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Comparative Performance Analysis of Modulation Formats for 5G Wireless System

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Abstract

The fourth generation (4G) of cellular networks, was initially roll out in 2009/10 by succeeding third generation (3G). The fifth generation (5G) is the forthcoming evolution of mobile technology expected to be used by 2020 with a wide range of services and usability beyond the use of 4G [1] [2]. Three main services, enhanced Mobile Broadband (eMBB), Ultra-reliable Low-latency Communication (URLLC) and massive Machine Type Communication (mMTC) will impose different requirements on the 5G air interface [2].

Orthogonal Frequency Division Multiplexing (OFDM) have been the most attractive one for the development of wireless communication system like 4G due to several advantages like ease of implementation, immunity to interference, high data rate etc. Whereas 5G will demand more from physical layer than the current OFDM can deliver. Therefore, more waveforms have been proposed to address the challenges of OFDM. In this thesis, we provide analysis and comparison for the candidate waveforms Filterbank multicarrier (FBMC) and Universal-filtered multicarrier (UFMC).

To obtain insightful analysis we will not only introduce the basic principle of the waveforms but also reveal the characteristics of each waveforms. Moreover, performance comparison in terms of Power spectral density (PSD), Bit error rate (BER) and spectral efficiency presented. Also computational complexity of waveforms in different cases evaluated. Mathematical analysis and characterizations are validated by computer simulation employing Mathlab. The result shows advantages and drawbacks for each modulation schemes. FBMC shows the best spectral leakage among both waveform candidates. This reveals to be almost insensitive to multiuser interference to support different use cases with in same bands. UFMC, reveals to be most promising which close to OFDM with advantage of better out-of-band (OoB) emission. Finally, some concepts which should addressed are underlined.

Keywords– *PSD, Spectral efficiency, computational complexity, OFDM, FBMC, UFMC.*

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List of Abbreviations

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

FMT .... Filtered Multitone

IDFT .... Inverse Discrete Fourier Transform

IFFT .... Inverse Fast Fourier Transform

IMT .... International Mobile Telephony

ITU .... International Telecommunication Union

LTE .... Long Term Evolution

METIS .... Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society

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

Rx .... Receptor

SMT .... Staggered Multitone

SNR .... Signal to Noise Ratio

TDMA .... Time division multiple access

Tx .... Transmitter

UFMC .... Universal Filter Multicarrier

Chapter 1

Introduction

1.1 Background Information

Cellular networks were originally designed for voice only application, using analogue transmission channels. This was the first generation (1G) simple voice call were all it was able to do. When digital technology evolved and more voice channels were required, second generation (2G) system emerged in the 1990s. The benefits of 2G were; digital transmission and enabled new services. These services are short message service (SMS) text messaging and lower rate internet data access. The low data rate services provided by 2G systems did not fulfill the need for mobile internet access. This lead to a demand for new standards which named as third generation (3G). 3G came along and offered faster data transfer speeds, up to 2 Megabits per second (Mbps) which is first mobile broadband. This leads to introduce new services such as: web browsing, email, video downloading, picture sharing and other smartphone technologies [38] [39].

The fourth generation (4G) of cellular networks, Long Term Evolution (LTE), was introduced around 2010 by succeeding 3G. 4G is intended to provide high speed, high capacity, low cost per bit, internet protocol (IP) based services etc. [23]. It has essentially been optimized to provide high data bandwidth to strictly synchronized devices like tablets and smartphones [20] [22]. In the near future, it is expected that the mobile internet will massively be used for machine-to-machine communications, introducing the concept of Internet-of-Things (IoT). The fifth generation (5G) is the forthcoming evolution of mobile technology expected to be in use by the year 2020 with a wide range of usability beyond the uses of 4G [1] [32].

In each generation there were enhancement of services coverage, data rate, addition of features etc. To achieve this, different type of technologies was applied. One of this are higher order modulations and multiple access schemes. The modulation technique adopted in 1G was frequency modulation (FM) for the voice signal and frequency division multiple access (FDMA). Whereby a user during a call was assigned a given frequency for transmission to a base station (uplink) and a given frequency for reception from the base station (downlink). The first proposal for 2G systems was based on time-division multiple access (TDMA) whereby each allocated bandwidth was slotted in time so that users could use the same spectrum. The modulation technique for 2G in United States and Japan was differential phase shift keying (DPSK) with raised cosine filtering, which is a non-constant envelope technique while in Europe Gaussian minimum shift-keying (GMSK) which is a constant envelope technique. The advantage of non-constant envelop technique is their bandwidth efficiency than constant envelop. In other way constant envelop techniques allows the power amplifier to operate near saturation without distorting the signal by ensuring that the envelope of the transmitted signal is a constant [11] [22]. TDMA is less efficient in handling the high data rate channels because it requires large guard periods to alleviate the multipath impact. Again, FDMA consumes more bandwidth for guards for avoiding inter carrier interference.

Later, the 2G standard uses two branches, one branch used the combination of FDMA and TDMA and the other introduced a new access scheme called Code Division Multiple Access (CDMA) [11]. In CDMA, multiple users spreading their signals over a wide bandwidth with use unique codes allowed for multiple users using the same spectrum at the same time. CDMA uses the spread spectrum technique, which spreads the bandwidth of the data uniformly for the same transmitted power. Usage of CDMA increased the system capacity and the data rate which is efficient to handle the multipath channel. This enabled the 3G systems to use CDMA as the access scheme each technology. However, 4G uses OFDMA and other technologies like single-carrier frequency division multiple access (SC-FDMA) instead of CDMA, which is used by 3G system [22]. The previous standards used Phase-shift keying, more spectral efficient modulation schemes such as 64-QAM (Quadrature Amplitude Modulation) is being used for 4G system.

The modulation scheme the current system 4G/LTE is based on Orthogonal Frequency Division Multiplexing (OFDM) waveform for the downlink and of the single-carrier frequency division multiple access (SC-FDMA) technique for the uplink [22].

OFDM is widely known multicarrier scheme and also the most employed in current standard for wireless communication including Third Generation Partnership Project (3GPP) LTE and Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard families due to the associated advantages. Such advantages are robustness against multipath fading by dividing the channel into narrow flat fading channels, efficient one-tap frequency domain equalization enabled by the use of Cyclic Prefix (CP), ease of implementation, straightforward and simple extension to very large multiple-input multiple-output (MIMO) and high gain beam forming solutions [5] [14].

Even though OFDM is the most prominent, it also exhibits some intrinsic drawbacks. This include out-of-band interference which caused by its rectangular pulse shape, the cyclic prefix insertion drives to spectral efficiency loss; and strict time and frequency synchronization is required to prevent subcarrier orthogonality [43] that guarantees a low level of intra and inter-cell interference. Additionally, OFDM signals may exhibit large peak-to-average-power ratio (PAPR) values [44], and this has a clear impact on the system energy efficiency. To overcame these limitations several alternative candidates modulation schemes have been studied in literature, such as Filter Bank Multicarrier modulation (FBMC) [10] , Universal Filter Multicarrier modulation (UFMC) [28], filtered OFDM (f-OFDM), Generalized Frequency Division Multiplexing (GFDM) etc.

In this thesis we provide a review of some of the best recently proposed waveforms alternatives to OFDM. Since many new waveforms have been proposed and we cannot take all in to our analysis. We only choose two typical candidates FBMC and UFMC. Because they got more attention in most of researchers and academicians.

1.2 Statement of the Problem

Performance parameters like network capacity, peak data rate, latency, spectral efficiency of 5G technologies are expected to be tens and thousands times better than 4G. Furthermore, low energy consumption as well as cost are also desired. In addition, 5G should enable machine to machine (M2M) communication at ultra-low cost and ultra-high reliability while supporting long year battery life [1]. In order to facilitate this requirements spectral efficiency, signaling efficiency, bandwidth and coverage should be significantly enhanced compared to 4G. To cope up these issues there are expected enabling technologies for 5G. Some of them are densification of networks, increased bandwidth, increased spectral efficiency and new air interface to achieve the data rate and capacity for 5G [2]. The air interface includes waveforms, multiplexing schemes, modulation schemes and coding schemes to reduce the latency in the air-link, and to increase spectral efficiency, connection density, throughput, area capacity density and energy efficiency [40].

Even if OFDM is the most prominent multicarrier technique in wireless standard, but also possess certain disadvantages like use of CP which costs on spectral efficiency of the waveform, large side lobes which limits the utilization of spectrum. Also OFDM requires stringent time synchronization to maintain the orthogonality between different user [43]. It is envisioned that there will be huge number of nodes communicating over the 5G network for mMTC services. Each user nodes are usually transmitting type of data asynchronously in narrowband. Waveform that require strict synchronization to achieve interference free communication are not suitable for mMTC. This may result for high interference between user nodes [47]. Additionally, high peak-to-average power ratio (PAPR) is also considered to be one of the biggest hurdles in OFDM which greatly reduce the performance, efficiency of non-linear OFDM amplifier. Therefore, OFDM is not likely to be considered for the next generation mobile communication system.

Hence, the key players of the wireless industry and research institutes conducted researches to address the drawbacks in OFDM for 5G network. For this, various type of modulation schemes has been proposed, which included in pulse shaping (which is subcarrier based filtering), subband filtering etc. FBMC [10], Generalized Frequency Division multiplexing (GFDM), UFMC [25] [18], f-OFDM, GFMC are some of proposed modulation schemes for 5G. However, there is lack of comprehensive and fair comparison among these candidate waveforms. Based on this, we are motivated to study some of proposed candidate modulation schemes to evaluate their performances. From proposed candidate modulation schemes we choose FBMC and UFMC modulation schemes. The performance evaluation is held by proposing the same frame-work with reference to that of CP-OFDM.

1.3 Objective

1.3.1 General Objective

The aim of this thesis is to evaluate the performance of FBMC and UFMC reference with that of CP-OFDM.

1.3.2 Specific Objectives

The above general objective is accomplished by the following specific tasks:

- Detail review and analysis of the cons and pros of OFDM.
- Analyze the basic working principle of each UFMC and FBMC modulation schemes.
- Observe the mathematical and diagrammatical background of the candidates modulation schemes.
- Propose a common frame work for the evaluation of modulation schemes.
- Analysis based on numerical evaluation and simulation with MATLAB simulation software.
- Analyze the performance of each modulation schemes on the proposed frame-work.
- Based on numerical evaluation and simulation, evaluate the performance of each modulation schemes on proposed frame
- Finally, from the results recommend the preferred modulation formats for 5G.

1.4 Methodology

In order to achieve the objectives described above in the specified time, the following techniques has been used. First of all, reviewed the previous works related to this work. This include study of previous wireless networks, new requirements of 5G wireless network and its differences from past generations. Secondly, asses starting from the reason for requiring of new modulation schemes up to identifying the proposed candidate modulation schemes. Then the candidate modulation formats will be reviewed in order to understand their operation principles and mathematical formulations. The next step is system designing, which is common frame work for the comparison. This includes, prepare mathematical model for calculating computational complexity, outlying work flow for the BER and identifying the input parameters for the simulation.

After that, MATLAB simulation software is implemented to build model of multicarrier modulation schemes in order to study their respective power spectrum density, bit error rate and spectral efficiency. By plotting BER graphs we can make a reasonable comparison between the three schemes, which are useful in showing how the transmitted signal distorted by noise in the channel. Also simulating the PSD allows us to examine how the out-of-bound leakage of modulation technique is. At same time, all the code will be tested and verified following the defined procedures. Next, perform result analysis and interpretation. Finally, the conclusions and future work for the thesis are given.

1.5 Literature Review

Recent works have been proposed to mention and investigate the candidate waveforms of 5G. Studies have already compared some of those modulation schemes individually to OFDM in a single-input single-output (SISO) case.

- An extensive comparison between OFDM and FBMC is provided in [5] in terms of spectral efficiency and complexity. They try to addressed the shortcomings of OFDM in cognitive radios and other applications and proposed that FBMC could be a more effective solution. Benefits of UFMC over OFDM are partially presented in [18], they compared their time-frequency efficiency when transmitting very small bursts and under very tight response time requirements. They proposed UFMC as best chose. In this paper analysis is limited to spectral efficiency aspects and the complexity aspects are not addressed.

- In [3] performance analysis of UFMC was performed and compared with that of CP-OFDM. The basis for the comparison were PSD and Peak to Average Power Ratio (PAPR). They found that the PSD result of UFMC outperform that of OFDM and the PAPR variation between the two was close to each other. The BER performance of UFMC also held. This limit the paper, because it was simulated by considering under additive white Gaussian noise (AWGN) channel.

- Compressive overview of the most promising modulation and multiple access schemes for 5G was present in [35]. They categorized and give an introduction of Orthogonal Multiple access (OMA) and Non-Orthogonal Multiple access (NOMA) schemes. They try to identifying the modulation schemes that are potentials for OMA. Some selected modulation schemes performance analysis was compared in terms of out-of-band leakage and bit-error rate. The authors are also focused on various type of NOMA candidates, including power-domain NOMA, code-domain NOMA, and NOMA multiplexing in multiple domains. Finally, they suggested that, there are new modulation schemes with less out-of-band leakage for orthogonal MA of 5G network. They also got more interest on NOMA for providing enhanced throughput and massive connectivity with improved spectral efficiency. The performance comparison was only bounded on two metrics.

- R. Gerzaguet et al. [8], proposed a more exhaustive comparison is, comparing FBMC, UFMC and GFDM in terms of PSD, spectral efficiency, peak-to-average-power ratio (PAPR) and complexity. Robustness to timing offset (TO) and carrier frequency offset (CFO) in a non-synchronous multi-user scenario is also studied. They concluded that, UFMC as interesting as the spectral efficiency is comparable to that of OFDM, which also preserves backward compatibility with well-known OFDM algorithms (channel estimation, MIMO detectors). They also found that FBMC and GFDM interference between adjacent bands is minor. However, the contribution of [8] is also limited since the spectral efficiency comparison was done considering an AWGN communication channel only. Similar to OFDM, guard intervals have to be inserted in UFMC to combat inter-symbol interference (ISI) when subject to a multi-path channel. This reduces the spectral efficiency of UFMC and GFDM compared to results in [8].

- P. Banelli et al. [7], provides a review of some modulation schemes alternative to OFDM and deemed as suitable candidates for the implementation of the air interface of future 5G cellular communications. They compare Filterbank FBMC, Faster-than-Nyquist (FTN) / Time-frequency-packed (TFS) Signaling and Single-carrier modulation (SCM) in terms of achievable spectral efficiency (ASE). The ASE was reported as a function of the ratio between the signal power and the noise power. ASE representing the spectral efficiency which a system may attain under the constraint of arbitrarily small bit error rate. They came to conclude and point out that for all the considered channels, FBMC gains can be even higher by means of a properly designed pulse.

