-to-Average Power Ratio which implies the r/p b/n power peak and average power. PAPR is one aspect of performance needed to be considered in 5G. Mathematically defined as below [59]:

$$PAPR = \frac{\text{Peak Power}}{\text{Average Power}} \tag{4.36}$$

In terms of PAPR the one with high PAPR needs more powerful amplified whereas the one with low PAPR needs less power amplifiers. Due to simplified structure in terms of PAPR the FBMC is best compromise compared to UFMC and OFDM. The SE for three waveform [bit $/\mathrm{s}/\mathrm{Hz}$] is given by the below mathematical equation [79]:

$$\eta_{OFDM} = \frac{m * N_{FFT}}{N_{FFT} + N_{CP}} \tag{4.37}$$

$$\eta_{FBMC} = \frac{m * S}{S + K - \frac{1}{2}} \tag{4.38}$$

$$\eta_{UFMC} = \frac{m * N_{FFT}}{N_{FFT} + L - 1} \tag{4.39}$$

The best spectral localization is obtained with the use of FBMC-OQAM also SE is high for FBMC. Spectral efficiency of OFDM PD-NOMA can be expressed as the equation below by combining equations 4.21,4.22 and 4.37:

$$\eta_{OFDMPD-NOMA} = \frac{m * N_{FFT}}{N_{FFT} + N_{CP}} * \left(\log_2 \left(1 + \frac{\mathrm{P}_1 \mid \mathrm{h}_1|^2}{\mathrm{P}_2 \mid \mathrm{h}_1|^2 + \sigma_n^2} \right) + \log_2 \left(1 + \frac{\mathrm{P}_2 \mid \mathrm{h}_2|^2}{\sigma_{\mathrm{n}}^2} \right) \right) \tag{4.40}$$

whereas for UFMC-PDNOMA its spectral efficiency given by the equation below by combining 4.21,4.22 and 4.39

$$\eta_{UFMCPD-NOMA} = \frac{m * N_{FFT}}{N_{FFT} + L - 1} * \left(\log_2 \left(1 + \frac{\mathrm{P}_1 \mid \mathrm{h}_1|^2}{\mathrm{P}_2 \mid \mathrm{h}_1|^2 + \sigma_n^2} \right) + \log_2 \left(1 + \frac{\mathrm{P}_2 \mid \mathrm{h}_2|^2}{\sigma_{\mathrm{n}}^2} \right) \right) \tag{4.41}$$

whereas for FBMC-OQAM-PD-NOMA its spectral efficiency given by the equation below by combining 4.21,4.22 and 4.38

$$\eta_{FBMC-OQAMPD-NOMA} = \frac{m * S}{S + K - \frac{1}{2}} * \left(\log_2 \left(1 + \frac{\mathrm{P}_1 \mid \mathrm{h}_1|^2}{\mathrm{P}_2 \mid \mathrm{h}_1|^2 + \sigma_n^2} \right) + \log_2 \left(1 + \frac{\mathrm{P}_2 \mid \mathrm{h}_2|^2}{\sigma_{\mathrm{n}}^2} \right) \right) \tag{4.42}$$

4.6 Outage Probability

The outage probability refers to the scenario when rate of user is lower than the desired rate. Let R_1, R_2 denotes the desired rate of user 1 and user 2 . Now let us derive the probability of outage for user 1 Rate of user 1 is given by [87, 88]:

$$C_{u_1}^{x_1} = \log_2 \left(1 + \gamma_{u_1}^{x_1} \right) < \hat{R}_1 \tag{4.43}$$

$$\gamma_{u_1}^{x_1} = \frac{a_1 \rho_s \beta_1}{a_2 \rho_s \beta_1 + 1} < 2^{\hat{R}_1} - 1 = R_1 \tag{4.44}$$

$$\beta_1 < \frac{\beta_1}{\left(a_1 - a_2 R_1 \right) \rho_s} \tag{4.45}$$

Outage probability for user l is given by [87, 88]

$$P_r \left\{ \beta_1 < \frac{R_1}{\left(a_1 - a_2 R_1 \right) \rho_s} \right\} \tag{4.46}$$

$$= \int_0^{\frac{R_1}{(a_1 - a_2 R_1) \rho_s}} f_{\beta_1} \left(\beta_1 \right) d\beta_1 \tag{4.47}$$

$$= 1 - \exp \left(- \frac{R_1}{\sigma_1^2 \left(a_1 - a_2 R_1 \right) \rho_s} \right) \tag{4.48}$$

Probability of outage user 2

User 2 decoding fails if either decoding of x_1 or x_2 fails

Probability of outage user 2 is given by [87, 88]:

$$P_r \left\{ C_{u_1}^{x_1} < \hat{\mathrm{R}}_1 \cup C_{u_2}^{x_2} < \hat{\mathrm{R}}_2 \right\} \tag{4.49}$$

$$C_{u_2}^{x_1} = \log_2 \left(1 + \gamma_{u_2}^{x_1} \right) < \hat{R}_1, \quad C_{u_1}^{x_1} < \hat{R}_2 \tag{4.50}$$

$$\Leftrightarrow \frac{a_1 \rho_s \beta_2}{a_2 \rho_s \beta_2 + 1} < 2^{\hat{R}_1} - 1 = R_1 \Rightarrow \log_2 \left(1 + \gamma_{u_2}^{x_1} \right) < \bar{R}_2 \tag{4.51}$$

$$\Rightarrow \beta_2 < \frac{R_1}{\left(a_1 - a_2 R_1 \right) \rho_s} \Rightarrow a_2 \rho_s \beta_2 < 2^{\beta_2} - 1 = \tilde{R}_2 \tag{4.52}$$

