HAWASSA UNIVERSITY
INSTITUTE OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Performance Comparison of Multiple Access Techniques for 5G networks and beyond

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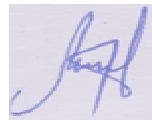
Declaration

This thesis is a presentation of my own research work and that any material used from other sources has been clearly identified and properly acknowledged and referenced.



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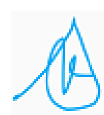

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Abstract

In wireless networks, the rapidly growing demands for wireless services are encountered by the shortage of the existing radio resources. More spectrum is needed not only to accommodate more users, but also to satisfy the demands of new services such as wireless gaming, TV on demand, Self-driving cars and high-speed mobile data. Filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC) and power domain non-orthogonal multiple access (PD-NOMA) have currently get attention because of their higher spectrum efficiency compared to OFDM, and they play an important role in increasing the capacity in future networks. Particularly, FBMC and UFMC is unlike OFDM, they can be eliminate cyclic prefix and reduce out of band emission by using different filters for each subchannels and for sub-band respectively, whereas PD-NOMA accommodate multiple users in the power domain through superposition coding and make them to access the whole spectrum simultaneously, while using successive interference cancellation (SIC) at the receiver side for signal detection. This thesis provide the performance comparison and analyze of FBMC, UFMC and PD-NOMA multiple access techniques in system-level performance with respect to spectrum efficiency, energy efficiency, bit-error rate, and PAPR. Results indicate that power domain NOMA perform better in spectral efficiency, energy efficiency and PAPR than FBMC and UFMC schemes. The results also reveal that PD-NOMA less perform than FBMC and UFMC in respect of bit error rate. From the results we conclude that the power domain based NOMA is good candidate to 5G network as compared to the FBMC and UFMC with cost of bit error rate.

Keywords *- Spectral efficiency, Bit error rate, peak to average power ratio, Universal filtered multicarrier, Filter Bank Multicarrier, Power domain Non-Orthogonal Multiple Access.*

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List of Abbreviations

2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AWGN	Additive White Gaussian noise
BER	Bit Error Rate
CDMA	Code division multiple access
CMT	Cosine-Modulated Multitone
CP	Cyclic Prefix
CSI	Channel state information
eMBB	Enhanced Mobile Broadband
eV2X	Enhanced Vehicle-to-everything
FBMC	Filter Bank Multicarrier
FDMA	Frequency division multiple access
FFT	Fast Fourier Transform
FMT	Filtered Multitone
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telephony
IOT	Internet of Things
ITU	International Telecommunication Union
LTE	Long Term Evolution
M2M	Machine to Machine
MA	Multiple Access
mMTC	Massive Machine Type Communications
MUD	Multiple User Detection
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OMA	Orthogonal Multiple Access
OoB	Out-of-Band Emission

OQAM	Offset QAM
PA	Power allocation
PAPR	Peak-to-Average Power Ratio
PD-NOMA	power domain Non-orthogonal multiple access
QAM	Quadrature Amplitude Modulation
SC	Superposition Coding
SIC	Successive Interference Cancellation
SMT	Staggered Multitone
SNR	Signal to Noise Ratio
TDMA	Time division multiple access
UFMC	Universal Filter Multicarrier

Chapter 1

Introduction

1.1. Background

The evolution of cellular networks was originally designed for voice only service, using analog transmission channels with circuit-switched networks. This is the first generation (1G) and is used for voice calls only by using a technology called Frequency Division Multiple Access [1]. When digital technology developed and more voice channels were required, the second generation (2G) system was lunched in the 1990s. The advantage of 2G are transmitting digital data and the launch of new services. This introduced new services are Short Message Service and low speed internet access [1]. The low data speed services provided using second generation system cannot meet the demand of users for mobile Internet access. This lead to a demand for new standards which named as third generation (3G). 3G emerged and provided faster data transmission speeds of about 2 Mbps, which was the first mobile broadband. This leads to introduce new services such as: web browsing, email, video downloading, picture sharing and other smartphone technologies [1]. After 3G, the fourth generation (4G) cellular network was launched in 2010. 4G is proposed to offer higher data rate, higher capacity, lower cost per bit and also service based on Internet Protocol [2]. It is basically optimized to offer high data rate for highly synchronized equipment's such as computer/tablet and mobile [3]. In the future, the mobile internet is expected to be widely used for machine-to-machine communication, introducing the concept of Internet-of-Things (IoT). The fifth generation (5G) is the succeeding development of mobile technology and its availability is beyond the scope of 4G use [4]. Each generation has improvements in service coverage, data speeds, and feature additions. To achieve this, different types of technologies are applied. One of them is multiple access schemes. The multiple access techniques used in 1G are frequency division multiple access (FDMA). Therefore, during user call it allocate a certain frequency for transmitting to the base station and a certain frequency for receiving from the base station. The first proposal for the 2G system is based on time division multiple access (TDMA), where each assigned spectrum is divided a time slot so that users can use the same spectrum. The modulation technique used for second generation in United States and Japan was differential phase shift keying (DPSK), while in Europe Gaussian minimum shift-keying (GMSK). TDMA is less efficient to support the high data speed channels because it needs large guard duration to improve the effect of multipath. Again, in FDMA more spectrum waste due to guards for minimizing inter-carrier interference.

And Code Division Multiple Access (CDMA) is another establish a multiple access techniques [3]. In CDMA multiple users spreading their signals over a wide spectrum through a unique code that makes many users to use the same frequency spectrum simultaneously. Code Division Multiple Access uses spread spectrum technology that spreads the spectrum of the data uniformly for the same transmitted power. Usage of CDMA increased the system capacity and the data speed which is efficient to handle the multipath channel. This allows 3G system to use Code Division Multiple Access as the multiple access scheme technology. However, fourth generation uses OFDMA for downlink and SC-FDMA for uplink instead of CDMA used in 3G systems [3]. Preceding standards used phase shift modulation techniques which improves spectral efficiency like 64-QAM used for 4G systems.

OFDM is widely known multicarrier technique and also the most employed in current standard for wireless communication which includes Third Generation Partnership Project (3GPP) LTE and Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard categories due to the associated advantages. This advantages are robustness against multipath fading by splitting the channel into subchannels, by using Cyclic Prefix (CP) it allow us to use one-tap frequency equalization efficiently, easy to implement, straightforward and easily extended to massive multiple-input multiple-output (MIMO) and beam forming high-gain solution [5] [6]. Although OFDM is the most prominent, it also has certain intrinsic drawbacks.

This drawbacks includes out-of-band leakage resulting from use of the rectangular pulse shape, spectrum efficiency loss resulting from inserting the cyclic prefix and strict synchronization in time and frequency domain is necessary to prevent subcarrier orthogonality that ensures a low level of interference between cell and within cell. Furthermore, the OFDM signal indicate a higher peak-to-average power ratio (PAPR) value which has a significant effect on the energy efficiency of the system [7]. In order to resolve these problems several alternative multiple access techniques have been recommended in the literature, namely Filter Bank Multicarrier modulation (FBMC), Universal Filter Multicarrier modulation (UFMC), filtered OFDM (f-OFDM) and Generalized Frequency Division Multiplexing (GFDM) from orthogonal multiple access and power domain and code domain based Non-orthogonal multiple access . In this thesis we provide the performance comparing and analyzing of multiple access techniques for 5G network and beyond alternatives to OFDM. Since many new multiple access schemes have been proposed, we cannot take all in to our analysis. We only choose three typical multiple access FBMC, UFMC and Power domain NOMA. Because they have received more attention from most researchers and scholars.

1.2. Review of Related Work

There are several researches conducted on the multiple access techniques performance evaluation for 5G network related. Some of them represented as follows as.

The authors in [9] conducted a comprehensive analysis and comparison of common candidate waveforms namely, OFDM, F-OFDM, OQAM F-OFDM and FBMC under a common framework with regarding to peak to average power ratio (PAPR) and bit error rate (BER). They proposed that FBMC outperform than F-OFDM in respect to PAPR, and BER which is the good 5G candidate. The presented analysis is limited to PAPR and BER aspects however, the spectral efficiency and energy efficiency aspects are not addressed.

The authors in [10] carry out performance comparison between different 5G multicarrier waveform candidate specifically, OFDM, UFMC, FBMC and GFDM respect to spectral efficiency, power spectrum efficiency, computation complexity and PAPR. They conclude that filter bank multicarrier (FBMC) is more suitable to realize requirement of 5G network than another multicarrier waveform candidate for 5G .The performance comparison was only limited between orthogonal multiple access schemes however, comparison with NOMA and energy efficiency and BER metrics are not addressed.

The authors in [11] presents the comparison and analysis of different 5G waveforms namely, UFMC and FBMC based on Offset-QAM with 4G system CP-OFDM respect to bit error rate in different channel fading. They also showed that FBMC outperform UFMC and CP-OFDM in terms of BER in different channel fading. The performance comparison and analysis was bounded on between Orthogonal multiple access and BER metrics only however, comparing waveform with NOMA schemes and spectral efficiency, energy efficiency and PAPR metrics are not addressed.

The authors in [12] carry out comparative analysis of the PD-NOMA with OFDMA techniques respect to spectral efficiency and energy efficiency. They also showed that power domain NOMA outperform OFDM respect to energy efficiency and spectral efficiency. The performance comparison was bounded on energy efficiency and spectral efficiency metrics however, comparing waveform with Power domain NOMA and BER and PAPR metrics are not addressed.

Authors in [13] conducted performance comparison of NOMA with OMA based on different power allocation strategies in respect to bit error rate and spectral efficiency. The results revealed that NOMA offers superior performance than OMA respect to spectrum efficiency whereas OMA better perform than NOMA in respect to bit error rate. This performance comparison is limited to bit error rate (BER) and spectral efficiency metrics. Another metric like energy efficiency and PAPR not investigated.

The authors in [14] presented the concept of NOMA for future wireless technology and compare performance of power domain NOMA with OFDMA .The result shows that power domain NOMA can gives enhanced spectral efficiency and best user fairness than OFDMA. These paper is limited to performance comparison in respect to spectral efficiency and user fairness however, energy efficiency, PAPR and BER metrics not addressed

The authors in [15] carryout performance analyses of power domain based NOMA under different multipath fading channels, modulation techniques and channel coding rates. It analyses performance PD-NOMA in terms of bit error rate (BER) based on AWGN, Rician and Rayleigh channel fading for different users and they identified a near-far effects in the performance of bit error rate between users. However, system level performance of BER and other metrics, namely spectral efficiency, energy efficiency and PAPR are not addressed.

As we summarize, it is clear that various research works has already been done on performance comparison on multiple access techniques for 5G network. However, in my survey the papers are done performance comparison between OMA schemes and/or between NOMA schemes in terms of different parameters. But do not clearly put performance comparison of FBMC, UFMC and PD-NOMA respect to spectral efficiency, energy efficiency, BER and PAPR.

1.3. Statement of the Problem

Wireless mobile communication systems have become more crucial in everyday life and a key factor in human and economic developments. Nowadays, most aspects of human activities are linked to mobile internet services such as multimedia streaming, entertaining, online gaming, business related activities like, mobile shopping and other modern life dependent services like, Self-driving cars. As a result, the growth of global mobile data traffic is expected to keep increasing exponentially. Therefore, efficient use of the limited available spectrum is a crucial and challenging task to meet the increasing number of connected devices and their demands on the development of next generation mobile systems.

To meet these demands, increasing the number of users that accommodated within a cell without increasing the number of Base Stations (BS), increasing data rate and improving battery life of user equipment are requirements need to be satisfied. Therefore, to fulfill these requirements it requires maximizing spectrum efficiency, minimizing power consumption and interference which lead to improved performance and capacity. For an efficient use of the limited available spectrum and improving system throughputs, several Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) schemes are under evaluation for 5G network and beyond. However, there is a lack of complete and fair comparison between these multiple access candidates. Depend on this, we are interested to analyze some candidate multiple access schemes and evaluate their performance. From the candidate multiple access techniques, we have selected FBMC and UFMC from the OMA scheme and power domain NOMA from NOMA schemes.

1.4. Objective

1.4.1. General Objective

The main objective of this thesis is to compare and analyze performance of FBMC, UFMC and PD-NOMA multiple access techniques for 5G networks and beyond.

1.4.2. Specific Objectives

- To analyze the mathematical and system model of FBMC,UFMC and PD- NOMA multiple access schemes
- To evaluate the performance of FBMC, UFMC and PD-NOMA respect to spectral efficiency, energy efficiency, BER and PAPR.
- To analyze the performance of FBMC, UFMC and PD-NOMA in terms of spectral efficiency, energy efficiency, BER and PAPR.

1.5. Methodology

In order to perform the objectives described above in the specified time, the following methodology will be followed.

- Literature review
- Design and description of systems using mathematical models
- Implementation (simulation) of the FBMC,UFMC and PD-NOMA multiple access using MATLAB
- Evaluating Performance of simulated FBMC,UFMC and PD-NOMA multiple access techniques
- Analysis comparison of FBMC, UFMC and PD-NOMA multiple access techniques.
- Finally, the conclusion of the thesis and future work are given

1.6. Scope and Limitation of the Thesis

The research areas of the next generation networks is wide and involving various researcher and companies. The area of interest is about 5G enabling technology, and more specifically about the new air interface, that is, the new multiple access. This thesis includes, description of FBMC, UFMC and PD-NOMA 5G multiple access schemes which has block diagram and mathematical analysis of these schemes. Then compare and evaluate them using performance parameters namely, spectral efficiency, energy efficiency, bit error rate and PAPR. The limitation of this thesis is simulation is carry out on two user scenarios, by considering all the assigned resource is accessed by two user.

1.7. Contribution of the Thesis

In future wireless communication systems there is some new demands such as multimedia streaming, wireless gaming, and high speed mobile internet. In order to meet these new demands in 5G, it needs to employ better performance in spectral efficiency, power efficiency and throughput multiple access to address the demands. To overcome these issues various OMA and NOMA multiples access schemes are investigated. This thesis work will provide insightful analysis in proposing better spectral efficiency, energy efficiency, BER and PAPR while comparing the three multiple access techniques. This results will be used as an input to a practical implementation of reliable and efficient multiple access for the industry

1.8. Thesis Organization

This document is organized into the following chapters. Chapter 1 Introduction: These chapter generally presents the background of thesis, objectives, literature review, methodology and scope of thesis. Chapter 2 review the fundamentals of 5G System in which background of 5G and the technologies proposed to meet requirement of 5G are reviewed. Chapters 3 and 4 present the simulation results and discussion for the comparison candidate's metrics. Finally, in Chapter 5 the conclusions and future work given.

Chapter 2

Fundamentals of 5G System

2.1. Background

Mobile communications and wireless networks are developing quickly through remarkable growth in area of mobile devices and users, mobile and radio access networks in addition to mobile applications and services. Fifth generation wireless network (5G) following the series of fourth generation (4G) and third generation (3G) standards. Since the emergence of the first 1G system, a new generation of wireless technology has been updated almost every 10th years. The development of each generation of mobile technology is to meet demand [1]. For example, the transition from 2G to 3G main objective was to meet the demands of the mobile Internet for users. Currently, the progression from 3.5G to 4G services has enabled users to obtain fast mobile data rate with less latency. This has changed the how users access and use the Internet using mobile devices [16]. Services such as self-driving cars, mobile TV, live broadcasting, mobile shopping, and online games have become important sources of income for service providers. From the perspective of resource usage, the provision of these services exceeds the capacity of 3G and 4G networks [3] [17].

Furthermore the total amount of data, the number of connected devices and data speed will continue to increase rapidly. Due to a lot of new applications beyond personal communication, the number of devices may meet tens or even hundreds of billions when 5G is implemented [5]. Unlike former generations of cellular networks, 5G systems will be required to support different types of services and newly developed applications [18]. For this reason, it is not enough to focus on increasing data throughput only. The Collaborative project is the preliminary preparation for 5G implementation and 5G standardization activities. Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society (METIS) [19], this project explains and describes 5G scenarios and provides detailed information on 5G network challenges. The fifth generation of non-orthogonal waveforms (5GNOW) [20], projects similarly focuses on non-orthogonal waveform for asynchronous signal transmission. The Physical Layer Wireless Security (PHYLAWS), CROWD project, 5G project partnership and Samsung are also another projects which works on 5G. This chapter provides 5G use cases, requirements, and enabling technologies.

2.2. Requirements of 5G and Use cases

Every time a new generation of technology is introduced, experts will come up with use cases to demonstrate the requirements for it. Similar to another generation, the 5G International Telecommunication Union (ITU) has established a 5G use case diagram; it is a triangular map that assigns an application category, namely improved mobile broadband, very large machine type communications, ultra-reliable and low-latency applications to each three corners and then graphs based on the specific application (voice, smart city, augmented reality, etc.) within the triangle based on the extent to which they share the characteristics of every category [3]. The following are the categories discussed about 5G use cases as shown in Figure 2.1.