1.6 Scope and Limitation of the thesis

As we know that, the research area of the new generation is vast and participated with different researchers, companies etc. The area that we are interested is on the enabling technologies of 5G, more specifically on new air interfaces which is new modulation schemes. In literatures to overcome the drawbacks of OFDM several alternative candidates have been intensively studied. This thesis includes, description of those most popular 5G candidate modulation schemes this include block diagram and mathematical analysis of selected modulation schemes. Then compare them in terms of specific performance features such as power spectral density, spectral efficiency in terms of time and modulation efficiency, bit error rate. We also compare their baseband end to end computational complexity using as a baseline reference the current waveforms used in 4G LTE. Finally based on the results we will discussed each candidate on 5G use cases. The limitation of this work is simulation is undertaken on single user scenarios, by assuming all the available resource is used by single user.

1.7 Thesis Organization

The rest of this document is organized in the following chapters. Chapter I Introduction: This chapter mainly deals with the background, objectives, literature review and methodology of study. The scope and limitation of the thesis also included. Chapter 2 review the fundamentals, requirements and enabling technology of 5G. In Chapter 3 the basics of candidate modulation formats and mathematical model are presented. Performance analysis and simulation results comparing the candidates are presented in Chapter 4 and 5. Finally, the conclusion and recommendations for future work of the study are given in Chapter 6.

Chapter 2

Fundamentals of 5G System

2.1 Background

Mobile communication and wireless networks are developing at high speed, with evidences of significant growth in the area of mobile subscribers and terminals, mobile and wireless access networks, and mobile services and applications. The fifth generation, 5G of mobile networks that will supersede the 4G and 3G families of standards. A new mobile generation has appeared almost every 10^{th} year since the first 1G system. Each generation of mobile technology has been motivated by the need to meet requirements [39]. For example, the transaction from 2G to 3G was mainly target to enable mobile internet. This was not highly succeeded until 3.5G. More recently, the transition from 3.5G to 4G services has offered users to access fast data speeds with lower latency rates. This changes the way that people access and use internet on mobile devices [8].

Self-driving cars, mobile television, live broadcasting, mobile shopping and other service has emerged as a great source of revenue for service provider. Providing these service is beyond the capacity of 3G and 4G networks from the point of view of resource utilization [1]. In addition to the sheer volume of data, the number of devices and the data rates will continue to grow exponentially. The number of devices could reach the tens or even hundreds of billions by the time 5G comes to fruition, due to many new applications beyond personal communications [4, 5].

Unlike previous generations of cellular networks, 5G systems will have to accommodate a variety of services and of emerging new applications, and, in order to do that, focusing only on the increase of the data throughput is not enough. Collaborative projects are preliminary for 5G implementation and standardization activities of 5G. Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society (METIS) [33], project explain and described the 5G scenarios and gives the details of challenges of 5G. 5th Generation Non-Orthogonal Waveforms (5GNOW) [34], project also focus on non-orthogonal waveforms for asynchronous signaling. There are also other projects which working on 5G including, Physical Layer Wireless Security (PHYLAWS), CROWD project, 5G project partnership, Samsung, etc. This chapter reveals use cases, requirements and enabling technologies of 5G.

2.2 Use cases and Requirements of 5G

Whenever a new generation of technology is introduced, experts spin up use cases seeking to prove the need for it. Like other generations there are listed use cases of 5G International Telecommunication Union (ITU) has developed a use case diagram for 5G;

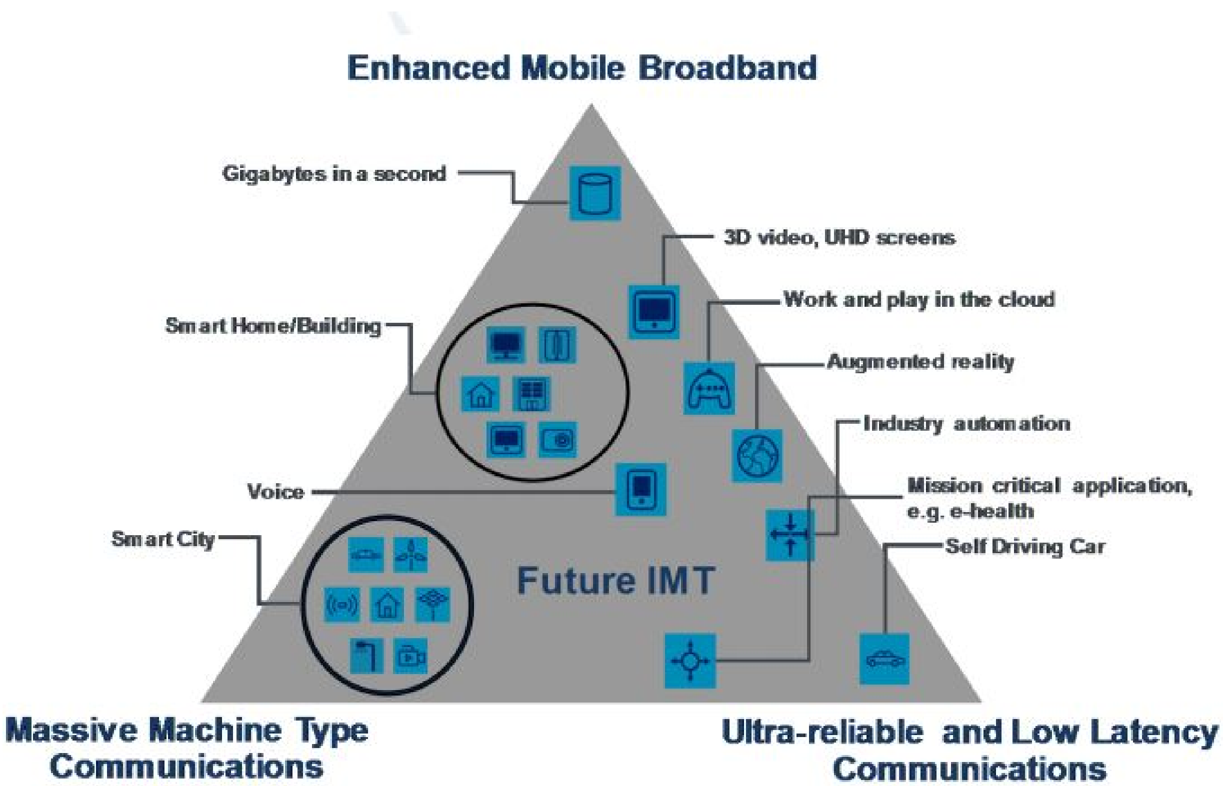


Figure 2.1: Major Application Categories of 5G [1]

it's a triangular map that assigns an application category to each corner (enhanced mobile, massive machine type communications, ultra-reliable and low-latency applications) and then graphs specific applications (voice, smart cities, augmented reality, etc.) within the triangle based on the extent to which they share the characteristics of each category [1]. The following are the categories discussed about 5G use cases.

2.2.1 Enhanced Mobile Broadband (eMBB)

Data will be one of the key use case driving the requirements for 5G. It goes far beyond basic internet access. This is because data is growing annually [31] and is expected to continue towards 2030. The main drivers for the increased traffic volume are the increase in size of content and the number of applications requiring high data rates. Also, streaming services (audio and video), interactive video and mobile Internet connectivity will continue to be used more broadly as more devices connect to the internet [5]. Many of these applications require always-on connectivity to push real time information and notifications to the users. Also cloud storage and applications are rapidly increasing for mobile communication platforms. This is applicable for both work and entertainment. Based on these drivers 5G is expected to deliver eMBB of 10 Gbps peak throughput and up to 10,000 times the current network capacity [1] [33]. Based on its requirements, eMBB needs to support a much wider range of code rates, code lengths and modulation orders than LTE [2].

2.2.2 Massive machine type communications (mMTC)

This scenario is being developed to cater the massive-machine networks to enable Internet of Things (IoT) at home and in business. Number of mobile devices such as mobile phones, tablets and smart watches have been exponentially increasing in the last few years and at the same time more and more applications such as video streaming/downloading, multi-player gaming which requires a large bandwidth are emerging [2]. Also, smart cities and smart homes, often referred to as smart society, will be embedded with dense wireless sensor networks. More and more household items such as fridges, ovens, heating systems, and even clothes are being developed as "smart devices" which can be connected with other devices via internet. Many of these services typically require a small amount of data to be transferred among the devices in a large network. The networks like these, called IoT are increasing by adding different kind of devices in household as well as industrial environments. The industry foresees as many as 50 billion of potential IoT devices in service by 2020 [2]. Very low power consumption, low cost, ability to handle a large number of connections and good scalability are desired in these type of system [2]. The task for 5G will be to integrate the management of these very diverse connected devices.

2.2.3 Ultra-Reliable Low-Latency Communications (URLLC)

In this use case, requirements for capability such as throughput, latency and availability are vital. This category includes new services that will transform industries with ultra-reliable/available low-latency links, such as remote control of critical infrastructure, self-driving vehicles, smart-grid control, industrial automation, drone control and coordination, and so on [1].

In industrial automation, wireless and mobile communications are becoming increasingly important for industrial application. Wires are expensive to install and maintain and the possibility of replacing cables with reconfigurable wireless links is a tempting opportunity for many industries. However, achieving this requires that the wireless connection works with a similar delay, reliability and capacity as cables and that its management is simplified. A smart grid can be seen as another network with low delays. A smart grid interconnects sensors that automated consumption and distribution of energy including gas and heat, using digital information. Low delays and very low error probabilities are new requirements that need to be addressed with 5G [40].

2.2.4 Fixed Wireless Networks

One of the top 5G use cases will be fixed wireless access. Fixed wireless will provide internet access to homes using wireless network technology rather than fixed lines. This may focuses on coverage of low populated remote areas which suffer from low data rates and unreliable solutions [32]. It is expected that the generous throughput of 5G networks will also suit it to bringing internet broadband access to sparsely populated areas that are not yet covered by wired technologies such as Asymmetric digital subscriber line (ADSL) and optical fiber. In this scenario network devices will have very low mobility, so Doppler effects will be negligible, and also latency will not be a key requirement [2].

The use cases and vision of the 5G system leads to requirements that the future mobile broadband system will need to meet. The following are some of 5G wireless network requirements [1] [37] :

- Peak Data rate:

  The peak data rate is the maximum theoretically achievable data rate which can be assigned to a single mobile station assuming error-free conditions when all the available radio resources are utilized for the corresponding link. The minimum requirement for peak data rate is 20 Gbps.

- Areal Capacity:

  In order to accommodate the explosive increase of future mobile data traffic, 5G radio access network should be able to scale-up system capacity by adding more cells in a target area, which is expected up to 10 Mbps/m2.

- Energy Efficiency:

  5G radio access technology design should aim for higher energy efficiency against increased device/network energy consumption required on 5G wireless communications up to 100 times higher than 4G.

- Massive Connectivity:

  Connectivity in 5G is simply not limited to mobile devices. Instead, every single unit mounting a modem function will connect together for any reasons of safety, communication, cozy life, and so on. 10 times more simultaneous IoT Connections than 4G is expected in 5G.

These requirements shall be fulfilled at similar cost and energy dissipation as today. According to METIS, the requirements are assess from the end user perspective [37]. These are summarized in Table 2.1.

Table 2.1: A selection of key requirements and respective application examples [37]

Requirements	Desired Value	Application Example
Data Rate	1-10 Gbps	Virtual reality office
Data volume	9 Gbytes/h in busy period 500 Gbytes/mo/subscriber	Dense urban information society
Latency	Less than 5ms	Traffic efficiency and safety
Connected devices	300,000 devices per AP	Massive deployment of sensors and actuators
Battery Life	One decade	Massive deployment of sensors and actuators

2.3 5G Enabling Technologies

There are technologies being developed to improve all the requirements identified in the above section, both as part of an evolution of LTE, and to enable new 5G networks. As discussed in different papers [1, 2, 32], in order to cater for the requirements of, 5G needs to achieve significant enhancements in addition to existing technologies. Some of the main technologies under research to achieve the data rate and capacity for 5G are:

2.3.1 Massive Multiple Input Multiple Output

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

The MIMO algorithms used in LTE standards can be divided into four broad categories: receive diversity, transmit diversity, beamforming, and spatial multiplexing. In transmit diversity and beamforming, transmit redundant information on different antennas. As such, these methods do not contribute to any boost in the achievable data rates but rather make the communication link more robust. In spatial multiplexing, however, the system transmits independent information on different antennas [2]. In LTE and LTE-A standards, MIMO technique became extended from point-to point to multi-user application with multi-user MIMO (MU-MIMO). MU-MIMO used to separate users by their spatial position, which can substantially boost the data rate, allowing for further network densification and increased capacity.

Radically departing from existing MIMO is a new generation of large antenna array techniques, commonly referred to as “Massive MIMO”, where the number of antennas at the base station is increased drastically (by an order of magnitude or more over current MIMO systems) to harvest further gains. There is currently no set definition of how many antennas a system must have to be considered Massive MIMO, but a system with greater than 8×8 antennas is generally considered a Massive MIMO system [2].

In present, Massive MIMO has gained significant momentum as potential candidate to increase capacity in multiuser networks. Massive MIMO envision with vast gains in spectral efficiency, increase in energy efficiency, and reduction in network interference, all of which are key to address the demands of a data-centric world where spectrum and energy are increasingly precious [6]. The basic concept in Massive MIMO, a base station is using M antenna to spatially multiplex K single antenna terminals where is $K << M$. The multiplexing takes the form of beamforming, also known as multiuser precoding, effectively creating transmitted signals that add up constructively on the spots where the terminals are located and destructively almost everywhere else Figure 2.2.

The success of such a spatial multiplex, in both uplink and downlink, relies on several important concepts. One of the most important concept is that the base station should have sufficiently good knowledge of the propagation channel in both directions, on which efficient downlink precoders and uplink detectors can be based. The acquisition of accurate

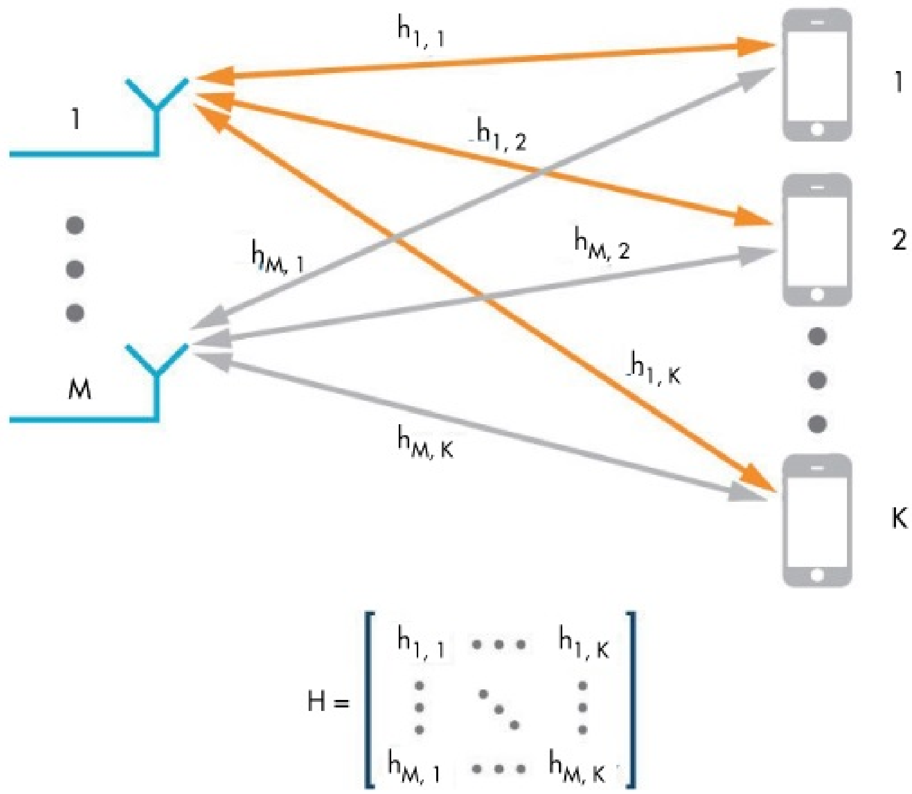


Figure 2.2: Simplified multi-user Massive MIMO system model, assuming time-division duplex and channel reciprocity [2].

instantaneous channel state information (CSI) at the base station is facilitated through time-division duplexing operation, and transmission of pilot waveforms by the terminals. On uplink, terminals transmit pilots and payload; subsequently on downlink, the base station beamforms to the terminals. Reciprocity of uplink-downlink propagation is essential to the use of uplink CSI for downlink precoding, and achieved in practice through calibration of the radio frequency (RF) chains. The reliance on reciprocity permits accurate channel training even in highway-speed mobility scenarios [2, 21].