$$\Rightarrow \beta_2 < \frac{R_2}{a_2 \rho_s} \tag{4.53}$$

On solving, outage occurs if

$$\beta_2 < \max\left\{\frac{R_1}{(a_1 - a_2 R_1)\,\rho_s}, \frac{R_2}{a_2 \rho_s}\right\} \tag{4.54}$$

$$P_r\left\{\beta_2 < \max\left\{\frac{R_1}{(a_1 - a_2 \beta_1)\,\rho_s}, \frac{R_2}{a_2 \rho_s}\right\}\right\} \tag{4.55}$$

$$\int_0^{\max}\left\{\frac{R_1}{(a_1 - a_2 R_1)\,\rho_s}, \frac{R_2}{a_2 \beta_s}\right\} f_{\beta_2}(\beta_2)\, d\beta_2 \tag{4.56}$$

$$1 - \exp\left(-\frac{1}{\sigma_2^2}\max\left\{\frac{R_1}{(a_1 - a_2 R_1)\,\rho_s}, \frac{R_2}{a_2 \rho_s}\right\}\right) \tag{4.57}$$

Outage probability for two users NOMA vs FBMC-PD-NOMA has been discussed in the above section with the behavior of outage probability vs SNR for NOMA and FBMC-PDNOMA. Different parameters are:

$$\sigma_{u2r}^2 = 2, a_1 = 0.2, a_2 = 0.8, \rho_s = \rho_r, \hat{R}_1 = 3, \hat{R}_2 = 0.5\frac{bps}{Hz} \text{ and } k^u = r^u = 60$$

The channel capacity of NOMA is given by the equation below:

$$C_{PD-NOMA} = B\log_2\left(1 + \frac{P_{Tx}}{P_z + P_{int}}\right) \tag{4.58}$$

Where P_{Tx} is the transmission power, P_z is the noise power, and P_{int} is the interference power

4.7 Computational Complexity

This section deals with the complexity of the system. In MCM the computational completxity of the system is evaluated in terms of multiplications and additions in the given equation. Complexity highly depends on the number of multiplication operations. Under this section the computational complexity of three advanced modulations are discussed with the concept of PD-NOMA for 5G applications.

The computational complexity of OFDM is given by the equation below [89, 91] :

$$C_{OFDM} = 2M_{FFT}(N) + 4(N + L_{CP}) + 4N_o \tag{4.59}$$

The above equation is for the multiplication.

Also the comutational complexity of FBMC/OQAM for PPN is given by the equation below for multiplication [90, 91] :

$$C_{FBMC/OQAM} = 4M_{FFT}(N) + 8NK + 4No(1 + L_{eq}) \tag{4.60}$$

For UFMC the computational complexity of the system is given by the equation below for multiplication [90] :

$$C_{UFMC} = M_{FFT}(2N) + 4N_o \tag{4.61}$$

Chapter 5

Result and Discussion

Here, the simulation results are provided to validate the most efficient advanced modulation techniques for 5G applications. Also, the simulation results provide PD-NOMA with efficient advanced modulation in terms of SE, BER, PSD, OP, capacity, and EE, as well as the advantages of efficient advanced modulation over conventional modulation techniques. For comparison purposes, the simulation parameters of FBMC and UFMC are highlighted in the table 5.1.

Table 5.1: Parameters for FBMC and UFMC

Name of parameters of FBMC	Values
Number of FFT	1024 and vary
Symbol Mapping	4,16,64 and 256QAM
Number of Guards	212
K	4
Number of symbols	100
Bits per sub carrier	2
SNR dB	30
Name of parameters of UFMC	Values
Number of FFT	1024 and vary
Sub band size	20
Number of sub bands	10
Sub band offset	156
Dolph chebyshev window design parameters	Values
Filter length	43
Side lobe attenuation	40 dB
Bits per sub carrier	4
CP of OFDM Length	43
Bw dB	5MHz
Total Transmit power	40dBm
Power coeifficients of $a_1$and a_2	0.2 and 0.8

5.1 FBMC, OFDM, and UFMC Interms of PSD

PSD deals with the variations of energy as a function of frequency. It shows which frequency variations are strong and weak. Side lobe variation is also determined by using the PSD concept. The interferences of side lobe radiation in advanced modulations are the focus considerations. Here in the figure 5.1, the PSD of the FBMC, OFDM, and UFMC are plotted in order to identify which have low OOBL and which have high OOBL. From the matlab simulation result, it has been determined that the FBMC waveform has a low OOBL while the OFDM waveform has a high OOBL. The OFDM waveform used in the above comparison fully occupied the given band. According to the comparison of OFDM and FBMC, the FBMC has lower side lobes while the OFDM has higher side lobes, resulting in lower utilization of the given spectrum.Having lower side lobes of FBMC allows for higher utilization of the given spectrum, which also leads to increased SE.