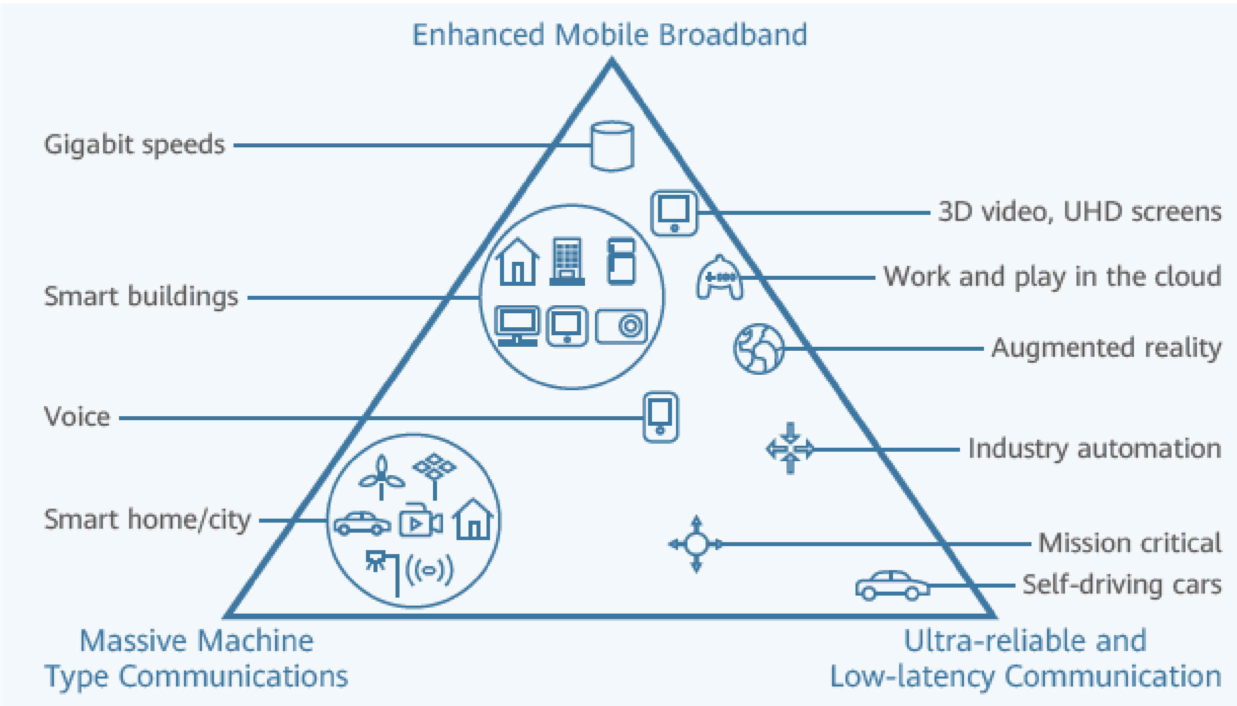


Figure 2.1: Major application categories of 5G and examples of related use cases [3]

2.2.1. Enhanced Mobile Broadband (eMBB)

One of the important use cases driving demands for 5G is mobile broadband. It goes far beyond basic mobile Internet connectivity and includes rich interactive work, media and entertainment. This is because data increases every year [21] and is expected to continue to grow in 2030. The main drivers of enhancing traffic size are increasing content size and increasing the number of applications demanding higher data speeds. Furthermore, as more devices connect to the Internet, more streaming media services (audio and video), interactive video and mobile Internet connections will continue to be used [5]. Many of these applications must always be connected to internet to send information and notifications in real time to users. There are also highly growing cloud storage and applications for mobile communication channels. This applies to both work and entertainment. Depend on these drivers, eMBB is predicted to offer peak throughput of up to 10 Gbps and up to 10,000 times the capacity of the existing network [3] [19]. The eMBB must accommodate a wider range of code rates, code lengths and modulation orders than LTE according to its requirements [22].

2.2.2. Massive Machine Type Communications (mMTC)

This scenario is being developed to provide the massive machine networks to realize the Internet of Things (IoT) at home and in business. Number of mobile devices such as mobile phones, tablets and smart watches have been exponentially increasing in the last few years and at the same time more and more applications such as video streaming/downloading, multiplayer gaming which requires a large bandwidth are emerging [22]. Also, smart cities and smart homes usually called as smart societies will be combined with a lot of wireless sensor networks. Most of house equipment's, such as refrigerators, ovens and heating systems have been designed as "smart devices" that interconnected to other devices through the Internet. Many of these services typically require the transfer of small amounts of data between devices on large networks. The networks like this, known as IoT are growing by interconnecting different types of equipment's in house as well as industrial environment. The industrial experts predicts that by 2020, up to 50 billion potential IoT devices in operation [22]. In this type of systems lower energy consumption, low-price, the capability to operate a massive number of connectivity and good scalability are required [22]. The mission of 5G is to incorporate the management of this different connected devices.

2.2.3. Ultra-Reliable Low-Latency Communications (URLLC)

In this use case, requirements for capability such as throughput, latency and availability are vital. This category includes new services that will transform industries with ultra-reliable / available low-latency links, such as remote control of critical infrastructure, self-driving vehicles, smart-grid control, industrial automation, drone control and coordination, and so on [3]. In industrial automation, mobile and wireless communications are highly important for industrial applications. Cable installation and maintenance costs are high and the ability to replace cables by reconfigurable wireless links is a great opportunity for a lot of industry. On the other hand, to achieve these, the operating delay, reliability, and capacity of the wireless connection are similar as cable and its management should be simplified.

A smart grid is another network which require low latency transmission. The smart grid interconnects sensors that use digital information to automatically consume and distribute energy, including natural gas and heating. Lower latency with extremely lower error rate are new requirements that 5G networks must address [23]

2.2.4. Fixed Wireless Networks

One of the key use cases for fifth generation could be fixed wireless access. Fixed wireless connections will provide Internet access for home that use wireless network technology rather than of fixed lines. This can be focused on serve remote thinly populated area affected by low data speed and unreliable solutions [24]. The superior performance of 5G network is also predicted to be sufficient to offer broadband Internet access in less populated area which have not yet been covered by wired technologies, like Asymmetric Digital Subscriber Line (ADSL) and optical fiber. In this case, the mobility of the network equipment will be very low, so the Doppler effects is insignificant, and latency is not a crucial requirement [22].

The use cases and vision of 5G systems have led to requirements that necessity be met by future mobile broadband systems. The following are some requirements for 5G wireless networks [3][26]:

- Peak Spectral efficiency:

The Peak spectral efficiency is the maximum ideally achievable data speed that can be allocated to a particular mobile station under the assumption of error-free conditions whenever all the radio resources that can be allocated are totally used for the corresponding link. The maximum spectrum efficiency target for the downlink should be 30bps/Hz, and for the uplink 15bps/Hz. A higher frequency band may have a higher bandwidth but lower spectral efficiency and a lower frequency band may have a lower bandwidth but higher spectral efficiency.

- High data speed

In fact, the higher date rate requirements of 5G technology will allow for fast data transmission. Whereas 4G offers a highest data rate of 100 Mbps, 5G is predicted to offer speeds of 1 Gbps to 10 Gbps, which mean that compared to 4G, it is a hundred times higher speed than current 4G. For example, it can take 10 minutes to download an HD video with current 4G LTE technology, while using 5G technology can take just seconds.

- High Capacity:

To support the highly increasing of mobile data traffic in the future, 5G wireless access networks must be able to enhance system capacity by making more user to access the same frequency band, adding more cells in the target area and in generally by improving bandwidth efficiency, which is expected to reach 10 Mbps/m2.

- Energy Efficiency:

The developing of 5G wireless access technology must focus on most energy efficiency rather than increasing device or network. This is due to energy consumption needed for 5G wireless communication is 100 times higher than that of 4G.

- Massive Connectivity:

The difference among 5G and 4G is that 5G is developed to accommodate different kinds of traffic, not just one type of traffic. At the same time, each traffic type will have different requirements. It is expected that, using 5G billions of machines and sensors will be connected to the network [26]. Mainly, billions of devices can be connected at a scale not seen before without human intervention. Mobile activities that need to be buffered on the 4G mobile network will happen almost immediately on the 5G mobile network, which mean that the Internet of Things is expected to make to a significant growth in the number of connections/devices on the wireless network (massive Internet of Things). Massive Internet of Things refers to a large number of Internet of Things devices and sensors that communicate with each other and generally transmit data that is not sensitive to delays. To accommodate devices with long battery life and low data rates, the huge Internet of Things must have high coverage and density [27]. Classic applications like sensors that support smart homes, smart logistics etc.

Table 2.1 The key requirements and corresponding application for 5G [8]

Requirements	Desired Value	Application example
Data Rate	1 to 10 Gbps	Virtual reality office
Data Volume	9 Gbyte/hour in busy period 500 Gbyte/month/subscriber	Stadium Dense urban information society
Latency	Less than 5 ms	Traffic efficiency and safety
Battery Life	One decade	Massive deployment of sensors and actuators
Connected devices	300000 devices per AP	Massive deployment of sensors and actuators
Reliability	99.999%	Teleprotection in smart grid network Traffic efficiency and safety

2.3. 5G Enabling Technologies

There are technologies being developed to improve all the requirements identified in the above section, both as part of an evolution of LTE, and to enable new 5G networks. As discussed in different papers [22] [24], in order to cater for the requirements of, 5G needs to achieve significant enhancements in addition to existing technologies. Some of the main technologies under research to achieve the data rate and capacity for 5G are:

2.3.1. Massive Multiple Input Multiple Output

A significance of the powerful signal processing enabled by the large number of antennas at the transmitter and/or receiver to enhance wireless communication link performance. This class of techniques, known as multiple input, multiple output (MIMO), used to multiply the capacity of a wireless connection without requiring more spectrum. MIMO methods can improve mobile communication in two different ways: by boosting the overall data rates and by increasing the reliability of the communication link.

The MIMO algorithms used in LTE standards can be divided into four broad categories: receive diversity, transmit diversity, beamforming, and spatial multiplexing. In transmit diversity and beamforming, transmit redundant information on different antennas. As such, these methods do not contribute to any boost in the achievable data rates but rather make the communication link more robust. In spatial multiplexing, however, the system transmits independent information on different antennas [16]. In LTE and LTE-A standards, MIMO technique became extended from point-to point to multi-user application with multi-user MIMO (MU-MIMO). MU-MIMO used to separate users by their spatial position, which can substantially boost the data rate, allowing for further network densification and increased capacity.

Fundamentally constructing from current MIMO, a new generation of large antenna array techniques commonly referred to as "massive MIMO", where the number of base station antennas has improved significantly by order of magnitude when compared to the current MIMO system. Currently, it has not been determined how many antennas a system must have in order to be considered as massive MIMO but systems with more than 8x8 antennas are usually considered as massive MIMO systems [22]. Today, massive MIMO has acquire important momentum as a good candidate for increasing the capacity of multi-user networks. Massive MIMO anticipates huge benefits in respect to spectral efficiency, energy efficiency and network interference reduction, all of which are crucial to meeting increasingly valuable data-centric world power and spectrum needs [28]. The basic concept of Massive MIMO is that the base station uses M antennas to spatially multiplex K single antenna terminals, where K << M. The multiplexing takes the form of beamforming also named as multiuser precoding, which effectively creates the transmitted signals, these signals are added up constructively at the terminal location and destructively at almost all another locations, as shown in Figure 2.2.

The success of this spatial multiplexing in the uplink and downlink is based on some important ideas. One of the very significant concepts is that the base station should have good knowledge of the transmission channels in both directions based on effective downlink precoders and uplink detectors.

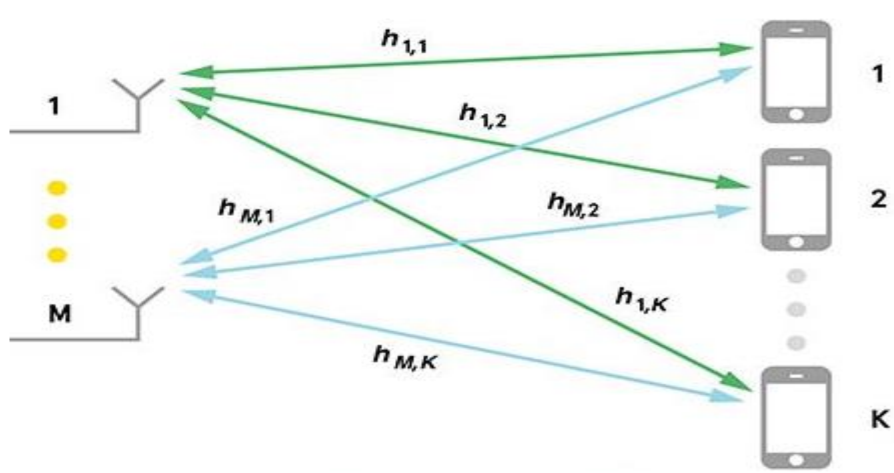


Figure 2.2: Simplified multi-user Massive MIMO system [28].

Time division duplex operation help to obtain accurate instantaneous channel state information (CSI) at the base station and pilot waveforms are transmitted by terminal. On the uplink, the terminal transmits the pilots and payload then on the downlink the base station beamforms to the terminals. The reciprocity of downlink and uplink transmission is important for the use of uplink channel state information for downlink precoding and is attained in practice by calibrating the radio frequency (RF) chain. Even in high-speed mobile scenarios, confidence in reciprocity can achieve accurate channel training [22] [26].

2.3.2. Millimeter Wave Mobile Communications (mmWave)

Some technological trends provide new opportunities for synergy to meet the very high bandwidth requirement of 5G wireless technology. One of them is millimeter wave (mmWave) communication, which uses a higher frequency than the radio waves that have been used for mobile phones for a long time. They are called millimeter waves because their wavelength range from 1 millimeter to 10 millimeters, while the length of radio waves used in today's smartphones is tens of centimeters. Fourth generation (4G) technology currently uses a lower frequency spectrum (usually less 1GHz) to transmit data at high speeds. Millimeter waves are transmitted at frequencies between 30 and 300 GHz, which can transmit large amounts of data at very high speeds and very short delays [22].

In the past, satellite and radar system operators used millimeter waves. Today, these frequency bands have received a lot of attention because some cellular service providers use them to send data between fixed points for short-range wireless technology, such as IEEE 802.11 ad wireless gigabit (WiGig) technology standards and wireless high-definition (HD) video transmission [24]. WiGig technologies operates on the 60 GHz frequency band, enabling device to communicates over short distances at higher data rate of up to 8 Gbits/s. However, the use of millimeter wave to connect mobile users to neighboring base station is a totally new techniques which is proposed for 5G network [20].

With many advantages such as high spectrum (for higher data transmission), higher resolution, low interference, good for deployment smaller cell, a larger number of antennas are packaged in a small area. Some of the challenging problems of millimeter wave are higher path loss, high rain attenuation and higher energy consumption. It is predicted that 5G wireless networks will be driven by a large amount of spectrum, higher coverage throughput enabling with very short wavelength allowing a huge number of micro-antennas to be installed in a particular area of millimeter-wave band equipment.

2.3.3. New Air Interfaces

Application requirements for different air interface technologies is complex and diverse, a unified new air interface with flexibility and adaptability is proposed to meet these requirements. New air interface consists of building blocks and configuration mechanisms such as adaptive waveform, adaptive protocols, adaptive frame structure, adaptive coding and modulation family and adaptive multiple access schemes. With these blocks and mechanisms, the air interface is able to accommodate wide variety of user services, spectrum bands and traffic levels [22]. The new air interface design can effectively improve spectral efficiency, increase connectivity, and reduce latency, thus facilitating the deployment of customized scenarios applied to the IoT and for high bandwidth-consuming scenarios such as virtual reality [23]. Huawei summarized the new air interface design in follow figure:

Figure 2.3: New air interface components [23]

One of adaptive channel coding is Polar code. Polar codes are a major breakthrough in coding theory. As described by [23], they can achieve Shannon capacity with a simple encoder and a simple successive cancellation (SC) decoder when the code block size is large enough. Beside this, Full-Duplex is one of duplex mode envisage technology for 5G. Which breaks the barrier of today's communications by supporting bi-directional communications without time or frequency duplex. By transmitting and receiving at the same time and on the same frequency, Full-Duplex has the potential to double the system capacity and reduce the system delay [23]. New multiple access technology includes both orthogonal and non-orthogonal multiple accessing are other enabling technology for 5G network. These are discussed as follow.

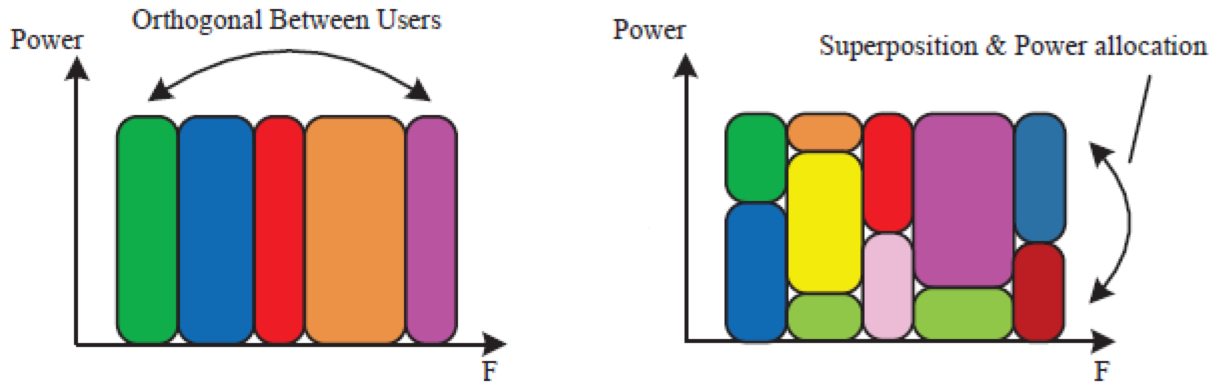


Figure 2.4: OMA and power domain-NOMA multiplexing [29]

- **Orthogonal multiple access (OMA)**

OMA is core to all previous and current wireless networks. For these systems, resource blocks are orthogonally divided in time, frequency, or code domains, and therefore there is minimal interference among adjacent blocks and makes signal detection relatively simple. For 5G OMA is proposed with new modulation schemes as enabling technologies. There are various types of modulation techniques for OMA, which are based on different principles, including pulse shaping, subband filtering, precoding, guard interval (GI) shortening, and mapping symbols in the delay-Doppler domain [30].

Modulation based on pulse shaping includes FBMC and GFDM, which are working with subcarrier-based filtering. Generally, modulations based on pulse shaping try to restrict transmit signals within a narrow bandwidth and thus mitigate the OoB leakage so that they can work in asynchronous scenarios with a narrow guard band. This is proposed as effective mechanism to reduce OoB leakage [22].

In the second technique, modulation based on subband filtering includes UFMC and f-OFDM. Which can effectively reduce OOB leakage and achieve better performance. Additional to pulse shaping and subband filtering there are also some other techniques proposed to suppress the OOB leakage and meet the requirements of 5G networks. Guard interval discrete Fourier transform spread OFDM (GI DFT-s-OFDM), spectrally-precoded OFDM (SP-OFDM), and orthogonal time frequency and space (OTFS) [22] are typical modulations.