2.3.2 Millimeter-Wave Mobile Communications (mmWave)

There are technological trends that offers new synergic opportunities for meeting the exploding bandwidth requirements in 5G wireless. Millimeter-wave (mmWave) communication is one of this, which use higher frequencies than the radio waves that have long been used for mobile phones. They are called millimeter waves because they vary in length from 1 to 10 mm, compared to the radio waves that serve today's smartphones, which measure tens of centimeters in length. 4G LTE technology currently uses lower frequency spectrum, generally below 1 gigahertz (GHz), to deliver data at great speed. mmWaves are broadcast at frequencies between 30 and 300 GHz. These frequencies can carry massive amount of data at very high speed and with very little latency [2].

Previously, operators of satellites and radar systems used millimeter waves. Now a day, this bands is getting lots of attention like, in some cellular service providers to use them to send data between stationary points, for short-range wireless technologies, including IEEE 802.11 ad Wireless Gigabit (WiGig) technology standard and WirelessHD (for wireless transmission of high-definition video) [32]. The WiGig technology, operating at 60 GHz spectrum enables devices to communicate for short range at high data rates up to 8 Gbits/s. But using millimeter waves to connect mobile users with a nearby base station is an entirely new approach which is envisioned for 5G network [34]. With several advantages such as large bandwidth (for higher data transfer), higher resolution, low interferences, favorable for smaller cell deployment, large number of antennas are packed in small size. Some of its challenging issues with mmWave are higher pathloss, high rain attenuation, higher power consumption. 5G wireless networks are expected to be driven by large amounts of bandwidth, enabling very high in-coverage throughput, and very small wavelengths enabling a large number of tiny antennas in a given device area featured in mmWave bands.

2.3.3 New Air interfaces

Application requirements for different air interface technologies is complex and diverse, a unified new air interface with flexibility and adaptability is proposed to meet these requirements. New air interface consists of building blocks and configuration mechanisms such as adaptive waveform, adaptive protocols, adaptive frame structure, adaptive coding and modulation family and adaptive multiple access schemes. With these blocks and mechanisms, the air interface is able to accommodate wide variety of user services, spectrum bands and traffic levels [2]. The new air interface design can effectively improve spectral efficiency, increase connectivity, and reduce latency, thus facilitating the deployment of customized scenarios applied to the IoT and for high bandwidth-consuming scenarios such as virtual reality [40].

Huawei summarized the new air interface design in follow figure:

Figure 2.3: New air interface components [40]

One of adaptive channel coding is Polar code. Polar codes are a major breakthrough in coding theory. As described by [40], they can achieve Shannon capacity with a simple encoder and a simple successive cancellation (SC) decoder when the code block size is large enough. Beside this, Full-Duplex is one of duplex mode envisage technology for 5G. Which breaks the barrier of today's communications by supporting bi-directional communications without time or frequency duplex. By transmitting and receiving at the same time and on the same frequency, Full-Duplex has the potential to double the system capacity and reduce the system delay [40].

New multiple access technology includes both orthogonal and non-orthogonal multiple accessing are other enabling technology for 5G network. These are discussed as follow.

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

  To support a massive number of and dramatically different classes of users and applications in 5G networks, various NOMA schemes have been proposed. NOMA is to utilize power and/or code domains in multiplexing to support more users in the same resource block. Three major types of NOMA are proposed power-domain NOMA, code-domain NOMA, and NOMA multiplexing in multiple domains which are considered as a promising MA scheme for 5G networks [35] [41].

  Power-domain NOMA supports multiple users within the same time/frequency/code resource block by distinguishing them with different power levels. Whereas, code-domain NOMA can support multiple transmissions within the same time-frequency resource block by assigning different codes to different users. Rather than multiplexing signal in single domain, some have been proposed to multiplexing in multiple domains, such as the power domain, the code domain, and the spatial domain. This types are called NOMA multiplexing in multiple domains [42].

- **Orthogonal multiple access (OMA)**

  OMA is core to all previous and current wireless networks. For these systems, resource blocks are orthogonally divided in time, frequency, or code domains, and therefore there is minimal interference among adjacent blocks and makes signal detection relatively simple. For 5G OMA is proposed with new modulation schemes as enabling technologies. There are various types of modulation techniques for OMA, which are based on different principles, including pulse shaping, subband filtering, precoding, guard interval (GI) shortening, and mapping symbols in the delay-Doppler domain [35].

  Modulation based on pulse shaping includes FBMC and GFDM, which are working with subcarrier-based filtering. Generally, modulations based on pulse shaping try to restrict transmit signals within a narrow bandwidth and thus mitigate the OoB leakage so that they can work in asynchronous scenarios with a narrow guard band. This is proposed as effective mechanism to reduce OoB leakage [10] [2].

  In the second technique, modulation based on subband filtering includes UFMC and f-OFDM. Which can effectively reduce OoB leakage and achieve better performance. Additional to pulse shaping and subband filtering there are also some other techniques proposed to suppress the OoB leakage and meet the requirements of 5G networks. Guard interval discrete Fourier transform spread OFDM (GI DFT-s-OFDM) [45], spectrally-precoded OFDM (SP-OFDM), and orthogonal time frequency and space (OTFS) [2] are typical modulations.

This thesis is focused on enabling technologies of 5G, which is the new air interface specifically, the modulation schemes. From the above listed candidate modulation schemes we choose UFMC and FBMC, to compare their performances in reference with CP-OFDM. This includes analyzing the mathematical models and transceiver schemes for all the alternatives considered. We also provide a comparative analysis of these modulations, highlighting their pros and cons, and discussing their ability to operate in the 5G reference scenarios.

Chapter 3

Modulation Techniques for 5G Systems

3.1 Background

The nature of future wireless application demands high data rates. Naturally dealing with unpredictable wireless channel at higher data rate communication is not an easy task. The idea of multi-carrier modulation has surfaced recently to be used for combating malevolence nature of wireless channel and providing high data rate communications [11].

According to Nyquist criteria, to support a higher data rate wider bandwidth is required. However, when the signal bandwidth becomes larger than coherence bandwidth, the channel became time dispersive. Time dispersion represents a distortion of the signal that is manifested by the spreading of the symbols in the time domain, also known as delay spread, and this is reflected by inter-symbol interference (ISI) phenomenon [49]. This is also reflected in frequency domain, by the inverse proportionality relation between coherent bandwidth and delay spread. In other word the higher the delay spread, the lower the coherent bandwidth and therefore the higher the channel frequency selectivity.

For broadband transmission the coherent bandwidth of channel is always smaller than the signal bandwidth. Thus is such conditions, the frequency selectivity effect cannot be avoided easily which has a random pattern at any given time. This fading occurs when the channel introduces time dispersion and the delay spread is larger than the symbol period. Frequency selective fading is difficult to compensate because the fading characteristics are random and may not be easily predictable. A very complex structure is needed at receiver which makes computational expensive equalization and channel estimation algorithms to estimate the channel [49]. When there is no dispersion and the delay spread is less than the symbol period, the fading will be flat. Practically flat fading is easily estimated and compensate with simple equalizer [20] [30].

At very high data rates transmission single-carrier transmission suffers from ISI problem. To overcome this problem multicarrier transmission has surfaced [9] [20]. Multicarrier modulation is a form of Frequency-Division Multiplexing (FDM), where data are transmitted across several narrowband carriers located at different frequencies. In conventional FDM system subcarrier signals are separated by guard bands. Multicarrier modulation divides the whole frequency band in too many subcarriers and the high data streams is divided in too many low-rate data streams to transmit in parallel on subcarriers [11] as shown in Figure 3.1 below.

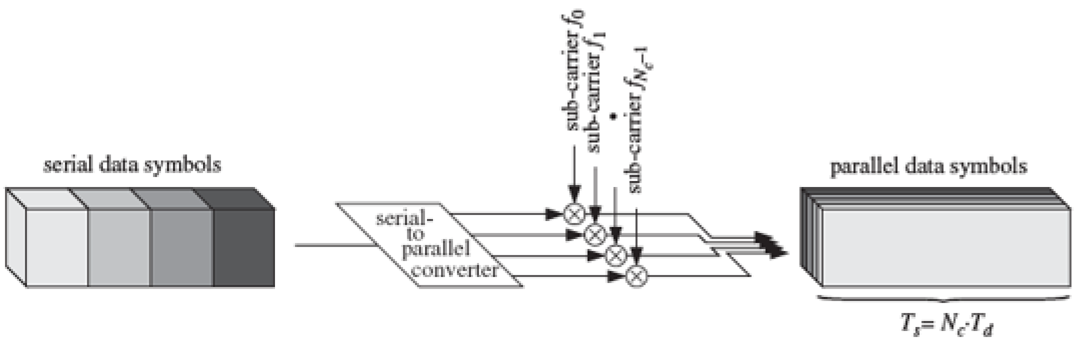


Figure 3.1: General block of Multicarrier modulation with 4 subcarriers [20]

The parallelization of data symbol across several subcarriers yields relatively long symbol duration. Here each symbols occupies narrowband but a longer time period. This clearly show that the delay spread will have any ISI effect on receiver. This can be say that the multicarrier approach turns the channel to flat fading channel and which can be estimated easily [11].

OFDM is widely-used multicarrier modulation and prominent technique in wireless communication. It has a clearly identified capacity for use in a more sophisticated manner with the help of associated technologies and techniques [4]. But due to certain limitations associated with it and with the upcoming requirements, it has been completed to search for alternative transmission techniques for the physical layer communication [1]. FBMC and UFMC can be introduced as a potential candidate that are capable of to overcome certain drawbacks associated with OFDM.

There is a detailed discussion in this chapter on OFDM, UFMC and FBMC techniques, including their developments, basic formulation and signal models used within this study. Each modulation technique is introduced in detail. The basic principle, system block diagram and mathematical formulation are also brought in to attention.

3.2 OFDM Transmission

OFDM transmission scheme is another type of a multichannel system. OFDM was introduced by Chang of Bell Labs in 1966 [4] [11]. It was improved by Weinstein and Ebert in 1971 with the introduction of guard interval, to provide better orthogonality in transmission channel affected by multipath propagation [6].

OFDM has been adopted for wireless standards such as IEEE 802.11a for wideband digital communication. It is also widely applied in a variety of wireless communication standards such as wireless Local Area Network (WLAN); Worldwide Interoperability for Microwave Access (WiMAX); digital video broadcasting terrestrial (DVB-T); the downlink of the current 4G cellular standard LTE employs OFDM on the physical layer.

3.2.1 Basic principle of OFDM

OFDM technique allows for parallel transmission of multiple data streams using orthogonal subcarriers. A general OFDM system overview is given in Figure 3.2 and the signal processing of OFDM trans-receiver is expressed as followed: The digital data bits are mapped to complex symbol Quadrature amplitude modulation (QAM)/ Phase-shift keying (PSK). This data symbols are converted to N streams which corresponds to subcarrier frequencies by serial to parallel converter. Then, this passed through an inverse fast Fourier transformation (IFFT) block to produce time sequence of the streams. In an OFDM signal, the complex values modulating the subcarriers in each symbol period are statistically independent of each other which are orthogonal. Orthogonality of sub-carriers will prevent interference between the closely spaced overlapping carriers. Due to orthogonal nature, spectrum of each sub-carrier has a null at the center frequency of the other carriers in the system which results in no interference between the carriers. The narrow bandwidth of each sub-carrier gives rise to low symbol rate and thus high tolerance to multipath delay spread, as the delay spread must

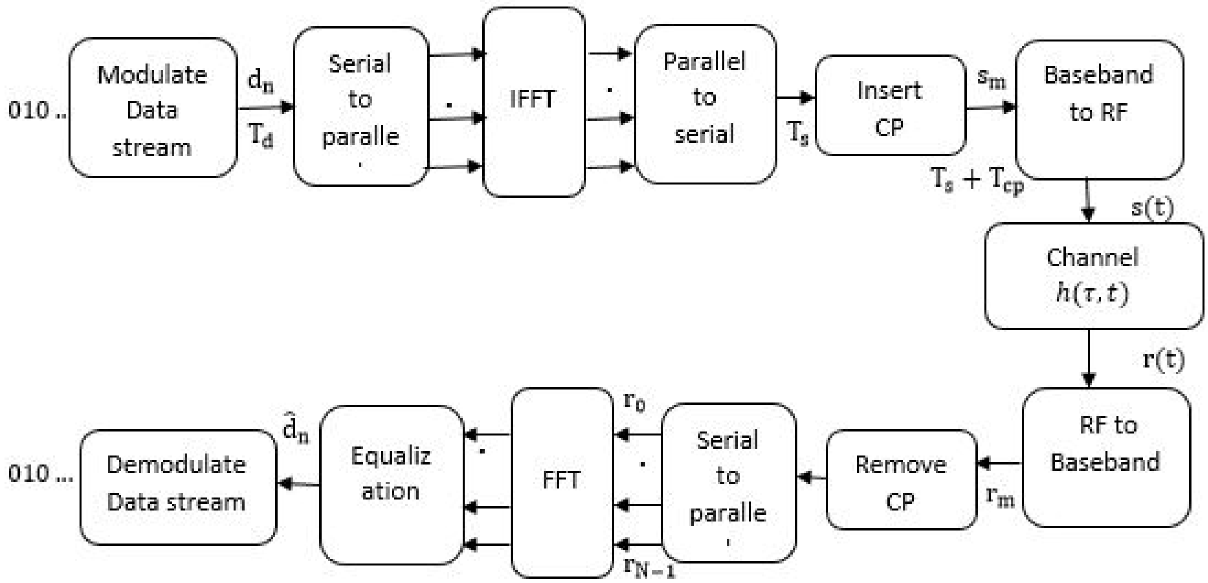


Figure 3.2: Physical layer block diagram of OFDM

be very long to cause significant ISI. This also enables the signal to be separated easily at the receiver side.