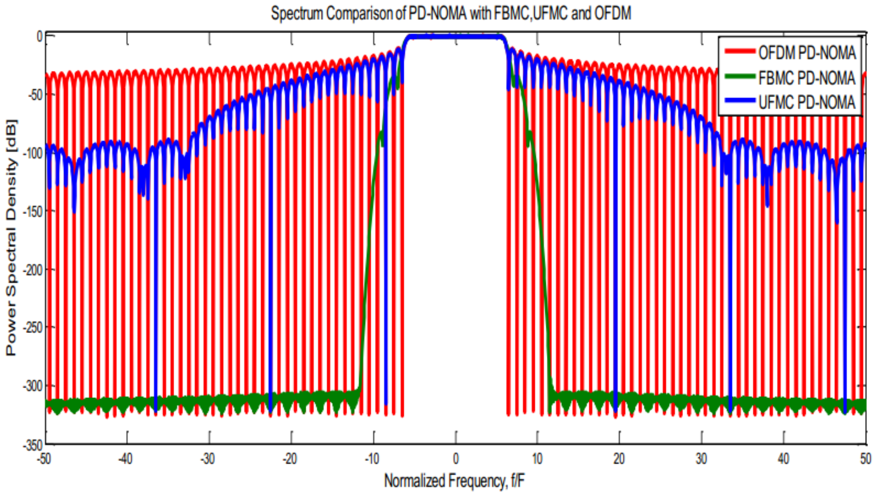


Figure 5.1: Spectrum of FBMC, OFDM, and UFMC in terms of PSD.

UFMC and OFDM are compared in that UFMC has a low side lobe and a low PAPR. In contrast, OFDM has a high PAPR, a high OOBE, and a large side lobe value. Specifically for the above-given parameters in the table, the PAPR for UFMC is 8.2379dB. The PAPR of OFDM is 8.884 dB. BER = 0 at SNR = 15 dB for UFMC reception as well. Having a lower side lobe of the UFMC allows for efficient utilization of the allocated spectrum. Therefore, effective spectrum use results in enhanced SE. In the above figure, it shows that the PSD for OFDM is around -30 dB, the PSD for UFMC is around -100 dB, whereas for

FBMC it is equal to around -325dB. Therefore, there is a lot of OOBE power leakage in the case of OFDM compared to UFMC and FBMC. High OOBE reduces the QoS transmitted. The OOBE must be sufficiently low in order to efficiently support different use cases within the same band. Also, low OOBE reduces the synchronization requirements. This effect is reduced by using advanced modulation in FBMC and OQAM-based PD-NOMA.

5.2 EE of FBMC, UFMC and OFDM

Energy efficiency is another important parameters for 5G waveforms. In this section the efficieny of energy considered with the total transitted power. Spectral leckage determines the effect of energy efficiency of 5G communication systems. The energy efficiency depends on the application. FBMC is an efficient waveform for applications which require high spectral efficiency, such as cellular networks, cognitive radio and satellite communications. UFMC is an efficient waveform for applications which require low latency and/or low complexity, such as wireless local area networks. OFDM is an efficient waveform for applications which require high data rates, such as broadband wireless access. From the three waveforms considered in this thesis work OFDM has the worst performance among all the three waveforms due to its significant spectral leakage. Whereas, FBMC and UFMC have similar performance due to their similar interference. As a reult shows, the less the spectral leakage is, the higher energy efficiency can be achieved.

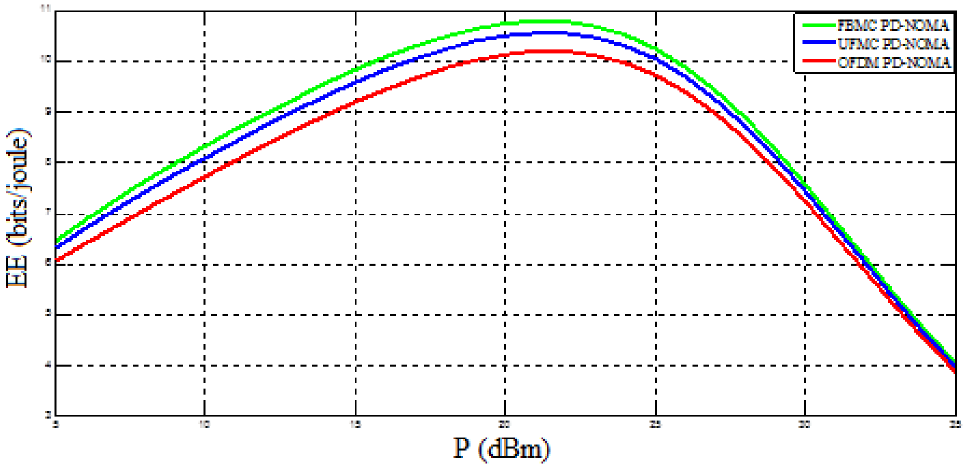
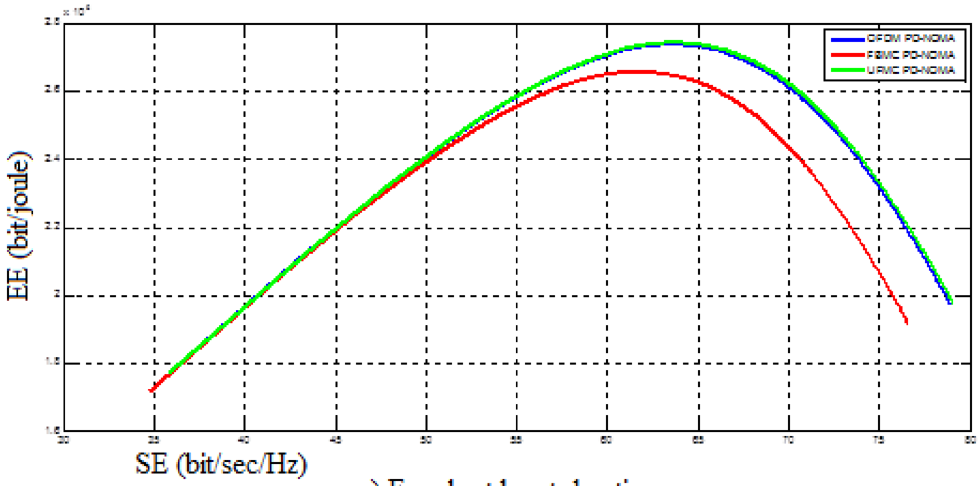
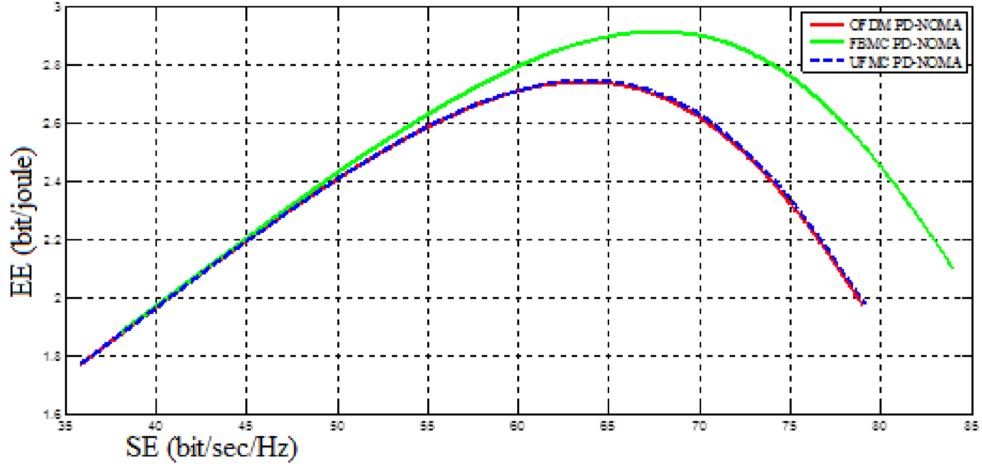