- **Non-orthogonal multiple access (NOMA)**

To support a massive number of and dramatically different classes of users and applications in 5G networks, various NOMA schemes have been proposed. NOMA is to utilize power and/or code domains in multiplexing to support more users in the same resource block. Three major types of

NOMA are proposed power-domain NOMA, code-domain NOMA, and NOMA multiplexing in multiple domains which are considered as a promising MA scheme for 5G networks [30]. Power-domain NOMA supports multiple users within the same time/frequency/code resource block by distinguishing them with different power levels. Whereas, code-domain NOMA can support multiple transmissions within the same time-frequency resource block by assigning different codes to different users. Rather than multiplexing signal in single domain, some have been proposed to multiplexing in multiple domains, such as the power domain, the code domain, and the spatial domain. This types are called NOMA multiplexing in multiple domains [30].

This thesis work is concentrate on the enabling technology of 5G, which is the new air interface particularly the multiple access techniques. From the candidate waveform techniques mentioned above, we selected UFMC and FBMC to compare their performance to the PD-NOMA nominated from NOMA. There is a detailed discussion of FBMC, UFMC and power domain NOMA techniques in this section, including their basic working principle, system block diagram and mathematical formulation.

2.4. Filter Bank Multicarrier (FBMC)

Multicarrier modulation is default choice for high data rate wireless communication. In multicarrier modulation system available channel bandwidth is efficiently subdivided into several sub-channels; each has its associated subcarrier. In present scenario, most commonly used multicarrier modulation technique is orthogonal frequency division multiplexing (OFDM). Even though OFDM has numerous advantages it has certain shortcomings.

Orthogonal Frequency Division Multiplexing (OFDM) using cyclic prefix is the most common techniques out of all multi-carrier waveforms and it has the advantages of simplicity and robustness against multipath fading by use of cyclic prefixes. However, it uses a cyclic prefix (CP), which occupies a certain amount of available spectrum, resulting in a loss of spectral efficiency and uses rectangular prototype filters and IFFT/FFT blocks, which causes low frequency sub-channel selectivity. In addition, Orthogonal Frequency Division Multiplexing (OFDM) uses rectangular windows to shape symbol in the time domain, resulting in large sidelobe power, sensitive to frequency offset, higher Peak to Average Power Ratio (PAPR). This large sidelobe level of OFDM takes us to allocate null subcarriers between subcarriers which carries information in order to avoid overlapping with adjacent subcarriers, which results the loss of spectral efficiency too. In order to overcome these disadvantages, Filter bank Multi-carrier (FBMC) has been candidate as an alternative OFDM techniques [33]. FBMC does not requirement to insert any guard interval between symbols to mitigate intersymbol interference. In addition, since it employs a frequency well-localized pulse shaping, therefore it offers a greater spectral efficiency [34] [35]. OFDM unable to satisfy the technical demands of multi-carrier multiple access communication in 5G multi-application scenario. The FBMC techniques can be classified as three families of multicarrier modulation techniques as follows:

I. Filtered Multitone (FMT):

FMT is form of FBMC, which subcarriers are separated by guard bands in between; this result for waste of bandwidth. To resolve inter channel interference it applies well designed filter [6]. As opposed to the OFDM, in FBMC-FMT the subcarrier channels have no overlapping of adjacent subcarrier bands and thus is less bandwidth efficient than the OFDM method. However, it does not require the guard interval like in OFDM [6], hence, improving the overall energy efficiency. As FBMC base on FMT has no overlap among subcarriers, it is based on the conventional frequency division multiplexing (FDM).

II. Cosine-Modulated Multitone (CMT):

This mode is the early FBMC modulation technology in the field of digital subscriber line (DSL) field of wireless applications recently. CMT system in which a parallel set of data symbols with pulse amplitude modulation (PAM) are transmitted, i.e., symbols constellation only has real part. Moreover, the PAM symbol sequences are passed through a filter bank with spectral overlap. Thus, the constraints in the filter design are smaller. To achieve the maximum bandwidth efficiency of the system, vestigial side-band (VSB) modulation is applied to each subcarrier. The cosine modulated filter bank, which has a high bandwidth efficiency and also a blind detection capability. However, a 90-degree phase shift is introduced to the adjacent subcarriers [30].

III. Staggered Multitone (SMT):

Staggered Multitone or more commonly known as offset QAM (OQAM) is another filter bank multi-carrier which is very similar to the Cosine-Modulated multi-tone types, but has some advantages. SMT consists of transmitting a group of complex-valued data symbols (QAM symbols) .These real and imaginary part of complex symbols are split and time staggered by half of the symbol period to generate OQAM symbols. OQAM symbols are transmitted in OQAM based FBMC instead of QAM.

Data symbols are $T/_2$ spaced in time domain and subcarriers are $1/_T$ spaced on the frequency axis. Therefore, in SMT the symbol rate can be increased by multiple of 2 and the symbol spacing can be reduced by half. Related to CMT and FMT, SMT has the good stop-band attenuation for given filter length and number of subchannels [37]. Since the FMT type does not attain maximum spectral efficiency [37]. In this thesis work, we are more attracted in OQAM-FBMC that overlap subcarriers in frequency domain and provides good spectral efficiency and has other benefits like low side lobe spectral leakage, no need of cyclic prefix, no strict synchronization and efficient realization technology through polyphase filter structure.

2.4.1. Working Principle of FBMC-OQAM System

The filter bank based multicarrier (FBMC) transmission introduces filter bank to the OFDM system and discard the cyclic prefix in order to improve flexibility of the system to deal with some limitations of OFDM. Filter bank can be designed with different properties to satisfy the communication requirement such as to reduce the sideband power loss and increase spectral efficiency. There are two types of FBMC implementations, the frequency spreading filter bank multicarrier (FS-FBMC) and the poly-phase network filter bank multicarrier (PPN-FBMC). The FBMC system block diagrams of the two implementations are as shown in Figure 2.5 and Figure 2.6. In frequency spreading filter bank multi-carrier, filtering operation performed on OQAM symbol in the frequency domain. Then feed the results to IFFT and perform KN point IFFT operation and then perform superposition and overlap operations [6]. Where K is the overlap factor for prototype filters. At receiver end, a sliding window selects KN points in every sample. Then apply the FFT size of the KN point and then perform equalization and filtering through the prototype filter. On the other hand, for PPN-FBMC, the OQAM symbols are fed to the N-point IFFT and then fed to the polyphase network for filtering. At receiver side, it performs filtering before N-point FFT and makes multi-tap equalization on a sub-carrier basis [37].

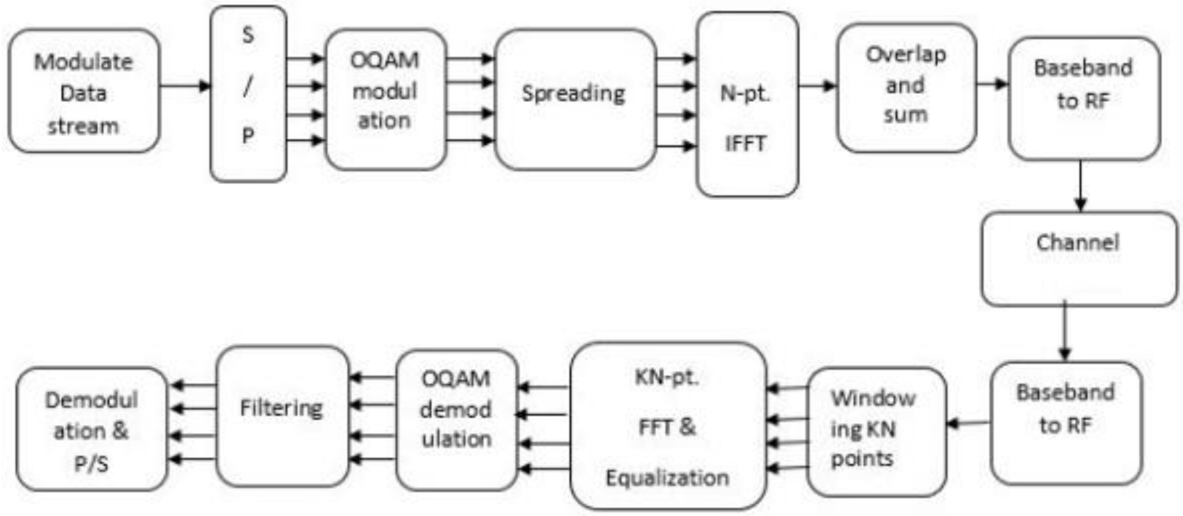


Figure 2.5: Block diagram of FS-FBMC [30].

The main processing blocks in polyphase network based FBMC are OQAM pre-processing, filter bank and OQAM post-processing. In FBMC, there is a systems which includes a set of filters that process the same inputs or results into the same outputs known as filter bank. There are two main kinds of filter bank, analysis filter banks and synthesis filter banks. Analysis filter bank (AFB) is applied to analyze the input signals based on the feature of each filter. Synthesis filter bank (SFB) is applied to filter the independent signals and sum-up an each signal to obtain a new combined composite signal. SFB and AFB realized through IFFT after that polyphase network structure and a polyphase network after that an FFT respectively.

At transmitter side the particular working principle of the FBMC-OQAM systems are in this way. Firstly, serial high-speed serial data stream converted in to parallel stream by serial to parallel converter and OQAM is employed to modulate symbol. The aim of OQAM preprocessor is to maintain orthogonality among subchannels. Then perform the IFFT operation on the transmit symbol. Secondly, using the polyphase network (PPN) perform the filtering operation after the iFFT. Mainly, the filter bank enable you to control the frequency response of the transmitted signals. Therefore, various mechanism are suggested for filter design. In this thesis work, we chose the filter suggested by the "Physical layer for dynamic spectrum access (PHYDYAS)" project, because it has a better localization and simpler equalization in the transmitter and receiver side [6]. The N-subcarrier filter is designed using complex modulation. This means that all other subcarrier filters can be found by the frequency shifted version of the prototype. Finally, the synthesized time-domain signal is superimposed and sent. In FBMC-OQAM systems, a prototype filters with superior time-frequency performance is applied, with better spectrum efficiency and good frequency domain out-of-band suppressing [6]. The developed prototype filter is a "PHYDYAS filter bank," h (t) is symmetrical and fulfills the near perfect reconstruction NPR conditions in the actual channel. The length of the filter is equal to $M(K - 1/2)$, K is the overlap factor of the prototype filters and M is the number of subchannels in the system [6].

The factor K or the overlap factor is referred as the number of symbol overlapped in the time domain. Whereas, in the frequency domain, K is referred as the number of frequency coefficient put in among the FFT inputs. K is an integer greater than one, however it is equal to 1 for a rectangular filter. The main idea in [6] is to perform the frequency-sampling technique to develop the Nyquist filters. The transmit filters is depend on a developed prototype filter $PT(t)$ and is modulated by carrier frequency $\boldsymbol{f_n}$. The basis pulse $h_n(t)$ is, a time and frequency shifted versions of the prototype filter $PT(t)$[6].

$$h_n(t) = PT(t)e^{j2\pi n\Delta f t + j\emptyset_n} \quad (2.1)$$

Where $PT(t)$ is low pass filters known as prototype filter using length of KN, Δf is subcarrier spacing and $\emptyset_n$ is phase difference. Hence, the impulse response of the filter is given by[6]

$$h(t) = 1+2\sum_{k=1}^{K-1} H_K{}^2 \cos\left(2\pi \frac{Kt}{KT}\right) \quad (2.2)$$

The frequency response definition related to the transceiver prototype filters is as follows [6]:

$$H(f) = 1 + 2\sum_{k=-(K-1)}^{K-1} H_k{}^2 \frac{\sin\left(\pi\left(f-\frac{k}{MK}\right)MK\right)}{MK\sin\left(\pi\left(f-\frac{k}{MK}\right)\right)} \quad (2.3)$$

Where:- T : the sampling period

M : the number of subchannel

H_k : the coefficient of the prototype filter

K: overlapping factor

The frequency domain coefficients of PHYDYAS with the overlapping factor $K = 4$ are.

$H_0 = 1$; $H_{\pm 1} = 09716$; $H_{\pm 2} = \frac{\sqrt{2}}{2}$; $H_{\pm 3} = 0.235147$

And they fulfill the equation

$$\frac{1}{K}\sum_{K=-k+1}^{K-1}|H_K|^2 = 1$$

The baseband signal processing at the transmitter side is presented in Figure 2.6.

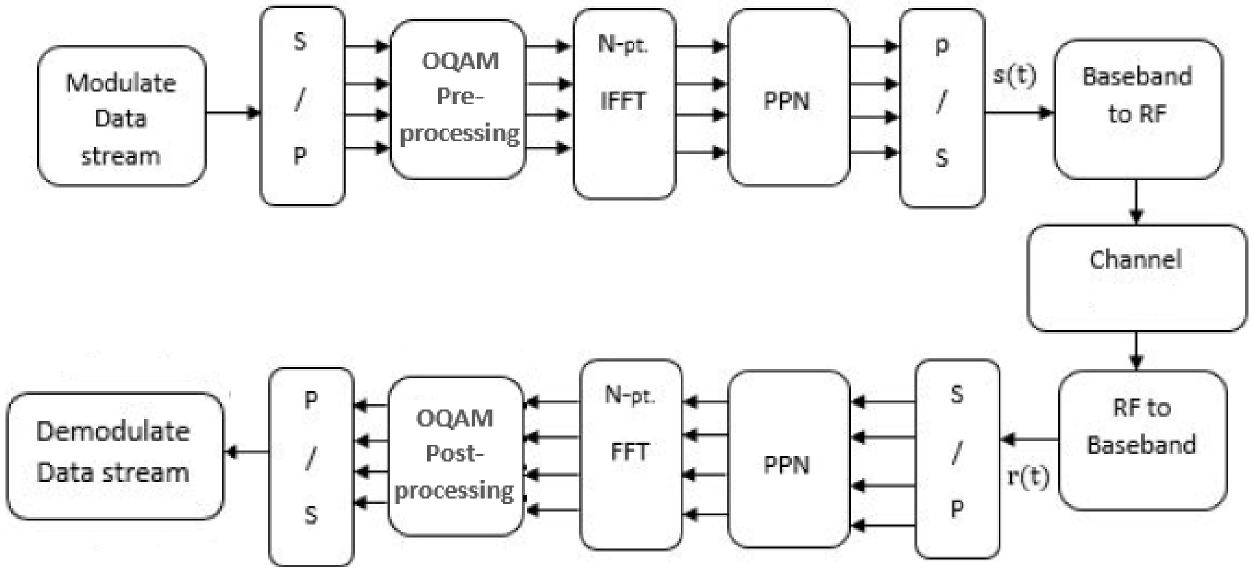


Figure 2.6: Block diagram of PPN-FBMC [30].

In the FBMC systems, any type of modulation can be used as long as the subchannels are differentiated. For instance, if only subchannels having even or odd indices are used, there is no overlap and QAM modulation can be adopted. On the other hand, if seek full rate, total subchannels must be used and particular modulation is required to handle the frequency domain overlap of adjacent subchannels.

Due to the overlap of adjacent subchannels, orthogonality is required. It is attained through applying the real parts of the iFFT input through even index and the imaginary parts of the iFFT input through odd index. However, this means that the capacity has been reduced by a factor of 2.

Therefore, the approach to meet full capacity is as follows: increase the symbol rate by factor 2 and for every subchannel use alternatively the real and the imaginary part of the iFFT. In this manner, the real and imaginary parts of complex data symbols will not be transmitted at the same time as in OFDM, however the imaginary parts is delayed for half the period of the symbol. The unit of time is half the inverse of the sub-channel spacing, which is T / 2

This is known as offset quadrature amplitude modulation (OQAM) and the term ‘offset’ indicates the time shift of half the inverse of the symbol duration (T) among the real parts and the imaginary parts of a complex symbols as shown in Figure 2.7. Note that this kind of modulation is used in single carrier of systems, to enhance the peak factor. In the current multi-carrier framework, the throughput is the equal with QAM as used in OFDM systems, however there is no guard time inserted between symbols [38].

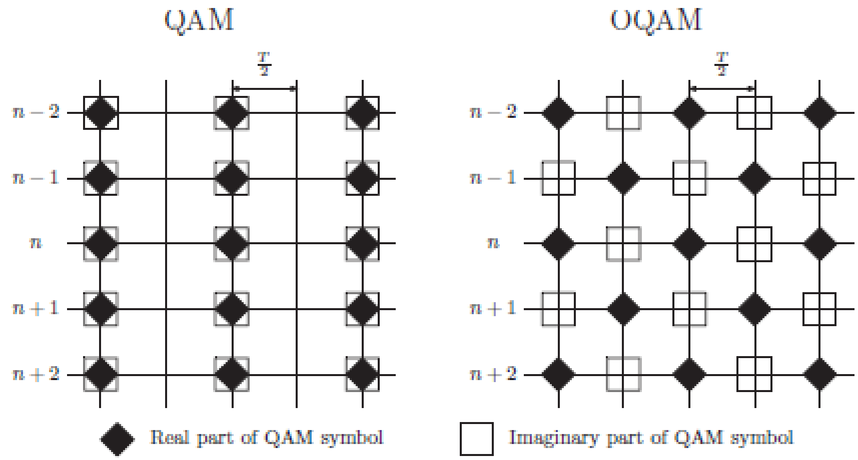


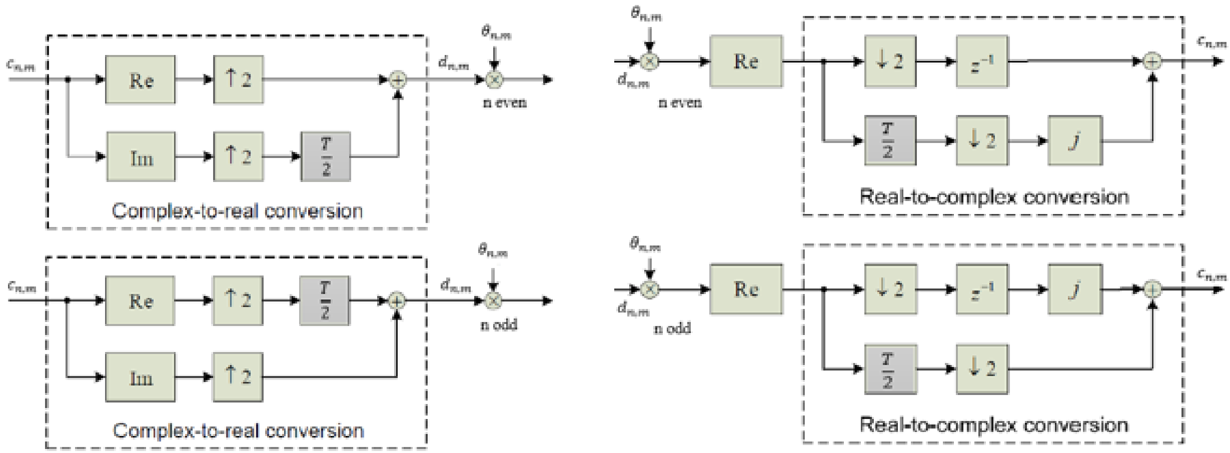
Figure 2.7: FBMC/OQAM symbol mapping on subcarriers [38].

