PERFORMANCE ANALYSIS OF MODULATION TECHNIQUES IN 5G COMMUNICATION SYSTEM

Ahmed Salah Aldeen Ali SAHAB

2021
MASTER THESIS
ELECTRICAL-ELECTRONICS ENGINEERING

Thesis Advisor
Assoc. Prof. Dr. Muhammet Tahir GÜNEŞER

PERFORMANCE ANALYSIS OF MODULATION TECHNIQUES IN 5G COMMUNICATION SYSTEM

Ahmed Salah Aldeen Ali SAHAB

Karabük University
Institute of Graduate Programs
The Department of Electrical-Electronics Engineering
Prepared as
Master Thesis

Thesis Advisor:
Assist. Prof. Dr. Muhammet Tahir GÜNEŞER

August 2021
KARABUK

I certify that in my opinion the thesis submitted by Ahmed Salah Aldeen Ali SAHAB titled "PERFORMANCE ANALYSIS OF MODULATION TECHNIQUES IN 5G COMMUNICATION SYSTEM" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Muhammet Tahir GÜNEŞER …………………
Thesis Advisor, The Department of Electrical-Electronics Engineering

This thesis is accepted by the examining committee with a unanimous vote in The department of Electrical-Electronics Engineering as a Master of Science thesis. 5/08/2021

Examining Committee Members (Institutions)		Signature
Chairman	: Assoc. Prof. Dr. Turgut ÖZTÜRK (BTU)	....
Member	: Assoc. Prof. Dr. M. Tahir GÜNEŞER (KBU)	....
Member	: Assist. Prof. Dr. Cihat ŞEKER (KBU)	....

The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Institute of Graduate Programs, Karabük University.

Prof. Dr. Hasan SOLMAZ ....
Head of the Institute of Graduate Programs

"I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well."

Ahmed Salah Aldeen Ali SAHAB

ABSTRACT

M. Sc. Thesis

PERFORMANCE ANALYSIS OF MODULATION TECHNIQUES IN 5G COMMUNICATION SYSTEM

Ahmed SAHAB

Karabük University
Institute of Graduate Programs
The Department of Electrical-Electronics Engineering

Thesis Advisor:
Assist. Prof. Dr. Muhammet Tahir GÜNEŞER
August 2021, pages 55

In recent years, there has been a world-wide search for both higher data rates and support for machine-to-machine communication (M2M), as well as the Internet of Things (IoT) in 5G mobile communications, also the main services in 5G such as enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-latency Communication (URLLC), and massive Machine Type Communication (mMTC) will impose the requirements on the 5G air interface.

The main modulation schemes that used in 4G is Orthogonal Frequency Division Multiplexing (OFDM), This scheme not capable of supporting these requirements of 5G because it has sideband leakage, as well as a high Peak to Average Power Ratio (PAPR) and low Data rate. To overcome this, there are several modulation schemes have been proposed. In this thesis, an analysis and comparison will be conducted of the Universal Filter Multi Carrier (UFMC), Filter Bank Multi Carrier (FBMC), and the Filtered Orthogonal Frequency Division Multiplexing (f-OFDM) with OFDM.

In order to achieve a detailed analysis, we will not only introduce the basic theory of these modulation schemes but will also show the characteristics of each modulation scheme. In addition, performance comparison in terms of the Average Power Ratio (PAPR) and the Peak to Power Spectral Density (PSD), in addition to the power of transmitted signal and Bit Rate were provided. Also Bit Error Rate (BER) in different cases examined. Mathematical analysis and characterizations are verified by employing MATLAB. The result demonstrates advantages and disadvantages for each modulation scheme. UFMC indicates the best BER among both modulation schemes. FBMC, demonstrates to be most promising which close to OFDM in BER with advantage of better PSD and Data Rate. Finally, some concepts that need to be discussed are illustrated.

Keywords : PSD, PAPR, OFDM, FBMC, UFMC, f-OFDM, 5G, Modulation Techniques.

Science Code : 92705

ÖZET

Yüksek Lisans Tezi

5G HABERLEŞME SISTEMLERINDE MODÜLASYON TEKNIKLERININ PERFORMANS ANALIZI

Ahmed SAHAB

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Elektrik Elektronik Mühendisliği Anabilim Dalı

Tez Danışmanı:
Dr.Öğr.Üyesi. Muhammet Tahir GÜNEŞER
Ağustos 2021, sayfa 55

Son yıllarda dünya, 5G mobil iletişimde makineden makineye iletişim (M2M), Nesnelerin İnterneti (IoT) desteğinin yanı sıra daha yüksek veri hızları ve ayrıca gelişmiş Mobil Geniş Bant (eMBB) gibi 5G'deki ana hizmetler arıyor Büyük Makine Tipi İletişim (mMTC) ve Ultra Güvenilir Düşük Gecikmeli İletişim (URLLC), 5G hava arayüzüne gereksinimleri empoze edecektir.

4G'de kullanılan ana modülasyon şemaları Ortogonal Frekans Bölmeli Çoğullamadır (OFDM), Bu şema, 5G'nin bu gereksinimlerini destekleyemez çünkü bir yan bant sızıntısı, yüksek Pik-Ortalama Güç Oranı ve düşük Veri hızı vardır. Bunun üstesinden gelmek için, birkaç modülasyon şeması önerilmiştir. Bu tezde Filter Bank Multi Carrier (FBMC), Universal Filter Multi Carrier (UFMC) ve Filtered Orthogonal Frequency Division Multiplexing (f-OFDM) OFDM ile analiz ve karşılaştırmalardır.

Ayrıntılı bir analiz elde etmek için, bu modülasyon şemalarının yalnızca temel teorisini tanıtmakla kalmayacağız, aynı zamanda her modülasyon şemasının özelliklerini de göstereceğiz. Ayrıca Peak to Power Spektral Yoğunluk (PSD), Ortalama Güç Oranı (PAPR), iletilen sinyalin gücü ve Bit Hızı açısından performans karşılaştırması sağlanmıştır. Ayrıca farklı durumlarda Bit Hata Oranı (BER) incelenmiştir. Matematiksel analiz ve karakterizasyonlar MATLAB uygulanarak doğrulanır. Sonuç olarak her bir modülasyon şeması için avantajları ve dezavantajları gösterir. UFMC ile en iyi BER elde edilmektedir. FBMC ice daha iyi PSD ve daha yüksek very hızıanalizi ile BER değeri OFDM'ye en yakın ve performansı yüksek metod olarak görülmektedir. Ayrıca bu çalışmada tartışılması gereken bazı kavramlar gösterılmış.

Anahtar Kelimeler: PSD, PAPR, OFDM, FBMC, UFMC, f-OFDM, 5G, modülasyon teknikleri,

Bilim Codu **:** 92705

ACKNOWLEDGEMENT

First of all, I greatfull to ALLAH for everything gave it to me, after that I would like to avail myself of this opportunity to express my thanks and appreciation my supervisor Dr. M. T. GÜNEŞER who guided me and helped me throughout this work. I wish to extend my thanks to Dr. Cihat ŞEKER who is one of the staff at the Department of Electrical and Electronic Engineering for his efforts and his givings. I would also like to express my thanks all the faculty members who have taught us. It's my pleasure to thank my family for supporting me. Also special thanks to my friends whose pushed me to the best. Finally, thanks for all my colleagues and people who I know for their supports and contributions.

CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

SYMBOLS AND ABBREVITIONS INDEX

ABBREVITIONS

5G	: 5th Generation of cellular communications
5GNOW	: 5th Generation Non-Orthogonal Waveforms
AWGN	: Additive White Gaussian
BER	: Bit Error Rate
CDMA	: Code division multiple access
CMT	: Cosine-Modulated Multitone
CP	: Cyclic Prefix
DFT	: Discrete Fourier Transform
FBMC	: Filter Bank Multicarrier
FDMA	: Frequency division multiple access
FFT	: Fast Fourier Transform
IDFT	: Inverse Discrete Fourier Transform
IFFT	: Inverse Fast Fourier Transform
IMT	: International Mobile Telephony
ITU	: International Telecommunication Union
LTE	: Long Term Evolution
mMTC	: Massive Machine Type Communications
OFDM	: Orthogonal frequency division multiplexing
OoB	: Out-of-Band Emission
OQAM	: Offset QAM
PAPR	: Peak-to-Average Power Ratio
PSD	: Power Spectral Density
QAM	: Quadrature Amplitude Modulation
SNR	: Signal to Noise Ratio
TDMA	: Time division multiple access
UFMC	: Universal Filter Multicarrier

PART 1

INTRODUCTION

In mobile wireless telecommunications, the standardization activities began with analog standards, which began to be implemented in the 1980s. New generations have been emerging at a pace of approximately every 10 years, so as to keep up with the demand of consumers, which has been increasing exponentially. The transition from analog to digital started with second generation (2G) systems as well as the use of mobile data services. Due to the 3G digital evolution, it was possible to make video calls on mobile devices, in addition to the global positioning system (GPS). The 4G networks pushed these data service limits further by providing efficient usage of time-frequency resources through the use of an air interface that is known as Orthogonal Frequency Division Multiplexing Access (OFDMA) [1].

Future wireless systems, presently represented by the generation of 5G, must be capable of offering services to individuals who travel constantly, must communicate between work and home, work with companions and family, and visit malls and relaxation facilities. While performing these abovementioned human tasks, these individuals use their cell phones to connect with the Internet, making use of venture time for assignments that are business-related, as well as diversion, or connecting to online networks. As a result of this, agility, and most often, very high speed, should be among the main capabilities that will be offered by the 5G network, as it is not able to be effectively delivered by the present generation, 4G [2].

Performance parameters, which include things such as network availability, peak data rate, spectral efficiency, and latency of 5G technologies are probably tens and thousands of times better than 4G. Apart from the low energy consumption, the cost is also attractive. In addition, 5G should allow machine to machine (M2M) communication with extremely low cost and extremely high reliability, while at the same time supporting long battery life. In order to facilitate these criteria, spectral efficiency, signal efficiency, bandwidth and coverage must be substantially enhanced compared to 4G. More 5G enabled technologies are expected to fix these issues. Some of them include network densification, increased bandwidth, increased spectrum efficiency and a new air interface to reach the data rate and capability of the 5G network. The air interface includes waveforms, multiplexing diagrams, modulation schemes, and coding schemes to minimize latency air links, increase spectral efficiency, communication density, throughput, area capacity density, and energy efficiency. Even though OFDM is presently the most widely used multi-carrier technology used in the networking wireless standard, it still has some disadvantages, such as the utilization of the CP, which costs the spectral efficiency of the waveform, and large side lobes such as limit the use of the spectrum. OFDM often necessitates very strict time synchronization to preserve the orthogonality between different users. It is envisaged that many nodes will be able to connect using the mMTC of the 5G network. Usually, all user nodes asynchronously pass the data form within the narrow range. The waveform, which involves precise synchronization to be able to achieve the interference-free communication, is not suitable for the mMTC. This can result in substantial interference between user nodes. Additionally, the peak-to-high average power ratio (PAPR) is a major hurdle that exists in the OFDM, which drastically decreases the output, as well as the efficiency of the non-linear amplifier of the OFDM. Therefore, the OFDM is unlikely to be considered for mobile communication systems in its next generation.

The big names in the wireless industry and research institutes have therefore conducted research to resolve the shortcomings in OFDM for 5G. Various types of modulation schemes have been proposed for this purpose, including pulse modulation (i.e. subcarrier based filtering), sub band filtering, etc. however, a lack of a detailed and fair comparison between these candidate waveforms. Based on this, we are excited to review some of the proposed candidate reform plans to evaluate their performance. We select FBMC, UFMC and f-OFDM modulation schemes from the suggested candidate modulation schemes. Performance is evaluated by proposing the same structure for CP-OFDM.

The aim of the current research was to conduct an evaluation and examination of the performance of FBMC, UFMC and f-OFDM compared to OFDM. The general goal is accomplished by means of the following basic steps:

- Study and analyze the advantages and the disadvantages of the OFDM.
- Research and review of FBMC, UFMC and f-OFDM.
- Provide the mathematical history and block diagrams of the four forms.
- Evaluating these forms through numerical assessment and simulation using the Matlab program.
- Based on numerical assessment and simulation, the four forms are evaluated in accordance with the proposed system.
- Finally, the preferred form for 5G is recommended from the results obtained.

We will use the following steps to achieve the goals outlined above. First, study the specifications of 5G networks and their differences from previous generations. Second, evaluations starting with our need to use advanced generations, including the need to establish various types of modulation, then researching the types of modulation in theory and in terms of mathematical equations, and then developing the method so that the types of modulation are in the same context so that we can calculate the different parameters of these types at the same time; Then explain the mathematical equations used to calculate these coefficients.

After that, the Matlab program is used to build a method to research the different parameters, which are the PSD, the SNR, the transmitted power in time domain, the PAPR and finally the bit rate, and this research is done by drawing detailed diagrams showing the difference between the three forms of modulation, from which we can make a reasonable comparison, then we will analyze and review these diagrams, finally the conclusion to the research, as well as future work to be conducted.

The remainder of this research was arranged in the following manner. Introduction to part 1 This part deals with the context, goals and research methodology. part 2 examines background of wireless generations, the basics, specifications and enabling 5G technology. The basics of the candidate modulation format, and the mathematical model and performance analysis are discussed in part 3. Simulation results comparing candidates are discussed in part 4. Finally, the conclusion to the research, as well as the recommendations for future studies to be conducted, are presented in part 5.

PART 2

OVERVIEW OF WIRELESS COMMUNICATION

2.1. BACKGROUND

By any measure, wireless communication is the fastest growing segment of the communications industry. As such, it caught the interest of the media and the imagination of the public. Exponential growth has been observed in cell phones over the past 10 years, and this development is continuing all over the world, with more than a billion mobile phone users expected in the near future. Cell phones have, in effect, evolved into a vitally important business tool and implementation of daily life in most developed countries, and in many developing countries they are rapidly replacing old wireline networks [3].

The presence of an increasing number of wireless networks that are used for many different purposes greatly complicates the allocation of frequency bands to particular requirements and purposes around the electromagnetic spectrum [4].