The sequence of OFDM signal samples at the output of IFFT is extended by the cyclic prefix (CP) in front of the sequence, which is the last sample of each OFDM symbols are transmitted before the next symbol. This consists of a number of the repeated samples taken from the end of the sequence. This CP is introduced at the transmitter and omitted at the receiver for the received signal at the input of the FFT to be a cyclic (not linear) convolution of the transmitted signal and the channel impulse response. Therefore, this results also in of ISI removal (there is no overlapping of the received symbols), although the symbols can be still distorted by the channel.

Finally, the incoming signal converted to analog signal by Digital-to-Analog (D/A) convertor and fed to radio frequency (RF) stage then transmitted. At the receiver side, the first samples of the CP are discarded as they affected by ISI the subsequent OFDM samples are kept for further processing. The time-domain samples of the received signal are demodulated in the FFT block. Due to the application of the CP at the transmitter and its removal at the receiver, ISI is eliminated, and the OFDM equalizer consists of N, one-tap equalizers that are supposed to equalize the distortions introduced by the frequency-selective channel to distinct subcarriers.

- Guard Interval/ Cyclic Prefix (CP):

  The frequent problem of ISI in high data rate communication is due to the fact that when data rate increases the time duration decreases. This gives rise of self-interference due to multipath delay spread, which decoded incorrectly at the receiver. The minimum requirement to avoid ISI is to keep time duration greater that the maximum delay of the channel [11]. This is one of the major drawback of single- carrier transmission. To avoid this problem guard interval is overhead which can be removed afterwards and the data can be recovered. The high level of robustness against multipath delay spread of OFDM result from the long guard interval used. The guard interval allows time for multipath signal from the previous symbol to die away before the information from the current symbol is gathered. So the multipath effects from one symbol cannot interfere with the next.

  The CP is a cyclic extension of each OFDM symbol, which is obtained by extending the duration of an OFDM symbol, while maintain orthogonality of sub-carriers. Thus, the CP duration (in samples) should be equal to the channel impulse response (in samples) minus one sample. The length for each guard interval must larger than the expected delay spread,

$$\mu \geq \left\lceil \frac{\tau_{max} N}{T_s} \right\rceil \tag{3.1}$$

  is the required discrete length of CP samples in order to prevent ISI [11].

3.2.2 Mathematical Description of OFDM

The mathematical expression of OFDM signal resulting from modulated N subcarriers can be expressed as

$$s(t) = \sum_{n=0}^{N-1} d_n e^{j2\pi f_n t} \qquad 0 \leq t \leq \ T_s \tag{3.2}$$

where d_n is complex data symbol which modulate the n-th subcarrier at the modulation interval, while T_s is the time duration of an OFDM symbol which is $T_s = NT_d$ and T_d is the serial symbol duration. The orthogonality of subcarriers is ensured, if the distance between neighboring subcarrier frequencies equals and subcarriers located at

$$f_n = \frac{n}{T_s} \qquad n = 0.........N-1$$

The output from the IFFT and after this there is cyclic prefix extension of this samples result for

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

As describe in the above subsection μ is the discreet length of the cyclic prefix. This sequence is passed through a digital-to-analogue converter whose output ideally would be the signal waveform $s(t)$with increased duration $\grave{T}_s$. The signal is up-converted and the RF signal is transmitted to the channel.

The output of the channel, after RF down-conversion, is the received signal waveform $r(t)$ obtained from convolution of $s(t)$ with the channel impulse response $h(t)$ and addition of a noise signal $n(t)$, i.e.

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

This passed through an analogue-to-digital converter, whose output sequence which is r(t) sampled at rate $1/Td$. Since ISI is assumed only present in the first samples of the received sequence, these samples are removed before multi-carrier demodulation. The ISI-free part m = 0,..........N-1, is multi-carrier demodulated by exploiting a FFT. The output of the FFT is the multi-carrier demodulated sequence consisting N complex-valued symbols.

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

Since ISI can be avoided due to the cyclic prefix, each sub-channel can be considered separately. Furthermore, when assuming that the fading on each sub-channel is flat and ISI is removed, a received symbol $\hat{d}_n$ is obtained from the frequency domain representation according to

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

where H_n is the flat fading factor and N_n represents the noise of the nth sub-channel. After the parallel to serial conversion of the output from FFT the complex data symbols are feed to QAM demodulator and transmitted bits are estimated.

3.3 FBMC Transmission

FBMC is another form of multi-carrier modulation. The first development in FBMC system were introduced by Chang and Saltzberg [4] [9]. In particular, Chang proposed a special way to transmit asset of parallel (real valued) pulse amplitude modulated (PAM) symbols using Vestigial Side-band modulation (VSB) [9]. Saltzberg, on the other hand, has followed up the original work of Chang and proposed another method called Staggered Modulated Multitone (SMT) [8]. FBMC techniques may be categorize in to three families of multicarrier modulation techniques and are presented below.

1. **Filtered Multitone (FMT) :**

   FMT is another form of FBMC, which subcarriers are separated by guard bands in between; this result for waste of bandwidth. To resolve inter channel interference it applies well designed filter [14]. As opposed to the OFDM, in FBMC-FMT the subcarrier channels have no overlapping of adjacent subcarrier bands and thus is less bandwidth efficient than the OFDM method. However, it does not require the guard interval like in OFDM [14], hence, improving the overall energy efficiency. As FBMC-FMT has no overlap among subcarriers, it is based on the conventional frequency division multiplexing (FDM).

2. **Cosine-Modulated Multitone (CMT) :**

   This mode is the early FBMC modulation technology in the field of digital subscriber line (DSL) field of wireless applications recently. CMT system in which a parallel set of data symbols with pulse amplitude modulation (PAM) are transmitted, i.e., symbols constellation only has real part. Moreover, the PAM symbol sequences are passed through a filter bank with spectral overlap. Thus, the constraints in the filter design are smaller. To achieve the maximum bandwidth efficiency of the system, vestigial side-band (VSB) modulation is applied to each subcarrier. The cosine modulated filter bank, which has a high bandwidth efficiency and also a blind detection capability. However, a 90-degree phase shift is introduced to the adjacent subcarriers [13].

3. **Staggered Multitone (SMT):**

   SMT or more commonly name by offset QAM (OQAM) is another type of filter bank multicarrier, that is very similar to the CMT topology, but presents some advantages. SMT consists of transmitting a set of complex-valued data symbols (in general QAM symbols) whose real and imaginary parts are separated and time staggered by one half of the symbol duration which result OQAM symbols. Which transmit OQAM symbols instead of QAM in OQAM-FBMC the data symbols are spaced at $T/2$ in the time domain and the subcarriers are spaced at $1/T$ along the frequency axis. Therefore, in SMT the symbol rate can be doubled and the symbol spacing can be halved. Compared to CMT and FMT, OQAM-OFDM has the highest stop-band attenuation for a fixed filter length and number of subcarriers [15]. Since the FMT method does not achieve maximum bandwidth efficiency [15], in this thesis we more interested on OQAM-FBMC, which overlaps subcarriers in frequency domain and provides highest bandwidth efficiency.

3.3.1 Basic Principle of FBMC

There are two kinds of implementations of FBMC, the frequency spreading filter bank multicarrier (FS-FBMC) and the poly-phase network filter bank multicarrier (PPN-FBMC). We discussed about them in this subsection. The block diagram of FBMC system are given in Figure 3.3 and Figure 3.4 below; In FS-FBMC OQAM symbols are filtered in frequency domain. Then the result feed to IFFT and performed KN-point IFFT followed by an overlap and sum operation [14]. Where K is the overlapping factor of the prototype filter. At receiver side, a sliding window selects KN points every samples. Then, FFT size of KN point is applied followed by equalization and filtering by prototype filter.

However, for PPN-FBMC OQAM symbol fed to N-point IFFT and then in to polyphase network for filtering. At the receiver, applies filtering before N-point FFT and multitap

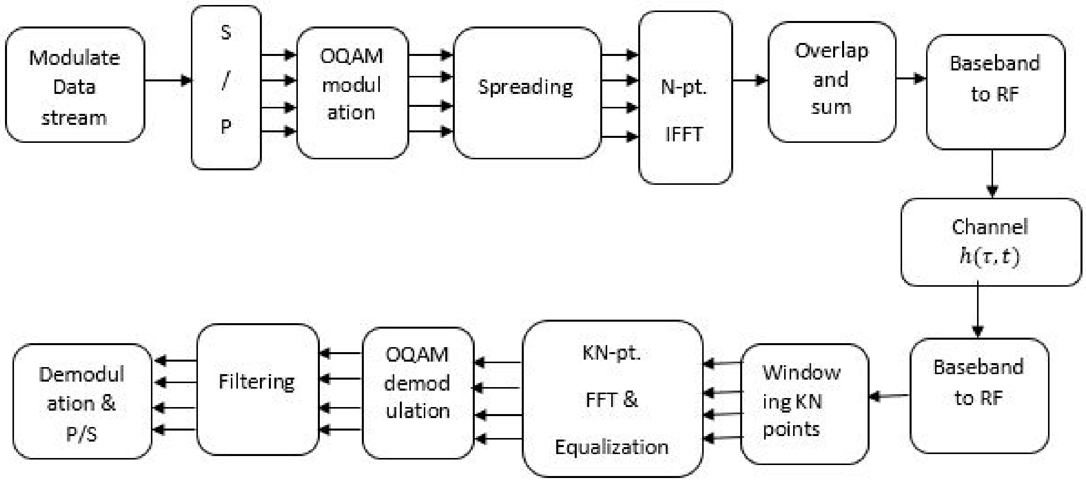


Figure 3.3: Physical layer block diagram of FS-FBMC

equalization is performed in subcarrier basis [15]. The main processing blocks in FBMC are

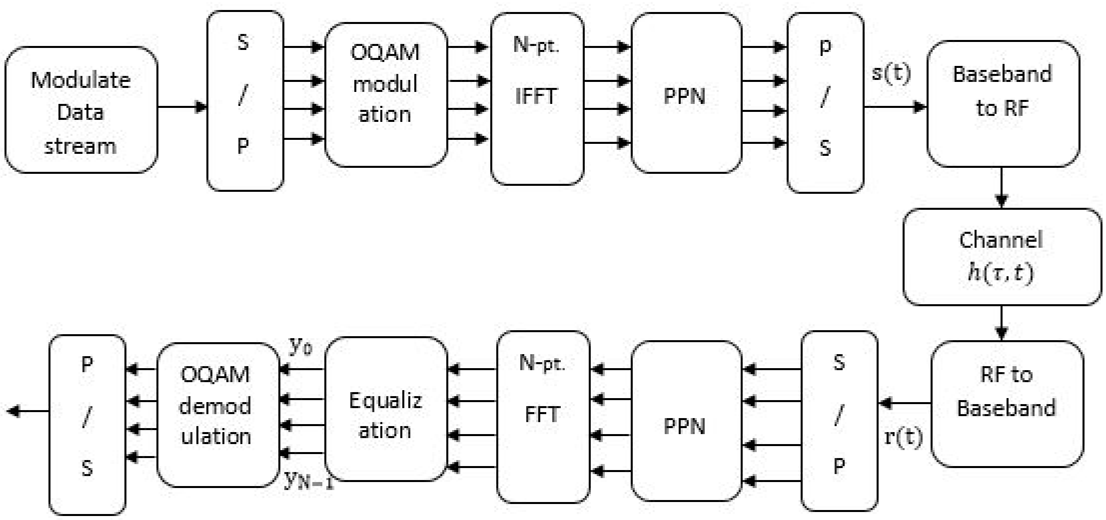


Figure 3.4: Physical layer block diagram of PPN-FBMC

OQAM pre-processing, filter banks, and OQAM post-processing. In FBMC, there is system that contain a group of filters which processes a common input or result into a common output called filter bank. There are two major types of filter banks, analysis filter bank (AFB) and synthesis filter bank (SFB). AFB is used for analyzing the input signal according to characteristics of each filter. SFB is used to filter the individual signals and added to get combined new composite signal. SFB and AFB implemented with IFFT followed by polyphase network structure or a polyphase network followed by an FFT respectively [50].

Mainly, the filter bank allows for the control of the frequency response of transmitted signal. Because of this, different mechanisms are proposed for filter designs. In this thesis we choose the filter proposed by Physical layer for dynamic spectrum access (PHYDYAS) projects [10]. The N-subchannel filter are designed by complex modulation. This mean all the rest subchannel filters are found by frequency shifted version of the prototype.

The key idea in [10] is to apply the frequency-sampling technique to design the Nyquist filter. The transmit filters are based on a specially designed prototype filter $p_T(t)$ and are modulated by carrier frequency f_n. The basis pulse $g_n(t)$ is, a time and frequency shifted versions of the prototype filter $p_T(t)$

$$g_n(t) = p_T(t)\, e^{j2\pi n \Delta f t + j\varnothing_n} \tag{3.7}$$

Where $p_T(t)$ is low pass filter called prototype filter with length of KN, Δf is subcarrier spacing and $\varnothing_n$ is phase difference. Then the impulse response of filter is given by

$$g[m] = 1 + 2\sum_{i=1}^{K-1} (-1)^i P_i \cos\left(\frac{2\pi k}{NK} m\right), \qquad g[0] = 0 \tag{3.8}$$

The frequency response of the filter with N subcarriers is obtained through the equation

$$G(f) = \sum_{i=-K+1}^{K-1} \bar{P}_i * \frac{\sin\left(\pi\left(f - \frac{i}{NK}\right) NK\right)}{NK\ sin\left(\pi\left(f - \frac{i}{NK}\right)\right)} \tag{3.9}$$

Where $\varnothing_n$ is phase, Δf is subcarrier spacing, $\bar{P}_i$ is filter coefficient, K is time overlapping factor which characterizes the prototype filter, the integer value typically set to K= 2, 3 ,4,... This determines how many blocks of symbols are superposed on each other. For FBMC [10] it has been decided to use an overlapping factor of 4. Filter coefficient P for filter length of

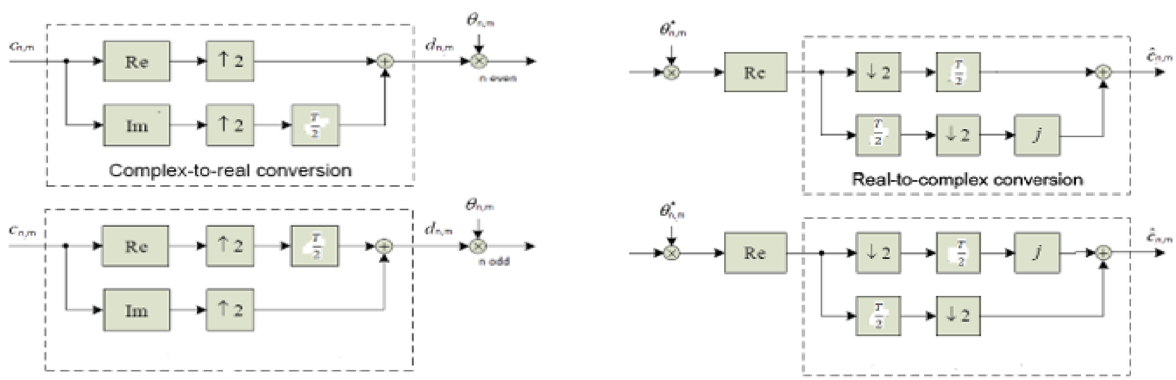
Table 3.1: PHYDYAS filter coefficient for K=4 [10]

Filter Coefficient	$\bar{P}_0$	$\bar{P}_1$	$\bar{P}_2$	$\bar{P}_3$
Value	1	0.97195983	0.70710678	0.23514695

$L_p = NK$ and K=4 given by Table 3.1.