The basic difference between OQAM based FBMC and FBMC is the transmission of Offset-QAM data symbols instead of QAM symbols. OQAM combined with the Nyquist constraint of the prototype filters is applied to ensure the orthogonality among neighbor symbols and neighbor subcarriers, while offering better spectral efficiency [38]. This process is performed by the OQAM pre- processing and OQAM post-processing block, as seen in Figure 2.8.

The QAM complex symbols are staggered and transformed to two real symbol through OQAM preprocessing. Let us assume the input QAM complex symbols are $C_{n,m}$.The real and imaginary part are complex symbols are separated to make two new symbols $d_{n,2m}$ and $d_{n,2m+1}$. And the next operation is multiplying by $\theta_{n,m}$. As shown in [6], the value of $\theta_{n,m}$ have different values for the different index of subchannels. The conversion is different for even and odd index of sub-channels.

$$d_{n,2m} = \begin{Bmatrix} Re[C_{n,m}]\,; & n\ even \\ IM[C_{n,m}]\,; & n\ odd \end{Bmatrix} \qquad d_{n,2m+1} = \begin{Bmatrix} IM[C_{n,m}]\,; & n\ even \\ Re[C_{n,m}]\,; & n\ odd \end{Bmatrix}$$

As mentioned above, a complex number symbol $C_{n,m}$, is splits into two real number symbols, one corresponding to the real parts and the other corresponding to the imaginary parts. Therefore the complex-to-real conversion makes the sample rate double.



(a) OQAM Pre-processor (b) OQAM Post-processor

Figure 2.8: The OQAM symbols modulation and demodulation process [34].

2.4.2. Mathematical Model of FBMC-OQAM

Let the signal of the transmitter is denoted [30] as:

$$a_{m,n} = a_{n,m}^{R} + ja_{n,m}^{I} \tag{2.4}$$

Where $a_{n,m}^{R}$ and $a_{n,m}^{\mathrm{I}}$ represents the real parts and the imaginary parts of the **n**th sub-carrier and the **m**th symbol, respectively. The real parts and imaginary parts of complex symbols for FBMC-OQAM signals are orthogonal at T/2, whereas T is the duration of transmitted signal

For simplicity, we only consider the baseband signal and ignore the radio frequency (RF) chain. The baseband transmitted signal for FBMC can be general expressed [30] as

$$s(t) = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} a_{n,m} g_{n.m}(t) \tag{2.5}$$

Where $\boldsymbol{a_{n,m}}$ the complex symbol is modulated by the $\mathbf{n^{th}}$ subcarrier during the symbol time index **m**, and $g_n(t)$ denote the synthesis basis which given [34] as

$$g_{n,m}(t) = h\left(t - \frac{mT}{2}\right) e^{\frac{j2\pi n}{T}t} e^{j\varphi m,n} \tag{2.6}$$

Where $g_{n,m}(t)$ is prototype filter with length of KN, $\boldsymbol{T}$ is QAM symbol period and $\boldsymbol{\varphi m, n} = \frac{\boldsymbol{\pi}}{\boldsymbol{2}}(n+m)$ is phase difference. Whereas K is the overlapping factor for prototype filters and N is number of subcarriers. For OQAM-FBMC the symbol period is decreased by half $T = \frac{\boldsymbol{T}}{2}$ where **T** is QAM symbol duration.

In conclusion, FBMC-OQAM baseband modulated signal can be expressed [30] as:

$$s(t) = \sum_{m=0} \sum_{n=0}^{N-1} \{ a_{n,m}^{R} g_{n,2m}(t) + a_{n,m}^{I} g_{n,2m+1}(t) \} \tag{2.7}$$

Where $\boldsymbol{a_{n,m}^{R}}$ and $\boldsymbol{a_{n,m}^{I}}$ are the real and imaginary part of $\boldsymbol{a_{n,m}}$ that transmitted through the subcarrier index of **n** during symbol time of index **m**.

On the receiving side of the FBMC-OQAM systems. A prototype filter set is also used, the performance is the same as the prototype filter bank at transmitter side and is symmetrical. First, the incoming signal is filtered by a filter bank prototype with different offset. Then restore the original signal through FFT and OQAM post-processor. OQAM post-processing function is taking the real part of the modulation signal from the subchannel and reconstructing the real number signal into a complex number signal by mutual conversion between the real parts and the complex parts.

To avoid inter-symbol interference and maintain orthogonality, the data symbols $\mathbf{d_{m,n}}$ must be phase adjusted using the phase terms $\boldsymbol{e^{j\varphi_{m,n}}}$**.** Therefore, every symbol it has a= $\pm\frac{\pi}{2}$ phase difference with neighboring symbol in time and frequency.

2.5. Universal Filtered Multicarrier (UFMC)

Universal Filtered Multi-Carrier (UFMC) is a promise candidate waveform for future wireless communication. It is also called unified filtering OFDM (UF-OFDM). UFMC is a multi-carrier waveforms which proposed by the 5GNOW research projects financed by the European Union [39] [40]. The UFMC techniques is designed according to the concept of frequency division multiplexing (FDM) in which it divides the incoming high data rate stream into different lower-rate sub-streams. As described in [41] UFMC is a kind of sub-band filtering based waveform, where a filtering operation is employed to a set of consecutive subcarriers, instead of filtering each sub-carrier individually used in FBMC.

Compared to the FBMC filter, the prototype UFMC filter has a significantly shorter duration. Generally, the duration is the same as that of the cyclic prefix employed in OFDM, while for FBMC filter, the length is a multiple of the data blocks, and therefore it is longer [41]

2.5.1. Working Principle of UFMC System

The system model of UFMC is represented in Figure 2.10. In this techniques, the entire spectrum is firstly divided into a number of sub-bands and number of subcarriers is assigned to subband.

Every sub-band has k subcarriers. The entire bit stream is grouped into B sub-bands. These grouped bits are modulated using the QAM modulation format then converted to a parallel stream using a serial-to-parallel converter. The frequency block B carries the subcarriers converted from the frequency domains into time domains through the IFFT block. This subband signal is then filtered by the filter length L, as shown in Figure 2.9. Filtering results in a significant reduction in out-of-band emission in the frequency domain. This reduces interference from neighboring subcarriers in resource blocks, through reducing out-of-band emissions.

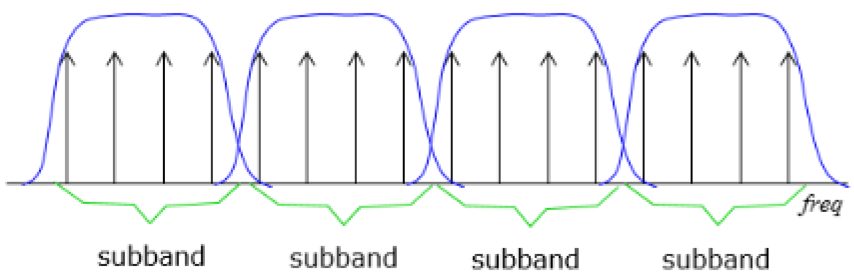


Figure 2.9: Subband Filtering [41]

In Universal filter bank multicarrier, we assume Dolph-Chebysheve filter used in [42], which proposes the method for developing UFMC. The length of filter depend on the size of sub-band which is the number of subcarriers in sub-band. The Chebyshev window minimize the main-lobe width, given a specific sidelobe height. It is characterized by an equiripple behavior, that is, it's all sidelobes have equal height. The results in a UFMC symbol length of N + L - 1 samples because of the linear convolution between outputs from IFFT.

In some early papers [43], the zero padded guard intervals were not used. This will reduces the performance in multi-path fading since the time dispersion of the channel cannot be reduced [45]. In another paper [44], there is block with an extra zero padded (ZP) of length L-1. A zero-padded is introduced in every UFMC block to handle the time dispersion. This adds some extra time overhead compared to OFDM, therefore enable use one-tap frequency domain equalizer (FDE) to perfectly mitigate channel time dispersion.

Lastly, the time-domain filtered data in all frequency block is summed to form a UFMC waveform. Therefore, compared to OFDM that performs a single joint IFFT by combining all subband blocks, it is necessary to perform a separate IFFT operation for each subband block and perform windowing to suppress interference. At the receiving end, after serial-to-parallel convertor, a 2N-point FFT must be used to demodulate every UFMC symbol [30].

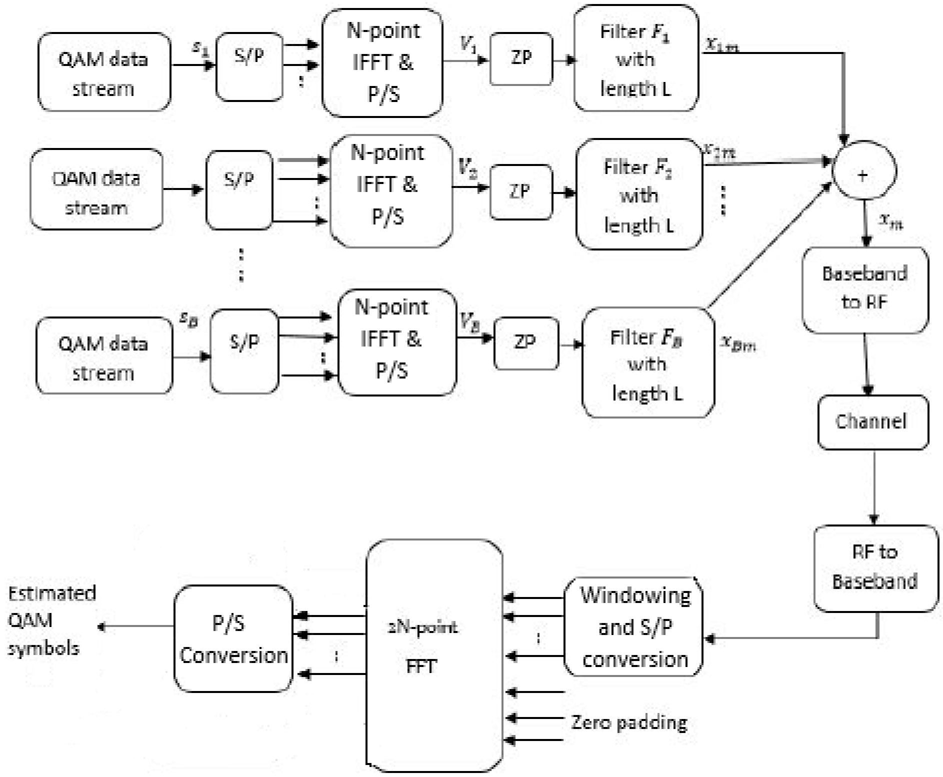


Figure 2.10: Block diagram of UFMC system [40].

2.5.2. Mathematical Model of UFMC

Let consider that the UFMC system transmit signal consists of N subcarrier and is divided into B sub-bands. Each sub-bands consist of $C = \frac{N}{B}$ subcarriers. Then each subband is filtered through a subband filter with length L and response from the all subband are summed.

For UFMC the filter we chosen for every sub-bands $\boldsymbol{i}$ is Dolph-Chebyshev with prototype filters $f_i(m)$ which is expressed [42] by:

$$f_i(m) = \frac{\cos\left(L\cos^{-1}\left[\beta\cos\left(\frac{\pi l}{L}\right)\right]\right)}{\cosh[L\cosh^{-1}(\beta)]} \quad , l = 0,1,2, \dots . L-1 \tag{2.8}$$

Where $$\beta = \cosh\left[\frac{1}{L}\cosh^{-1}(10^{\alpha})\right], \ \alpha = 2,3,4 \tag{2.9}$$

Where α represent the attenuation of side lobe. The side-lobe suppressing now applied between resource blocks, instead of among subcarriers. The symbol duration of N+L-1 samples is produced by the filter length and the FFT size. The input of the UFMC waveform generator block is a group of constellation QAM mapped symbols S. The S number of symbols are allocated into subband blocks B, whereas each subband blocks is made up of **C** subcarriers. If B are number of subband blocks then, this B data vector are processed using IFFT sub matrix respectively. The time-domain signal $v_i(n)$ of the i^{th} subband before filtering is attained through parallel to serial convertor (P/S) and N-point IFFT of $s_i(1)$. Vector $s_i(1)$ is the C ×1 array of QAM symbol loading subband $\boldsymbol{i}$ at time l [45]. For every block of N QAM symbols, add the filtered signals of every subband to get a discrete baseband UFMC signals, which is converted to the analog domain and transmitted in the RF, which is given [45]as

$$x(m) = \sum_{i=0}^{B-1} \sum_{n=0}^{L-1} v_i(n) f_i(m-n) \qquad (2.10)$$

Where: m = 0, 1,…, $N + L - 1$ samples

$$v_i(n) = \sum_{n=0}^{N-1} s_{i,n} e^{\frac{j2\pi n}{N}} \qquad (2.11)$$

This sequence is goes with a digital-to-analogue convertor those output ideally would be the signal waveform $x(t)$ with length of $\mathrm{N + L - 1}$. The signal is up-converted and the RF signal is transmitted to the channel. After down-conversion of RF signal which is the output of the channel, the received signal waveform y_m acquired. The discrete-time baseband that corresponds to the received signal is expressed as:

$$y_m = Hx(m) + n \qquad (2.12)$$

It describes a classic linear model of the received signal can recover the QAM symbol using additional signal processing techniques like the FFT and an equalizer. The processing of signal at the receiver can be in frequency domain based on FFT. Same as OFDM, a single tab frequency domain equalizer can be applied to equalize the effects of the radio channel and the combination of each subband filter.

2.6. Power domain NOMA

In the current OMA scheme, different users are assigned to different orthogonal resource blocks in the time domain, frequency domain, or code domain to prevent interference between users. This resource sharing limits the OMA scheme because of shortage in the numbers of orthogonal resources blocks and less spectrum efficiency. However, due to the rapidly growing of the mobile internet with the highly expansion of the Internet of Things, 5G systems will need to great improve in spectrum efficiency and number of connectivity. To meet these requirements, different technologies have been explored, including massive MIMO (multiple input multiple output), millimeter wave communications, and non-orthogonal multiple access (NOMA). The operation of

NOMA depend on supporting a massive number of user through non-orthogonal resource allocation. It has the ability to support various users sharing time or frequency on the same radio resource through power or code domain multiplexing schemes.

NOMA has been recognized as a very promising 5G radio access technology, but to fulfill its promises, it requires a SIC at receiver, so each user can demodulates and decode the signal from other users that share the same NOMA channel, apart from his own signal. There are two major classifications of NOMA technology, they are code domain and power domain based multiplexing. The Code domain NOMA (CD-NOMA) facilitates the separation of users at the receiver by using redundancy through coding/spreading. While, in Power domain NOMA (PD-NOMA) enables the separation of users by assigning different power levels for different user according to their channel condition and at receiver side they carry out SIC for users having higher channel gain [46]. With this regard, PD-NOMA provides the flexibility of resource assignment to increase the performance of NOMA.

In power domain NOMA various users signal will superimposed and the combined signal will be transmitted through the common channels at the transmitter end. At the receiver sides, SIC is employed to detect the desired signal. Let briefly describe this superposition coding and successive interference cancellation:

Superposition Coding (SC)

Superposition coding (SC) is a technology that simultaneously transmits information to different receivers across a single source [47]. By another way, it makes the transmitter to transmit information from multiple users simultaneously. To perform Superposition coding practically the transmitter necessary encodes information in applicable to every user. As an example for a two user's scenario, the transmitter must have two point-to-point encoder which maps their corresponding input to a complex-valued sequence of the two-user signal. Figure 2.11 is a schematic diagram how superposition coding works, where the QAM constellation of user 1 with more transmit power superimposed with the constellation of user 2 with less transmit power . It can be said that SC is a recognized non-orthogonal technology, which can obtain capacity in a scalar Gaussian transmission channel [47].

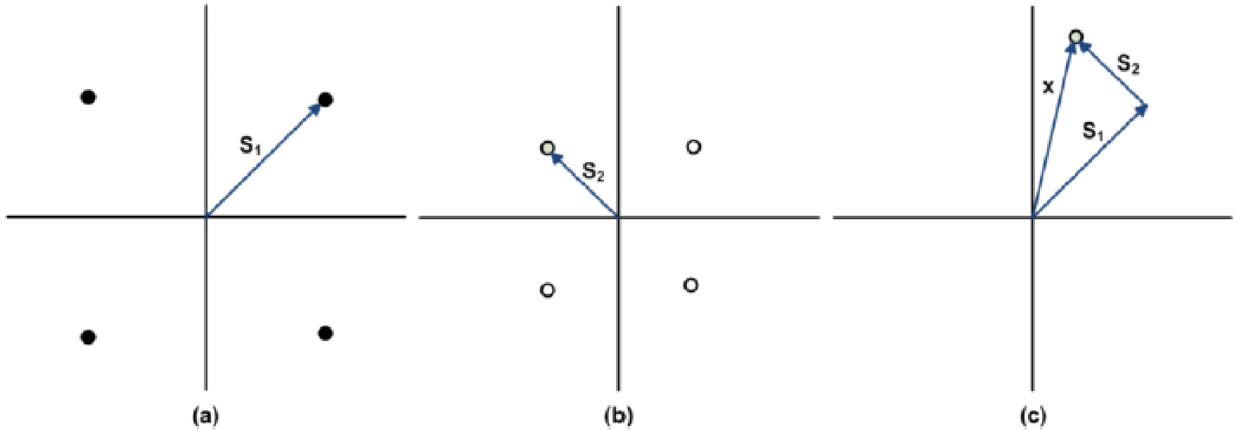


Figure 2.11: An example of SC encoding [49].