Mobile communication technology is a field that is experiencing a groundbreaking paradigm change, that has been undergoing quite a significant transformation and is very commonly used in order to connect to people all across the globe. In very remote areas of the world, in places where even things such as electricity cannot be taken for granted, people are able to connect and interact as a result of mobile communication technology, which has progressed and expanded from analog voice assistance into powerful systems that are able to now deliver thousands of applications, with various uses, to billions of consumers around the world. [5] Figure 2.1 presents a depiction of the timeline for the different network communication systems, which are known as generations. As a result of these systems, modern wireless communication systems have been continuously used as a tool to be used in meeting the increasing needs of humans [5].

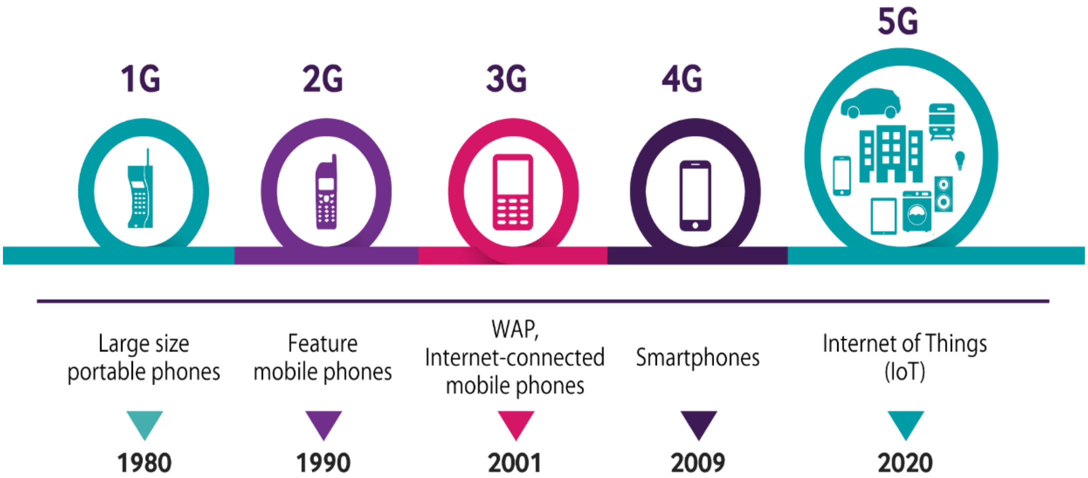


Figure 2.1. Evolution of mobile communication from 1G to 5G [6].

In mobile communications, the 1st generation made use of analog transmission, and it used analog transmission for speech services. [7] the main technologies being AMPS (Advanced Mobile Phone System) developed in North America. NMT (Nordic Mobile Telephony) jointly developed by, at that time, government-controlled public-telephone network operators in the Nordic countries and TACS (Total Access Communication System) used. for example, in the United Kingdom first-generation mobile communications systems were restricted to voice services and for the first time made mobile telephony available to ordinary people [8].

The 2nd generation, which came into use in the early 1990s, introduced the use of digital radio transmission. Although voice was still the target service, using digital transmission also permitted restricted data services for second generation mobile communications systems. In the beginning, various different 2nd-generation technologies, which included the Global System for Mobile Communication (GSM) were jointly developed via collaboration by many European countries, whereas Digital AMPS (D-AMPS), as well as Personal Digital Cellular (PDC) were developed and only used in Japan, and CDMA-based IS-95 technology was developed at a somewhat later point [8].

As time passed, the GSM spread across Europe, and then to other areas of the world, and it gradually ended up dominating the technologies of the 20th century. Mainly as a result of the success of the GSM, the system of the 2nd generation have also allowed mobile telephones to evolve from something that had been used by a relatively small portion of individuals into a networking tool that has now become a necessary, and even vital part of life for the majority of the population of the world. Moreover, today, in several areas of the world, the GSM is not just the dominant technology, but in some cases, it is actually the only accessible mobile communication, regardless of the introduction of the technologies that were provided by the 3rd and 4th generations [8].

The 3rd generation, which is also known as 3G, began in early 2000, and with this generation, a serious move toward the use of high-quality mobile broadband was observed, which allowed for fast wireless access to the Internet. This was specifically facilitated by a 3G evolution that is known as High-Speed Packet Access (HSPA). Additionally, although all of the earlier mobile communications technologies were optimized for paired-spectrum operation, which entailed a separate spectrum for device-to-network and network-to-device links, as a result of the Frequency-Division Duplex (FDD), the very first implementation of unpaired-spectrum mobile communication, which was based on the Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) technology that was developed by the Chinese, and was based on the Time Division Duplex (TDD) was seen with 3G [9].

Presently, we are experiencing the 4th generation (4G) of mobile connectivity, which is embodied by long-term evolution (LTE) technology, and then followed by HSPA; hence, it offers much higher quality and much improved mobile broadband experience with regards to higher attainable end-user data speeds. This is provided as a result of a transmission that is OFDM-based, which allows for bandwidth transmission that is wider, in addition to multi-antenna technologies that are more advanced. Furthermore, while 3G allows for mobile communication in the unpaired spectrum as a result of a particular radio-access technology, known as TD-SCDMA, the LTE supports the FDD service, as well as TDD service, that is to say, service in both paired and unpaired spectra that is within single-standard radio-access technology. [5] By means of the LTE, convergence of the world into one single global technology for use with mobile communication has occurred, which is used by practically all mobile network operators and is accessible for both paired and unpaired spectra. Later on, the evolution of the LTE also expanded mobile communication network operations into unlicensed spectra [9].

OFDM is among the modulation types that are used by modern wireless and telecommunications systems. This system uses a technique by which it encodes digital data on a number of carrier frequencies to form a common type of digital broadband communication, which is has been used commonly to attain high data rates, as well as withstand multi-path fading in wireless communication technology. OFDM is currently being used worldwide to attain the high data rates that are now required for data-intensive applications, and it is currently used in audio, cellular, and 4G mobile network technologies. Its modulation format has been utilized in the Wi-Fi arena, such as in 802.11a, 802.11ac. OFDM makes use of the Cyclic Prefix (CP) to minimize its general spectral efficiency. Its basis is that of the concept of the modulation of each data stream on sub-carriers and then splitting the high-bit data stream into several lower bit-rate data. Conventionally, the basic block of OFDM makes use of the Fast Fourier Transform (FFT). Multicarrier modulations, which are also known as schemes, capable of delivering a high data rate.

Preliminary interest and the discussions that have taken place with regards to the potential 5G standard have grown over the past year have evolved into a full-blown conversation that has gained not only the attention, but also the imagination of researchers and engineers all across the globe. [10] There are some suggestions for the future of 5G mobile communication technologies, which may be able to offer some additional benefits to the modern cellular system, such as the use of UFMC, FBMC, f-OFDM, as well as Generalized Frequency Division Multiplexing (GFDM).

2.2. LITERATURE REVIEW

A lot of researchers have been studied the 5G system from many points, some of them studied the modulation schemes and they compared them to OFDM, here some of the works that studied.

- In reference [5], the author’s comparing between FBMC and OFDM in terms of Frequency response and BER vs SNR in different types of QAM over the AWGN channel, they proposed FBMC is a more suitable solution. Also, the comparison between FBMC, f-OFDM and OFDM is presented in [11] which is compares FBMC, f-OFDM and OFDM in terms of PSD and BER vs SNR, they also make comparing in AWGN channel, they concluded that f-OFDM is very closed to OFDM, benefits of UFMC when compared to OFDM were presented, in part, in [12], they compared their power spectral density and BER vs SNR, they proposed UFMC as best chose.
- A much more extensive comparison was proposed in [13], they comparing between UFMC and FBMC referenced to OFDM in terms of PSD and BER vs SNR under the ETU channel, they concluded that FBMC is better. However, this work is limited because they are using also AWGN channel and insert CP in UFMC to withstand ISI when it is subjected to a multipath channel.
- Pooja Rani et al. [14], provides a review of multi-carrier modulation techniques that used in 5G, they also studying and comparing between FBMC, UFMC and OFDM in terms of PSD and PAPR but in a theoretical way and obtain numerical results, the limit of this work is the comparison in a theoretical way without graphs, and didn’t obtain very important parameters BER vs SNR.
- In [15] performance analysis of UFMC was performed and compared with that of OFDM and FBMC in terms of PAPR, they found that the PAPR of UFMC is better than others, the limitation of this paper does not include other parameters to compare also comparing it under AWGN channel.

2.3. BASICS OF 5G SYSTEM

Mobile communication has become a commodity every day. In recent decades, its development has comprised the use of expensive technology for a only a select few individuals when compared to the commonplace systems that are used today by the majority of people around the world. Mobile broadband is presently, and will remain a significant part of the future cellular networking; however, future wireless networks will, to a large extent, have a much wider variety of use cases. [13]

While the 1st to the 4th mobile network generations interconnected people via the provision of better voice services and faster data services, there is an expectation that 5G will be able to do more and connect much better. [16] 5G was designed in line with meeting the very extensive increase in data and communication that exists in the digital world of today, and the IoT, with billions of devices connected, and the inventions of tomorrow. Initially, 5G would be able to operate in conjunction with the existing 4G networks, prior to an introduction of completely stand-alone networks, which would occur in subsequent launches as well as coverage expansions. In addition to the fact that it will have provide faster communication and have greater capacity, its fast response time, which is referred to as latency, is a significant benefit of 5G. Latency refers to the time that it takes for a device to respond to another device over a wireless network. The 3G networks exhibited a normal response time of about 100 ms, while that of 4G was approximately 30 ms, and 5G would have from low to 1 ms, which would almost immediately open up a whole new world of connected apps [17].

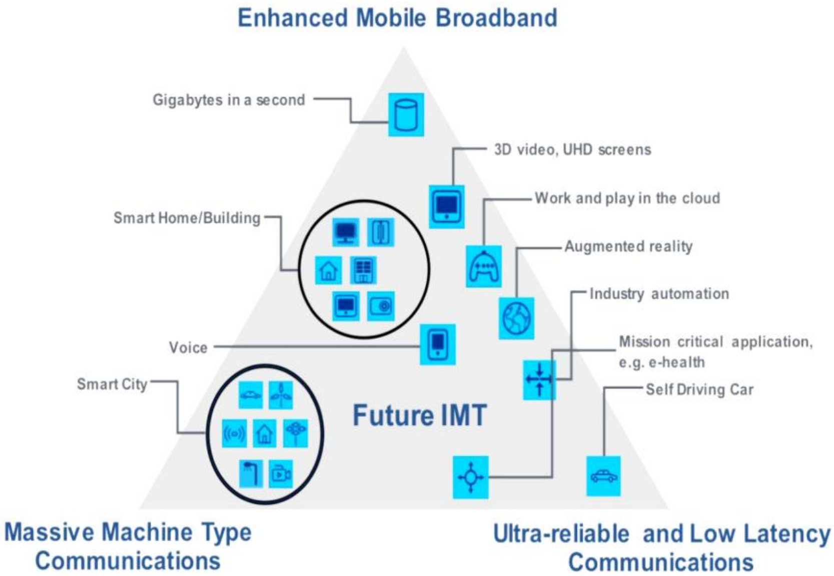


Figure 2.2.Usage scenarios of IMT for 2020 and beyond [6].

IMT is expected to extend and support various usage scenarios and applications beyond the existing IMT by 2020 and beyond. As seen in Figure 2.2.[6] In addition, a wide range of technologies will be closely related to these planned different applications and use scenarios for IMT for both 2020 as well as beyond. Mobile systems of the future will be extremely heterogeneous and will be set apart by their vast array of possible applications for wireless communication, which will range from enhanced Mobile Broadband (eMBB) over Ultra-Reliable Low Latency Communications (URLLC) to enhanced Machine-Type Communications (eMTC). [18] The use scenarios for IMT for both 2020 as well as beyond include the following:

Enhanced Mobile Broadband (eMBB): Mobile Broadband in used in cases of the use of human-centric for access to services, content, and data on the Internet. There will be continuing growth for the demand for mobile broadband, which will contribute to an increase in the use of mobile broadband. [19] The eMBB use scenario would also involve areas and specifications for new applications, as well as the mobile broadband applications that existing today, to improve performance and provide an increase in consistent user experience. [20] Such a use scenario would include a range of scenarios, which would include hotspots and wide-area coverage with a variety of requirements. With a hotspot, that is to say, an area that has a high user density, extremely high traffic capacity is necessary [21].

Ultra-Reliable Low-Latency Communication (URLLC): The use case for URLLC has very specific specifications for capabilities, which include the latency, throughput, and availability. Some examples of this would be the wireless control of industrial production or manufacturing processes, remote medical surgery, smart grid delivery automation, transport protection, etc [21].

Enhanced Machine-Type Communication (eMTC): The use case for eMTC is characterized by an extremely large number of devices that are connected to each other, which usually transmit a relatively low amount of non-delay-sensitive data. They must be low-cost devices that exhibit a lengthy battery life.[22] Additional use cases, which are not currently foreseen, are likely to arise. Flexibility would be required for potential ITMs to adjust to any new use cases exhibit a vast range of specifications [21].

IMT systems of the future will encompass a wide range of various features, and depending on the given circumstances, as well as the varying requirements of many different countries, it will be necessary for the IMT systems of the future to be built in a highly scalable way, so that it is not necessary to introduce all of the features in every network [21].

As was explained above, although all of the key capabilities will be, to some extent, applicable in most of the use cases, the significance of some of the key capabilities may vary a great deal depending on the use cases or scenarios. Figure 2.3 illustrates the importance that each of the main capabilities has for use scenarios, such as eMBB, being ultra-reliable, and having low-latency communication as well as massive machine-type communication. This will be achieved via the use of an indicative scale that will consist of three measures, comprising high, medium and low [21].