Figure 5.2: FBMC, OFDM, and UFMC in terms of EE.

Interms of EE versus SE the FBMC outperforms both OFDM and UFMC for large burst which ranges from 0 to 180ms which was shown in fig 5.3b of SE. The value of CP and filter length are 43 while the value of N=512 EE vs SE. the simulated result is shown as fig 5.3 a and b for short and larg burst duration.



a) For short burst duration



b) For larger burst duration

Figure 5.3: FBMC, OFDM, and UFMC in terms of EE vs SE.

5.3 BER of FBMC, UFMC, and OFDM

BER is one of the most important metrics to measure the modulation waveforms for 5G applications. Taking OFDM as a reference and comparing the BER of FBMC vs OFDM vs UFMC. In this simulation, the BER for OFDM, UFMC and FBMC. OFDM system has CP,

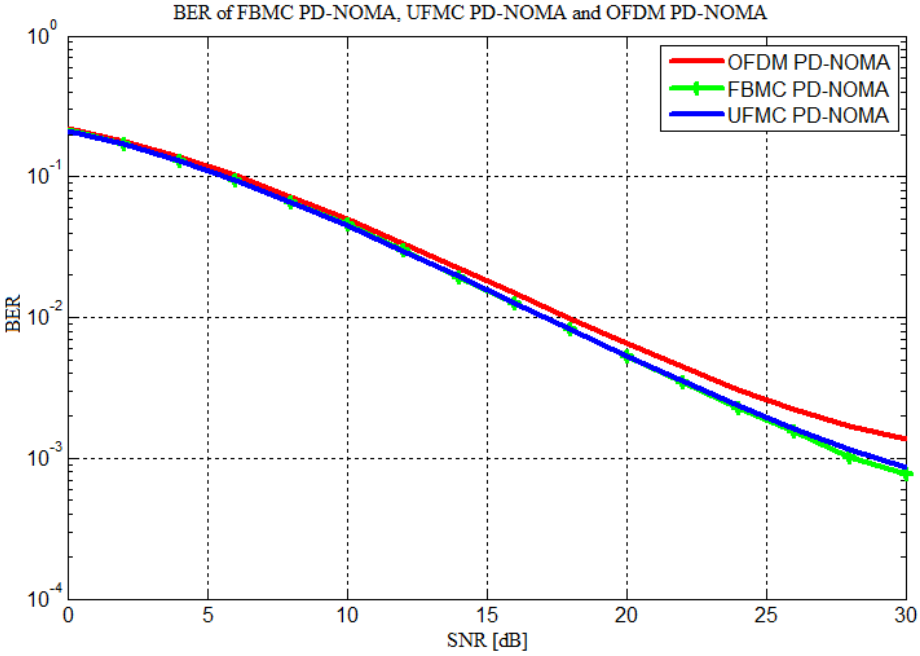


Figure 5.4: FBMC, OFDM, and UFMC in terms of BER.

which reduces the performance and modulation scheme is QAM, and number of subcarriers 1024, while FBMC is modulated with OQAM and no CP is used for the same subcarriers number. The simulation result indicate that FBMC performs better than OFDM and UFMC in wireless mobile channel. Due to the absence of the cyclic prefix, the FBMC has better SE than the OFDM for increasing SNR. Also no CP for UFMC Fig.5.4 indicates that FBMC has lower BER for the range of SNR [0 : 30 dB].

Despite its high transceiver complexity resulting from the large filter length puts FBMC/OQAM with PPN on the second complex next to OFDM as shown in the figure 5.14 below, but the FBMC exhibited low OOBE, low BER, and the most optimal spectral efficiency owing to OQAM modulation. Therefore, it is the most suitable for both eMBB and URLLC applications. Additionally, UFMC is suitable for mMTC applications owing to its short data burst.