Successive Interference Cancellation (SIC)

To decode the superimposed signal transmitted to every receiver, NOMA uses Successive Interference Cancellation [47]. SIC feasibility is by exploiting specifications of the signal strength differences between the signals of interest. The fundamental concept of successive Interference Cancellation is decoding user's information are sequentially. In this technique after decoding the signal of one user, it is subtracted from the composite signal before decoding the signal of the next users. When SIC is employed, the signal of one user is decoded and considering another user signal as an interference, however in latter they decoded and the signal of the former has been removed. On the other hand, to describe how to SIC working, users are sorted based on their signal strengths therefore the receiver can decode the stronger signal first, then subtract it from the superposed signal and separate the weakest signal from the rest [47]. Note that every users are decoded by considering the other interfering users signal as noise. Figure 2.12 shows the decoding technique for the superimposed signal at the receiver end. Here the constellation point of user 1 is decoded first from the received signal. Then, the constellation point of user 2 is decoded in regard to the constellation point of user 1 decoded.

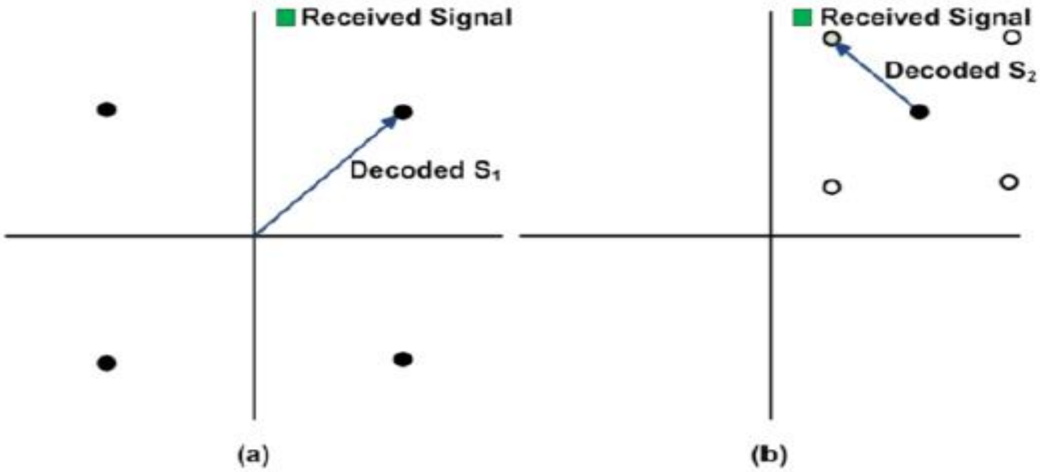


Figure 2.12: An example of SIC decoding [47].

Power Allocation for power domain NOMA.

The total bandwidth allowed to serve users is divided over a fixed number of subcarriers. Every subcarriers is then assigned a fraction of the available transmit power that the base station is allowed to use. An equal division is the simplest way to divide the power among subcarriers since it reduces the complexity of the scheduling process; therefore, a many number of papers dealing with NOMA consider this division

Power allocation is done such that the amount of power assigned to a subcarriers is common to all subcarrier, and Intra-subcarrier power allocation is responsible for assigning different power levels to users sharing the same subcarrier. Therefore, the amount of power assigned to a specific subcarrier distributed among the users multiplexed over that subcarrier. There are several power allocation algorithms which are commonly used in NOMA, such as fractional transmits power allocation (FTPA) algorithm and fixed power allocation (FPA) algorithm [50].

1. **Fixed Power Allocation (FPA):**

Power is divided between paired users on subcarrier **c** based on a fixed ratio. Wherever a fraction of subcarrier power is allocated to a single user and the remaining power is allocated to the other user that can be [50] seen as(αP_c, $(1-\alpha)P_c$) , $\alpha(0 < \alpha > 0.5)$. Despite Pc, the fixed ratio remains uniform for all subcarrier. Though FPA is low complex, it is considered ineffective due to the inconsideration of users channel conditions in determining power levels.

Thus, there is no need to communicate the power assigned to users via signaling since it remains unvaried and it can be easily determined based on the decoding order of users, which in turn reduces the SIC complexity.

2. **Fractional Transmit Power Allocation (FTPA):**

Another technique called Fractional Transmit Power Allocation (FTPA) can be also used to divide Pc between paired users. This technique is quite more complex than FPA since the amount of power assigned depends on the channel gains of scheduled users as given by Eq. 2.14 FTPA used for the multiplexed pair of users, which provides a suboptimal solution [50].

$$P_{c,i} = \frac{|h_i|^{-\beta}}{\sum_{j=1}^{n(c)} |h_j|^{-\beta}} P_t \qquad 2.14$$

Where $\boldsymbol{\beta}$ is fractional quantity of power ranging from 0 to 1 such that if $\beta = 0$ an equal power scheme is considered for users pair. Growing in the fractional quantity of power linked to the amount of power allocated to the user with lower channel conditions. The fractional quantity of power fixed in the subchannels. Compared to FPA, FTPA produces higher complexity regarding the increased amount of downlink signaling.

2.6.1. Working Principle of PD-NOMA System

In power domain NOMA, different power level is allocated to various users according to their channel gain to attain higher system performance. Especially, information signals from multiple users are superimposed at the transmitting end. Apply successive Interference Cancellation (SIC) at the receiver end to decode the signals step by step up to the required user signal is achieved. Let us briefly review uplink and downlink power domain NOMA.

I. Downlink PD-NOMA Network

Considering a downlink NOMA communication with a single antennas base station (BS) and single antenna L number of users with different channel gains. As seen in Figure 2.13, L-user downlink NOMA the BS transmitter non-orthogonally transmits L different signals by superposing them on the same spectrum resource, however all L UE receivers receive their required signal with the interferences resulting from the information of another UEs. In order to find the required final signal, every SIC receiver first decode the highest interference signal and after that subtract it from the superimposed signal. Since every UE receives all signals, which means that there are useful and interfering signals on the same channel, superposing various signals through different power levels is important to distinguish every signal and execute SIC on a given UE receiver.

Similarly considering that the signals of NOMA users are superposed with a power level which is inverse relationship to the their channel gains and that is low power assigned for the user with high channel gain while high power assigned for the user with lower channel gain. Therefore, the user with better channel condition (who receives strong interference because of high power allocated to the information of lower channel condition users) can suppress entire interfering signals. In any case, the user with lowest channel condition (who receives low interference because of low power allocated to the information of better channel condition users) cannot suppress any interference [46].

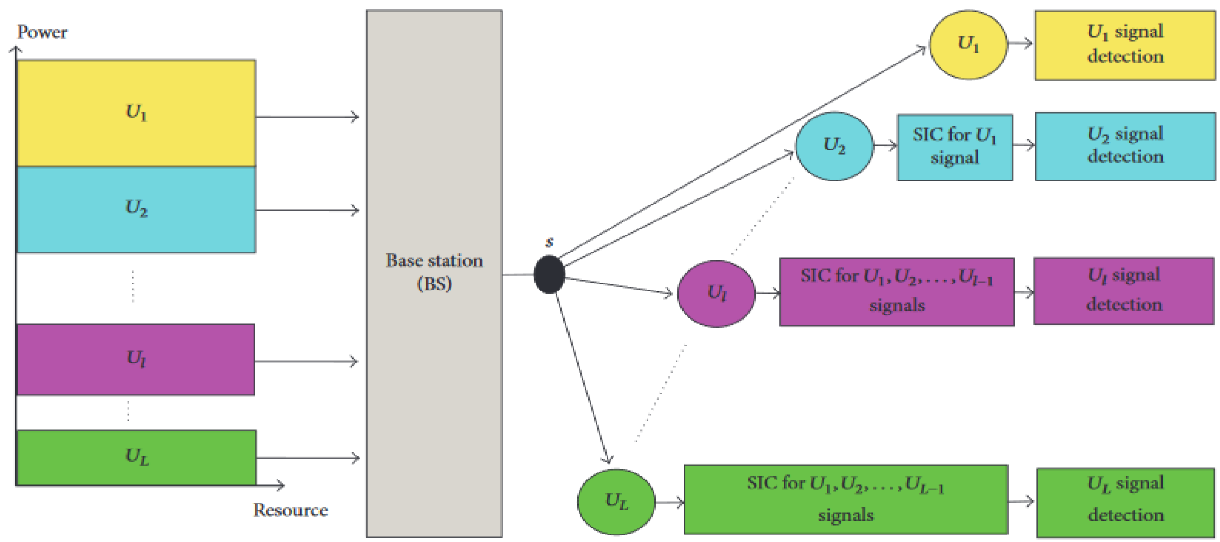


Figure 2.13: Downlink PD-NOMA network [46].

The received signal at i[th] user can be given [46] as:

$$y_l = X_{sc} + W_n = \sum_{i=1}^{L} \sqrt{a_i P}\, x_i + W_n \qquad (2.15)$$

Where W_n is additive Gaussian noise with a variance of σ^2.

X_{sc} is superposed signal of user L

a_i is power allocation coefficient for user i

P is total transmit power

x_i is transmit signal of user i

II. Uplink PD-NOMA Network.

In uplink communication NOMA the working principle is somewhat different from the downlink communication NOMA. As shown in Figure 2.14 uplink non-orthogonal multiple access many transmitters from individual UEs non-orthogonally transmitted to a particular receiver at BS through same spectrum resources. Independently, each UE transmits its own signal with a controlled transmit power or maximum transmit power based on the differences of channel gain between the NOMA users. At BS, all received signals are desired signals, although they will interfere with each other. Due to different transmitters, every signal received at the SIC receiver (BS) will experience a different channel gain [46]. Note that in order to perform SIC and decoded signals at the base station, the distinction between different message signals needs to be maintained. Therefore, conventional transmission power control (basically to equalize the received signal power from all users) is unfeasible in NOMA-based system [46]. In the figure below considering a general L-user uplink NOMA system ,in which L users transmit to the same BS through the same resources with maximum transmit power or controlled transmit power. The base station applies SIC to decode signal of each users that receives the composite signal of L different users. The user's received signal with the better channel gain is decoded first because it may be the strongest at the BS. Therefore, the user with the higher channel gain will get interference from all other users in the NOMA group. After that, the next higher channel gain user signal is decoded and so on. Therefore, in the NOMA uplink, the attainable data speed for users includes relatively weak user interference on all channels. In other words, the user with the higher channel gain will get interference from all users, whereas the user with the lowest channel gain will enjoy interference-free data rates [46].

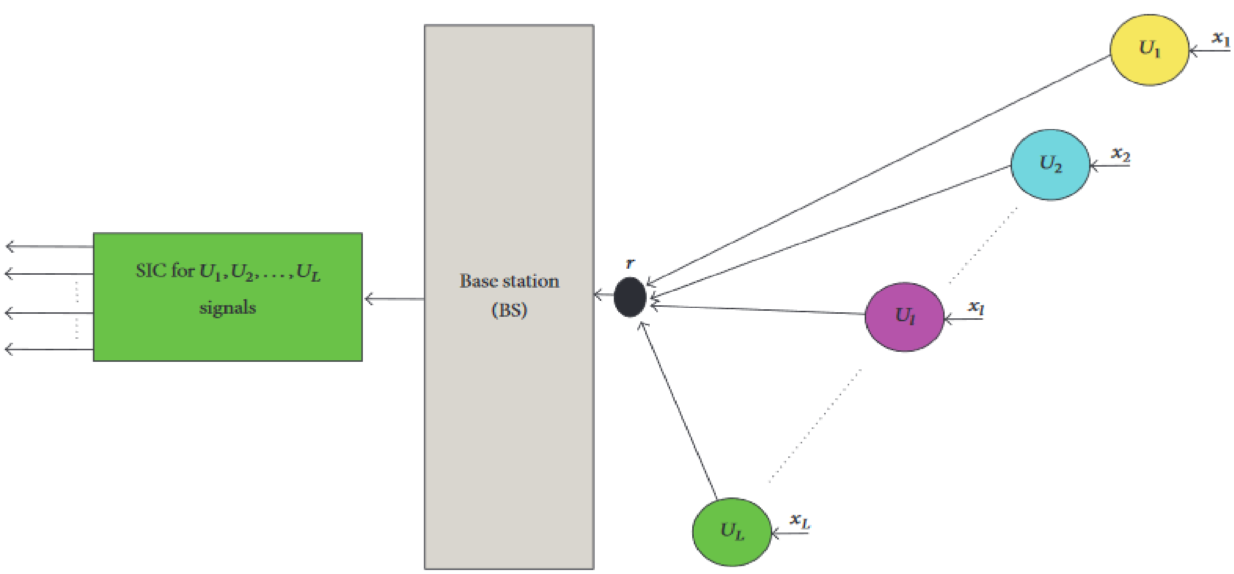


Figure 2.14: Uplink PD-NOMA network [46].

Consider a single-cell multi-user downlink power domain NOMA cellular system, assuming that there is one base station in the cell, **n** users, and every user is connected with one antenna, as seen in Figure 2.16. The system block diagram of power domain based NOMA is showed in Figure 2.15.

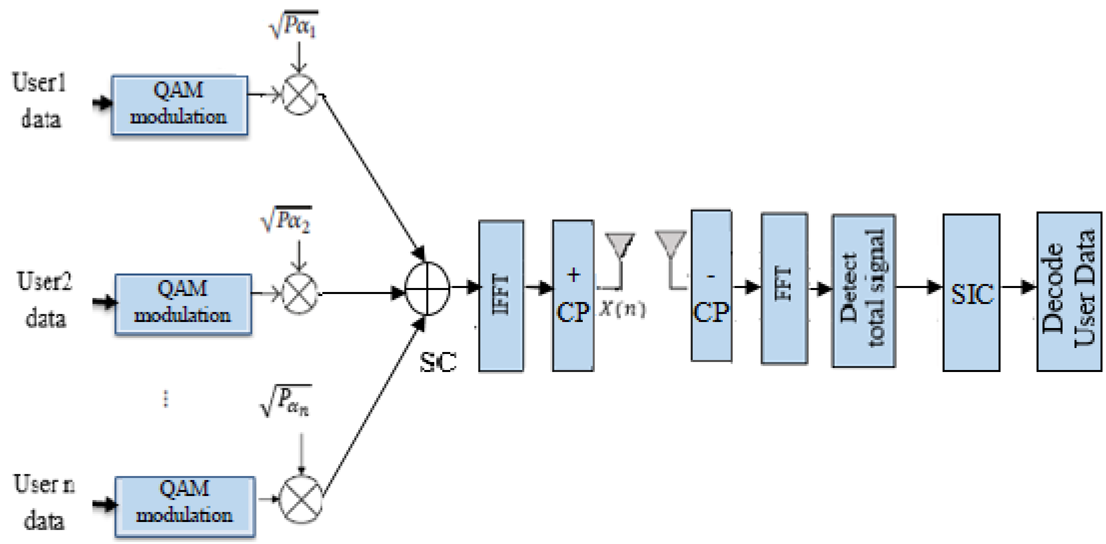


Figure 2.15: Block diagram of power domain NOMA [48].

Multicarrier downlink NOMA system is expressed by considering **n** users around a base station as seen in Figure 2.16. Users are randomly distributed and served using one base station and the total bandwidth $\boldsymbol{B}_{\mathbf{tot}}$ contains of $\boldsymbol{N}_{\mathbf{sc}}$ number of orthogonal subcarrier in frequency domain. Assuming that the transceiver is connected with one antenna, and **N** users share $\boldsymbol{N}\mathbf{sc}$ subcarrier through superposing codes.

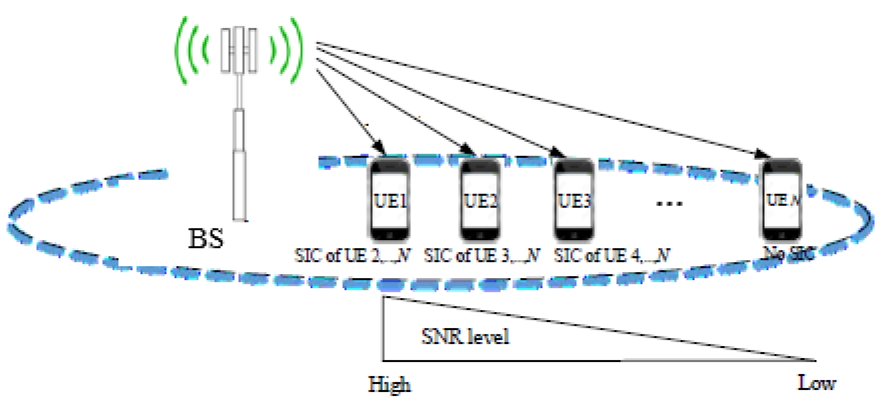


Figure 2.16: N different user distribution scenarios [48].

The BS allocates different power levels according to the user's situation to achieve system fairness and uses SIC to provide detecting capabilities on the Receiver side. Therefore, more power is assigned to user which has lower channel gain, which is more remote users and less power to users with higher channel gain. In other words, NOMA exploits the heterogeneity of users' distribution and then allows the separation in the power domain.