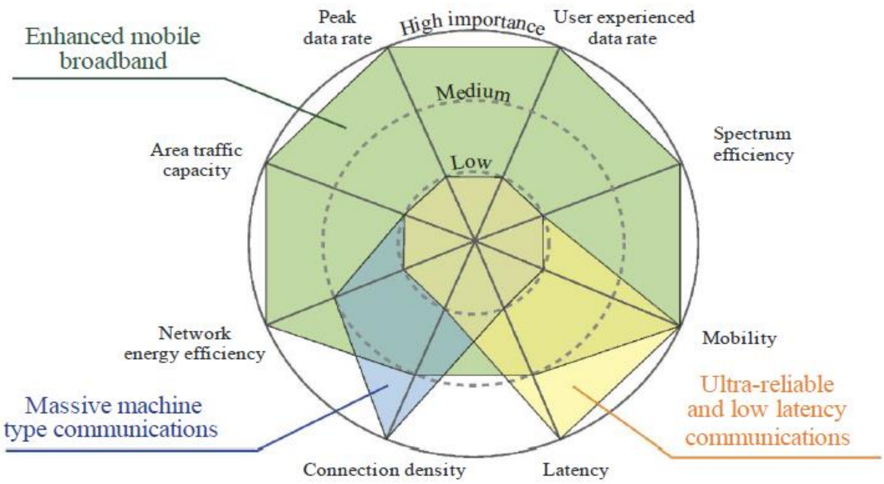


Figure 2.3. The importance of key capabilities in different usage scenarios [6].

Once the mobile broadband scenario has been improved, the area traffic capacity, user experience data rate, peak data rate, spectrum and energy efficiency, and mobility will all be highly important; however, the user experience data rate and mobility will not have equal importance in every use case at the same time. As an example, in mobile hotspots, it is expected that users will encounter higher data rates but will also experience lower mobility when compared to the case of wide-area coverage.

In some of the low-latency and ultra-reliable communication scenarios, the most important aspect will be low latency; for example, in applications that are safety-sensitive. A capability such as this will also be necessary in some cases that require high mobility; for example, in things such as transport safety, while, as an example, higher data rates may be of less importance [21].

In a scenario such as massive machine-style communication, it is necessary to have high connection density, so as to accommodate the tremendous number of devices that will be connected to the network, which are only able to be transmitted periodically, at a bit rate that is low, and have very low or very zero mobility. For a use scenario such as this, a low-cost device that has a long operating life is an essential requirement [21].

It is possible that other capabilities may also be required for IMT-2020, which, in turn, would make IMTs of the future much more flexible, reliable, and secure, while at the same time providing a wide range of services in the intended use scenarios:

2.3.1. Flexibility of spectrum and bandwidth

The spectrum and bandwidth flexibility of the system pertain to the flexibility that the system design has in accommodating varying scenarios and, more specifically, its ability to function at a full range of frequencies, which include frequencies that are higher and channel bandwidths that are broader than those that are currently the case [1].

2.3.2. Reliability

The reliability of the system pertains to the ability of the system to provide a service that has a very high degree of availability [1].

2.3.3. Resilience

The resilience of the system pertains to the ability that the network has to continue functioning in a correct manner, both during and/or after a disturbance that is either natural or man-made, such as, for example loss of main power.

2.3.4. Privacy and Security

The security and privacy of the system pertains to a variety of things, such as the encryption and the integrity protection of user data, as well as signaling, in addition to the privacy of end-users and preventing the unauthorized tracking of these users, and network security against theft, hackers, man in the middle of attacks, denial of service, and so on [23].

2.3.5. Operational lifetime

The operational life time of the system pertains to the operating time per energy storage capacity, which is of specific importance for machine-type devices that require an extremely long battery life, that is to say, of more than 10 years, which are quite difficult to regularly maintain as a result of physical or economic complications [23].

2.4. 5G ENABLING TECHNOLOGIES

2.4.1. Massive MIMO

At the core of the achieving higher spectral efficiency in a cellular system lies advanced MIMO techniques. Multi-user MIMO (MU-MIMO) is able to provide enhanced multiplexing gains, and while it has been included in the 3GPP L TEA advanced standard, [22] MU-MIMO remains an evolving technology, which has thus been upgraded to the latest MIMO technology. The system comprises hundreds of antennas, which are known as ‘a large array’ of antennas. The main goal to be provided by this technology is to enhance the benefits of MIMO, yet on a much larger scale. Marzetta [24] showed that an extremely large number of antennas located at the base station actually out-numbered the amount of consumer terminals, and that it was possible for, fast fading, intercellular interference, and uncoordinated noise to be observed. The MIMO system is massive, and it serves tens or hundreds of user terminals via the use of hundreds of antennas located at the base station, which are all at the same time-frequency slot. The MIMO is also known as the hyper MIMO, full dimension MIMO, or large MU-MIMO system.

It is expected that the utilization of antennas in the MIMO system will be low-cost as well as efficient. Selection of the antenna relays in the requirements of the channel, as well as the size of the antennas, via the reduction of the size as a result of increased power, is thus transmitted from the transmitter into space [24].

As a result of the increase in the number of antennas used at the base station, the spectral efficiency is thus improved, and reliable communication can be obtained via utilization of these systems. Accomplishing the transmission of data that occurs between the user terminals and the base station is performed via the uplink and downlink. In the MIMO system, the uplink process comprises a combination of the signals that have been received, which provide large array gains [25].

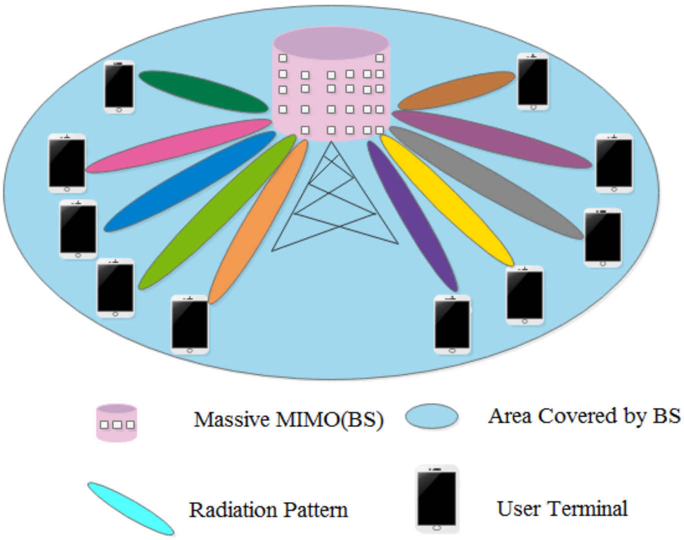
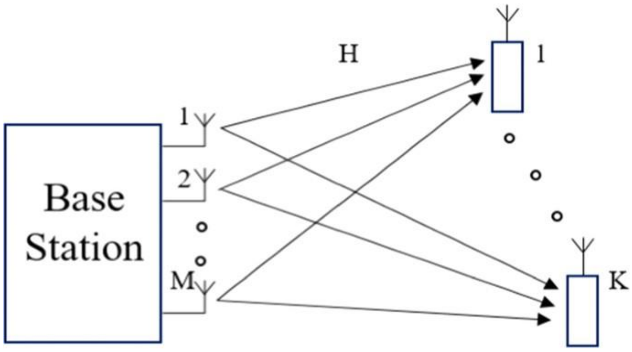


Figure 2.4. Base station antennas are directed to each user terminal using Massive MIMO Technique.

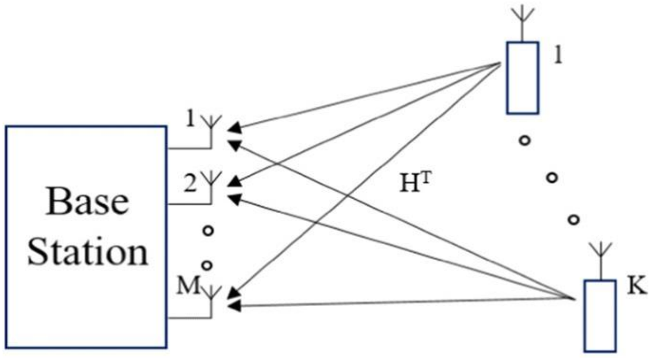
In the downlink process, as is illustrated in Figure 2.3, the base station comprises a high number of antennas, which are used to direct the energy beam toward the exact direction where the individual user terminal is located. As a result of this, it is possible to reduce the magnitude, as well as the strength of the signal, which, in turn, allows the system to achieve high energy efficiency [24].

Massive MIMO systems utilize a processing technique that comprises a very simple linear signal. In this technique, linear pre-coders are utilized in the process of downlinking and, while linear decoders are utilized in the process of unlinking, and the huge antenna arrays that are utilized at the base station are much larger than those utilized at the user terminals, and the base station and user terminal are orthogonal in formation, and the user terminal is orthogonal to each other. [24]

The basic concept of Massive MIMO can be seen in Figure 2.4, where the base station uses M antennas for spatially multiplexed terminals k < < M single antenna terminals. Attaining success with such a spatial multiplex, for both unlinking and downlinking, is the result of a number of important principles. Among the most important of these is the requirement that the base station has enough knowledge of the propagation channel, in both of the directions in which efficient uplink detectors and downlink precoders can be based [26].



(a) Downlink



(b) Uplink

Figure 2.5. Simplified multi-user Massive MIMO system model.

2.4.2. Millimeter (mm)-Wave Signals:

It will be necessary for 5G systems to provide significant improvements in network capacity to satisfy the increasingly rising demand for traffic. 5G will bring a variety of new technologies, which will make it possible for both the networks and devices to better utilize the limited number of spectrum resources.

Insufficient to maintain pace with the increase in mobile data requirements, which is expected in future to reach as high as gigabits per second.

It is only possible for this to be accomplished using a much larger spectrum than that which is currently available for IMT systems via the framework of the International Telecommunications Union (ITU).

As a result of the high fragmentation that exists within the existing spectrum in various regions around the world, as well as the long time that is required for reframing of the spectrum, the use of frequency bands that are both broader and contiguous, and at higher frequencies, will be a successful step forward.

Millimeter (mm)-wave bands that range of 30 to 300 GHz, in which the usable bandwidth is a great deal wider than that of the cellular networks that are used today, would be suitable for 5G communication systems [22].

It is indeed true that the spectrum that is available at these frequencies may be as much as 200 times higher than all the cellular allocations presently available, which are under 3 GHz at the current time. Additionally, combining the very small wavelengths that exist in the mm-wave bands with the developments in the low-power CMOS RF circuits will allow for a great deal of miniaturized antennas to be put into small dimensions. Such multiple-antenna systems can then be used in the creation of very high electrically operated arrays, which are produced at the base station, within the skin of a cellular telephone, or possibly, even in a chip. As a result of the limited range that mm-wave signals possess, it would be necessary for 5G systems to have a high number of picocells, which would have a radius or about 100 to 200 m, and each one would utilize high directional antennas to thus increase the range and spatial separation [22].

By combining these dramatically increased bandwidths with the spatial multiplexing gains of the high-dimensional multiple-antenna transmissions, mm-wave systems would be able to deliver the possibility of an enormous increase in capacity relative to existing commercial networks [22].

2.5. NEW AIR INTERFACE

2.5.1. Non-Orthogonal Multiple Access (NOMA)

Non-orthogonal multi-access (NOMA) has recently gained a great deal of attention, as it is an exciting and novel multi-access scheme to be used for LTE enhancement as well as 5G systems. In NOMA, the multiplexing of power-domain users is implemented, which exploits the channel disparity that exists between users, to increase the efficiency of the spectrum, and thus depend on much more advanced receivers for the separation of multi-user signals on the receiver side. Actually, NOMA, as is indicated in its name, is a method that is both non-orthogonal and multi-access, in which there is an intentional introduction of the mutual interference between users [26].

Also in NOMA, more than one user can be paired, and thus share common radio services, in either time, or via the frequency code. [27] From an information-theoretical standpoint, it is well-known that non-orthogonal consumer multiplexing that uses superposition coding (at the transmitter) as well as successive interference cancellation (SIC) (at the receiver) does more than simply outperform orthogonal multiplexing, it is additionally optimal with regards to achieving the capacity region of:

downlink or a broadcast channel

uplink or a multiple-access channel.

On the contrary, NOMA has been able to capture the evolution of system processing capacities, which, as is known, generally follows Moore's law, via placing focus on receiver processing that is more advanced. [28] For intercellular interference (ICI) mitigation, network-assisted interference cancellation and suppression (NAICS), which includes SIC, was discussed, and reported on in LTE Release 12. Hence, NOMA presents a promising direction for the expansion of the Third Generation Partnership Project (3GPP) work on NAICS, as it is expected to be much simpler, from viewpoint of synchronization, as well as from that of signaling, for the application of more advanced receivers to intracellular, rather than intercellular interference. As an example, for downlink NOMA, the signals of the users of multiplexed NOMA are sent from the exact same transmitter; hence, there are not any synchronization problems and problems with overhead signaling can be minimized, because the information related to the decoding and demodulation of the other users, which is multiplexed with one specific user, can thus be exchanged with the information of that user. Currently, downlink NOMA is being discussed as a study item for LTE Release 13 at 3GPP, under the title ‘Downlink multiuser superposition transmission’ [29].

In NOMA, the URLLC UEs transmit from the same mini-slot that the packet is generated from; hence, there is minimal access latency, which is limited to a LU of 1 mini-slot. On the other hand, it is known that URLLC signals can cause interference with the transmission of eMBB signals over the entire time-frequency resource plane. As a result of the latency constraints in URLLC, it is necessary to treat the eMBB signals as noise in the process of decoding the URLLC packets in the ENs. On the opposite, a variety of techniques can be adapted to resolve the interference with the URLLC signal [19].

2.5.2. Orthogonal Multiple Access (OMA)

OMA is at the center of both the previous and the current wireless networks, and multi-access time-division (TDMA) as well as multi-access frequency-division (FDMA) systems are utilized in 2G (2nd generation) systems, while multi-access code-division (CDMA) systems are utilized in 3G (3rd generation) systems, and multi-access orthogonal frequency-division (OFDMA) systems are utilized in 4G (4th generation) systems. For systems such as these, orthogonal division of the resource blocks into frequency, time, or code domains is necessary; hence minimal interference exists between the adjacent blocks, which makes signal detection must more easy [11].