The figure 5.5 shows the SE of the three waveforms for FBMC, OFDM, and UFMC. This result is generated by varying the duration of the burst from 0 to 30. Since the numbers for

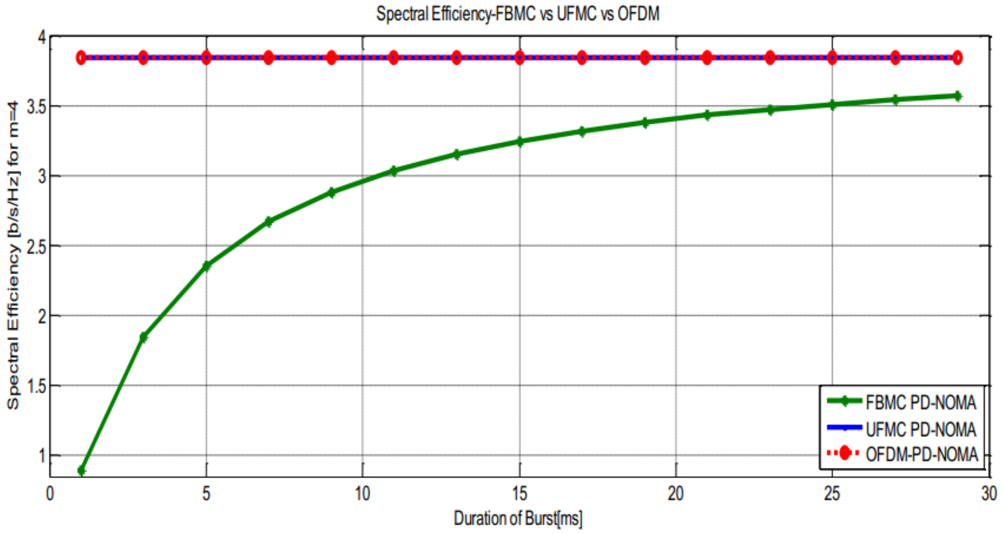


Figure 5.5: Shows the spectral efficiency of FBMC vs UFMC vs OFDM.

CP and filter length are equal, the UFMC and the OFDM overlap each other over the given burst. From the result, it is observed that the FBMC SE increases with an increase in the duration of bursts. It is greater than the other two if the duration of the burst is larger. For larger burst the spectral efficiency of FBMC is greater as it is shown in figure 5.6 below.

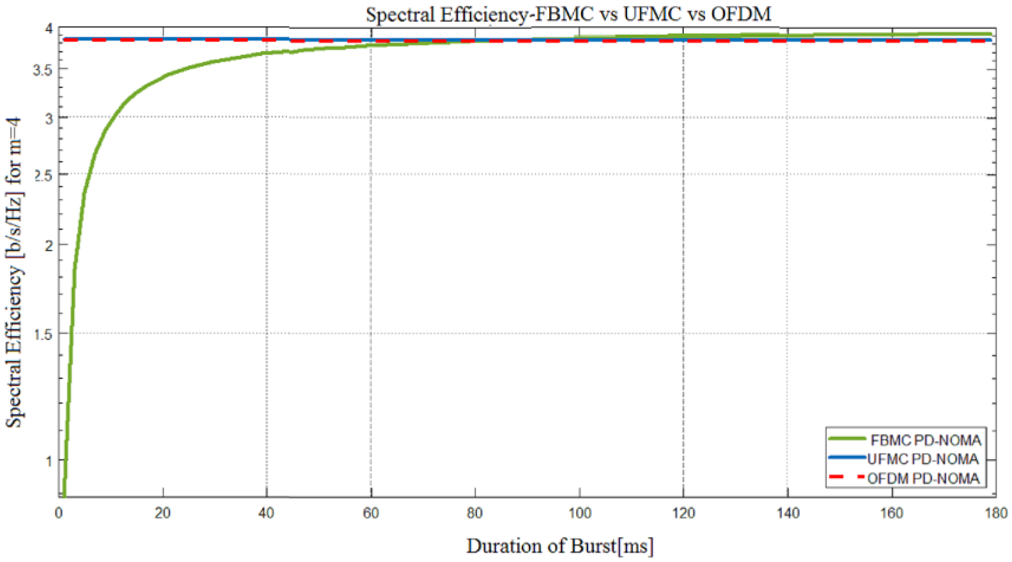


Figure 5.6: Shows the spectral efficiency of FBMC vs UFMC vs OFDM for larger burst.

FBMC-OFDM: Prototype filter comparison

Having different values of prototype filter the OFDM and FBMC have been analyzed

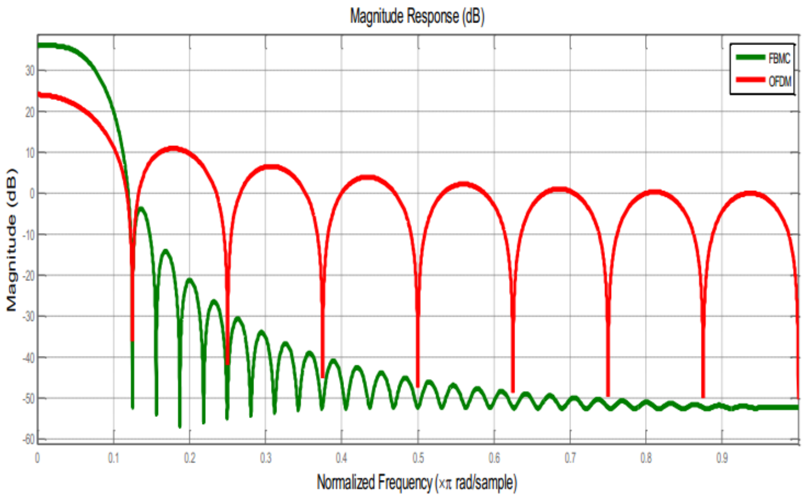


Figure 5.7: Having different values of prototype.