2.6.2. Mathematical Model of PD-NOMA

The entire system bandwidth is B_{tot}, the number of orthogonal subchannel used for communication is N, and the bandwidth of every subchannel is $B_s = \frac{B_{tot}}{N}$. The base station transmits a superposed signal of multi-user on each subchannels and the total transmission power of the base station is P_T. If the number of superimposed users on the k^{th} subchannel is n , the superimposed signal $X(n)$ transmitted by the base station on the N subchannel can be represent [48] as

$$x(m) = \sum_{K=0}^{N-1} \left(\sum_{i=1}^{n} \sqrt{P\alpha_i} X_i \right) e^{\frac{j2\pi Km}{N}} \quad for\ m = 0,1,2 \ldots N-1 \tag{2.16}$$

Where: X_i is complex modulated symbol of **ith** user on **kth** subcarrier
n is number of users
α_i is power allocated factors for the **ith** user

After superposing the signal to mitigate interference between symbols and allow frequency domain equalization at receiver copy from the superposed signal tail is added as CP. At receiver side the received signal $\boldsymbol{y}$ with noise signal w. After removing the CP at the receiver end, perform an N-point length of FFT operation. The discrete-time baseband equivalent received signal is given [48] as

$$y_n = h_n x(m) + w_n \tag{2.17}$$

Where: y_n is received signal n^{th} user.
h_n is channel gain for user n
$x(m)$ is superposed transmitted signal
w_n is additive Gaussian noise

Chapter 3

Performance Analysis of multiple access Techniques

3.1. System Model

To compare the performance of FBMC, UFMC and PD-NOMA based communication systems considered system model is expressed in Figure 3.1. This system contains of two users (i.e., UE1 and UE2), these two users supported by single BS. The users' (UEs) and the base station (BS) are equipped through single antennas and the data for the two users is modulated using QAM with modulation order (M) of 16.

For the PD-NOMA, two users (i.e., UE1 and UE2) access the same subchannel at same time using superposition coding techniques. The transmitted signal is expressed by [29]:

$$x = \sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2 \tag{3.1}$$

Where P is total transmission power α_1 is power allocation coefficients for user UE_1 and α_2 is power allocation coefficients for user UE_2 where $\alpha_2 = (1 - \alpha_1)$, X_1 and X_2 is the transmitted signal for user 1 and user 2 respectively.

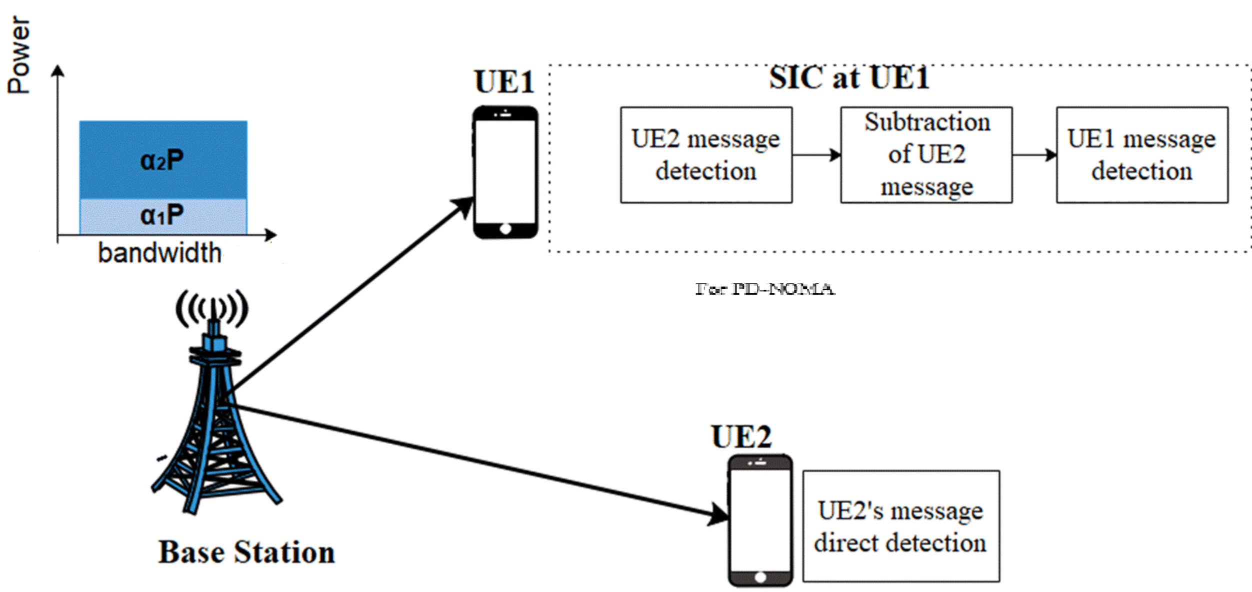


Figure 3.1: System model for FBMC, UFMC and PD-NOMA [29].

Where as in FBMC total subchannel divided into two subchannels and two users (i.e., UE1 and UE2) allocated to the different subchannels, in which the symbols are filtered through pulse shaped by prototype filter. The efficiently implementation of this structure is attained through using an Offset-QAM staggering, an FFT and a polyphase filtering as discussed in chapter two.

In Universal filtered multicarrier, the input QAM symbols are grouped in subband blocks and modulate and filter each subband blocks independently and added together every filtered blocks. This realized using B number of N-pt. FFT and Dolph-Chebysheve filter [42].

As discussed in Chapter two the key difference among FBMC, UFMC and power domain NOMA are the number of users access one subcarriers at same time. In FBMC and UFMC not more than one user access one subcarrier simultaneously. Whereas in PD-NOMA two users access one subcarrier at the same time, the incoming QAM symbols of each user are efficiently implemented by windowing and modulation is attained by only performing an N point FFT and superposed together in power domain, after that forwarded to channel

There are different type of metrics for comparison of multiple access techniques. From them we compare in respect to spectral efficiency, energy efficiency, bit error rate and Peak to average power ratio metrics. These three multiple access techniques are compared on the following performance metrics.

3.2. Spectral Efficiency

Spectrum efficiency defined as the rate at which information can be transmitted within a given spectrum in a particular communication system. It measures the efficiency of physical layer protocols or media access control use limited spectrum. Spectral efficiency appears in many ways in the literature. In order to compare the spectrum efficiency, we chose the defined by [49], which is most suitable for multiple access technologies. Which defines spectral efficiency as the product of the time efficiency and the maximum efficiency of multiple access schemes

$$\boldsymbol{\eta_{MA} = \eta_t * \eta_{max}} \tag{3.2}$$

Where $\boldsymbol{\eta_t}$ is time efficiency and $\boldsymbol{\eta_{max}}$ is maximum efficiency of multiple access schemes excluding guards interval and any overheads.

The time efficiency measures time overhead presented in transmission. It is defined similar to [44] as:

$$\eta_t = \frac{D_L}{D_L + \mathbf{T_{overhead}}} \tag{3.3}$$

Where D_L is the number of samples in transmitted signal dedicated to data transmission and $\mathbf{T_{overhead}}$ is the overhead sample which will be cyclic prefix, filter tails, zero padding etc.

For all multicarrier waveforms $D_L = S * N$ where, **S** represents the number of symbols in a block (burst) and N is FFT size.

In an OFDM modulation, there is an overhead that is cyclic prefix which introduced among symbols. Where as in UFMC, the filter length and zero padding causes overhead. Several papers [50] they did not use zero padding block in UFMC. Now, let us assume that UFMC using zero padding, which add extra overhead in time. The overhead time of FBMC is due to the long tail filter of all subchannel signal that is independent from the number of symbols in the block.

The overhead sample for each multiple access [51] are:

For OFDM,

$$T_{overhead} = S * L_{CP} \tag{3.4}$$

Where S is the number of symbols in block (burst) and L_{CP} is sample length of cyclic prefix.

For UFMC,

$$T_{overhead} = S * (L_{ZP} + L_F - 1) \tag{3.5}$$

Where **S** is the number of transmitted symbols in block (burst), L_{ZP} is length of zero padding and L_F is filter length.

For FBMC,

$$T_{overhead} = N * \left(K - \frac{1}{2}\right) \tag{3.6}$$

Where N is the size of FFT and K is overlap factor of filter.

Time efficiency of each candidates became [51]

$$\eta_{t-OFDM} = \frac{S*N}{S*N+S*L_{cp}} = \frac{N}{N+L_{CP}} \tag{3.7}$$

$$\eta_{t-UFMC} = \frac{S*N}{S*N+S*(L_{ZP}+L_F-1)} = \frac{N}{N+(L_{ZP}+L_F-1)} \tag{3.8}$$

$$\eta_{t-FBMC} = \frac{S*N}{S*N+N*\left(K-\frac{1}{2}\right)} = \frac{S}{S+\left(K-\frac{1}{2}\right)} \tag{3.9}$$

From Shannon's capacity theorem, the attainable data rate of the two user's (UE1and UE2) of orthogonal multiple access (OMA) schemes for downlink can be expressed as [52]

$$R_1 = \gamma \log_2\left(1 + \frac{P_1|h_1|^2}{\gamma N_o}\right) \tag{3.10}$$

$$R_2 = (1-\gamma) \log_2\left(1 + \frac{P_2|h_2|^2}{(1-\gamma) N_o}\right) \tag{3.11}$$

Where: γ : Bandwidth coefficient

h_k : Channel coefficient of k user

P_1 and P_2 : the power allocated for user 1 and 2 respectively

Where γ are represents the bandwidth allocation coefficient and then, the sum capacity of OMA of the two users with bandwidth of B is written as

$$C_{OMA} = B\left[\gamma \log_2\left(1 + \frac{P_1|h_1|^2}{\gamma * B * N_o}\right) + (1-\gamma)\log_2\left(1 + \frac{P_2|h_2|^2}{(1-\gamma) * B * N_o}\right)\right] \tag{3.12}$$

Where $\boldsymbol{\gamma}$ denotes the bandwidth coefficient allocated to UE1 and the remaining bandwidth being allocated to UE2. Assuming equivalent bandwidth and power assigned to all user the overall data rate of OMA, i.e. $\gamma = 0.5$.

The general spectral efficiency for downlink transmission are defined [52] as

$$\boldsymbol{\eta}_{SE} = \frac{\sum_{m=1}^{M} C_m}{B} \tag{3.13}$$

Where:

M: number of sub channel

C_m: Sum capacity for sub channel m

B : Total bandwidth of system

The maximum achievable Spectral Efficiency for two user's scenario of downlink orthogonal multiple access (OMA) schemes can be written as

$$\boldsymbol{\eta}_{max} = \gamma \log_2\left(1 + \frac{P_1|h_1|^2}{\gamma * B * N_o}\right) + \gamma \log_2\left(1 + \frac{P_2|h_2|^2}{\gamma * B * N_o}\right) \tag{3.14}$$

Whereas in PD-NOMA two users allocated to the same subchannel at the same time where the user with better channel condition (UE_1) first decodes the signal of the user with bad channel condition (UE_2) and remove its signal from received superposed signal and then decodes user one signal (UE_1) without interference from user two signal. Assuming successful decoding without error propagation, using Shannon capacity theorem the achievable the data rates with power domain NOMA for UE1and UE2 is represented as [51] [52].

$$R_1 = \log_2\left(1 + \frac{P_1|h_1|^2}{N_o}\right) \tag{3.15}$$

$$R_2 = \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + N_o}\right) \tag{3.16}$$

The sum capacity of Power domain NOMA with assuming that the transmission bandwidth is B are represented as

$$C_{PD-NOMA} = \mathrm{B}\left(\log_2\left(1 + \frac{P_1|h_1|^2}{B * N_o}\right) + \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + \mathrm{B} * N_o}\right)\right) \tag{3.17}$$

Where: N_o is the noise power.

The maximum attainable Spectral Efficiency for two users' scenario of PD-NOMA schemes for downlink transmission can be written as

$$\boldsymbol{\eta}_{PD-NOMA(Max.)} = \log_2\left(1 + \frac{P_1|h_1|^2}{B*N_o}\right) + \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + \mathrm{B}*N_o}\right) \tag{3.18}$$

To summarize this the spectrum efficiency referring to the data rate at which information can be transmitted through a fixed spectrum by multiple access scheme results:

Spectral efficiency for FBMC-OQAM system is represented as:

$$\eta_{FBMC} = \left(\frac{S*N}{S*N+N*\left(K-\frac{1}{2}\right)}\right) * \left(\gamma \log_2\left(1 + \frac{P_1|h_1|^2}{\gamma*B*N_o}\right) + \gamma \log_2\left(1 + \frac{P_2|h_2|^2}{\gamma*B*N_o}\right)\right) \tag{3.19}$$

Whereas, spectral efficiency of UFMC system with zero padding is expressed as

$$\eta_{UFMC} = \left(\frac{S*N}{S*N+S*(L_{ZP}+L_F-1)}\right) * \left(\gamma \log_2\left(1 + \frac{P_1|h_1|^2}{\gamma*B*N_o}\right) + \gamma \log_2\left(1 + \frac{P_2|h_2|^2}{\gamma*B*N_o}\right)\right) \tag{3.20}$$

Our system is power domain NOMA based on OFDM multicarrier therefore, it cannot achieve its maximum spectral efficiency due to the addition of a cyclic prefix of length $\boldsymbol{L_{CP}}$. Therefore, overall spectral efficiency of power domain NOMA system is given as:

$$\eta_{PD-NOMA} = \left(\frac{S*N}{S*N+S*L_{cp}}\right) * \left(\log_2\left(1 + \frac{P_1|h_1|^2}{B*N_o}\right) + \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + \mathrm{B}*N_o}\right)\right) \tag{3.21}$$

Where **N** is the size of FFT, $\boldsymbol{L_{CP}}$ length of cyclic prefix, $\boldsymbol{L_F}$ filter length of UFMC, $\boldsymbol{L_{ZP}}$ length of zero padding, **K** overlapping factor and **S** is number of symbols per block.

3.3. Energy Efficiency

In the past, a many research work has been done to enhance the performance of the system throughput. But, with the rapidly increase of wireless data traffic, the energy consumption of wireless networks has also growing rapidly. As a result, finding a balance between high data speed and energy saving is a critical works for the next generation of wireless communication systems. Energy efficiency is usually referred as the ratio of throughput to the power consumption. The number of bits per joule is usually used to measure the energy efficiency performance of wireless networks [53]. For energy efficient transmission, it is required to transmit the maximum amount of throughput through a given energy.

Given a total of energy ΔE that is used in a time ΔT, where ΔE = PΔT. Hence, the energy efficiency (EE) is written [54] as

$$\text{EE} = \frac{\text{R}\Delta\text{T}}{\Delta\text{E}} = \frac{\text{R}}{\text{P}} \;\; bits/joule. \tag{3.22}$$

The total power consumption contains transmission power and circuit power consumption. The circuit power consumption is the extra power consumed by devices, such as analog-to-digital converter, digital-to analog converter, synthesizer, and mixer during the transmission and signal processing [53]. P_c is represent the extra device power consumption that is circuit power . Therefore, the overall power consumption is given as $\text{P} + P_c$. Energy efficiency can be redefined where circuit power consumption (P_c) to be taken into consideration. As a result, the energy efficiency is expressed as

$$\text{EE} = \frac{\text{R}\Delta\text{T}}{\Delta\text{E}} = \frac{\text{R}}{\text{P+P}_\text{c}} \;\; bits/joule. \tag{3.23}$$

Note that the circuit power consumption P_c is independent of the transmission power. From (4.13) $\text{SE} = \frac{\text{R}}{\text{B}}$, where R is system throughput and B is system bandwidth. Hence, the energy efficiency is redefined [45] as

$$\text{EE} = \frac{\text{R}}{\text{P+P}_\text{c}} = \text{SE}\left(\frac{\text{B}}{\text{P+P}_\text{c}}\right) \;\; , bits/joule. \tag{3.24}$$

Spectral efficiency of FBMC, UFMC and PD-NOMA are given in (3.19), (3.20) and (3.21) respectively.

3.4. Bit Error Rate

Bit error rate is an important parameter used to evaluate communication systems that transmit digital data from one place to another. When transmitting data on the data link, errors can be occurred into the system. If so, the reliability of the system can be compromised. Therefore, it is essential to evaluate the performance of the system and bit error rate gives an ideal way to achieve this. It evaluates the performance of the system from end-to-end, including the transmitter, receiver, and the medium in between. BER is describe as the rate at which errors happen in the transmission system.

I. BER for FBMC/OQAM systems

Assume that the noise power affecting the QAM and OQAM demodulators is N_0. Obviously, OQAM can be considered as a special case of QAM because it only splits QAM symbols into two symbols. This means that for M-ary QAM or OQAM symbol the BER expression for FBMC representing [53] as

$$\text{BER}= \frac{2(\sqrt{M}-1)}{\sqrt{M}\log_2 M} erfc\left[\sqrt{\frac{3\log_2 M|h_k|^2}{2(M-1)} . \frac{E_b}{N_o}}\right] \tag{3.25}$$

Where E_b the bit energies for user

N_o : Noise power spectral density

M: QAM order

$h_{k=}$ Channel gain for user **k**

Erfc (x) $\cong \frac{2}{\sqrt{\pi}} \int_x^{\infty} exp(-y^2)\, dy$

Assume that total bandwidth divide equally for two user's i.e. $BW_1 = BW_2 = BW/2$ and modulation order of QAM (M) = 16. Bit error rate of FBMC/OQAM for user 1 and user 2 written as:

$$BER_1 = \frac{2(\sqrt{M}-1)}{\sqrt{M}\log_2 M} erfc\left[\sqrt{\frac{3\log_2 M|h_1|^2}{2(M-1)} \cdot \frac{E_{b1}}{N_o}}\right] \tag{3.26}$$

$$BER_2 = \frac{2(\sqrt{M}-1)}{\sqrt{M}\log_2 M} erfc\left[\sqrt{\frac{3\log_2 M|h_2|^2}{2(M-1)} \cdot \frac{E_{b2}}{N_o}}\right] \tag{3.27}$$

Therefore, total bit error rate of FBMC/OQAM at system level is the sum of bit error rate of two users:

$BER_{total} = BER_1 + BER_2$

II. BER for UFMC systems

The difference among UFMC and OFDM is that set of subcarrier of UFMC is filtered. At the receiver end, every sub-band required to execute the reverse process of the filter.