However, OMA is only able to support a limited number of users because of the limitations that is has with regards to the number of orthogonal resource blocks that it possesses, which restrict both the capacity and the SE of the current networks. To serve both a massive number of extremely different groups of users, and applications, in 5G networks [11].

With Orthogonal Multiple Access (OMA), it is possible to achieve the target quality-of-service guarantees by designing each of the services separately. However, since the types of URLLC and mMTC traffic are typically comprise short and brittle transmissions that occur at time instants randomly, the resources that are statically allocated to these services will, most of the time, remain unused, and thus will be wasted [11].

This thesis focuses on enabling 5G technology, specifically the latest air interface, modulation schemes. From the above-mentioned candidate modulation schemes, we choose UFMC and FBMC to compare their performance with CP-OFDM. This involves the study of mathematical models and transceiver schemes for all the alternatives to be considered. Also included will be a comparative overview of each of these modulations, which will outline their advantages as well as their disadvantages, and explain the ability that they must work in 5G reference scenarios.

PART 3

MODULATION TECHNIQUES FOR 5G SYSTEMS

3.1. BACKGROUND

Mobile broadband traffic is expected to rise by 1000 times over the coming decade. The increasing frequency of bandwidth-hungry applications, including those such as multimedia file sharing and high-definition video streaming has resulted in the need for much higher data speeds as well as low latency connections. When the time comes that 5G is in operation, IoT development will become expedited until such time that IoT applications, including smart home appliances and smart cars, become a part of our daily lives that is the driving force behind things such as artificial intelligence (AI) and virtual reality (VR). The resulting increase in the internet traffic would thus require constant connectivity, in addition to efficient management systems and an infrastructure that is able to support such a high number of number of devices. The performance targets for 5G include such things as a peak data rate of 20 Gbits/s, connection density of 106 devices/km^2, and a latency of 1-ms; hence, this would require enhancement of the new 4G cellular infrastructure. At the center of this progress lies the development of alternative waveforms which will be able to achieve much better spectral efficiency at varying input power levels and, as well, increase bandwidth [30].

Multicarrier modulation is a need for wireless communication in this new age of technology. For this reason, various multi-carrier modulation techniques have been suggested in an attempt to satisfy the growing number of users and the demand for higher data rates. [14] The basic concept of multi-carrier transmission that is used to overcome such a limitation is the division of the data stream into lower data rate K sub-streams, and to then transmit these sub-streams to subcarriers that are adjacent to them, as is illustrated for K = 8 in Figure 3.1 [31].

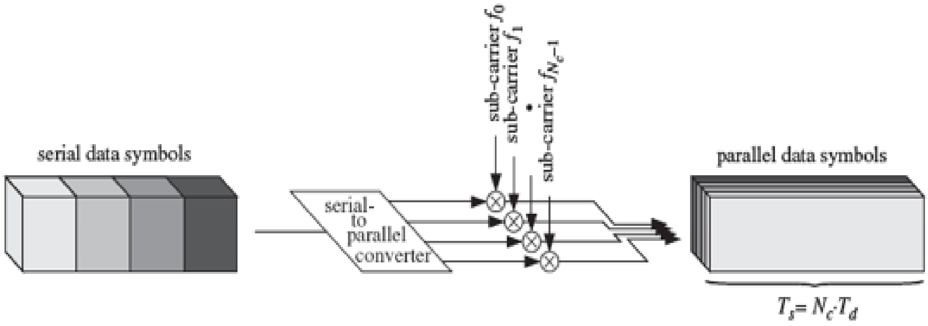


Figure 3.1. The multicarrier concept.

OFDM is currently among the most frequently used modulation techniques. It is used in Long Term Evaluation (LTE) and LTE advanced due to its easy and efficient modulation process and can support high data transmission rates but needs a highly synchronized system and cyclic prefix used in waveform generation to make it less spectral efficient. Next generation wireless communication systems require a modulation technique that can support high spectral efficiency as well as high data transmission rates [30].

New modulation techniques have been proposed for this purpose in the literature. UFMC and FBMC tend to be attractive among the available techniques. In FBMC, each subcarrier is independently filtered, resulting in a reduction in intercarrier interference (ICI). However, filter length is much greater than the OFDM systems, making it unsuitable for fast data transmission of bursts. UFMC is a novel multi-carrier modulation technique with the advantages of OFDM and FBMC. In OFDM, one filter is applied to the whole band, while in FBMC, the filters are applied to each subcarrier individually. In UFMC, the filter is used on sub band blocks, i.e. subcarrier groups [30].

3.2. OFDM TRANSMISSION

OFDM is also considered advantageous because it makes use of overlapping subcarriers to create parallel and modulated data streams. [32] Such an approach is advantageous as it increases the efficiency of bandwidth relative to other approaches. The orthogonal method is used to avoid intercarrier interference. [33] The basic concept of the CP-OFDM system comprises the utilization of narrow subcarriers that are mutually orthogonal. It is the most used waveform that is used in the LTE. Its signal architecture comprises a substantial number of closely-spaced subcarriers, as well as a cyclic prefix (CP) length that is used to transmit the data and control the information [14].

3.2.1. Basic Principle of OFDM

In the transmitter of the OFDM system, all the data symbols are first converted to one parallel stream, which comprises the series stream, via the S/P block. These modified symbols are then mapped to each of the subcarriers using an inverse fast Fourier Transform (IFFT) operation, after which, all the time domain signals are converted from the parallel stream into a series stream, and then to the P/S block. Next, application of the CP is performed, so as to reduce the effect of the inter-symbol interference (ISI). [34] As a final step, amplification of the RF signals is performed using a high-power amplifier (HPA). In the OFDM system, the receiver contains an inverted structure that is relative to the transmitter. Additionally, for restoration of the desired signal, it is necessary to use a very simple CP single-tap equalizer, in the receiver. However, all of the OFDM subcarriers have a high side-lobe power, which results in a reduction in the channel bandwidth [35].

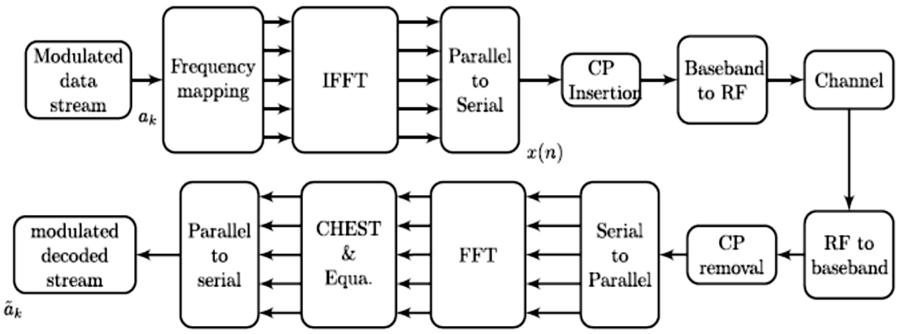


Figure 3.2. OFDM block diagram.

3.2.2. Mathematical Description of OFDM

The mathematical expression of the OFDM signal generated by the modulated N subcarriers can be expressed as: [36]

$$s(t)=\sum_{n=0}^{N-1} d_n e^{j2\pi f_n t} \qquad 0\leq t\leq T_s \tag{3.1}$$

where d_n is complex data symbol that modulates the n-th subcarrier at the modulation interval, while T_s is the time duration of an OFDM symbol which is $T_s = N\, T_d$ and T_d is the serial symbol duration. [31] The orthogonality of the subcarriers shall be ensured if the difference between the neighboring subcarrier frequencies is equal and the subcarriers located at:

$$f_n = \frac{n}{T_s} \qquad n = 0 \ldots \ldots \ldots \ldots \ldots N-1 \tag{3.2}$$

Performance from the IFFT and afterwards there is a cyclic prefix extension of these samples result for: [37]

$$s_m = \frac{1}{N}\sum_{n=0}^{N-1} d_n e^{\frac{j2\pi nm}{N}} \qquad m = -\mu \ldots \ldots \ldots N-1 \tag{3.3}$$

The discreet duration of the cyclic prefix is defined in subsection μ above. This sequence will then be passed through a digital-to-analog converter (DAC), with an output that will preferably be the signal waveform, *s(t)*, with an increased duration, $\grave{T}_s$. Next, the signal will be up converted, followed by transmission of the RF signal to the channel.

Following down-conversion of the RF, the channel output will be the received signal waveform, *r(t)*, that was obtained as a result of the convolution of *s(t)* with the impulse response, *h(t)*, and as added noise signal, *n(t)*, as is given below: [38]

$$r(t) = \int_{-\infty}^{\infty} s(t-\tau)h(\tau,t)d\,\tau + n(t) \tag{3.4}$$

This sequence will then be passed through an analog-to-digital converter (ADC), with an output sequence that is *r(t)* sampled, at a rate of *1/Td*. Since it is believed that ISI only exist in the first of the samples in the sequence that was obtained, these samples will be discarded prior to performing the multi-carrier demodulation. The ISI-free component of *m* = 0, N-1 is a multi-carrier demodulation that will be performed using a FFT. The FFT output will then be a demodulated multi-carrier sequence that consists of complex N symbols.

$$\hat{d}_n = \sum_{n=0}^{N-1} r_m e^{-\left(\frac{j2\pi nm}{N}\right)} \qquad n = 0 \ldots \ldots \ldots N-1 \tag{3.5}$$

Since ISI can be avoided by using the cyclic prefix, each sub-channel can be regarded separately.

Additionally, if it is believed that the fading on each sub-channel was at an ISI when it was removed, the symbol that is received will be $\hat{d}_n$, which is obtained from the Frequency Domain Representation, as is given below:

$$\hat{d}_n = H_n d_n + N_n \tag{3.6}$$

Where H_n is the fading factor, and N_n is the noise of the *nth* sub-channel. After the serial conversion of the output from FFT, the complex data symbols are fed to the QAM demodulator, and the transmitted bits are estimated.

3.3. FBMC TRANSMISSION

The FBMC performs the transmission of data via the filtering of each of the sub-carriers individually, rather than filtering the whole sub-band. The regulation of frequency and time domain localization is conducted via the utilization of prototype filters, resulting in low side-lobe levels when compared to the CP-OFDM. It is possible for the FBMC signal to achieve much better spectral efficiency, because it does not utilize CPs and adheres to the Nyquist rate. When compared to the CP-OFDM, the steep slope at the signal band edges, the low side-lobes, and its ability to use more subcarriers during transmission all result in an enhancement in the spectral efficiency in the performance of the wireless transmitter. [14] That said, the difference between the OFDM and FBMC systems lies in the fact that the FBMC system makes use of offset quadrature amplitude modulation (OQAM). [39]

3.3.1. Basic Principle of FBMC

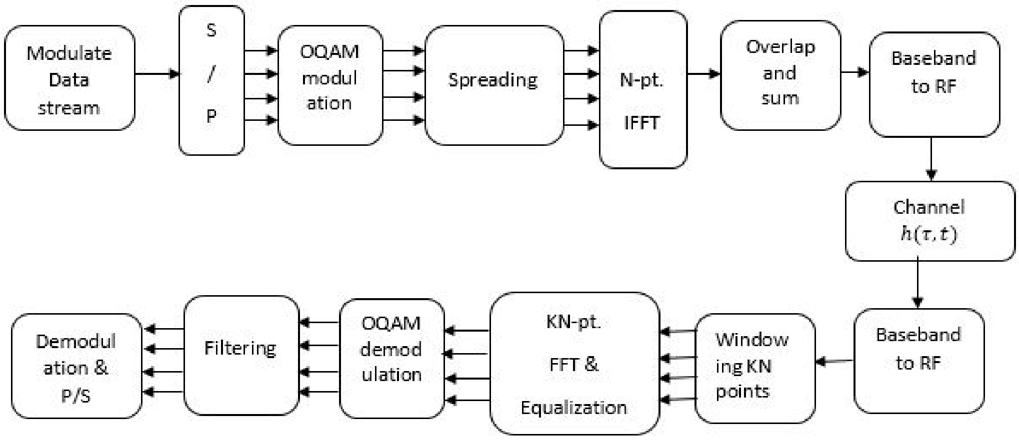


Figure 3.3. FBMC Block diagram.

In the FBMC system, each of the subcarriers is filtered, so as to be able to reduce the OOB spectrum power. In the transmitter of the FBMC system, all of the data symbols are first converted from the S/P series stream to parallel streams. Next, symbols that occur simultaneously are modulated, so as to offset the OQAM signal. [32] Following this, the modulated OQAM signal is then converted into a signal that is filtered by each of the subcarriers, via the use of a synthesis filter bank that consists of an IFFT, as well as a poly-phase network (PPN). [40] As a final step, the antenna then transmits the amplified FBMC signal. [41] The FBMC system receiver comprises an inverted structure that corresponds to the FBMC transmitter. The FBMC system possesses lower OOB power, which corresponds to both the UFMC and OFDM systems, and is an exceptional benefit. However, the FBMC system is characterized by quite high system complexity. Additionally, because FBMC system makes use of a multi-carrier system, it also has a high PAPR [42].

3.3.2. Mathematical Description of FBMC

In a simplistic way, only baseband signals ate used, thus ignoring radio frequency (RF) chains. The signal transmitted by FBMC can be written in a general form [43].

$$s(t) = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} d_{n,m} g_{n,m}(t) \tag{3.7}$$

Where $d_{n,m}$ is the complex symbol modulated by the nth subcarrier during the time index of the symbol m, and $g_n(t)$ represents as

$$g_n(t) = p_T(t) e^{j2\pi n \Delta f t + j\emptyset_n} \tag{3.8}$$

For OQAM-FBMC, the duration of the symbol is reduced by half and $\grave{T} = \frac{T}{2}$, where T is the duration of the QAM symbol.

$$g_{n,m}(t) = p_T\left(T - m\frac{T}{2}\right) e^{j2\pi n \Delta f t} e^{j(m+n)\frac{\pi}{2}} \tag{3.9}$$

Finally, the modulated signal of OQAM-FBMC can be expressed as:

$$s(t) = \sum_{m=0}^{\infty} \sum_{n=0}^{N-1} d_{n,m}^R \, g_{n,m}(t) + d_{n,m}^I g_{n,2m+1}(t) \tag{3.10}$$

Where the variables $d_{n,m}^R$ and $d_{n,m}^I$ are the real and imaginary part of $d_{n,m}$ expressed by the subcarrier index of *n* during symbol time of index *m*.