The basic difference of OQAM/FBMC is transmit OQAM data symbol instead of QAM symbols. OQAM combined with Nyquist constraints on the prototype filter is used to guarantee orthogonality (in the real field) between adjacent symbols and adjacent carriers while providing maximum spectral efficiency [10]. This process held by OQAM pre/post-processing block Figure 3.5.

The QAM complex symbol staggered and changed to real symbols by OQAM preprocessing. Let's say the incoming QAM modulated symbol be $c_{n,m}$ .The real and imaginary parts are separated to form two new symbols $d_{n,2m}$ and $d_{n,2m+1}$. After this the second operation is multiplied by $\theta_{n,m}$. As described in [14], the value of $\theta_{n,m}$ have different value for the index of each subcarrier. The conversion is different for even and odd numbered sub channels.



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

Figure 3.5: Block diagram of the OQAM symbol arrangement and demodulation process in FBMC-OQAM [16]

$$\theta_{n,m} = \begin{cases} 1, j, 1, j. \dots \dots Even\ subcarrier\ index\ n \\ j, 1, j, 1. \dots ..\ odd\ subcarrier\ index\ n \end{cases} \tag{3.10}$$

At the receiver the reverse of this operation is presented which is post-processing. First from the incoming sequence take the real part and multiplied by conjugate of $\theta^*{}_{n,m}$. Then this data convert to complex data by which two successive real-valued symbols (with one multiplied by j) form a complex value data $c_{n,m}$ which is de-staggering. In FBMC the real to complex conversion decrease the sample rate by factor of 2 in order to keep up the bit rate.

3.3.2 Mathematical description of FBMC

For simplicity, we only take into account baseband signals, ignoring radio-frequency (RF) chains. The baseband transmitted signal of FBMC can be written in general form

$$s\left(t\right) = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} d_{n,m}\ g_{n,m}(t) \tag{3.11}$$

Where $d_{n,m}$ is the complex symbol modulated by the nth subcarrier during the symbol time index m, and $g_n(t)$ represent the synthesis basis which described in equation 3.7.
For OQAM-FBMC the symbol duration is reduced by half and $\grave{T} = \frac{T}{2}$ where T is QAM symbol duration.

$$g_{n,m}\left(t\right) = p_T \left(t - m\frac{T}{2}\right) e^{j2\pi n\Delta ft} e^{j(m+n)\frac{\pi}{2}} \tag{3.12}$$

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

$$s(t) = \sum_{m=0}^{\infty} \sum_{n=0}^{N-1} d^{R}{}_{n,m} g_{n,2m}\left(t\right) + d^{I}{}_{n,m} g_{n,2m+1}\left(t\right) \tag{3.13}$$

Where $d^{R}{}_{n,m}$ and $d^{I}{}_{n,m}$ are the real and imaginary part of $d_{n,m}$ which conveyed by the subcarrier index of n during symbol time of index m.

At the receiver, the analysis filters are based on a specially-designed prototype filter $p_R(t)$, the impulse response of analysis filter given by

$$g^{*}{}_{k}\left(t\right) = p_R\left(t\right) e^{-2\pi jk\Delta ft - j\varnothing_n} \quad k = 0, 1 \ldots . N-1 \tag{3.14}$$

For mathematical analysis for now, ignoring channel impairments, the input signal at the AFB equals the transmit signal of the SFB which is in distortion free noiseless channel.

After the incoming signal $r(t)$ passes through filter, the continuous time output signal can be calculated

$$y_k(t) = g^*{}_k(t) * r(t) \tag{3.15}$$

$$y_k(t) = \sum_{m}^{\infty} \sum_{n=0}^{N-1} d_{n,m} p_R(t) * p_T(t - mT) e^{-2\pi jk\Delta ft - j\varnothing_k} e^{2\pi jn\Delta f(t-mT)+j\varnothing_n} \tag{3.16}$$

$$y_k(t) = \sum_{m}^{\infty} \sum_{n=0}^{N-1} d_{n,m} p_R(t) * p_T(t - mT) e^{j2\pi(n-k)\Delta ft + j(\varnothing_n - \varnothing_k)} \tag{3.17}$$

The prototype filters are designed to satisfy the condition that the output signal does not bring ISI to its neighboring symbols in the time domain. The composite impulse response should be zero at the sampling times except the original one:

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

Where $t_s = iT$is the sampling point at time axis. The demodulated signal at n-subcarrier and m-th symbol can be expressed as;

$$d^R{}_{n,m} = Re\left\{\int s(t)\, g^*{}_{n.2m}(t)dt\right\} \tag{3.18}$$

$$d^I{}_{n,m} = Re\left\{\int s(t)\, g^*{}_{n.2m+1}(t)dt\right\} \tag{3.19}$$

3.4 UFMC Transmission

UFMC is a multicarrier modulation format that has been proposed by the EU-funded 5GNOW research project [27] [25]. UFMC scheme is developed based on the principle of frequency division multiplexing (FDM) in which it divides the input data stream into several lower rate sub-streams. As described in [17] UFMC is a type of sub-band filtering based waveform, where a filtering operation is applied to a group of consecutive subcarriers instead of per subcarrier filtering used in FBMC.

3.4.1 Basic principle of UFMC

The system model of UFMC is depicted in Figure 3.6. The overall bit streams are grouped in to B sub-bands. These grouped bits are modulated by QAM or PSK modulation format, then converted to parallel streams by serial to parallel converter. The frequency block B carrying subcarriers converted from frequency-domain to time-domain by a frequency block specific IFFT module. Then this signals filtered by filter length L. Filtering leads to substantial reduction in out-of-band leakage in frequency domain. This minimize the harmful interference from adjacent subchannels of the neighboring resource block which eliminate out of band emissions.

For UFMC, we adopt Dolph-Chebysheve filter used in [28], which proposes the method for designing UFMC. The length of filter depends upon the size of sub-band that is the number of carriers in sub-band. The Chebyshev window minimizes the main-lobe width, given a particular sidelobe height. It is characterized by an equi-ripple behavior, that is, its sidelobes all have the same height. The results in a UFMC symbol length of $N + L - 1$ samples because of the linear convolution between output from IFFT.

In some previous [2, 18] papers the guard intervals was discarded. This reduces the performance in case of severe multi-path since the time dispersion of the channel cannot be mitigated [47]. In other paper there is block with an extra zero padded (ZP) of length L-1. A zero-padded or guard interval is introduced in each UFMC block to cope with the time dispersion. This adds some extra time overhead compared to OFDM but enables a perfect mitigation of the channel time dispersion using a simple 1-tap frequency domain equalizer (FDE).

At the end filtered time- domain data in each frequency block is added to form a UFMC waveform. Hence, in contrast to OFDM where a single joint IDFT is performed by combining all frequency block, separate IDFTs operations are required to be performed on each frequency block and windowing perform for interference suppression.

At the receiver, after serial to parallel conversion, a 2N-point FFT must be taken to demodulate each UFMC symbol. FFT followed by an equalizer, and including a timing synchronization block, which is able to estimate the delay correctly for performing FFT.

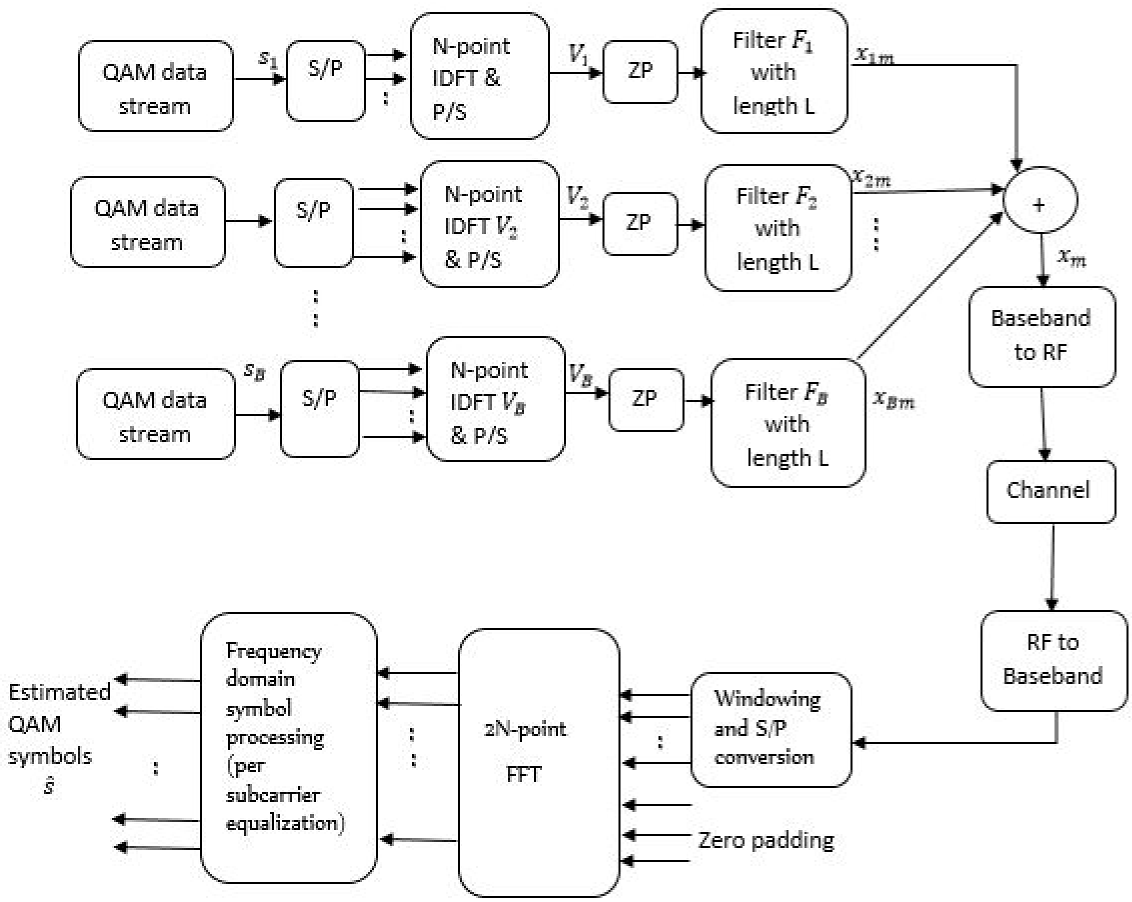


Figure 3.6: Physical layer block diagram of UFMC

3.4.2 Mathematical model of UFMC

Let assume that the UFMC transmit signal consists of N subcarriers and is divided into B sub-bands. Each sub-bands containing $\frac{N}{B}$ subcarriers. The input to the UFMC waveform generator block is a set of constellation QAM mapped symbols S. The symbols S are divided into frequency blocks S where each frequency block is made up of $p$sub carriers. If B are number of frequency blocks, then. This B data vectors are processed with IDFT submatrix (each of dimension NxP) respectively. Then each subband is filtered by a subband filter of length L and response from the different subband are summed.

Different type of filters with dimension ((N+L-1)x N) may use for filtering operation [28]. F_i is a Toeplitz matrix, composed of the filter impulse response, performing the linear convolution. For UFMC the filter choosen is Chebysheve filter which is given by:

$$F_{i,l} = \frac{\cos\left(L\cos^{-1}\left[\beta\cos\left(\frac{\pi l}{L}\right)\right]\right)}{\cosh[L\cosh^{-1}(\beta)]}, \quad l = 0, 1, 2....L-1 \tag{3.20}$$

where

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

where α represent the attunation of side lobs The side-lobe suppression now works in between resource blocks, instead of in-between subcarriers. The symbol duration of $N+L-1$ samples is generated by the filter length and the FFT size. The discrete time signal to be converted to analog domain and transmitted at RF is expressed as

$$x_m = \sum_{i=1}^{B} F_i V_i s_i \tag{3.21}$$

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

$$x_m = \sum_{i=1}^{B}\sum_{l=0}^{L-1}\sum_{n=0}^{N-1} s_{i,n} e^{\frac{j2\pi n}{N}} \; F_i\,(l) \tag{3.23}$$

This sequence is passed through a digital-to-analogue converter whose output ideally would be the signal waveform $x(t)$ with duration $N+L-1$. The signal is up-converted and the RF signal is transmitted to the channel.

The output of the channel, after RF down-conversion, is the received signal waveform $y(t)$ obtained from convolution of $x(t)$ with the channel impulse response $h(\tau - \ t)$ and addition of a noise signal $n(t)$, i.e.

$$y\,(t) = \int_{-\infty}^{\infty} x\,(t-\tau)\,h\,(\tau, t)\,d\ \tau + n\,(t) \tag{3.24}$$

This passed through an analogue-to-digital converter, whose output sequence $y_{m,}$ $m = 0......2N-1$ which is $y(t)$ sampled at rate $1/Td$. The discrete-time baseband equivalent received signal is given by

$$y_m = H\left(\sum_{i=1}^{B} F_i V_i s_i\right) + n \tag{3.25}$$

This describes classical linear model, of received signal and further signal processing techniques like equalizers and FFT can be used to recover QAM symbols. The receiver processing can be frequency-domain FFT-based. Similar to OFDM, single-tap per-subcarrier frequency domain equalizers can be used which equalize the joint impact of the radio channel and the respective subband-filter.

If the channel impulse response is ideally Delta-Dirac function δ(t), time domain pre-processing is not used and CFO and timing offset are not taken into account, the estimated from m-th symbol y_m can be written as:

$$\hat{s}_i = \sum_{i=1}^{B} y_{i,m} e^{\frac{j2\pi k}{N}} \qquad k = 0, 1.\dots\dots\dots 2N - 1 \tag{3.26}$$

In contrast to OFDM, UFMC groups sub-carriers into several sub-bands, applying filtering on them separately which reducing out-of-band emission without losing OFDM advantages.

Chapter 4

Performance Analysis of Modulation Techniques

4.1 System Model

In Figure 4.1 a simplified physical layer model of a multicarrier transmitter is depicted. The information bits 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 on to symbols from M-QAM constellation and forwarded to the next block at the symbol rate of $R_s = \frac{R}{log_2 M}$ symbols /second.