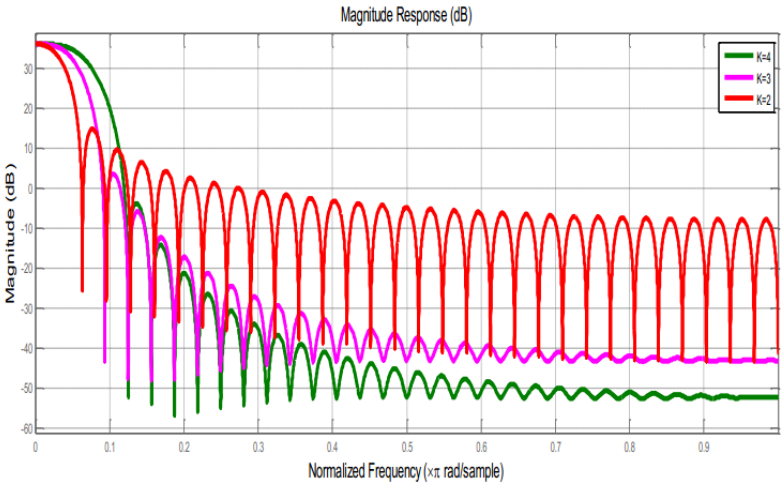


Figure 5.8: Increasing the value of k from 2 to 4.

As the value of k goes from 2 to 4 it becomes more linear and the out of band is also reduced

5.4 Outage Probability

The below simulation result shows the OP of FBMC based PD-NOMA and non FBMC based NOMA for 5G applications evaluated. The two users are located at different locations user 1

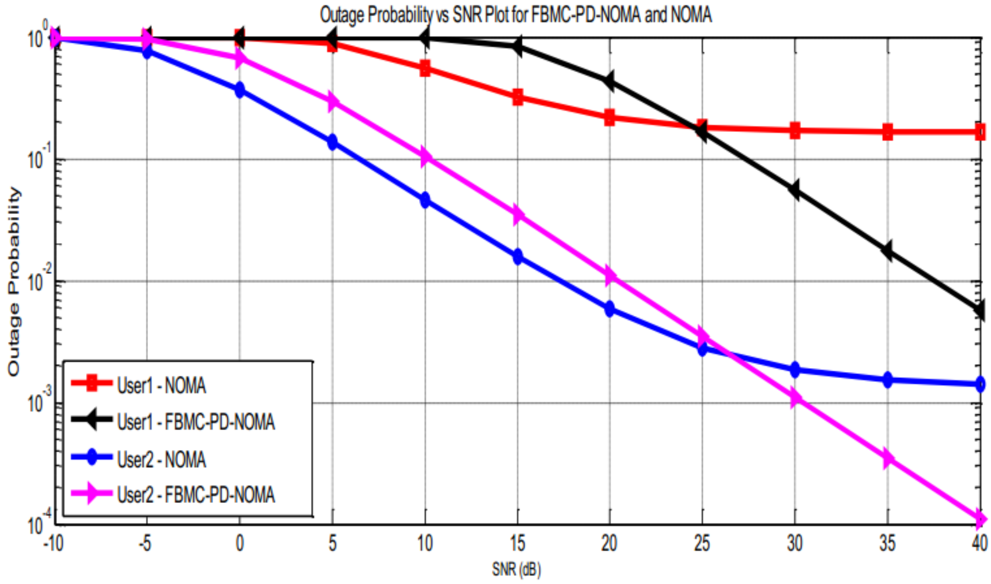


Figure 5.9: Outage probability of FBMC-PD-NOMA.

is far from BS and user 2 is near to BS. The one with the lowest OP performs the best. Figure 5.9 shows the OP of two users versus the SNR for FBMC based PD-NOMA and NOMA without FBMC. In terms of outage probability for two users, the FBMC-based PD-NOMA outperforms compared to NOMA without FBMC or OQAM in both cases for user 1 and user 2. The simulation result shows that the lowest OP means the best performance.

5.5 Sum Rate

The simulation result below shows that the sum rate of different parameters for 5G applications.

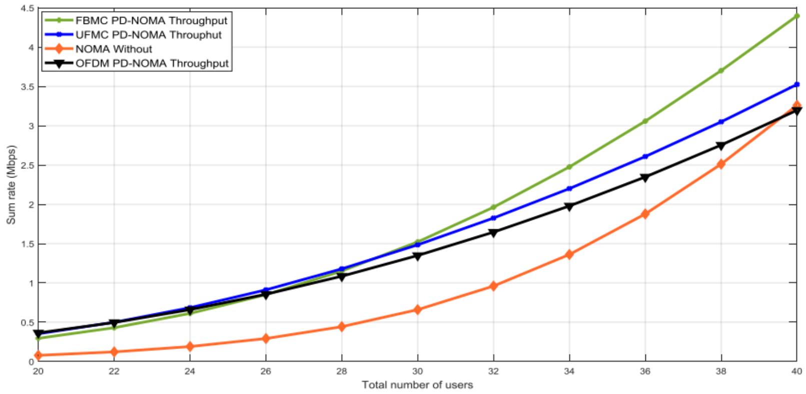


Figure 5.10: Sum rate versus total number of users.

5.6 Capacity

In 5G communication, the capacity of the system is limited by interference. PD-NOMA with FBMC/OQAM reduces the effect of interferences. The Matlab simulation shows the simulated results in terms of interference. It is known as in the case of high interference the logarithimic capacity of the system decreases specially for OFDM-PD-NOMA it is very less compared to FBMC PD-NOMA and UFMC PD-NOMA.