The analysis filters in the receiver are based on the specially designed prototype filter $p_R(t)$, the impulse response of the prototype filter provided by [44].

$$g_k^* = p_R(t) e^{j2\pi n \Delta f t - j\emptyset_n} \quad k = 0,1 \dots \dots . N - 1 \tag{3.11}$$

For mathematical study, while ignoring channel impairments, the input signal at the AFB is equal to the transmit signal of the SFB, which is in a distortion free, noiseless channel.

After the incoming signal *r(t)* passes through the filter, the continuous output time signal can be determined [45].

$$y_k(t) = g_k^*(t) * r(t) \tag{3.12}$$

$$y_k(t) = \sum_m^{\infty} \sum_{n=0}^{N-1} d_{n,m} p_R(t) * \ p_T(t - mT) e^{-2\pi jk\Delta f t - j\emptyset_k} e^{2\pi jn\Delta f(t-mT)+j\emptyset_n} \tag{3.13}$$

$$y_k(t) = \sum_m^{\infty} \sum_{n=0}^{N-1} d_{n,m} p_R(t) * \ p_T(t - mT) e^{j2\pi(n-k)\Delta f t + j(\emptyset_n - \emptyset_k)} \tag{3.14}$$

The prototype filters are designed to satisfy the condition that the output signal does not introduce the ISI to its adjacent time domain symbols. The composite impulse response should be zero at sampling times, except for the initial one:

$$p_R(t) * p_T(t)|t_s = iT \begin{cases} 1, & i = 0 \\ 0, & i \neq 0 \end{cases} \tag{3.15}$$

Where t_s = *iT* is the sampling point of the time axis. The demodulated signal at the n-subcarrier and m-th symbols can be expressed as:

$$d_{n,m}^R = Re\left\{\int s(t) g_{n,2m}^*(t) dt\right\} \tag{3.16}$$

$$d_{n,m}^I = Re\left\{\int s(t) g_{n,2m+1}^*(t) dt\right\} \tag{3.17}$$

3.4. UFMC TRANSMISSION

UFMC is an enhancement for CP-OFDM waveforms that is utilized in 4G LTE wireless transmitters. [46] It operates by exploiting the disadvantages of CP-OFDM, while attempting to hold onto its own advantages, which include possessing a high PAPR, MIMO capability and stability. UFMC filters groups of consecutive sub-carriers, and then minimizes the out-of-band and ICI emissions that occur between adjacent users during the asynchronous transmissions, which actually results in a shorter impulse response in the time domain. [14]

3.4.1. Basic Principle of UFMC

UFMC works by filtering each of the sub-bands, which contain orthogonal multi-carriers, to minimize the OOB power. In the UFMC system, each of the sub-band signals is converted to a series stream via the P/S block. Next, the signal that is received is then applied to the RF chain, which is in the UFMC receiver. The signal that is received is then converted to a baseband signal by the RF chain. After this, an ADC is used to convert the signal from baseband to digital, after which pre-processing of the time-domain is performed. Following this, the series data stream is converted to a parallel data stream via the S/P block, and then the time-domain of the parallel data stream is thus converted to a frequency-domain stream via the 2N-FFT operation. [47] After completion of the 2N-FFT operation, all the odd computer-numbered data symbols are first selected, and then matched. The spectrum in the UFMC system exhibits lower OOB power, which corresponds to the spectrum in the OFDM, which is an excellent benefit. However, because the UFMC system makes use of multi-carriers and their overlaps, it has a high PAPR, and such characteristics can cause a distortion in the signal of the UFMC system [47].

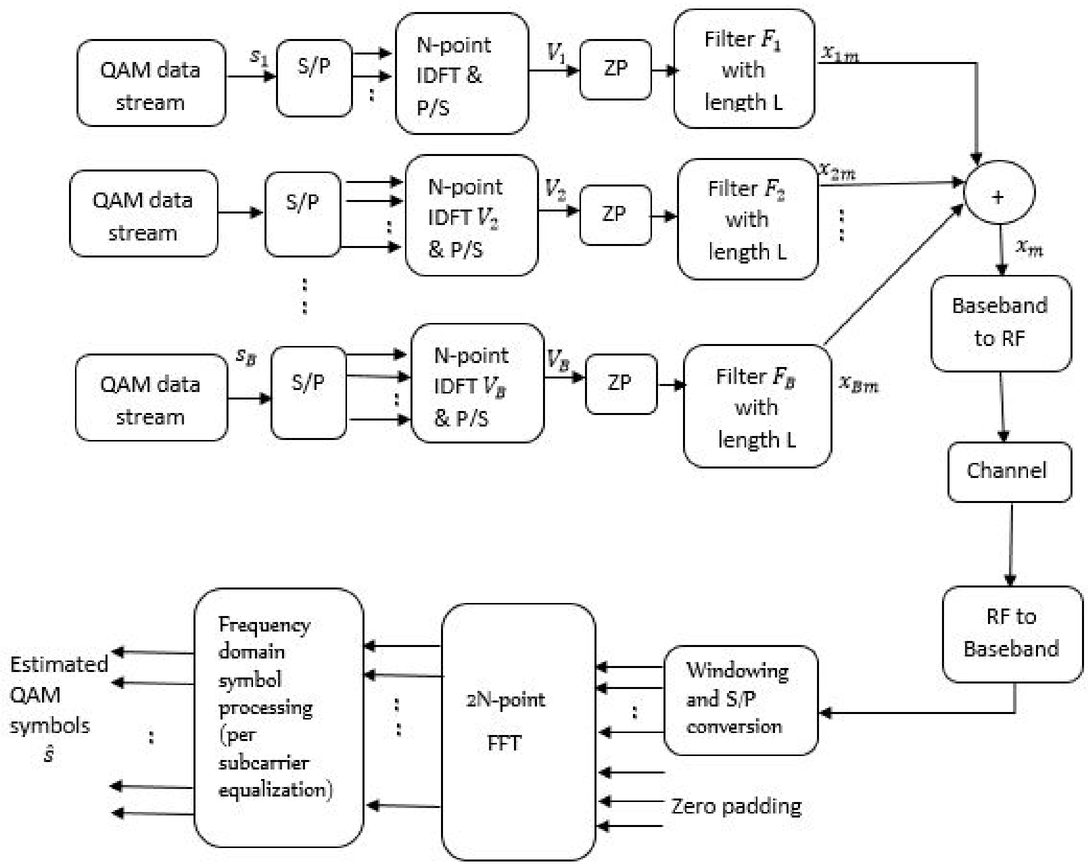


Figure 3.4. UFMC Block diagram.

3.4.2. Mathematical Description of UFMC

Let us suppose that the transmission signal of the UFMC comprises N sub-carriers and is divided into B sub-bands, wherein each of the sub-bands contains $\frac{N}{B}$ sub-carriers. let us also suppose that the input into the UFMC waveform generator block comprises one set of QAM constellation-mapped, S, symbols, and these symbols, S, are divided into frequency blocks, S, where in each frequency block then comprises a *p*sub carrier. If B represents the number of frequency blocks, then. These B data vectors are processed with the IDFT submatrix (each of the N*P dimensions) respectively. Next, each of the sub-bands is filtered using a sub-band filter that has a of length of L, and all of the responses from these different sub-bands is then summed up.

Various types of filters with dimensions ((N+L-1)*N) can be used for filtering operations. F_i is a Toeplitz matrix, which consists of a filter impulse response that performs a linear convolution. The filter chosen for UFMC is the Chebysheve filter given by: [48]

$$F_{i,l} = \frac{\cos(L\, cos^{-1}\left[\beta \cos\left(\frac{\pi l}{L}\right)\right]}{\cos[L\, cosh^{-1}(\beta)]}, l = 0,1,2 \ldots . L - 1 \tag{3.18}$$

Where

$$\beta = \cosh\left[\frac{1}{L}\, cosh^{-1}(10^{\alpha})\right],\ \ \alpha = 2,3,4 \tag{3.19}$$

where α represent the attunation of side lobs, the side-lobe suppression is now functioning in between resource blocks, instead of in-between subcarriers. The period of the N+L-1 samples is created by the length of the filter and the size of the FFT. The discreet time signal that is to be transformed into an analog domain and then transmitted to the RF can be expressed as is given below:

$$x_m = \sum_{i=1}^{B} F_i V_i s_i \tag{3.20}$$

$$x_m = \sum_{i=1}^{B} F_i \left(\sum_{n=0}^{N-1} s_{i,n} e^{\frac{j2\pi n}{N}}\right) \tag{3.21}$$

$$x_m = \sum_{i=1}^{B} \sum_{l=0}^{L-1} \sum_{n=0}^{N-1} s_{i,n} e^{\frac{j2\pi n}{N}} F_i(l) \tag{3.22}$$

This sequence will then be passed through a DAC, with an output that will preferably be the signal waveform, *x(t)*, with length N+L-1. Next, the signal will be up converted, followed by transmission of the RF signal to the channel.

Following down-conversion of the RF, the channel output will be the received signal waveform, *r(t)*, that was obtained because of the convolution of *s(t)* with the impulse response, $h(\tau - t)$, and as added noise signal, *n(t)*, as is given below:

$$y(t) = \int_{-\infty}^{\infty} x(t-\tau)\ h(\tau, t)\ d\ \tau + n(t) \tag{3.23}$$

This sequence will then be passed through an ADC, with an output sequence that is y_m; *m*=0................ 2N-1 which is *y(t)* sampled at *1 / Td*. The received signal is given by a discrete-time baseband equivalent signal. [49]

$$y_m = H(\sum_{i=0}^{B} F_i V_i s_i) + n \tag{3.24}$$

This describes the classical linear model, received signal and additional signal processing techniques such as equalizers and FFT can be used to retrieve QAM symbols. The processing of the receiver can be based on the frequency-domain FFT. Like OFDM, by using single-tap equalizers for each sub-carrier frequency domain, it is possible to equalize the dual impact caused by the radio channel and its respective sub-band filter.

If the channel impulse response is preferably a Delta-Dirac function $\delta(t)$, then preprocessing of the time domain is not performed, and the timing offset, and CFO are not taken into consideration. Hence, the approximate *m*th symbol, y m, can be written as is given below:

$$\hat{s}_i = \sum_{i=1}^{B} y_{i,m} e^{\frac{j2\pi k}{N}} \qquad k = 0,1 \dots\dots\dots\dots..2N - 1 \tag{3.25}$$

In comparison to OFDM, UFMC groups sub-carriers into multiple sub-bands, applying filtering to them separately, which eliminates out-of-band emissions without losing OFDM advantages.

3.5. F-OFDM TRANSMISSION

F-OFDM is now known to be another contender for communication networks of the future, beyond 5G. F-OFDM also makes use of OFDM as its main waveform and then applies a sub-band filter to each of the sub-bands that has multiple sub-bands.[50] Filtered-OFDM can use this bandwidth in such a way that the entire spectrum is split into many smaller sub-bands. Each of these sub-bands will have a customized waveform to satisfy the requirements of the target services provided by the network.

This implies that parameters such as cyclic prefix (CP) and spacing between sub-carriers in each sub-band will be compatible with the design of the operation [51].

3.5.1. Basic Principle of f-OFDM

The f-OFDM system has a structure that is quite similar to the classical CP-OFDM. The main difference lies in the fact that the allocated device bandwidth is divided into sub-bands in f-OFDM systems. The transmission of the baseband signal to each of the sub-bands is then also filtered via the use of a band-limited filter prior to the signals passing through the wireless multi-path fading channel. A representation of the f-OFDM transmitter is given in Figure 3.5. The implemented sub-band based filtering is used to reduce inter-sub-band interference, which eliminates sidelobe leakage, as a result of the suppression of OOB emissions. [52] With regards to modulation of the f-OFDM, filtration is conducted following the IFFT block, so as to decrease the amount of OOB, thus also decreasing the amount of interference that will occur between adjacent signals [52].

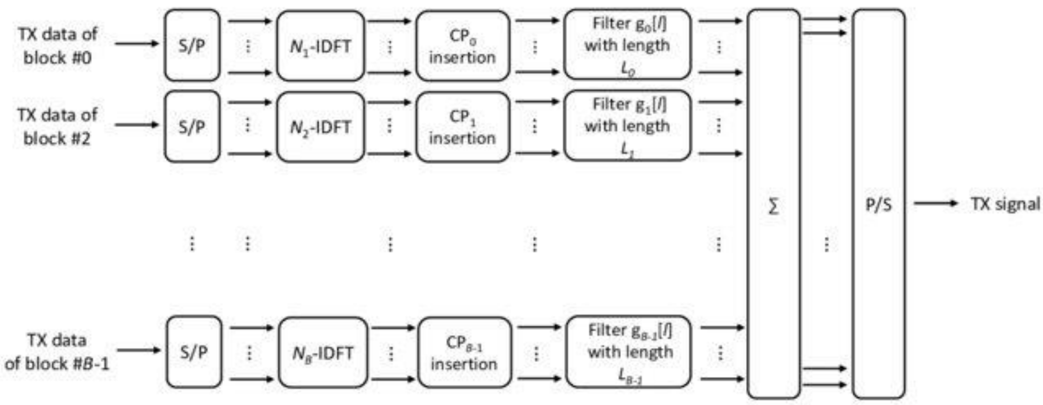


Figure 3.5. f-OFDM Block diagram.