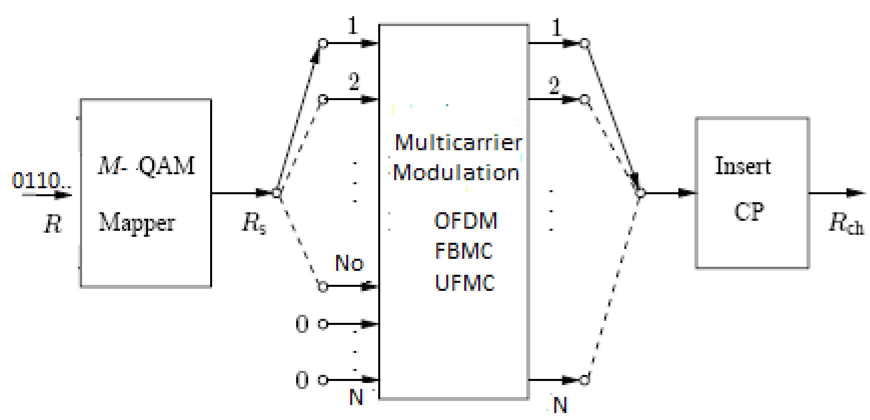


Figure 4.1: Multicarrier Modulation System Model

Then the multicarrier modulation is performed. From the total N subcarriers N_o are data filled with QAM modulated symbols and the remaining have zero input. After the multi-carrier modulation N complex samples are generated. These samples are converted to serial data and cyclic prefix is added. After that the sampled data is forwarded to digital to analog conversion at the rate of $R_{ch} = R_s.\frac{N}{N_0}(1 + L_{cp})$ where L_{cp} is the length of cyclic prefix on OFDM.

As already discussed in Chapter 3 the main different between OFDM, FBMC and UFMC are in the block multicarrier modulation and insertion of CP. In OFDM the efficient implementation of this windowing and modulation is achieved by only performing an N point FFT. Where as in FBMC the symbols are pulse shaped by porotype filter, that is longer than the number of subcarriers N has to be designed and implemented accordingly [10]. The efficient implementation of this structure is obtained by deploying an Offset-QAM staggering, an FFT and a polyphase filtering [10]. In UFMC, the incoming QAM symbols are grouped in blocks and modulating and filtering each blocks separately and sum up each filtered blocks. This implemented using B number of N-pt. FFT and Dolph-Chebysheve filter [10].

At the receiver side the invers operations are executed in reverse order. First the cyclic prefix is removed in case of OFDM and then the samples are transformed in to subcarrier symbols. In the three system the equalizer has to be deployed in order to compensate for the frequency selective of the channel. For OFDM and UFMC this equalizer has length 1 and for FBMC its multitap. After the demodulation process is finished the complex symbols are detected. We ignore here encoder and the process of bit generating.

For comparison of modulation formats there are different type of metrics. From the transmitter side we compare them with their power spectral density and spectral efficiency. At the receiver side they are compared using bit error rate and on end-to-end use metrics computational complexity. The three multicarrier modulations are compared on the following performance metrics. These metrics are explained in the next section.

4.2 Power Spectral Density

Power Spectral Density (PSD) function shows the strength of the variations of energy as a function of frequency. It shows at which frequencies variations are strong and at which frequencies variations are weak. The power spectrum of the overall multicarrier modulation signal can be found by summing the power spectra of all individual subcarriers for any symbol period [26]. Which derived by summing the power spectra of individual subcarriers, under the assumption that the data at each subcarrier are statistically independent and mutually orthogonal. Side-lobe radiation is determined by PSD model of MC signal. The interferences of side-lobe radiation in these multicarrier modulations are the focus of consideration.

4.3 Bit Error rate

The other performance metrics of modulation techniques is the bit error rate (BER). When the data is transmitted over the channel there is a possibility of errors being introduced in to system. If errors are introduced into the data, then the integrity of the system may be compromised. As a result, it is necessary to assess the performance of the system and BER. BER assess the full end to end performance of a system including the transmitter, receiver and the medium between the two. As the name implies, BER is the rate at which error occur in transmission system. The main reason for the degradation of transmission channel and the corresponding BER is the noise and multipath propagation channel, which have random nature. For the analysis of the channel characteristics, the noise following a Gaussian probability function while the propagation model follows Rayleigh or Rician channel model. This helps to undertake channel using statistical analysis techniques [49].

In a multipath channel, the transmitted signal reaches the receiver as a train of pulses. Since a multipath channel reflects signals at multiple places, a transmitted signal travels to the receiver through several paths that may have different lengths and hence different associated time delays. Fading occurs when these signals travelling through different paths interfere with each other. For our BER simulation we choose Rayleigh fading channel model. Rayleigh fading is a statical model for the effect of propagation environment on a radio signal. It assumes that the power of a signal that has passed through communication channel will vary randomly or fade according to Rayleigh distribution the radial component of the sum of the two uncorrelated Gaussian random variables [48]. It is reasonable model for signal propagation in heavily built up in urban environment, in which when there is no line of sight between transmitter and receiver.

4.4 Spectral Efficiency

Spectral efficiency, spectrum efficiency or bandwidth efficiency refers to the information rate that can be transmitted over a given bandwidth in a specific communication system. It is a measure of how efficiently a limited frequency spectrum is utilized by the physical layer protocol, and sometimes by the media access control. Spectral efficiency is vital to meet extreme data rate requirements. The spectral efficiency is presented in many ways in the literature. For our comparison of the spectral efficiency we choose the definition proposed by [27] which is more applicable for multicarrier modulations. Which defined the spectral efficiency as the product of time efficiency and modulation efficiency.

$$\eta_{MC} = \eta_t * \eta \tag{4.1}$$

Where time η_t *and* η are time and modulation efficiency of multicarrier modulation schemes. Modulation efficiency depends on the modulation order, the number of active resource blocks, coding rate. Same as [8], for this simulation we only consider the modulation order, which is directly related to number of loaded bits in each subcarriers. But in [8] they are not considering the effect of zero-padding in UFMC. In our methodology, we do not take in to account potential gain introduce by minimizing the impact of OoB by inserting guard bands. Literally, when the modulation schemes have been designed to fulfill a very low OoB radiation, few guard carriers at each side of the band allow for nearly null. This concept were evaluated in [18].

The time efficiency measures time overhead introduced in transmission. It is defined similar to [18] as:

$$\eta_t = \frac{D_L}{D_L + T_{overhead}} \tag{4.2}$$

Where D_L is the number of samples in transmitted signal dedicated to data transmission and $T_{overhead}$ is the overhead sample which will be cyclic prefix, filter tails, zero padding etc. For all multicarrier modulations $D_L = \beta * N$ where, β denotes the number of transmitted multi-carrier symbols in a burst and N is FFT size.

In an OFDM modulation there is an overhead which is cyclic prefix which inserted between symbols. Where as in UFMC there is an overhead which caused by the filter and zero padding. In some papers [8] they do not introduce zero padding structure on UFMC. For now, let's consider UFMC with zero padding, this overhead in time. The overhead time in FBMC is introduce by long tail filters in each subcarrier signal which is independent from the length of burst. The overhead sample for each can modulations are:

$$OFDM, \qquad T_{overhead} = \beta * L_{CP} \tag{4.3}$$

Where β is the number of transmitted multicarrier symbol in burst and L_{CP} is sample length of Cyclic prefix.

$$UFMC, \quad T_{overhead} = \beta * (L_{ZP} + L_{UFM} - 1) \tag{4.4}$$

Where β is the number of transmitted multicarrier symbol in burst and L_{UFM} is filter length.

$$FBMC, \quad T_{overhead} = N * (K - \frac{1}{2}) \tag{4.5}$$

Where N is the size of FFT and K is overlapping factor of filters.
Time efficiency of each candidates became

$$\eta_{t-OFDM} = \frac{\beta * N}{\beta * N + \beta * L_{CP}} \quad = \frac{N}{N + L_{CP}} \tag{4.6}$$

$$\eta_{t-UFMC} = \frac{\beta * N}{\beta * N + \beta * (L_{ZP} + L_{UFM} - 1)} \quad = \frac{N}{N + (L_{ZP} + L_{UFM} - 1)} \tag{4.7}$$

$$\eta_{t-FBMC} = \frac{\beta * N}{\beta * N + N * (K - \frac{1}{2})} \quad = \frac{\beta}{\beta + (K - \frac{1}{2})} \tag{4.8}$$

To summarize this the spectral efficiency referring the number of bits that can be transmitted using the modulation scheme per second per Hertz of bandwidth results:

$$\eta_{OFDM} = \frac{N * m}{N + L_{CP}} \tag{4.9}$$

$$\eta_{UFMC} = \frac{N * m}{N + L_{ZP} + L_{UFM} - 1} \tag{4.10}$$

$$\eta_{FBMC} = \frac{\beta * m}{\beta + (K - \frac{1}{2})} \tag{4.11}$$

Where m is number of bits in each subcarrier, N is the size of FFT, L_{CP} length of cyclic prefix, filter length of UFMC L and K overlapping factor.

4.5 Computational Complexity

Computational complexity is a computer science concept that focuses on the amount of computing resources needed for particular kinds of tasks [51]. In Multicarrier modulation the computational complexity is evaluated in terms of number of real multiplications and addition to compute the modulation.

In this section we will give formulas for computational complexity of each candidate modulations for our simplified model. We consider the signal generating operation of multicarrier signal, as well as the recovery of the subcarrier signal and equalization. We do not consider the operation involved in channel encoder decoder, channel estimation or calculation of the equalizer coefficients. Assumptions:

- We assume that the multicarrier modulation is the only signal processing at the transmit side. That is to say there is no channel matched transmit processing.
- Complex multiplication can be carried out with three real multiplications [51].
- For the addition, its straightforward to say that complex addition requires two real multiplication.
- The transmitter and the receiver are perfectly synchronized.

We assume that total number of subcarriers N are available and from them N_o are occupied with symbols. The complexity on channel encoder is not considered here.

4.5.1 Computational Complexity of OFDM

To transmit one block of OFDM symbol, the number of real valued multiplication and addition as followed:
For FFT, the number of real multiplication and addition of N-point FFT/IFFT using split-radix algorithm are given by

$$M_{FFT} = Nlog_2N - 3N + 4,\ multiplication \tag{4.12}$$

$$A_{FFT} = 3Nlog_2N - 3N + 4,\ addition \tag{4.13}$$

The basic block for OFDM transmitter is IFFT and complexity computed as

$$M_{OFDM}{}^{tx} = M_{FFT} + 4\left(N + L_{CP}\right), \qquad L_{CP} - CP\ length$$

$$A_{OFDM}{}^{tx} = A_{FFT} + 2(N + L_{CP})$$

The basic block for OFDM receiver is FFT with considering the equalizers. The basic principle of OFDM is divide the total bandwidth in to N of FFT points, so the channel equalization can often reduce as single-tap coefficient per subcarrier. The equalizer requiring N multiplication between complex equalizer coefficients and complex FFT outputs [20].

$$M_{OFDM}{}^{rx} = M_{FFT}(N) + 4N_o \tag{4.14}$$

The total complexity of OFDM is given by

$$M_{OFDM} = M_{OFDM}{}^{tx} + M_{OFDM}{}^{rx} \qquad A_{OFDM} = A_{OFDM}{}^{tx} + M_{OFDM}{}^{rx}$$

$$M_{OFDM} = 2M_{FFT}(N) + 4\left(N + L_{CP}\right) + 4N_o \qquad multiplication \tag{4.15}$$

$$A_{OFDM} = 2A_{FFT}(N) + 4(N + L_{CP}) + 2N_o \qquad addition \tag{4.16}$$

4.5.2 Computational Complexity of FBMC

The transmitter and receiver structures of an FBMC system are composed of the filtering through N-parallel polyphase components working at twice the symbol rate, by an FFT/IFFT also working at twice the symbol rate and, at the receiver, by the linear equalizers also working in $T/2$ where T is QAM symbol rate.

The basic blocks which perform multiplication and addition are polyphase filter networks, OQAM pre/post-processing, IFFT/FFT assuming that the filter length $L_p = KN$. The OQAM processing is considered to be multiplication free it only consists of trivial multiplications by +1 and j [15].

As described in [10], the transmitter consists of N-point IFFT, N-branch polyphase filters with length of $l_p = KN$ and frequency shifting/phase rotation to get polyphase filters from the prototype. The N-branch polyphase filter with length KN real multiplication and addition became;

$$M_{ppn} = 4NK \quad and \;\; A_{ppn} = 8N(K-1) \tag{4.17}$$

The frequency shifting to get filter networks on occupied subchannels perform multiplication of :

$$M_{ppn} = 4N_o \quad and \;\; A_{ppn} = 2N_o \tag{4.18}$$

Because of the staggering of real and imaginary part, the IFFT and the polyphase networks on double of the QAM symbols rate. Real number of multiplication and addition of FBMC transmitter became:

$$M_{FBMC/OQAM}{}^{tx} = 2(Nlog_2N - 3N + 4) + 4NK + 4N_o \tag{4.19}$$

$$A_{FBMC/OQAM}{}^{tx} = 2(3N(log_2N - 1) + 4) + 4N(K-1) + 2N_o \tag{4.20}$$

At the receiver same operation is held in reverse order. Starting from polyphase filtering followed by FFT then multitap channel equalization per subcarriers with an equalizer length of L_{eq} and phase rotation. Phase rotation can be embedded in the equalization coefficient resulting in complexity equal to

$$M_{FBMC/OQAM}{}^{rx} = 4NK + 2\left(Nlog_2 N - 3N + 4\right) + 4L_{eq}N_o \tag{4.21}$$

$$A_{FBMC/OQAM}{}^{rx} = 4N(K-1) + 2\left(3N(log_2 N - 1) + 4\right) + (4L_{eq} - 2)N_o \tag{4.22}$$

The total computational complexity of OQAM FBMC based on implementation of polyphase network became

$$M_{FBMC/OQAM} \quad = 4M_{FFT} \ \ (N) + 8NK + 4N_o(1 + L_{eq}), \ multiplication \tag{4.23}$$

$$A_{FBMC/OQAM} \ = 4A_{FFT} \ \ (N) + 8N\left(K-1\right) + 4L_{eq}N_o \quad \ addition \tag{4.24}$$

4.5.3 Computational Complexity of UFMC

There are works which have been done to minimize the computational complexity of UFMC. Some are try to minimize the point on IFFT block at the transmitter. We consider the scheme which presented in [28]. The transmitter is however replaced by an equivalent scheme implementing the filtering operations in the frequency domain and use smaller IFFT's size for each blocks to generate the signal.

Let's we have B data blocks which found by dividing total number of subcarrier N. Each blocks have maximum of N/B subcarrier. The transmitter modulates each of the B sub-bands as follows; first frequency domain symbols are brought to time domain using an N_{SB}-point IFFT, where N_{SB} is the IFFT size on each subbands. This time-domain signal is then brought back to the frequency domain by a $2N_{SB}$ -point FFT. Then, the filtering is performed in the frequency domain and the sum of all subbands are sum and converted into the time domain by 2N -point FFT then transmitted. This resulted transmission complexity as follow:

- B number of IDFT with N_{SB}-pt. result $M_{FFT}(N_{SB})$ and $M_{FFT}(2N_{SB})$ to brought frequency domain

- Filtering each blocks with length L which result complexity of $2N_{SB}$

$$M_{UFMC}{}^{tx} = B\left[M_{FFT}\left(N_{SB}\right) + M_{FFT}\left(2N_{SB}\right) + 8N_{SB}\right] + \ M_{FFT}\left(2N\right) \tag{4.25}$$

$$A_{UFMC}{}^{tx} = B\left[A_{FFT}\left(N_{SB}\right) + A_{FFT}\left(2N_{SB}\right)\right] + 2(B-1)2N_{SB} + A_{FFT}\left(2N\right) \tag{4.26}$$

At the receiver three basic steps are performed. First windowing the incoming time domain signal and then this brought back to the frequency domain by a 2N -point FFT to demodulate each UFMC symbol. After frequency domain filtering and equalization QAM data symbols are recover.

$$M_{UFMC}{}^{rx} = M_{FFT}(2N) + 4N_o \tag{4.27}$$

$$A_{UFMC}{}^{rx} = A_{FFT}(2N) + 2N_o \tag{4.28}$$

Using mathematical analysis, the performances of the waveforms are discussed in this chapter. Based on the results discussed here, on the next chapter simulation and result discussion are held.