Hence, the BER of M-QAM in the UFMC system can be written as [56]

$$BER = \frac{1}{KB}\sum_{i}^{B}\sum_{k=1}^{K} \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M} Q\left(\sqrt{\frac{3E_b}{N_o}|r_k|^2 \cdot \frac{\log_2 M}{M-1}}\right) \tag{3.28}$$

Where : K : number of subcarriers in each sub-band

r_k : equivalent filter response corresponding to the **kth** subcarrier

B: the number of sub-bands

E_b : the bit energies for users

N_o : Noise power spectral density

M: QAM order

Q(x) $\cong \frac{1}{\sqrt{2\pi}} \int_x^{\infty} exp\left(-\frac{y^2}{2}\right) dy$

Assume that total bandwidth divide equally for two user's i.e. $BW_1 = BW_2 = BW/2$ and modulation order of QAM (M) = 16. Bit error rate of UFMC for user 1 and user 2 written as:

$$BER_1 = \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M}\ Q\left(\sqrt{\frac{\log_2 M}{M-1}.\frac{3E_{b1}}{N_o}|r_k|^2}\right) \tag{3.29}$$

$$BER_2 = \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M}\ Q\left(\sqrt{\frac{\log_2 M}{M-1}.\frac{3E_{b2}}{N_o}|r_k|^2}\right) \tag{3.30}$$

Therefore, total bit error rate of UFMC at system level is the sum of bit error rate of two users:

$$BER_{total} = BER_1 + BER_2$$

III. BER for PD-NOMA systems

To find the BER of near user (UE_1) is the probability under the condition that no error occurred when detecting far user (UE_2) symbols at near user (UE_1). Then, the bit error rate of UE_1 under the condition that UE_2 symbols are detected correctly [57] is

$$\boldsymbol{BER_1} = \frac{1}{2}\left[2 * Q\left(2\sqrt{\frac{E_{b1}}{N_o}}.|h_1|\right) - Q\left(\frac{(\sqrt{E_{b2}}+\sqrt{E_{b1}}).|h_1|}{\sqrt{N_o}}\right) + Q\left(\frac{(2\sqrt{E_{b2}}+\sqrt{E_{b1}}).|h_1|}{\sqrt{N_o}}\right) + Q\left(\frac{(\sqrt{E_{b2}}-\sqrt{E_{b1}}).|h_1|}{\sqrt{N_o}}\right) - Q\left(\frac{(2\sqrt{E_{b2}}-\sqrt{E_{b1}}).|h_1|}{\sqrt{N_o}}\right)\right] \tag{3.31}$$

Whereas the bit error rate of far user (UE_2) is given by:

$$\boldsymbol{BER_2} = \frac{1}{2}\left[Q\left(\frac{(\sqrt{E_{b2}}+\sqrt{E_{b1}}).|h_2|}{\sqrt{N_o}}\right) + Q\left(\frac{(\sqrt{E_{b2}}-\sqrt{E_{b1}}).|h_2|}{\sqrt{N_o}}\right)\right] \tag{3.32}$$

Where: E_{b1} and E_{b2} : the bit energies for user 1 and 2

$E_{b1}=\alpha_1 * E_b$ and $E_{b1}=\alpha_2 * E_b$

N_o : Noise power spectral density

h_k : Channel gain for user **k**

$$Q(x) \cong \frac{1}{\sqrt{2\pi}}\int_x^{\infty} exp\left(-\frac{y^2}{2}\right) d$$

Therefore, total bit error rate of power domain NOMA at system level is the sum of bit error rate of two users: $BER_{total} = BER_1 + BER_2$

3.5. Peak to Average Power Ratio

The PAPR of a multiple access signals is defined as the ratio of the maximum power to the average power of the transmitted signal over the data block period. This mean that it is a measures the power of all symbols compared to the average power of the total symbol over a length of symbols. If PAPR of entirely symbols is one, then the transmitter can send constant power.

The PAPR for an FBMC signal $g(t)$ is given by [58]:

$$PAPR[g(t)] = \frac{\max_{(0\le t\ge T)}(|g(t)|^2)}{E[|g(t)|^2]} \tag{3.33}$$

Where $\max_{(0\le t\ge T)}(|g(t)|^2)$ is the peak power of the signal and $E[|g(t)|^2]$ is the average power of the signal. If variation of PAPR between symbols is high then the power amplifier will saturated which results erroneous output. The complementary cumulative distribution function (CCDF) is useful tools to evaluate the PAPR performance of multiple access schemes. CCDF is a measure of the probability that the instantaneous power of the signal exceeds a certain value above its average power. It means the probability of PAPR exceeding a threshold (γ):

I. PAPR for FBMC

For FBMC-OQAM signals, complementary cumulative distribution function (CCDF) of PAPR is given by [58] [59]:

$$\begin{aligned} CCDF(PAPR) &= Pr(PAPR_{FBMC} > PAPR_{TH}) \\ &= 1 - Pr(PAPR_{FBMC} < PAPR_{TH}) \\ &= 1 - (1 - e^{-\gamma})^{K*N} \quad , \end{aligned} \tag{3.34}$$

Where $\gamma = \mathrm{PAPR_{TH}}$.

K is the overlapping factor

N is the number of subcarriers.

II. PAPR for UFMC

The PAPR UFMC signals have about $\left(\frac{N+N_F}{N}\right)$ times higher PAPR than OFDM signals under same system settings, which mean the same number of active subcarriers and effective symbol power per subcarrier [60].

$$\begin{aligned} CCDF(PAPR) &= Pr(PAPR_{UFMC} > PAPR_{TH}) \\ &= 1 - Pr(PAPR_{UFMC} < PAPR_{TH}) \\ &= 1 - (1 - e^{-\gamma})^{N} \quad , \end{aligned} \tag{3.35}$$

Where: $PAPR_{UFMC} = \left(\frac{N+N_F}{N}\right) * PAPR_{OFDM}$

$\gamma = \mathrm{PAPR_{TH}}$.

N is the number of subcarriers

N_F is filter length

III. PAPR for PD-NOMA

The distribution of PAPR of OFDM based power domain NOMA systems is similar to OFDM systems [61]. Therefore, for power domain NOMA signals, CCDF of PAPR is given by:

$$CCDF(PAPR) = Pr(PAPR_{PD-NOMA} > PAPR_{TH})$$

$$= 1 - Pr(PAPR_{PD-NOMA} < PAPR_{TH})$$

$$= 1 - (1 - e^{-\gamma})^N \quad (3.36)$$

$where\ \gamma = PAPR_{TH}$

N is the number of subcarriers.

Chapter 4

Result and Discussion

The comparison between the FBMC, UFMC and PD-NOMA multiple access schemes is presented in this section. Table 4.1 lists the general simulation parameters in this work and the performance evaluation is done using MATLAB platform.

Table 4.1 Simulation parameters

General parameters		Remark
Modulation type	16 QAM	
FFT size	1024	
Subcarrier spacing	30 KHz	
Number of bits per symbol	4	
Number of users	2	
System Bandwidth	30MHz	
BW coefficient(OMA)	0.5	
Channel	AWGN channel	
FBMC parameter		
Overlapping	K=4	For better side-lobe
UFMC parameters		
length of zero padding	72	[44]
Sub-band size	12	
Filter length	80	[44]
Equivalent filter impulse response	1	[53]
PD-NOMA parameters		
Power allocation schemes	Fractional Transmit Power Allocation	
Fraction Power allocation factor (β)	0.6	[51]
Channel Gain	5(UE1) and 1(UE2)	[59]
Length of CP	72	as in LTE

The parameters used in this simulation may changes according to for each comparison metrics. The result for performance comparisons of FBMC, UFMC and PD-NOMA schemes with QAM modulation are simulated. QAM is chosen because it is commonly used modulation type for data transmission as it provides superior level of spectral efficiency than other form of modulations. To focus link level performance, we only assuming single transmitting antenna at the base station equipped with single antennas of users' equipment. Also perfect channel estimation is assumed; which help us to highlight the performance difference between multiple access schemes.

4.1. Spectral Efficiency

In this section, the spectral efficiency of candidate multiple access techniques is compared in terms of different parameters namely, number of symbols in block and SNR.

In figure 4.1, shows spectral efficiency comparison of FBMC, UFMC and PD-NOMA versus SNR of the system by fixing number of symbols per block constant. We evaluate the Spectral efficiency of multiple access schemes given signal noise ratio (SNR) of system which range from 0 to 18 and also taken 28 number of symbols per block (sub frame).

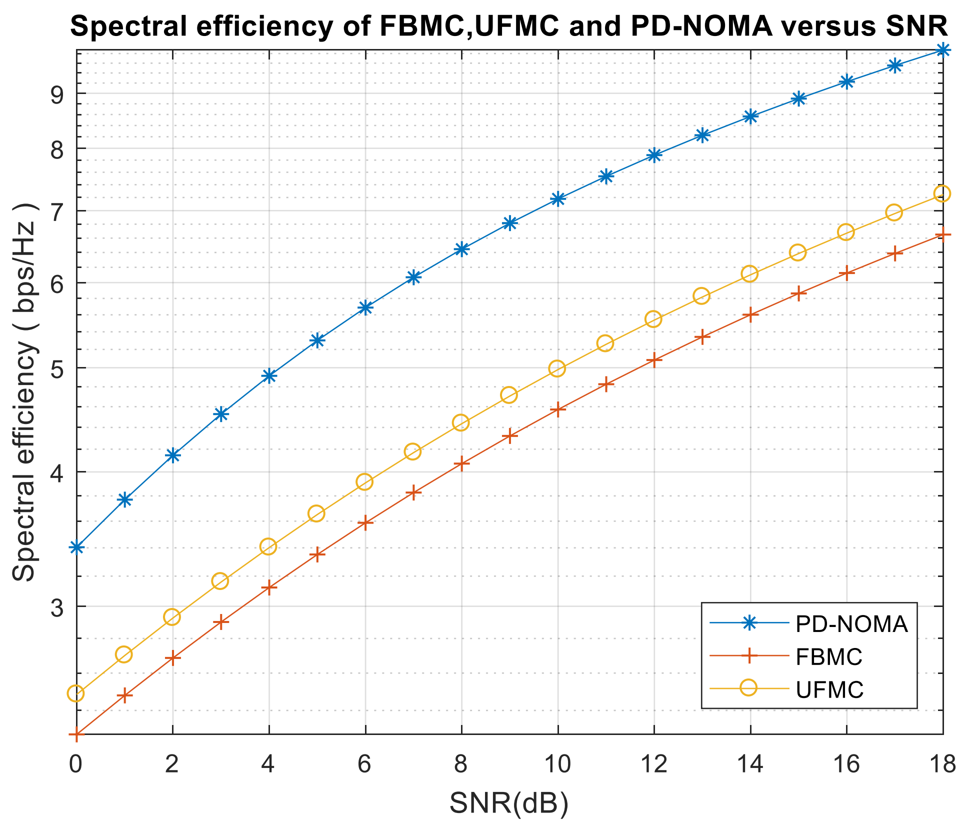


Figure 4.1: Spectral efficiency of FBMC, UFMC and PD-NOMA in terms of SNR

As seen from Figure 4.1, PD-NOMA performs the higher spectral efficiency than FBMC and UFMC. This is due to that in the FBMC and UFMC multiple access schemes one subchannel is accessed only by one user, whereas in power domain NOMA one subchannel accessed by two user through assigning different power level. Consequently, the spectral efficiency of FBMC and UFMC became degrade and performs lower spectral efficiency to that of PD-NOMA.

Figure.4.2, shows spectral efficiency for FBMC, UFMC and PD-NOMA versus number of symbols per block performance when SNR multiple access is constant. As discussed in Chapter 3, UFMC and PD-NOMA the spectral efficiency does not changes as number of symbol for each block changes and it depends on number of FFT. However, for FBMC-OQAM, it depend on the number of symbols per block, and the loss of spectral efficiency results from the transient state of the shaping filter if considered that there is no transmission during this time. Therefore, there is no equal loss per symbol and the spectral efficiency enhanced with number of symbol per block to attain an asymptotic level which is the maximum spectral efficiency. Where SNR of system taken is 10dB as [46]. These results clearly demonstrate that power domain NOMA outperform UFMC and FBMC-OQAM respect to spectral efficiency even if spectral efficiency of FBMC-OQAM increase as number of symbols per block is increase

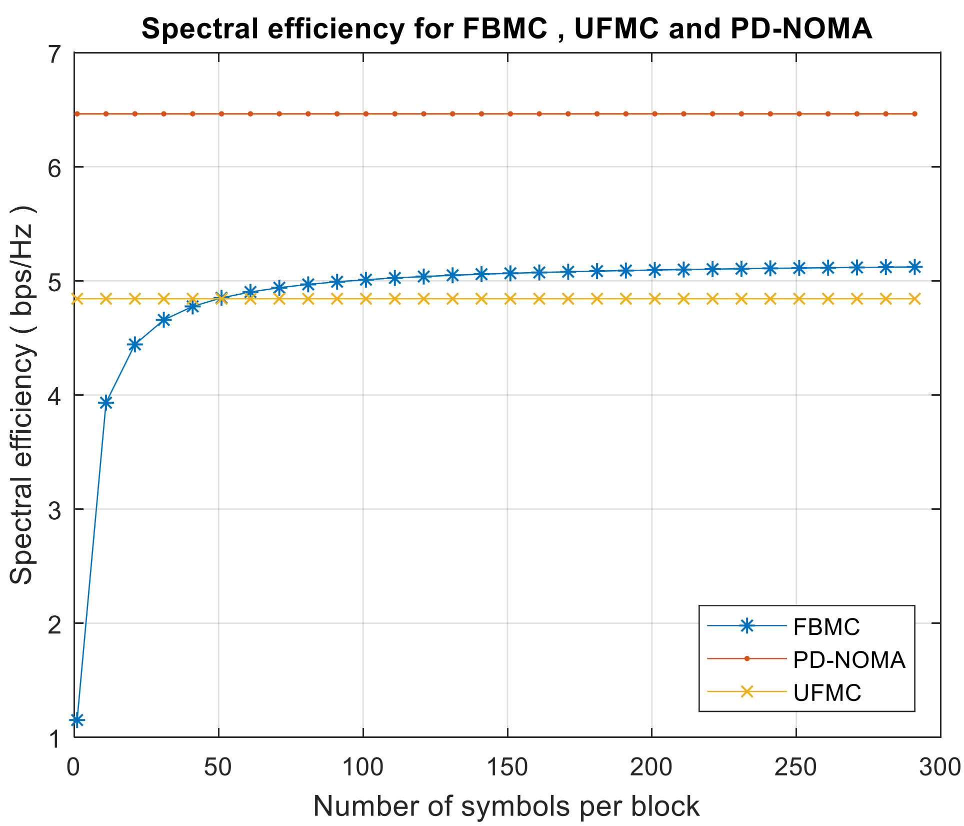


Figure 4.2: Spectral efficiency of FBMC, UFMC and PD-NOMA in terms of number of symbols

4.2. Energy Efficiency

In this section, we provide the simulation results to demonstrate the achievable EE performance of the downlink systems, specifically FBMC, UFMC and PD-NOMA. Figure 4.3 presents the performance of energy versus spectral efficiency. The interval of transmit power of BS is from 5dBm to 35 dBm and power consumed by circuit are 25 dBm [54].

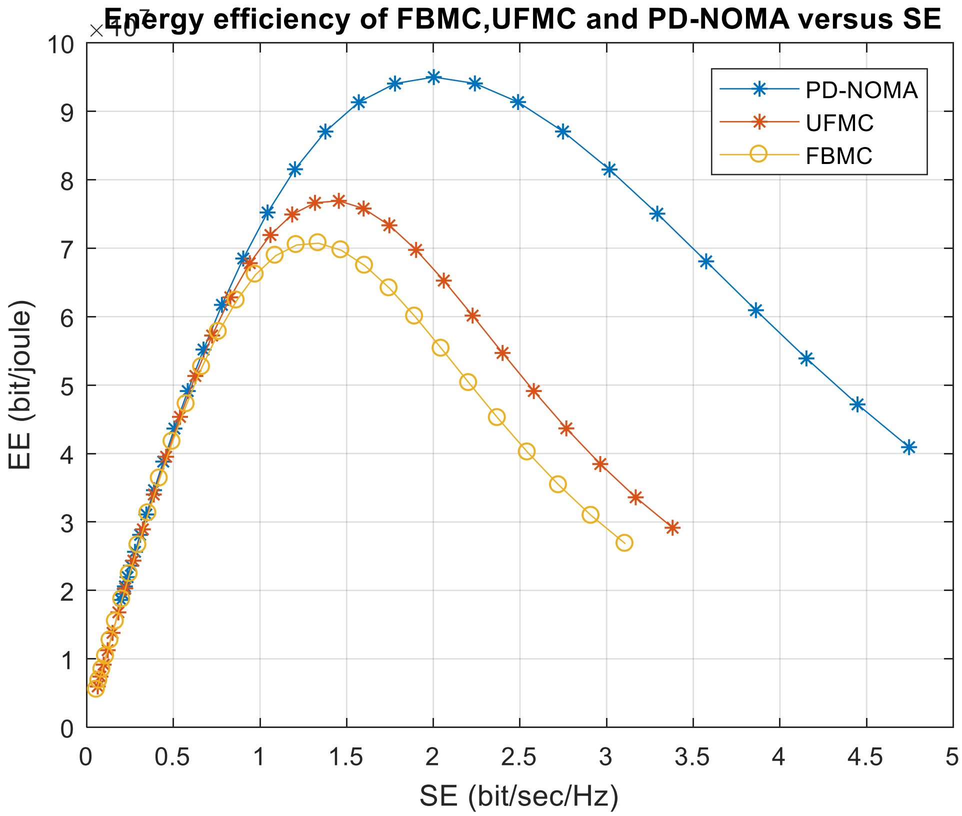


Figure 4.3: Energy efficiency of FBMC, UFMC and PD-NOMA

From Figure 4.3, we can see that at low region of spectral efficiency (SE), the Energy efficiency (EE) increase as the spectral efficiency increase. It is due to the fact that at this region the circuit power dominate in the total power consumption, in order to compensate the impact of the circuit power consumption on the EE it need to increase transmit power. Thus, increasing transmit power makes spectral efficiency increase. Alternatively, in the higher region of spectral efficiency, the transmission power dominate in the total power consumption and there is only a minimal gain in spectral efficiency when the transmit power is increased. Therefore, after attaining maximum EE of the system, as seen in figure 4.4, extra increasing the transmit power reduces EE performance of system. From this figure we also seen that the PD-NOMA schemes are superior to FBMC and UFMC schemes in terms of EE performance due to the multiplexing gains in NOMA, which means that the increase of data rate brought by the PD-NOMA is higher than the negative effect of interference between users.