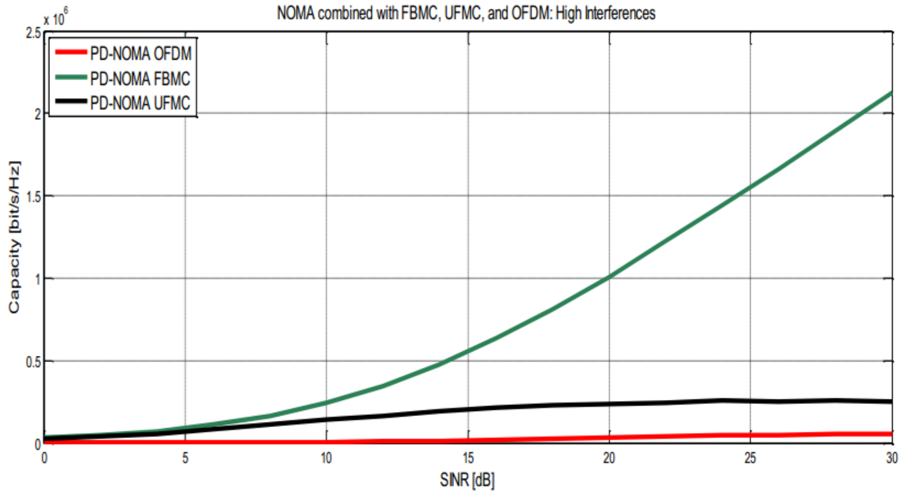


Figure 5.11: Capacity of FBMC, OFDM, and UFMC using NOMA in high interference.

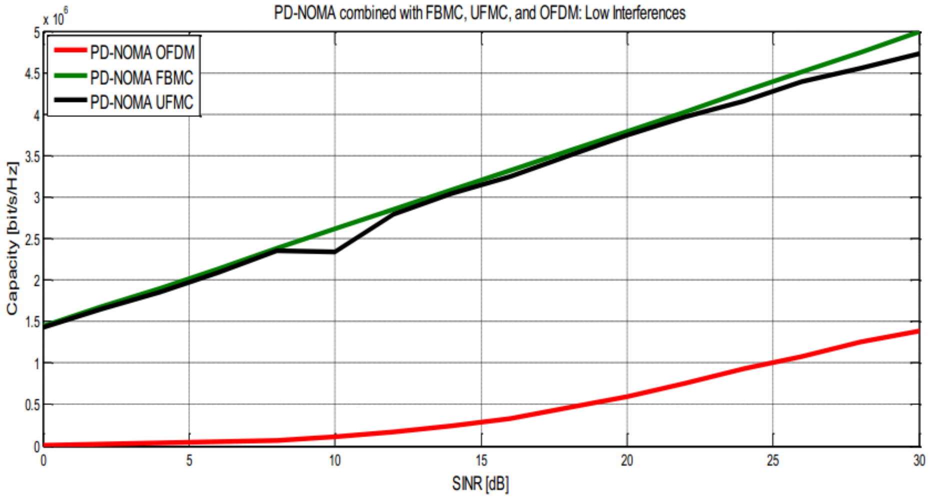


Figure 5.12: Capacity of FBMC, OFDM, and UFMC using NOMA in low interference.

According to the simulation results, high interference reduces the channel's capacity. even if the one with FBMC performs better. In low interference cases, the interferer transmits at lower power and the highest power level is assigned to the NOMA user. The channel capacity is increased when PD-NOMA is used with effective advanced modulation. As a result, FBMC/OQAM-based PD-NOMA is the one that significantly increases channel capacity. In the case of PD-NOMA-FBMC/OQAM, by using OQAM, the full capacity of the transmission can be achieved while PD-NOMA and FBMC/OQAM are combined or integrated together. From the result of figure 5.11 the maximum capacity value obtained for FBMC/OQAM based PD-NOMA is eight times greater than UFMC based PD-NOMA and fourty times greater than OFDM based PD-NOMA. From figure 5.12 in case of low interference FBMC/OQAM based PD-NOMA capacity is 3.5 times greater than OFDM based PD-NOMA and 0.05 times greater than UFMC bsaed PD-NOMA. From the simulation result in terms of capacity versus SNR NOMA-FBMC outperforms NOMA-OFDM. Therefore FBMC based PD-NOMA increases the capacity when compared with the other type of modulation based PD-NOMA.

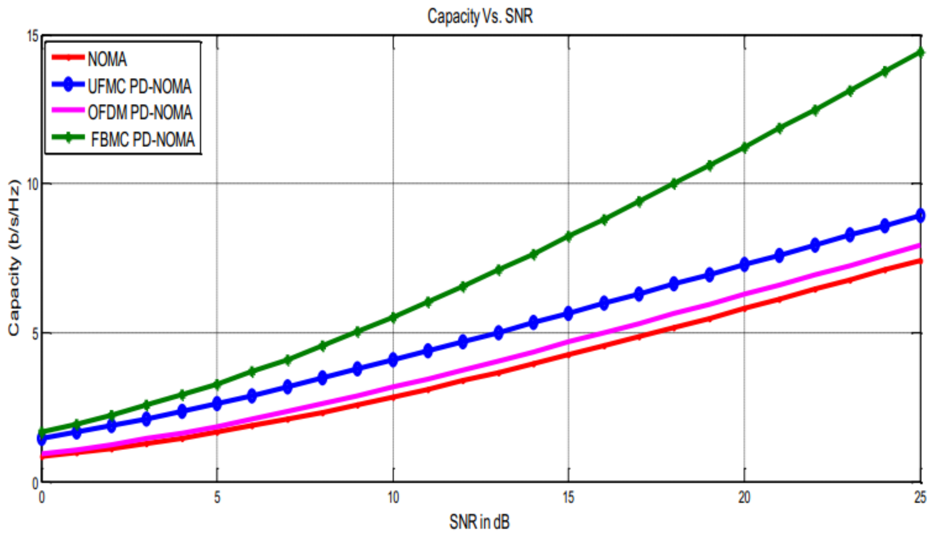


Figure 5.13: Capacity versus SNR.