Chapter 5

Simulation Results and Analysis

The comparison between the candidate multicarrier modulation schemes is presented. Table 5.1 lists the general simulation parameters in this work and the performance evaluation

Table 5.1: Parameters in simulation

Parameters	**Value**	**Remark**
FFT size	64/1024	Can vary
Subcarrier spacing	15 KHz	Same as LTE
Symbol mapping	16-QAM	More efficient scheme
UFMC parameters		
Filter length	73	proposed Lcp+1
Sub-band size	12	as Proposed in [28]
Guard interval	72	Equal with CP
Size of FFT, N_{SB}	64	was proposed to minimize computational complexity
FBMC parameters		
Overlapping	K= 4	For better side-lobe [10]
Prototype Filter	PHYDYAS filter	[10]
OFDM parameters		
Length of CP	72	as in LTE

is done using MATLAB platform. Some sources of the codes are available on GitHub. The parameters considered in this simulation may vary accordance with each comparison metrics. The following results are simulated and obtained under multipath channel, which compared the performance of OFDM, FBMC and UFMC for QAM schemes. QAM is chosen because it is widely sued for data transmission as it enables better level of spectral efficiency than other form of modulations. To focus link level performance, we only assuming single transmitting antenna at the base station and single user at the with single receiving antenna. Also perfect channel estimation is assumed; which help us to highlight the performance difference between modulation schemes. Furthermore, CP-OFDM and UFMC employ guard intervals to prevent ISI.

5.1 Power Spectral Density (PSD) Comparison

In this section the normalized power density spectrum of an OFDM, FBMC and UFMC symbol with sub-carriers versus the normalized frequency is depicted. In Figure 5.1, in order to see the out of bound emission of each modulation formats, we choose 64 number of subcarriers, overlapping factor 4 and 12 subband size for UFMC. For UFMC, we have used the Dolph-Chebyshev filter with stopband attenuation of 40dB. In the literature, this has been widely advertised as the best compromised choice [10]. The length of filter is equal with the length of CP plus one. The prototype filter for that of FBMC is PHYDYAS filter, with length of $L = NK$, where $K = 4$. Figure 5.1 presents a set of PSD plots of CP-OFDM, FBMC and UFMC.

From the PSD graph, the energy is mainly located in the main lobe, it is intuitively clear that the three modulations have different side-lobe radiations. There is advantage of having lower OoB emission to support asynchronous transmission. From the Figure 5.1 the two modulations achieve much lower leakage compared to CP-OFDM. Among them, due to short length of the filter, UFMC has a poor OoB emission before 40dB attenuation. As seen in the figure UFMC attains -60 dB around normalized frequency 33. Whereas, OoB response for FBMC decays completely before a normalized frequency 20. One of strict specification for CR physical layer design is signal should have extremely low OoB radiation. So FBMC can

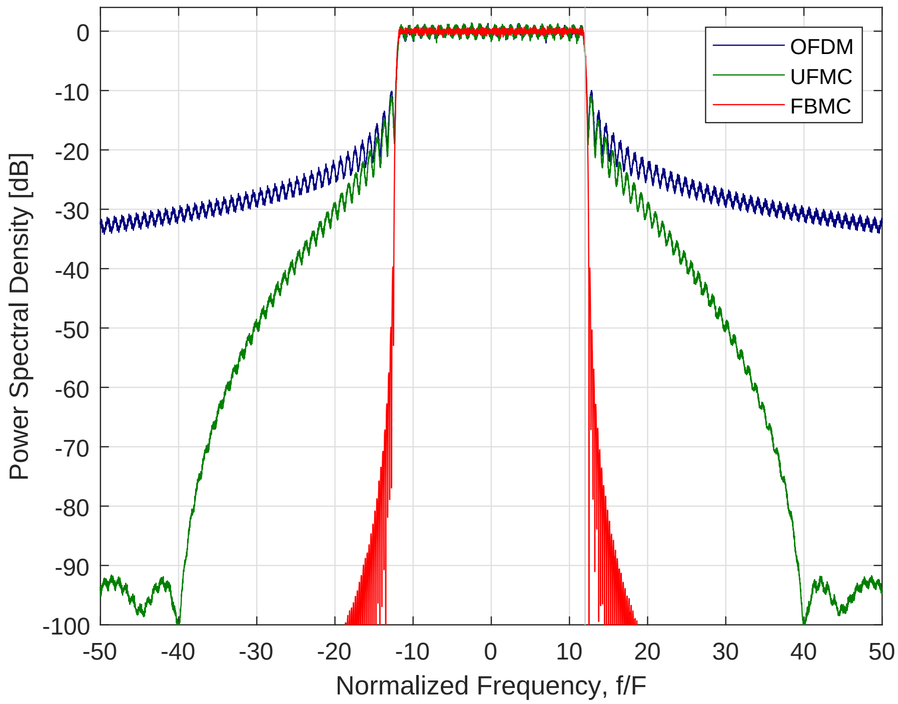


Figure 5.1: Power Spectral Density of OFDM, UFMC, FBMC. In this plot number of subcarriers are 64 with spacing 15 kHz.

attain interference level -60dB easily, which is sufficient to meet the regulatory constraints for TV white space (TVWS) CR imposed by Federal Communications Commission (FCC).

5.2 Spectral Efficiency

In this section, the spectral efficiency of candidate modulation formats is evaluated in terms of time and modulation efficiency, expressed in bit per second per Hertz versus the time duration of the burst. We consider the parameter based on LTE 10 MHz with QAM symbol mapping, FFT size of 1024. For OFDM size of CP 72 samples. For that of UFMC, we use a Dolph- Chebyshev filter of length 73, L_{ZP} 72 with block size of 12. Let's observe the outputs by alternating the parameters.

As discussed in Chapter 4, CP-OFDM and UFMC the spectral efficiency doesn't depend on the burst duration and it's a function of FFT size, the modulation order and the modulation parameters. Whereas FBMC, it depends on the frame duration. To compare the

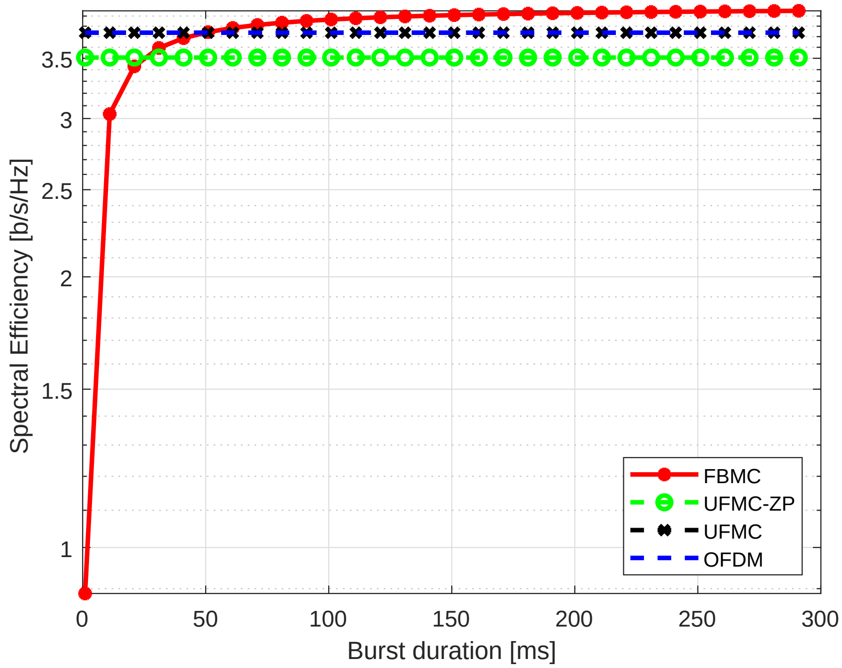


Figure 5.2: Spectral efficiency of candidate waveforms at FFT size N=1024.

waveforms fairly, we compute the number of bits that can be transmitted by modulation schemes given a modulation efficiency and a transmission time 0.1 to 300ms. The results are depicted as follow.

As seen from Figure 5.2, UFMC performs the same spectral efficiency to that of OFDM without considering guard interval. Consequently, in frequency selective channel the removal of this guard interval pay-off for degradation of the BER. So for our analysis we are considering UFMC with ZP to mitigate ISI. Consequently, the spectral efficiency of UFMC became degrade and performs lower spectral efficiency to that of OFDM. Whereas the spectral efficiency of FBMC does not depend on the type of transmission channel, because unlike UFMC and OFDM there is no extra guard interval to mitigate the frequency selectivity of the channel.

These results clearly demonstrate that the use of FFT size $N = 1024$ and $K = 4$ of FBMC will not well applied for short transmission time. Whereas, CP-OFDM and UFMC spectral efficiency does not depend on the burst duration and it is a function of FFT size and modulation parameters.

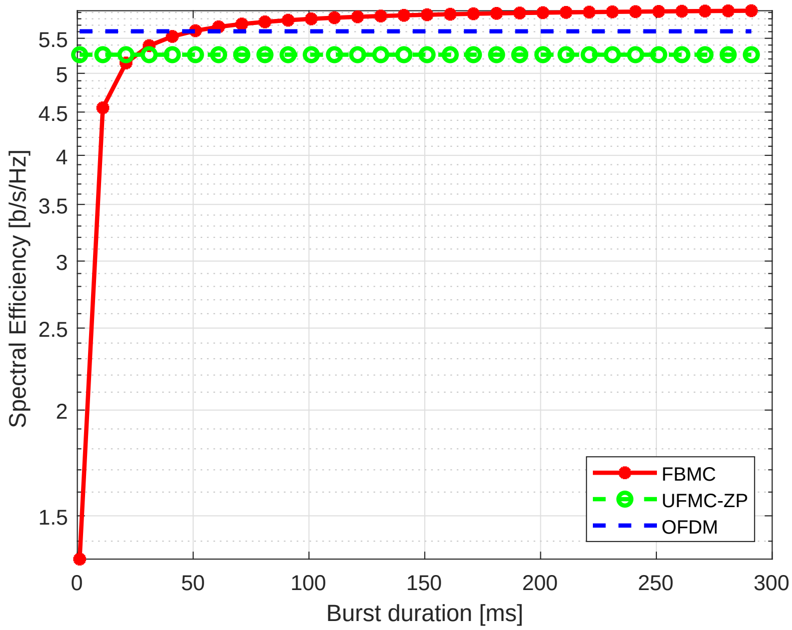


Figure 5.3: Spectral efficiency of candidate waveforms at FFT size N=1024, and six bits are loaded on each subcarrier.

Spectral efficiency of the multicarrier modulations also performs by increasing the number of bits loaded in each subcarrier. For the comparison taking the constant number of subcarrier and varying the number of bits in subcarriers we get different values. Figure **??** shows the output by increasing the number of loaded bits in each subcarrier.

5.3 Bit Error Rate (BER)

The BER performance is represented and investigated to understand the performance of UFMC and FBMC system for a convenient comparison with conventional CP-OFDM. In this section, the error performance and the robustness of each modulation schemes against multipath channel analyzed. For the simulation, we assume the carrier frequency 2.5 GHz. The considered channel model that used for BER performance evaluation is ITU Vehicular A model. The characteristic of this channel is given by Table 5.2. The table indicates the relative delay and the average power for the taps of the multipath channel.

Please note that the BER is further impacted by the receiver design concept using equalization algorithms and applying interference cancellation methods as an example. Channel fading is assumed to be static at least for the duration of the symbol. Also perfect channel state information and perfect synchronization are assumed. All waveforms have total number of subcarrier N=64 and the resulting subcarrier spacing is assumed to be 15 kHz. The measurements of the BER presented for 300 channel realizations and 30 number of symbols for each channel realizations for the three of waveforms.

Table 5.2: ITU-R Vehicular A Channel power delay profile

Relative Tap delay (ns)	Average Power (dB)
0	0.0
310	-1
710	-9
1090	-10
1730	-15
2510	-20

Figure 5.4, shows BER versus signal-to-noise ratio (SNR) performance of waveforms when the Doppler frequency is zero (f_d=0 Hz) in frequency selective channel. As discussed [3], lower BER achieved at lower SNR within AWGN channel. Nevertheless, this result is not achieving here due to frequency selectivity of the channel which costs more SNR. Compared to AWGN channel case, the BER performance is significantly degraded.

CP-OFDM has the better performance in the lower Doppler frequency, since the ISI caused by multipath has been completely canceled by the insertion of CP. Also, UFMC curve as almost merged with the CP-OFDM. Which resulted from added zeros with equal length of the CP. While for that of FBMC, since the bandwidth of each subcarrier is small enough to make the corresponding channel approximately flat, the ISI introduced by pulse shaping is nearly imaginary. Therefore, FBMC is approximately orthogonal in the real domain and this leads to achieve good BER performance. But when it compared with UFMC and OFDM, additional 1.4 dB is displayed at BER of 10^{-3}.

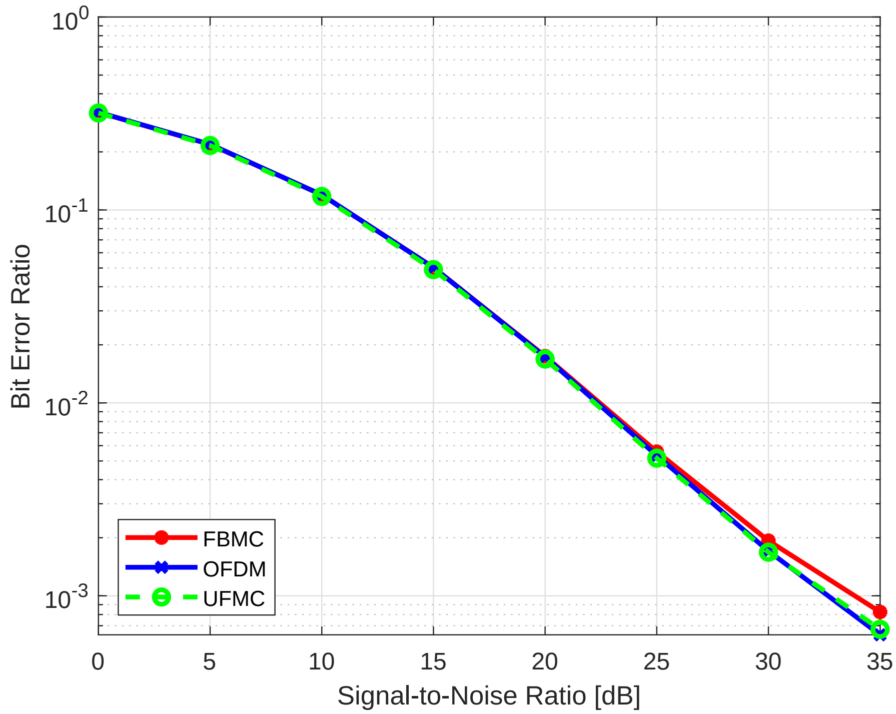


Figure 5.4: BER versus SNR curve for Candidate modulation formats in ITU-R Vehicular A model for 64 number of subcarriers and f_d =0 Hz.