3.5.2. Mathematical Description of f-OFDM

With regards to the unified expression, it is assumed that application of the spectrum shaping filter is conducted for the whole passband, that is to say, the total number of sub-bands = 1. The structure of the f-OFDM transmitter is given in Figure 3, following the application of the appropriately designed spectrum shaping filter, h(t), to the whole sub-band. The s(t) of the f-OFDM system can be written as is given below:

$$s(t) = \sum_{n=-\infty}^{\infty} s_n(t-nT) = \sum_{n=-\infty}^{\infty}\left(\left[\sum_{k=0}^{k=1} a_{n,k} e^{j2\pi kf(t-nT)}\right] \otimes h(t-nT)\right) \quad (3.26)$$

Where $\otimes$ denotes the convolution operation [50].

3.6. SYSTEM MODEL FOR SIMULATION

A simplified physical layer model of a multi-carrier transmitter is shown in Figure 4.1. The information bits will arrive at the input at a rate of R bits / s. In the first block, the information bits are collected in groups of $log_2\,M$ bits and mapped to symbols from the MQAM constellation and forwarded to the next block at the symbol rate of $R_s = \frac{R}{log_2 M}$ symbols / second.

Then the modulation of the multicarrier is carried out. Out of the total N Subcarriers No data is loaded with QAM modulated symbols and the rest has zero input. Complex samples are produced after multicarrier modulation N. These samples are converted to serial data and cyclic prefixes are inserted. After that the sampled data is forwarded to a digital analog conversion at the rate of $R_{ch} = R_s.\frac{N}{N_0}\left(1 + L_{cp}\right)$ where L_{cp} is the duration of the cyclic prefix on OFDM.

As discussed in last sections, the differences between OFDM, FBMC, UFMC and f-OFDM are the modulation of block multicarrier and the insertion of CP. In OFDM, the efficient implementation of this windowing and modulation is accomplished only by the efficiency of the N point FFT. If, as in FBMC, the symbols are pulse formed by a porotype filter, that is longer than the number of subcarriers N, it is necessary that it is both designed and implemented in this regard.

The efficient implementation of this structure is accomplished by the deployment of Offset-QAM stunning, FFT and polyphase filtering. In UFMC, the incoming QAM symbols are grouped into blocks and modulate and filter each block separately, summarizing each filtered block. This has been implemented using the number B of N-pt. Filter FFT and Dolph-Chebyshev [53].

The opposite operations on the receiver side are performed in reverse order. As a next step, the removal of the CP is performed in the case of OFDM and then the samples are translated into subcarrier symbols. The equalizer must be deployed in the three systems in order to compensate for the selective frequency of the channel. For OFDM and UFMC, this equalizer has a duration of 1 and a multitap for FBMC. Complex symbols are identified after the demodulation process is completed. We neglect the encoder and the bit-generating method here.

There are various types of metrics for comparing modulation formats. From the transmitter side, we compare them with their spectral density and spectral quality. They are contrasted at the receiver side using the bit error rate and at the end-to - end use the metrics computational complexity. The three multicarrier modulations are compared to the following performance metrics. These metrics are explained in the following section.

3.6.1. Power Spectral Density

The PSD function provides an understanding of how intense the energy variations are, as a function of the frequency. It also provides an indication of which frequency variations are high, as well as which are small. Determination of the power spectrum for the whole multi-carrier modulation signal can be performed by summing up the power spectra of each of the sub-carriers for each symbol duration. It is possible to obtain this by summing up the power spectra of each subcarrier on the assumption that these data from each of the sub-carriers are mutually orthogonal, as well as statistically independent. Side-lobe radiation is calculated by the MC signal PSD model. The interference of side-lobe radiation in these multi-carrier modulations is the subject of concern. Integration of PSD provides the energy of the specific frequency range. [54]

$$PSD = \frac{Energy\ (W)}{Frequency\ (Hz)} \tag{3.27}$$

3.6.2. Bit Error Rate

The other performance metrics for modulation techniques are the Bit Error Rate (BER). Whenever data is being transmitted over a channel, a risk always exists that errors could be made in the system. If errors are made in the data, the integrity of the system can be compromised. As a consequence, the performance of the system and of the BER must be evaluated. BER measures the complete end-to - end output of the system, including the transmitter, receiver and medium between the two. As is suggested by its name, BER is the rate at which error occurs in the transmission system. For the study of the channel characteristics, the noise followed the Gaussian probability function, whereas the propagation model followed either the Rayleigh or Rician channel model. This helps to channel the use of statistical analysis techniques [55].

In a multipath channel, the transmitted signal enters the receiver as a pulse train. Since a multi-path channel redirects signals to multiple locations, the signal is transmitted to the receiver by traveling along various paths, which could have different lengths, which would result in varying associated time delays. Fading is seen when these signals cause interference with each other as they travel along their different paths. We use flat fading channel model for our BER simulation.

Flat fading is a static model that is used for the radio signal effect of the propagation setting. Flat fading infers that, after it has passed through a communication channel, random variations or fading can occur in the signal strength. This is dependent on the Rayleigh distribution of the radial portion of the sum of the two uncorrelated Gaussian random variables. It is a rational model that can be used for signal transmission in urban an environment in which no line of sight exists between the transmitter and receiver.

3.6.3. Transmitted Power

When explaining any modulation system, there is a very basic property of these systems, the property comprises the power fluctuations that exist following modulation of the signal. With regards to multi-carrier communication, a significant number of sub-carriers are simultaneously introduced in the creation of a multi-carrier system. [36] In this thesis, we measure the transmitted power and demonstrate the schemes are better than others, the measurement is by calculating the square of the absolute value of the transmitted signal.

$$P_s = |Tx_s|^2 \tag{3.28}$$

3.6.4. Peak to Average Power Ratio

Both multicarrier modulation techniques are afflicted by the same downside, which is a higher PAPR. Since in multicarrier modulation, the input data stream is split into several sub-streams known as sub-carriers. These sub-carriers are then independently modulated at various carrier frequencies and can provide a broad PAPR when combined coherently for transmission purposes. If in the same step, N signals are applied, then they will generate a peak power that will be N times that of the average signal power. Multicarrier signals therefore have a very large PAPR, which is highly sensitive to the nonlinearity that exists in the high-power amplifier. [14] PAPR in multi carrier modulation can be defined as:

$$PAPR = \frac{Peak\ Power}{Average\ Power} \tag{3.29}$$

Measurement of the effectiveness of the PAPR reduction technique can be observed via the complementary cumulative distribution function (CCDF) [44].

3.6.5. Bit Rate

One of the most important thing in 5G is Bit Rate, The necessity that exists now be able to support the global mobile data traffic explosion is, without-a-doubt, the main driving force behind 5G. [10] in this thesis we calculate Bit Rate for every modulation schemes and show which of them is higher than others.

PART 4

COMPARATIVE ANALYSIS STUDY

4.1. SIMULATION RESULTS

A comparison is made between the candidate multicarrier modulation schemes. Table 4.1 lists the general simulation and performance assessment parameters for this study and the performance evaluation is carried out using the MATLAB platform. The parameters considered in this simulation can vary depending on each comparison metric. The following results are simulated and obtained using a multi-path channel that compared the performance of OFDM, FBMC and UFMC for QAM schemes. QAM is chosen because it is commonly used in LTE standard [56].

Table 4.1. Simulation parameters.

Parameters	Value
FFT Size	64/1024
Subcarrier spacing	15 KHz
Symbol mapping	16-QAM
UFMC Parameters	
Filter Length	73
Guard interval	72
Size of FFT , N_{SB}	64
FBMC parameters	
Overlapping	K=4
Prototype Filter	PHYDYAS filter
OFDM parameters	
Length of CP	72
f-OFDM parameters	
Length of CP	0

Regarding the link level output, it is assumed that there is only a single transmission antenna at the base station and single user at the single receiving antenna. Perfect channel estimation is also assumed, which allows us to highlight the difference in output between modulation schemes. In addition, CP-OFDM and UFMC use guard intervals to prevent ISI from occurring.

The MATLAB program was divided into three main codes to calculate (PSD, BER vs SNR, PAPR, Transmitted Power and Bit Rate), These main programs call other four codes these four codes were built to calculate parameters for every modulation scheme.

4.1.1. Power Spectral Density (PSD)

The normalized power density spectrum of OFDM, FBMC, f-OFDM and UFMC symbols with subcarriers versus the normalized frequency is shown in this section. In Figure 4.1, to see the outbound emission of each modulation format, we select 64 subcarrier numbers, overlapping factors 4 and 12 sub band sizes for UFMC. The Dolph-Chebyshev filter is used for UFMC, with a 40-dB stopband attenuation. This has been widely publicized in literature as the best possible compromised choice. The length of filter is equal in length to that of the CP plus one. The prototype filter for FBMC is PHYDYAS filter, with a duration of L = NK, where K= 4. Figure 4.1 displays a set of PSD plots of CP-OFDM, FBMC, f-OFDM and UFMC.

From the PSD graph, the energy is primarily concentrated in the main lobe, and it is intuitively obvious that the four modulations have different side-lobe radiations. There is a benefit of lower OoB emissions to enable asynchronous transmission. From Figure 4.1, other modulations can achieve much less leakage when they are compared to the CP-OFDM. Among these modulations, because of the short duration that the filter has, the UFMC will have a weak OoB emission prior to the attenuation of 30 dB. As seen in the figure UFMC, it reaches-50 dB around the normalized frequency 30. And f-OFDM better than UFMC, it reaches – 100 dB around normalized frequency 30. Whereas OoB 's response FBMC decays completely before the normalized frequency 20. One of the important requirements for CR physical layer design is signal should have extremely low OoB radiation.

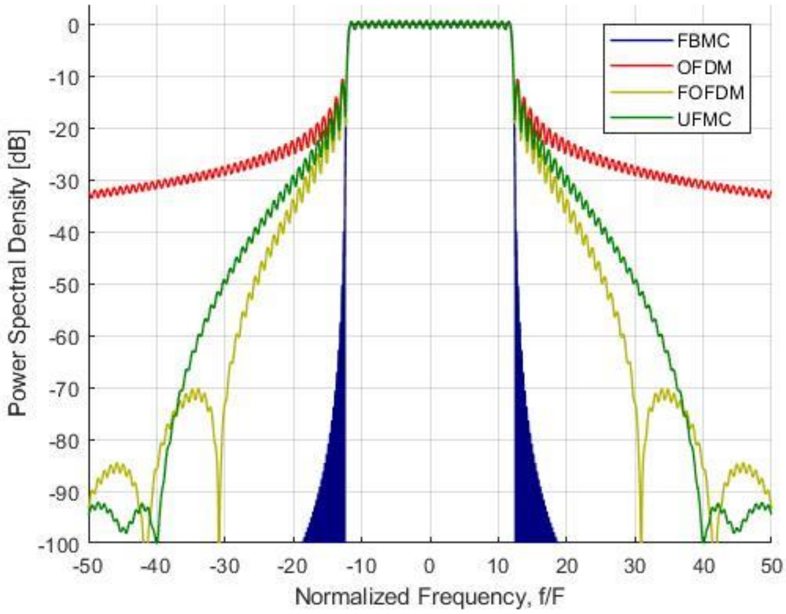


Figure 4.1. Representation of the Power Spectral Density of the f-OFDM, OFDM, FBMC, and the UFMC.

4.1.2. BER vs SNR IN Doubly Flat Channel

The performance of the BER is interpreted and examined in order to understand the performance of the FBMC, f-OFDM and UFMC systems for a convenient comparison with the traditional CP-OFDM and theory of CP-OFDM. In this section, the error performance and robustness of each modulation system against a multi-path channel is analyzed. We assume a carrier frequency of 2.5 GHz for the simulation. The considered channel model used for the assessment of BER performance is a Doubly flat model.

Please notice that the BER is further influenced by the principle of the receiver design using equalization algorithms and using interference cancelation methods as an example. Channel fading is supposed to be at least unchanged for the length of the symbol. Perfect channel state details and full synchronization are often presumed. Both waveforms have the total number of subcarriers N=64 and the corresponding subcarrier spacing is believed to be 15 kHz. The BER measurements provided for 300 channel realizations and 30 number of symbols for each channel realization for the three waveforms.

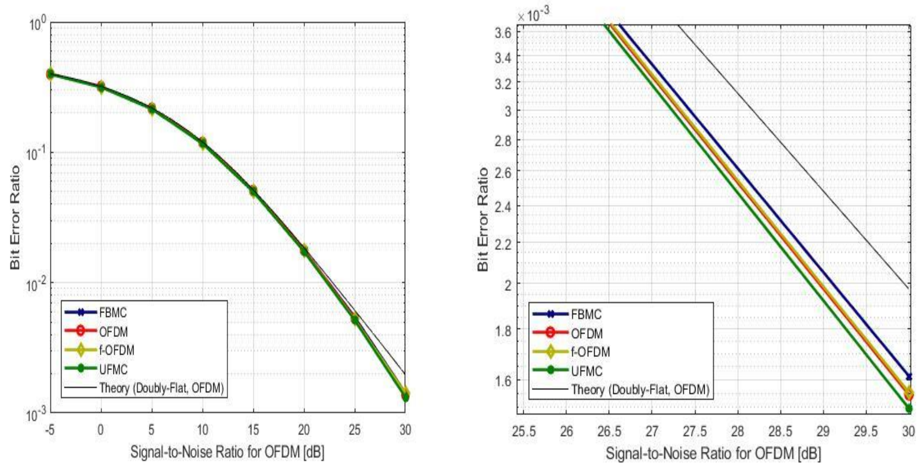


Figure 4.2. BER vs SNR with 16QAM.

From the Figure 4.2, UFMC appears better than FBMC, f-OFDM and OFDM, they need about 0.5 dB to reach UFMC, for 30 dB the BER is about 10^{-3}, the curves were extremely equal to theory curve.