5.7 Computational Complexity

In this section a comparision of computational complexity for different waveforms with PD-NOMA performed. The below simulated result is obtained by considering low complexity of FBMC/OQAM with PPN as it is discussed in chapter 3 and chapter 4 for two classes of FBMC (i,e FS-FFT and PPN-FFT).Computational coplexity focuses the number of operations at the transmitter and at the receiver. In section 4.7 the computational complexity formula of FBMC/OQAM for PPN, OFDM and UFMC are given. For three advanced modulations with PD-NOMA the size of N = 1024. The PPN filter bank multicarrier allows a high complexity reduction introduced by extra filtering operations at both the Tx and at the Rx. From the simulation result the complexity of FBMC/OQAM for PPN is greater than the complexity of OFDM because of filtering operation and many tap equalizers for interferenceand it is less than the complexity of UFMC. Also the complexity of UFMC is greater than that of both OFDM and FBMC/OQAM PPN.

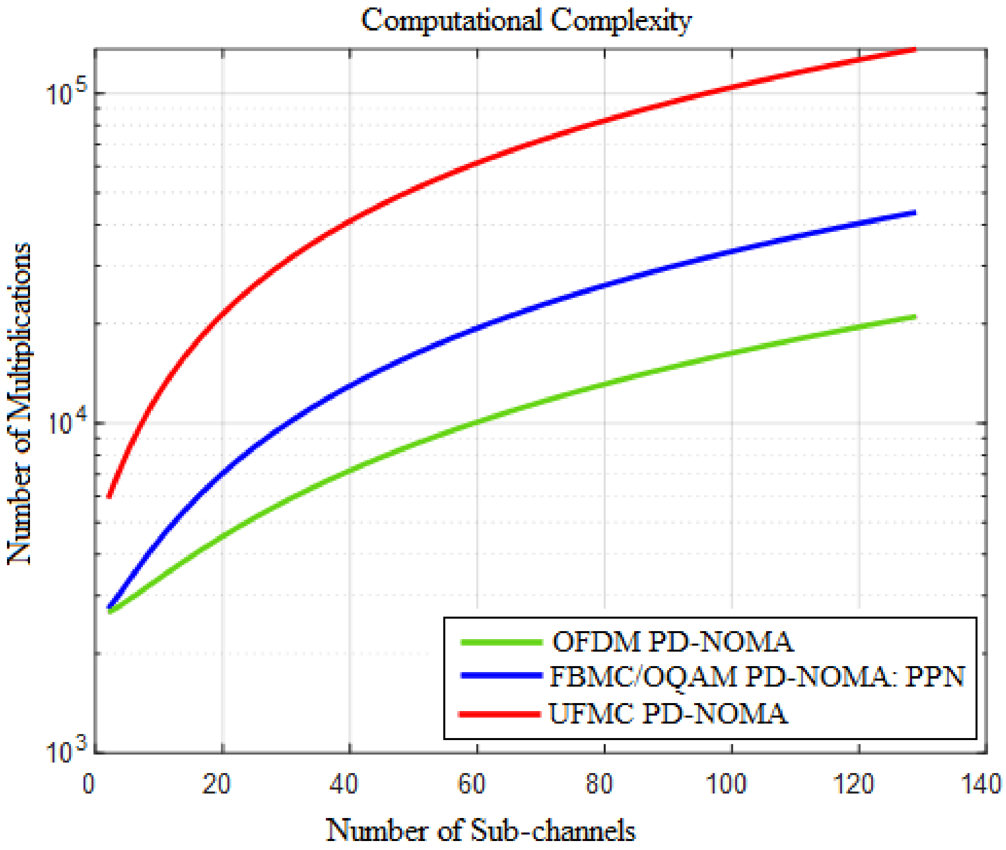


Figure 5.14: Computational Complexity of FBMC/OQAM, UFMC and OFDM

Chapter 6
Conclusion and Recommendations

6.1 Conclusion

In this research works, the performance evaluation of PD-NOMA combined with advanced modulation techniques for 5G cellular networks applications has been presented. The proposed combined scheme allows two users simultaneously to be multiplexed over the shared resource blocks by using power allocation strategies to enhance the performance of the system.

The simulation results reveals that, the combined techniques increases the overall system throughput when the FBMC and UFMC were used. Besides, the FBMC has a higher throughput than OFDM because of its higher usable bandwidth and no CP overhead. Furthermore, the FBMC-based PD-NOMA scheme has better spectral efciency, energy efciency, PSD, BER, and outage probability. Therefore, it can be concluded that, FBMC/OQAM-based PD-NOMA outperforms NOMA UFMC and NOMA-OFDM in terms of the outage probability and BER as well as capacity and sum rate. However, the system complexity of the OFDM is less complex than the FBMC/OQAM based PPN and UFMC.

6.2 Recommendations

This thesis focuses on a few parameters, but other parameters are also considered.

NOMA employs some controllable interference via non-orthogonal resource allocation and realizes overloading at the cost of slightly increased receiver complexity, which should be considered

The data and reliability of 5G wireless communication can be enhanced by using multiple antennas at the Tx and Rx, thereby creating MIMO channels, and with efficient modulation, which should be investigated.

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