The figure 4.4 shows that the effects of NOMA power allocation coefficient on energy efficiency for α_1 ε {0.2,0.3,0.4} where transmit power interval for BS is from 5dBm to 35 dBm and power circuit are 25 dBm [54].

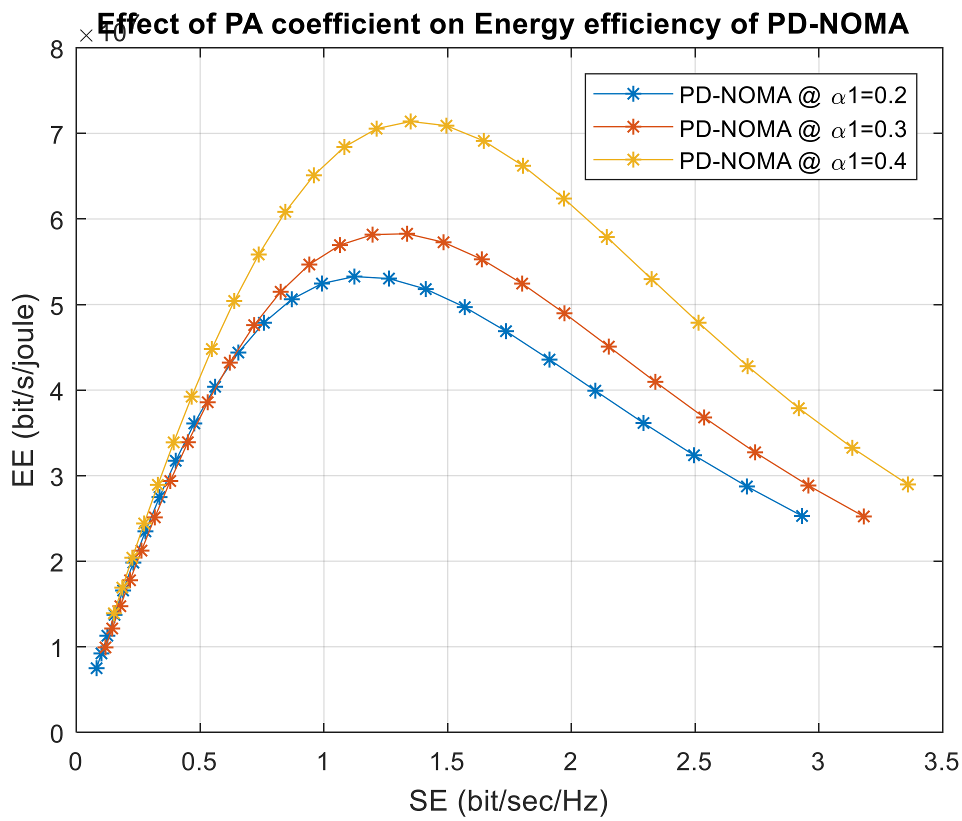


Figure 4.4: Effects of PA coefficient on Energy efficiency of PD-NOMA

As shown in figure as power allocation coefficients increase energy efficiency of system also increase. This is due to the throughput of PD-NOMA system increase as PA coefficient increase at constant transmit power. This resulting PD-NOMA energy efficiency increase as $\boldsymbol{\alpha_1}$ increase.

Figure 4.5, shows that the performance of energy efficiency against circuit power (Pc) of the FBMC, UFMC and PD-NOMA systems when a transmit power is 30dBm [54].

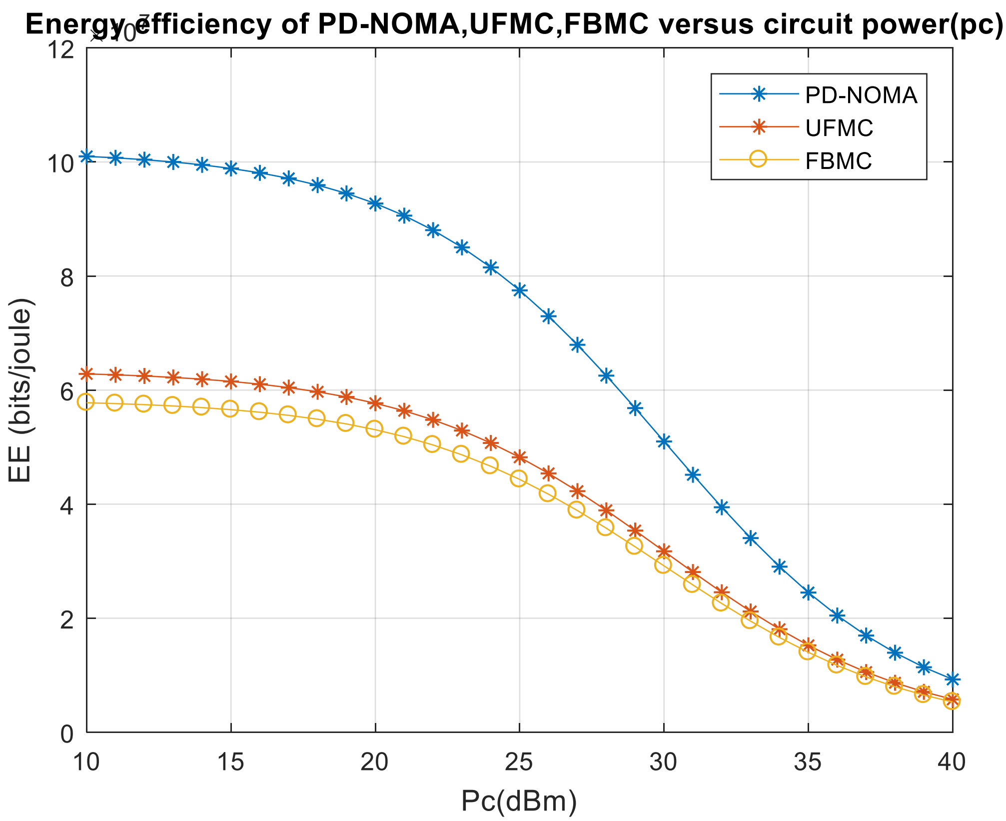


Figure 4.5: Energy efficiency of FBMC, UFMC and PD-NOMA versus Pc

As we see from figure 4.5, the performance of energy efficiency decrease as circuit power of system is increase. This is because of the total power consumption increases as circuit power consumption increase, however SE remains unchanged due to transmit power is constant, resulting in decrease EE as Pc is increased.

4.3. Bit Error Rate

The BER performance is represented and investigated to understand the performance regarding to QoS and data rate of system. The bit error rate performance of power domain NOMA evaluated in respect of different power allocation coefficient pairs as seen in Figure 4.6. As observed from this figure, when the power levels of users converge with each other, BER performance become decreases because it is difficult to suppress the interference of the other user.

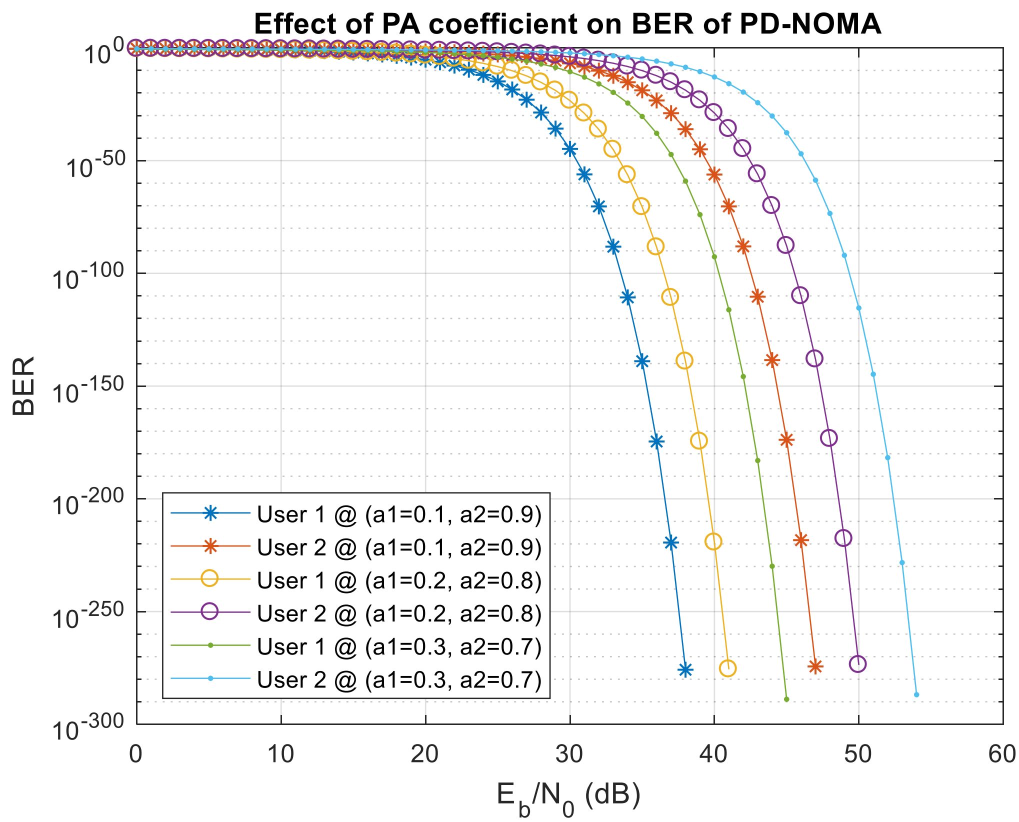


Figure 4.6: BER performance of PD-NOMA by applying different power allocation of two users.

From the result we conclude that if power allocation coefficient of the first user increase, the minimum distance between symbols increase, however the effect of the interference form second user increase this results BER performance is degrading.

Figure 4.7, shows that comparison of bit error rate performance for FBMC and UFMC with PD-NOMA systems at constant power allocation coefficient by varying SNR of the systems.

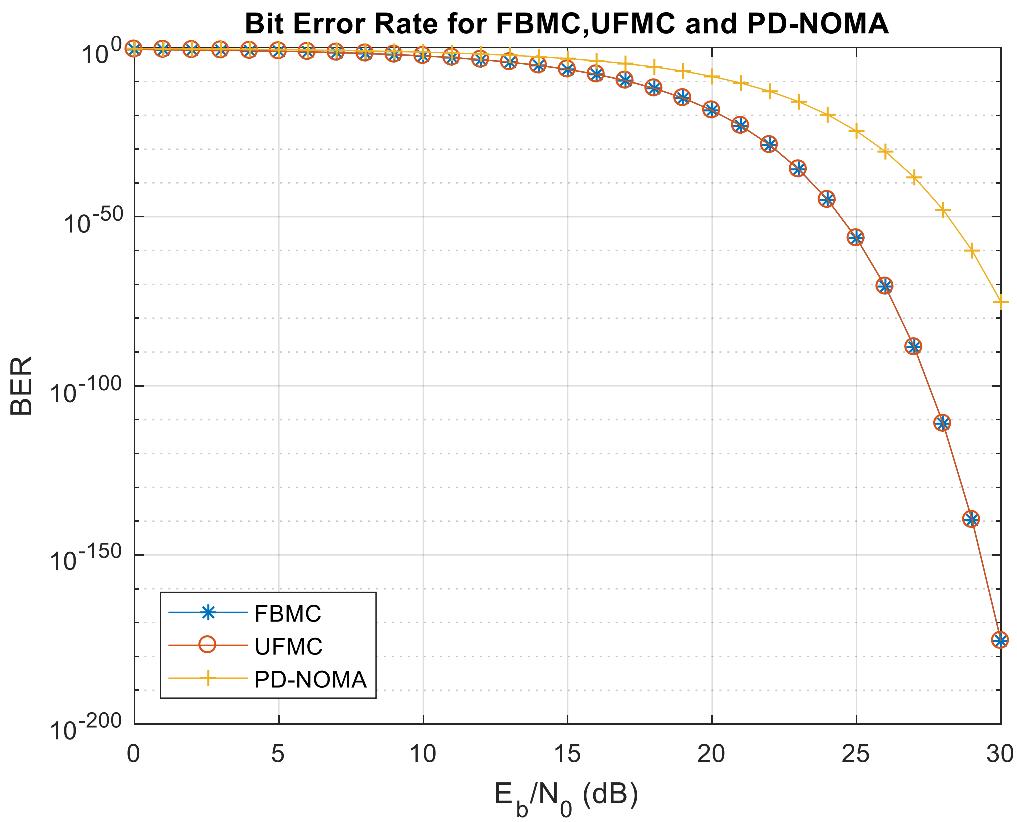


Figure 4.7: Bit error rate FBMC, UFMC and PD-NOMA

As shown in figure 4.7, bit error rate of PD-NOMA system less perform than FBMC and UFMC system. This is because in PD-NOMA two users are access the same subchannel this makes increase inter user interference results decrease BER performance.

4.4. Peak to Average Power Ratio

PAPR is the ratio of the peak power of a sample at a given transmitted symbol to the average power of symbol. The CCDF or Pr [PAPR $>$ $PAPR_0$] represents the probability of the signals having a higher PAPR than threshold $PAPR_0$. Figure 4.8, shows the comparison of CCDF performance for FBMC, UFMC and PD-NOMA multiple access schemes.

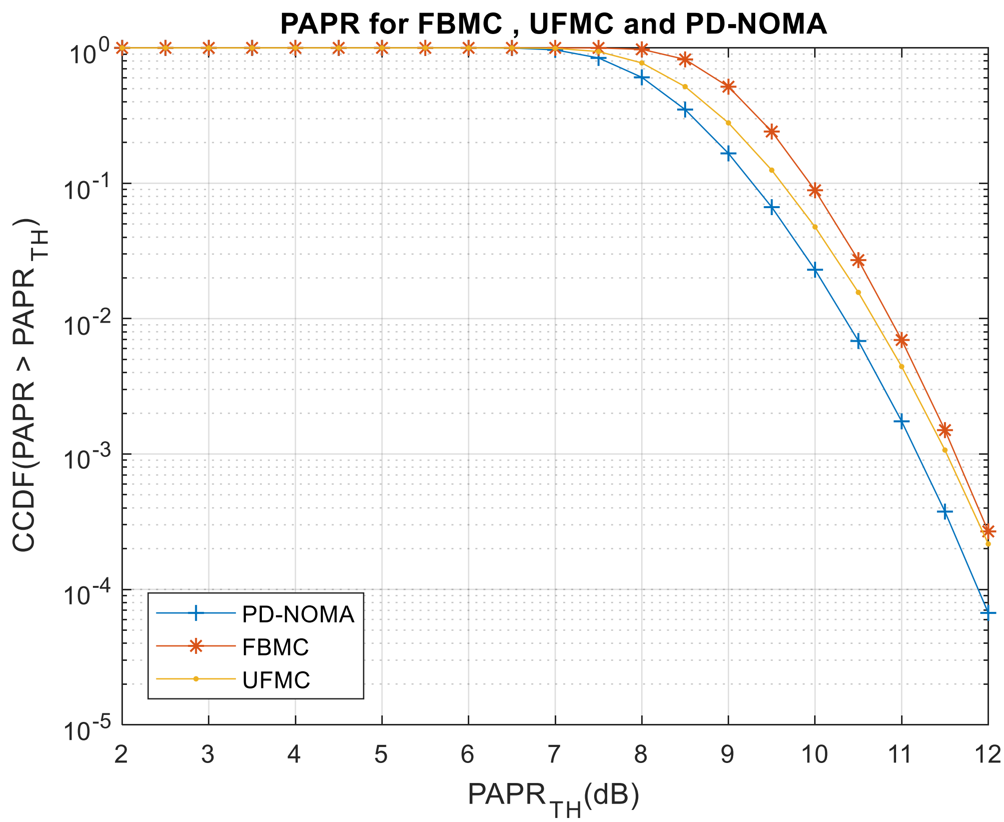


Figure 4.8: PAPR of FBMC, UFMC and PD-NOMA

We can see from Figure 4.8 that the PAPR of the Power domain NOMA signal is less than PAPR of FBMC and UFMC signal. If PD-NOMA signal is feed to a non-linear device such as high power amplifier, the output will be less distorted than FBMC and UFMC signal and resulted in less erroneous signal. Transmitting distorted signal leads to loss of the useful information.

Chapter 5

Conclusion and Recommendation

5.1. Conclusion

In wireless networks, the rapidly growing demands for wireless services are encountered by the shortage of the existing radio resources. OFDM is a robust and most common technology applied in various transmission systems actually, that is the core technologies of 4G system. In 5G network in addition to enhancing the current mobile data, also there are new services such as TV on demand, wireless gaming, machine to machine communication, IoT etc. The very stringent requirements of 5G network has pushed to look for another solutions. FBMC and UFMC orthogonal multiple access adopted to decrease out-of-band emission using filter bank while achieving the various demands of 5G network. PD-NOMA is another promising multiple access techniques, which makes a difference from previous techniques of wireless networks by using non-orthogonality. They also got great attention currently because of their higher spectral efficiency (SE) than OFDM and they play a significant role in improve the capacity of future networks.
In this thesis, performance comparison of 5G candidate multiple access schemes namely, FBMC, UFMC and PD- NOMA in respect to spectral efficiency, energy efficiency, BER and PAPR investigated. The result shows that advantages and drawbacks for each multiple access schemes. Based on result spectral efficiency, energy efficiency and PAPR performance PD-NOMA was better perform as compared with FBMC and UFMC Multiple access with cost of their bit error rate performance.

Overall, this thesis concluded that PD-NOMA is a good candidate for 5G generation mobile communication as compared to FBMC and UFMC based on Spectral efficiency and PAPR parameters with cost of their bit error rate parameters.

5.2. Recommendation and Future Work

Some possible extensions of the future work

- This thesis was also limited to only four parameters, others parameters should also be investigated.
- In this thesis user grouping effect on performance in power domain NOMA is not addressed, however user grouping schemes can enhancing performance of NOMA, therefore it should be studied
- The simulation result was limited to AWGN channel model, response of non-fading channels condition like Rayleigh, Nakagami and Rician should also be investigated.
- The data rate and reliability of wireless communication links can be enhanced by using multiple antennas at both ends, thereby creating MIMO channels should be investigated.

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