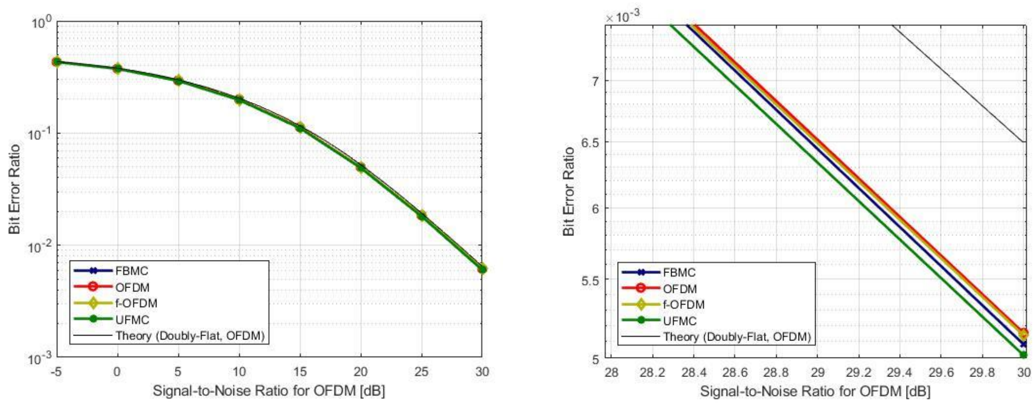


Figure 4.3. BER vs SNR with 64 QAM.

For 64QAM the curves show is identical but when we zoomed it they appear that UFMC also is better than others. f-OFDM and OFDM are identical, but they need small value of SNR to reach UFMC, for 30 dB the BER is about 10^{-2}.

A higher-order modulation, including 16-, 64-, and 256-QAM, is used in most wireless communications. LTE and LTE-Advanced mobile device uses 64-QAM to modulate OFDM symbols. Although the highest-order modulation 256-QAM and 1024-QAM are discussed in 3GPP. These are both connected to LTE and LTE-Advanced and are incoming 5G.

As shown in Figure 4.4, even if the SNR value is increased to 30 dB, it cannot reach BER 10^{-2} for 256-QAM. Figure 4.5 shows the BER of 1024-QAM against the obtained SNR under the Doubly flat channel for candidate waveforms. Compared to the 256-QAM scenario, the performance of the BER is reduced dramatically. The SNR penalty needed to achieve a BER of 10^{-1} is 5 dB from that of 256-QAM and 10 dB from that of 64-QAM for the four waveforms. Whereas the four waveforms behave differently at a higher SNR value. At BER of 0.01 there is a corresponding SNR penalty between waveforms, FBMC and OFDM needs more than 0.1dB SNR than UFMC to achieve BER of 0.01, and f-OFDM needs more than 0.4d B SNR than UFMC.

As the modulation order increases, the constellation has become denser, and a higher SNR is required to maintain the BER. Therefore, for each waveform, higher-order modulation schemes themselves need a higher SNR receiver at a given error rate compared to a lower-order one. However, in conjunction with mitigation techniques such as channel estimation, channel equalization using higher-order modulation can achieve the maximum data rate within a given bandwidth.

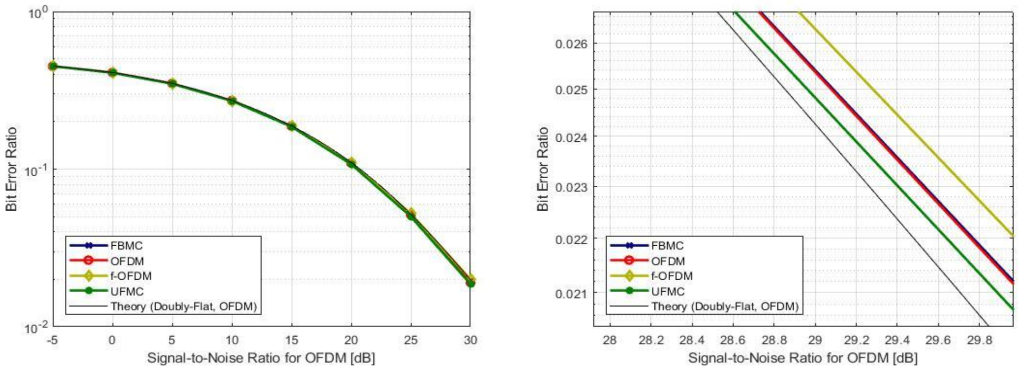


Figure 4.4. BER vs SNR with 256 QAM.

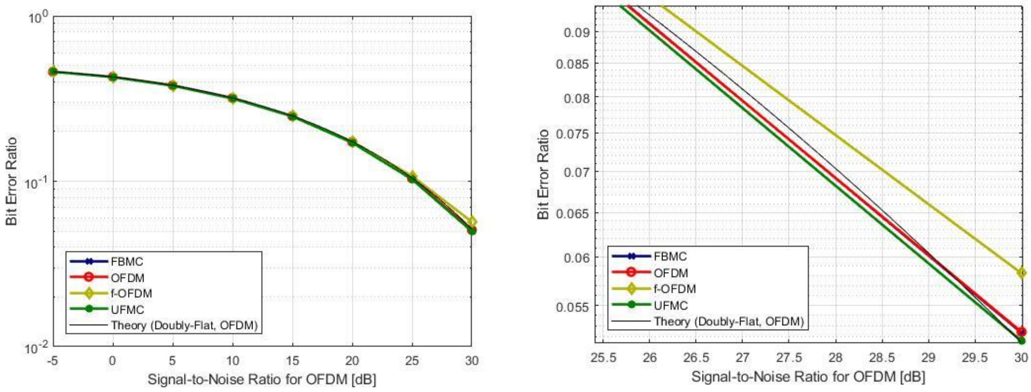


Figure 4.5. BER vs SNR with 1024 QAM.

4.1.3. Transmitted power

In this section the simulated transmitted power of an OFDM, FBMC, f-OFDM and UFMC with time is depicted, from the transmitted power graph shown in Figure 4.6, the power of OFDM, f-OFDM and FBMC are identical, but UFMC transmitted power separates into number of symbols in time, there is advantage of separate the power to mitigate Inter Symbol Interference ISI.

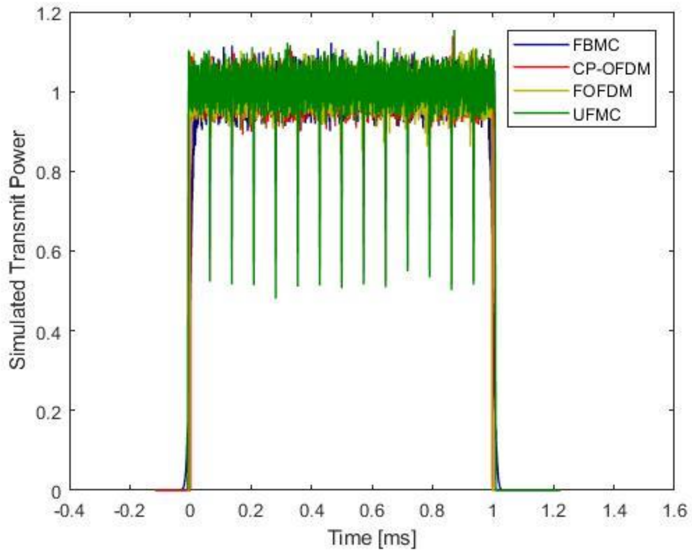


Figure 4.6. Simulated transmitted power.

4.1.4. Peak to Average Power Ratio

In this section, the PAPR of the different waveforms is compared, the results are shown in Figure 4.7. Looking at Figure 4.7, it can be seen that no significant difference exists between them, but when we zoom the graph, we find that FBMC has a lower PAPR than other modulation schemes, OFDM, f-OFDM and UFMC require 0.1 dB to reach FBMC.

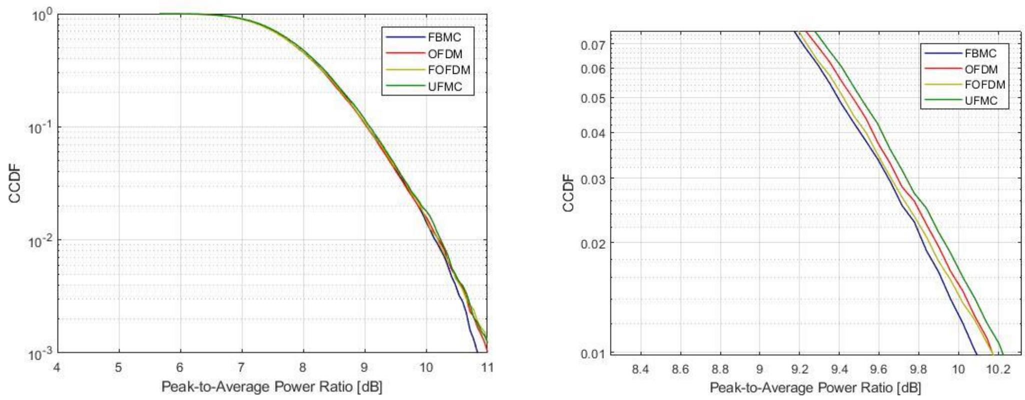


Figure 4.7. PAPR for OFDM, FBMC and UFMC.

4.1.5. Bit Rate

In this section we use the modulation form 64 QAM. From the simulation screen we take this figure 4.8 it is obvious that FBMC and f-OFDM have a higher data rate compared to OFDM and UFMC, FBMC and f-OFDM has 23.0Mb/s, UFMC has 22.66 Mb/s and OFDM has 21.50 Mb/s.

	CP-OFDM	FBMC	UFMC	FOFDM
Bit Rate [Bits/s]	21504000	23040000	22662295	23040000

Figure 4.8. Data Rate for various modulation schemes.

4.2. DISCUSSION OF RESULTS

As a result, the best OoB emission is obtained with FBMC with the overlapping factor K = 4. The reason why they have different spectrum leaks depends, to a large extent, on the type of filter used. FBMC has lower spectral side lobes due to the use of pulse-shaped filters instead of rectangular windows used in the OFDM system. The lower OoB emission allows the transmitter to produce more subcarriers with data that improve the spectral efficiency of 5G device scenarios. The lower side lobes of FBMC tend to be almost indifferent to multi-user interference. f-OFDM performs a lower OoB leakage compared to OFDM and UFMC due to block filtering but is outperformed by FBMC.

The other outcome of the simulation was BER vs SNR. The lower the BER result for the four modulations, the higher the SNR and the better contact efficiency. Even though the higher order of QAM has degraded the BER efficiency of modulation schemes. The result shows that BER vs SNR are extremely identical for four types of modulation schemes, and when it different it has a small value to reach other one.

Third result from simulation is Simulated Transmitted Power, for OFDM, f-OFDM and FBMC the transmitted power is extremely identical but with UFMC is different, it’s appeared that UFMC has different Simulated Transmitted Power because UFMC filtering every carrier separately so every transmitted power for every carrier appear alone.

PAPR is another critical metric of the waveform design, from the result it's clear that four types of modulation are very close to each other but in advantage FBMC is better than others, that occurs because FBMC filtering all data after ADC not like f-OFDM filtering every carrier severally or OFDM whose doesn't filter any data.

The last one was Data Rate which measured in bit/second, from the simulation it's clear that FBMC and f-OFDM have a higher data rate compared with other tow, UFMC in the middle between FBMC and OFDM, FBMC and f-OFDM have a high data rate because it doesn't have any guard interval like UFMC and doesn't have Cyclic Prefix (CP) like OFDM. The table below is making a small comparison between these different schemes.

Table 4.2. Comparison of 5G modulation schemes

schemes	characteristics	advantages	disadvantages
OFDM	Filtering and inserting of CP are not applicable	Low complxity in design.	Cyclic prefix exist. Low data rates. Higher OoB leakage.
FBMC	The filtering is done in the frequency domain (before IFFT)	Lower OoB leakage. High data rates. No cyclic prefix. Asynchronous transmission.	High PAPR. High BER.
UFMC	This scheme filters every single subband.	Good spectral efficiency. Lower OoB leakage. No cyclic prefix.	Low data rates. Larger FFT size at receiver increases complexity.
f-OFDM	After inserting CP the filtering is applied	High data rates. Low complxity in design.	Cyclic prefix exist. Very sensitive to frequency and time offsets.

PART 5

CONCLUSION AND FUTURE WORK

5.1. CONCLUSION

In the 4G system, the basic technology is OFDM it used for many communication systems. In the 5G system, we need to improve the data rate, PSD and PAPR to serve new services like M2M, IoT etc, and OFDM cannot cover these services. The speed of inventions and requirements, which have increased the number of users, has driven researchers and academics to look for a different solution. These different facilities should be provided by the 5G air interface technology. Modulation schemes are also key requirements.

This thesis proposes an analysis of the performance of 5G modulation schemes in the common framework. FBMC, f-OFDM and UFMC are compared to CP-OFDM in terms of Power Spectral Density, Bit Error Rate, Transmitted Power in Time Domain, Peak to Average Power Ratio and Bit Rate. In each term, the transmitted data had the same parameters and propagated through the same channel. The results demonstrate the advantages and drawbacks of each modulation scheme.

From the results it was noted that the PSD performance was better with FBMC than with UFMC, f-OFDM and CP-OFDM, and with UFMC and f-OFDM in the middle between FBMC and CP-OFDM, the BER performance of FBMC, f-OFDM and CP-OFDM is extremely similar, but UFMC's BER is better than others with a small SNR value. Transmitted time domain power shows that FBMC, f-OFDM and CP-OFDM are both the same, but UFMC is different because it filters every subcarrier severally. According to the PAPR graph, the FBMC is better than others, finally with the Bit Rate the FBMC and f-OFDM have a higher Bit Rate compared to the other two and this is the advantage of the FBMC and f-OFDM over the UFMC and the CP-OFDM.

It appears from all the results that FBMC modulation techniques are an interesting choice. It has better PSD, better PAPR and Bit Rate, even in other parameters it is extremely like OFDM, which means that FBMC can be implemented easily.

5.2 FUTURE WORK

In this thesis, modulation schemes for the 5G system have been discussed, two more choices can be considered:

- In this work, we have studied modulation techniques with a single user, more than one user is a point to research.
- When we compared the four types of modulation, we assumed that every system is perfectly synchronized, a synchronization problem in the environment also a good point to research.

REFERENCES

1. A. F. Demir, M. H. Elkourdi, M. Ibrahim, and H. Arslan, "Waveform design for 5G and beyond," ***5G Networks Fundam. Requir. Enabling Technol. Oper. Manag.,*** no. December, pp. 51–76, 2018, doi: 10.1002/9781119333142.ch2.

2. M. Abas Taher and K. Hussein Kutheir, "FBMC as 5G candidate for high speed mobility," ***IOP Conf. Ser. Mater. Sci. Eng.,*** vol. 557, no. 1, 2019, doi: 10.1088/1757-899X/557/1/012040.

3. A. Goldsmith, ***Wireless communications,*** vol. 56, no. 5–6. 2004.

4. G. Kalivas, ***Digital Radio System***. 2009.

5. A. N. Ibrahim and M. F. L. Abdullah, "The potential of FBMC over OFDM for the future 5G mobile communication technology," ***AIP Conf. Proc.,*** vol. 1883, no. September, 2017, doi: 10.1063/1.5002019.

6. S. Rangan and N. Y. U. W. Dec, "Understanding 5G Standards," pp. 1–42, 2016.

7. P. Sharma, "Evolution of Mobile Wireless Communication Networks-1G to 5G as well as Future Prospective of Next Generation Communication Network," ***Int. J. Comput. Sci. Mob. Comput. - not index,*** vol. 2, no. August, pp. 47–53, 2013, [Online]. Available: http://www.ijcsmc.com/docs/papers/August2013/V2I8201317.pdf.

8. M. Scharfstein and Gaurf, "5G NR The Next Generation Wireless Access Technology," ***J. Chem. Inf. Model.,*** vol. 53, no. 9, pp. 1689–1699, 2013, doi: 10.1017/CBO9781107415324.004.

9. A. Othman, "5G System Architecture & Implementation," 2019.

10. J. G. Andrews *et al.*, "What will 5G be?," ***IEEE J. Sel. Areas Commun.,*** vol. 32, no. 6, pp. 1065–1082, 2014, doi: 10.1109/JSAC.2014.2328098.

11. Y. Cai, Z. Qin, F. Cui, G. Y. Li, and J. A. McCann, "Modulation and Multiple Access for 5G Networks," ***IEEE Commun. Surv. Tutorials,*** vol. 20, no. 1, pp. 629–646, 2018, doi: 10.1109/COMST.2017.2766698.

12. G. Bochechka, V. Tikhvinskiy, I. Vorozhishchev, A. Aitmagambetov, and B. Nurgozhin, "Comparative analysis of UFMC technology in 5G networks," ***2017 Int. Sib. Conf. Control Commun. SIBCON 2017 - Proc.,*** pp. 2–7, 2017, doi: 10.1109/SIBCON.2017.7998465.

13. J. B. Doré, R. Gerzaguet, N. Cassiau, and D. Ktenas, “Waveform contenders for 5G: Description, analysis and comparison,” ***Phys. Commun.,*** vol. 24, pp. 46–61, 2017, doi: 10.1016/j.phycom.2017.05.004.

14. P. Rani, “Performance Evaluation of Multi-carrier Modulation Techniques for Next Generation Wireless Systems,” vol. 8, no. 5, pp. 508–512, 2017.

15. K. K. Kishore, P. R. Umar, and V. J. Naveen, “Comprehensive Analysis of UFMC with OFDM and FBMC,” ***Indian J. Sci. Technol.,*** vol. 10, no. 17, pp. 1–7, 2017, doi: 10.17485/ijst/2017/v10i17/114337.

16. Qualcomm, “Making 5G NR a reality,” no. December, 2016.

17. E. M. F. E. Series, “EMF Explained Series 1,” no. March, 2018.

18. R. Nissel, S. Schwarz, and M. Rupp, “Filter Bank Multicarrier Modulation Schemes for Future Mobile Communications,” ***IEEE J. Sel. Areas Commun.,*** vol. 35, no. 8, pp. 1768–1782, 2017, doi: 10.1109/JSAC.2017.2710022.

19. A. Matera, R. Kassab, O. Simeone, and U. Spagnolini, “Non-Orthogonal eMBB-URLLC radio access for cloud radio access networks with analog fronthauling,” ***Entropy,*** vol. 20, no. 9, pp. 1–27, 2018, doi: 10.3390/e20090661.

20. P. Popovski, K. F. Trillingsgaard, O. Simeone, and G. Durisi, “5G wireless network slicing for eMBB, URLLC, and mMTC: A communication-theoretic view,” ***IEEE Access,*** vol. 6, no. 648382, pp. 55765–55779, 2018, doi: 10.1109/ACCESS.2018.2872781.

21. ITU-R, “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond,” ***Itu-R M.2083-0,*** vol. 0, p. https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M, 2015.

22. S. Talwar, D. Choudhury, K. Dimou, E. Aryafar, B. Bangerter, and K. Stewart, “Enabling technologies and architectures for 5G wireless,” ***IEEE MTT-S Int. Microw. Symp. Dig.,*** 2014, doi: 10.1109/MWSYM.2014.6848639.

23. P. M. AFIF OSSEIRAN, JOSE F.MONSERRAT, *5G MOBILE AND WIRELESS COMMUNICATIONS TECHNOLOGY*. 1390.

24. R. S. Yarrabothu and P. Telagathoti, “Massive Mimo and Beamforming Techniques of 5G Networks,” ***Int. J. Eng. Adv. Technol.,*** vol. 9, no. 1S5, pp. 139–142, 2019, doi: 10.35940/ijeat.a1034.1291s52019.

25. H. M. E. Misilmani and A. M. El-Hajj, “Massive MIMO design for 5G networks: An overview on alternative antenna configurations and channel model challenges,” ***Proc. - 2017 Int. Conf. High Perform. Comput. Simulation, HPCS 2017,*** no. March 2018, pp. 288–294, 2017, doi: 10.1109/HPCS.2017.52.

26. F.-L. Luo and C. Zhang, *Signal Processing for 5G Algorithms and Implementation*, First edit.

27. Z. Wu, K. Lu, C. Jiang, and X. Shao, "Comprehensive Study and Comparison on 5G NOMA Schemes," ***IEEE Access,*** vol. 6, no. c, pp. 18511–18519, 2018, doi: 10.1109/ACCESS.2018.2817221.

28. O. Kucur, G. Karabulut Kurt, M. Z. Shakir, and I. S. Ansari, "Nonorthogonal Multiple Access for 5G and beyond," ***Wirel. Commun. Mob. Comput.,*** vol. 2018, no. 12, pp. 2347–2381, 2018, doi: 10.1155/2018/1907506.

29. M. Baghani, S. Parsaeefard, M. Derakhshani, and W. Saad, "Dynamic Non-Orthogonal Multiple Access and Orthogonal Multiple Access in 5G Wireless Networks," ***IEEE Trans. Commun.,*** vol. 67, no. 9, pp. 6360–6373, 2019, doi: 10.1109/TCOMM.2019.2919547.

30. O. Olukoya and D. Budimir, "Evaluation of waveform candidates for 5G wireless communications," ***Proc. Eur. Microw. Conf. Cent. Eur. EuMCE 2019,*** no. May, pp. 347–349, 2019.

31. H. Schulze and C. Lüders, *Theory and Applications of OFDM and CDMA*. 2005.

32. Behrouz Farhang-Boroujeny, "OFDM versus Filter Bank Multicarrier," ***IEEE Signal Process. Mag.,*** 2011, doi: 10.5916/jkosme.2018.42.4.312.

33. A. J. Ramadhan, "Overview and implementation of the two most important candidate 5G waveforms," ***J. Theor. Appl. Inf. Technol.,*** vol. 97, no. 9, pp. 2551–2560, 2019.

34. S. Kanapala and S. J. Hussain, "BER Analysis of Filter Bank Multicarrier for 5G Wireless Communications," ***Int. J. Recent Technol. Eng.,*** vol. 7, no. 5, pp. 211–214, 2019.

35. C. An, B. Kim, and H.-G. Ryu, "Waveform Comparison and Nonlinearity Sensitivities of FBMC, UFMC and W-OFDM Systems," pp. 83–90, 2016, doi: 10.5121/csit.2016.61508.

36. D. E. Rennes, "Thèse Peak to Average Power Ratio Analysis and Reduction of Cognitive Radio Signals," 2009.

37. K. Fazel and S. Kaiser, *Multi-Carrier and Spread Spectrum Systems: From OFDM and MC-CDMA to LTE and WiMAX:* ***Second Edition***. 2008.

38. J. Nadal, "Filtered multicarrier waveforms in the context of 5G : novel algorithms and architecture optimizations To cite this version : HAL Id : tel-01829015 Jérémy Nadal Filtered Multicarrier Waveforms in the Context of 5G : Novel Algorithms and Architecture Optim," 2018.

39. C. An and H. G. Ryu, "Design and Performance Comparison of W-OFDM Under the Nonlinear HPA Environment," ***Wirel. Pers. Commun.,*** vol. 98, no. 1, pp. 983–999, 2018, doi: 10.1007/s11277-017-4904-x.

40. L. Li, Y. Wang, and L. Ding, “On the bit error probability of OFDM and FBMC-OQAM systems in Rayleigh and Rician multipath fading channels,” ***IEICE Trans.*** *Commun.*, vol. E102B, no. 12, pp. 2276–2285, 2019, doi: 10.1587/transcom.2017EBP3451.

41. F. Schaich and T. Wild, “Waveform contenders for 5G - OFDM vs. FBMC vs. UFMC,” ***ISCCSP 2014 - 2014 6th Int. Symp. Commun. Control Signal Process. Proc.,*** no. May, pp. 457–460, 2014, doi: 10.1109/ISCCSP.2014.6877912.

42. H. Ryu, “5G Candidate Waveforms Comparison Regarding Time-Frequency Resources in the Nonlinear HPA,” ***Twelfth Int. Conf. Digit. Telecommun.*** *5G*, no. c, pp. 13–17, 2017.

43. R. Nissel and M. Rupp, “OFDM and FBMC-OQAM in Doubly-Selective Channels: Calculating the Bit Error Probability,” ***IEEE Commun. Lett.,*** vol. 21, no. 6, pp. 1297–1300, 2017, doi: 10.1109/LCOMM.2017.2677941.

44. I. A. Shaheen, A. Zekry, F. Newagy, and R. Ibrahim, “Performance evaluation of PAPR reduction in FBMC system using nonlinear companding transform,” ***ICT Express,*** vol. 5, no. 1, pp. 41–46, 2019, doi: 10.1016/j.icte.2018.01.017.

45. S. Patchala and M. Sailaja, “Analysis of Filter Bank Multi-Carrier system for 5G communications,” ***Int. J. Wirel. Microw. Technol.,*** vol. 9, no. 4, pp. 39–50, 2019, doi: 10.5815/ijwmt.2019.04.04.

46. A. Iqbal, S. Shah, and M. Amir, “Adaptive Investigating Universal Filtered Multi-Carrier (UFMC) Performance Analysis in 5G Cognitive Radio Based Sensor Network (CSNs),” ***Int. J. Eng. Work. Kambohwell Publ. Enterp. ISSN,*** vol. 4, no. 1, pp. 5–9, 2017, [Online]. Available: http://www.kwpublisher.com/paper/investigating-universal-filtered-multi-carrier-ufmc-performance-analysis-in-5g-cognitive-radio-based-sensor-network-csns.

47. V. Vakilian, T. Wild, F. Schaich, S. Ten Brink, and J. F. Frigon, “Universal-filtered multi-carrier technique for wireless systems beyond LTE,” ***2013 IEEE Globecom Work. GC Wkshps 2013,*** no. December, pp. 223–228, 2013, doi: 10.1109/GLOCOMW.2013.6824990.

48. S. Sidiq, F. Mustafa, J. A. Sheikh, and B. A. Malik, “FBMC and UFMC: The Modulation Techniques for 5G,” ***2019 Int. Conf. Power Electron. Control Autom. ICPECA 2019 - Proc.,*** vol. 2019-Novem, 2019, doi: 10.1109/ICPECA47973.2019.8975581.

49. Y. Xu, H. Chu, and X. Wang, “Joint Timing Offset and Channel Estimation for Multi-User UFMC Uplink,” ***IEEE Wirel. Commun. Lett.,*** vol. 9, no. 2, pp. 236–239, 2020, doi: 10.1109/LWC.2019.2949800.

50. X. Yang, S. Yan, X. Li, and F. Li, “A unified spectrum formulation for OFDM, FBMC, and F-OFDM,” ***Electron.,*** vol. 9, no. 8, pp. 1–15, 2020, doi: 10.3390/electronics9081285.

51. O. E. Ijiga, O. O. Ogundile, A. D. Familua, and D. J. J. Versfeld, “Review of channel estimation for candidate waveforms of next generation networks,” ***Electron.,*** vol. 8, no. 9, pp. 1–50, 2019, doi: 10.3390/electronics8090956.

52. F. A. P. De Figueiredo, N. F. T. Aniceto, J. Seki, I. Moerman, and G. Fraidenraich, “Comparing f-OFDM and OFDM performance for MIMO systems considering a 5G scenario,” ***IEEE 5G World Forum, 5GWF 2019 - Conf. Proc.,*** no. Ml, pp. 532–535, 2019, doi: 10.1109/5GWF.2019.8911702.

53. M. Bellanger, “FBMC Physical Layer: A Primer,” ***PHYDYAS, January,*** pp. 1–31, 2010, [Online]. Available: http://www.ict-phydyas.org/teamspace/internal-folder/FBMC-Primer_06-2010.pdf.

54. S. Thiyagarajan and S. Veerappan, “Performance Analysis of UFMC and its Comparison with CP-OFDM,” ***Int. J. Eng. Tech.,*** vol. 4, no. 2, pp. 776–780, 2018, [Online]. Available: http://www.ijetjournal.org.

55. W. F. Sharpe, G. J. Alexander, and J. V Bailey, ***Fifth edition Инвестиции.***

56. S. Sesia, I. Toufik, and M. Baker, ***LTE - The UMTS Long Term Evolution.*** 2011.

RESUME

Ahmed SAHAB graduated first and elementary education in this city. He completed high school education in Assaba engineering High School, after that, he started undergraduate program in Aljabal Algharbi University Department of Engineering in 2007. Then in 2019, he started master program in Karabuk University Department of Electric Electronics Engineering.