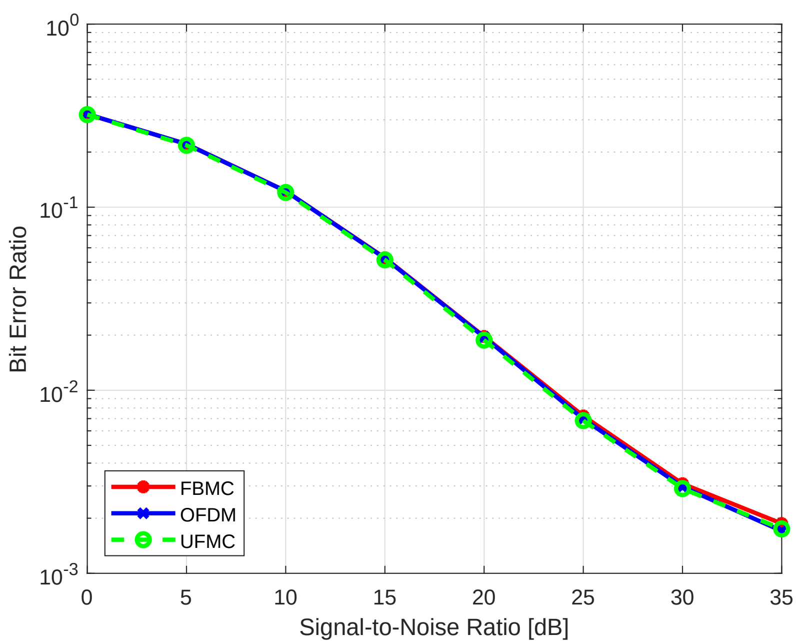


Figure 5.5: BER versus SNR curve for candidate modulation formats in ITU-R Vehicular A model for 64 number of subcarriers and 4 number of bits per symbol with f_d=300 Hz.

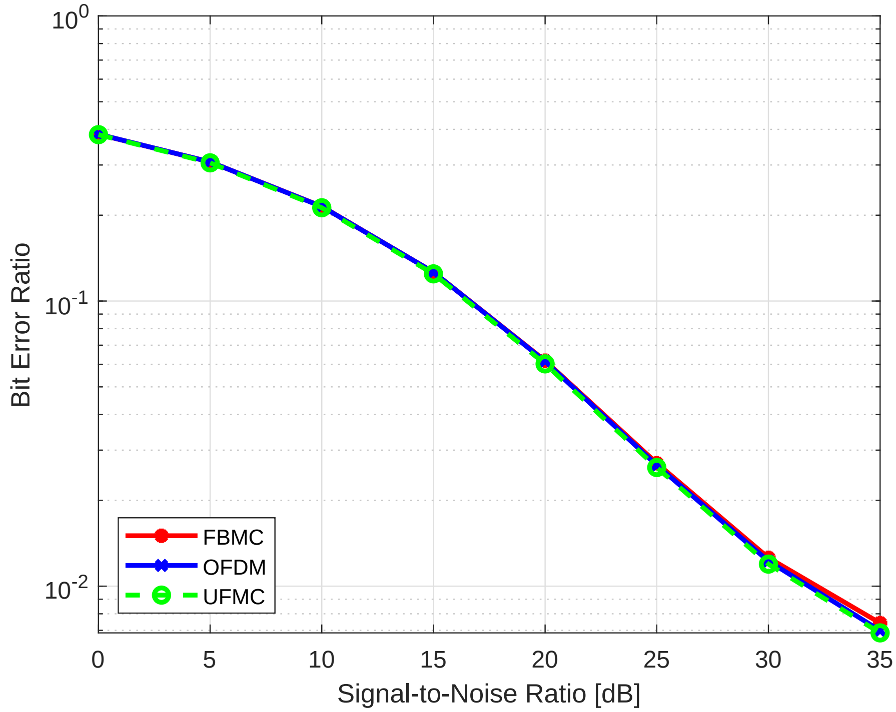


Figure 5.6: BER versus SNR curve for candidate modulation formats in ITU-R Vehicular A model for 64 number of subcarriers and 64-QAM with f_d=300 Hz.

The second analysis was working by increasing the Doppler spread (f_d=300 Hz). Which mean that the user moving with speed of 130 km/h there is high mobility. As we can see Figure 5.5, since the delay spread became longer and channel became more frequency selective which is difficult to estimate and tracked accurately, the performance of the three of waveforms degrades significantly.

Higher-order modulation such as 16-QAM, 64-QAM and 256-QAM are utilized in most of wireless communications. LTE and LTE-Advanced mobile system apply 64-QAM for the symbol modulation of OFDM. Although the highest-order modulation 256-QAM and 1024-QAM implementation discussed by 3GPP Release 12. These all are pertaining to LTE and LTE-Advanced and considered for incoming 5G. In this section, the robustness of waveforms against multipath channel with higher-order modulation is analyzed.

As seen in Figure 5.7, even if SNR value is increased to 35 dB it cannot to reach BER of 10^{-2} for 256-QAM. However, as seen in Figure 5.6 64-QAM attains BER of 10^{-2} at SNR of

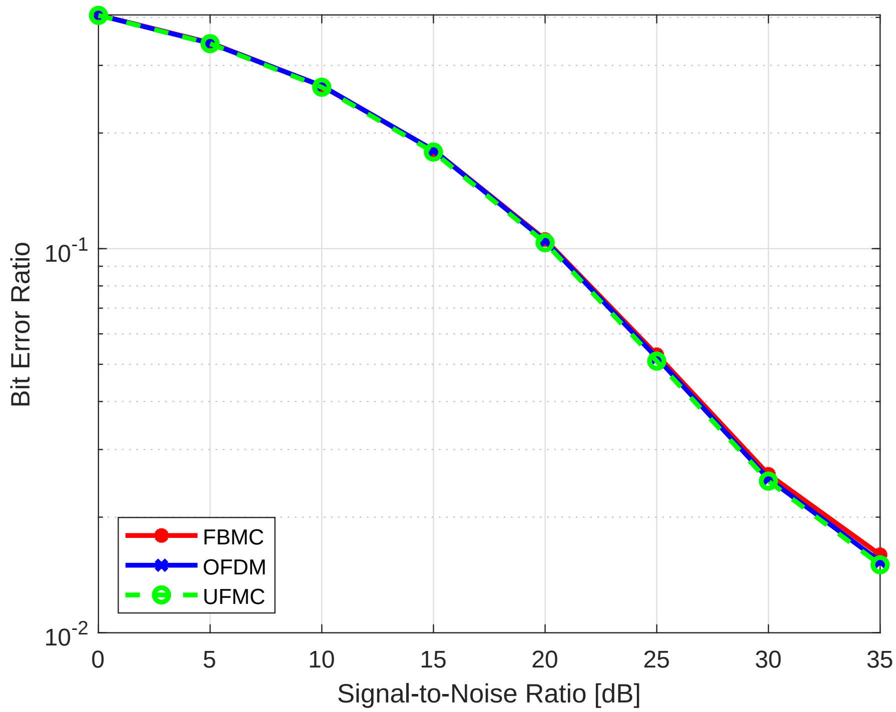


Figure 5.7: BER versus SNR curve for candidate modulation formats in ITU-R Vehicular A model for 64 number of subcarriers and 256-QAM f_d=300 Hz.

32 dB for UFMC and OFDM, 32.2 dB for FBMC. Figure 5.8 plots the BER of 1024-QAM against received SNR under fast-fading channel for candidate waveforms. Compared to 256-QAM case, the BER performance is significantly degraded. The SNR penalty required to achieve a BER of 10^{-1} is 6.5 dB from that of 256-QAM and 15.5 dB that of 64-QAM for the three of waveforms. Whereas, at higher SNR value the three waveforms perform differently. At BER of 0.05 there is different SNR penalty between waveforms, FBMC require more 1 dB SNR than UFMC and OFDM to achieve BER of 0.05.

As the modulation order increases the constellation became denser and higher SNR is needed to preserve the BER. Due to this, for each waveforms the higher-order modulation schemes require in themselves a higher receiver SNR for a given error rate, compared to lower-order. However, in combination with mitigation techniques like channel estimation, channel equalization the use of higher-order modulation can deliver the highest data rate within a given bandwidth.

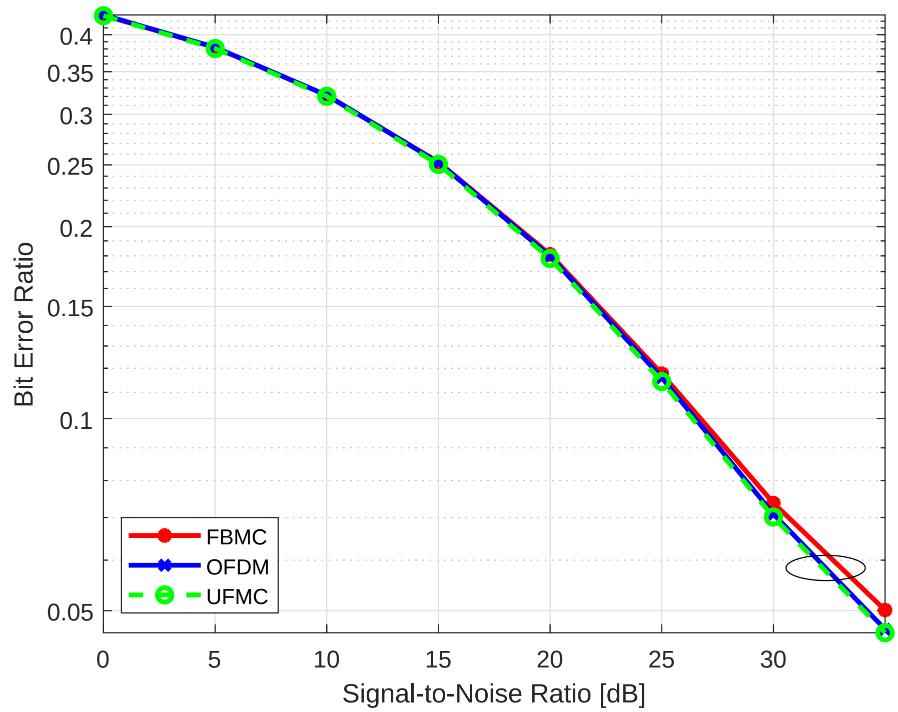


Figure 5.8: BER versus SNR curve for candidate modulation formats in ITU-R Vehicular A model for 64 number of subcarriers and 1024-QAM f_d=300 Hz.

5.4 Computational Complexity

In this section, we perform a comparison of the computational complexity for the different modulation schemes in a single antenna configuration. We focused on the downlink, in which there is no overhead due to guard bands between different users. Those complexity curves are obtained considering low complexity equivalent implementations of the transceivers presented in Section 4.5

The numerical complexity of candidates waveforms as a function of the length of transmitted data sequence is illustrated in Figure 5.9. When the number of transmitted symbol became increase the real number of multiplication also increases.

The second analysis were obtained by assessing the numerical overhead modulation schemes in two different cases. In this evaluation, the FFT size equal to $N = 1024$ is considered for the three of modulation schemes. We also assume 10 MHz transmission bandwidth with subcarrier spacing 15 KHz. The maximum number of subcarrier fitting to given

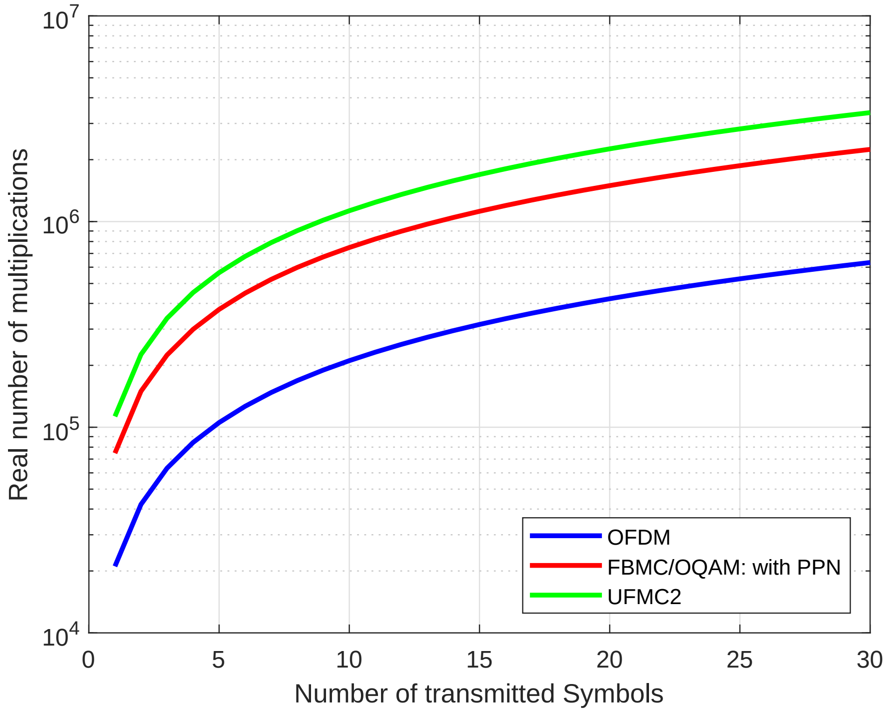


Figure 5.9: Computational complexity of candidate waveforms of 5G.

bandwidth is 666. For asynchronous transmission to minimize the interface there are guard subcarriers. For this analysis the number of guard subcarriers are proposed by [19]. Accordingly, the number of subcarrier that actually caring data symbols became; for FBMC $No = 664$ less guard band, CP-OFDM $No = 586$ and $No = 658$ to that of UFMC. Only complexity due to processing the data symbol is considered. The channel estimation, channel encoding/ decoding, synchronization and pilot symbol generation are not considered here.

In the first case, ITU-R Vehicular A propagation channel model, which is medium delay spread is considered. As discussed in [46], with Vehicular A-model , its sufficient to use 1-tap equalizer in FBMC i.e Leq=1, by assuming that the receiver is well synchronized both in time and frequency. Longer equalizers would be to compensate synchronization imperfections and might be preferred practice, but this choice gives a lower bound for the FBMC complexity. In OFDM, the CP length is assumed to be $Lcp = 1/14$ of useful symbol duration.

In the second case we assume the more frequency-selective Vehicular B channel. This were assumed in WiMAX and 3GPP-LTE system development. Now we have to use longer subchannel equalizer in FBMC with $Leq = 5$ and the guard intervals in OFDM has to be increased and Lcp=1/8 of the useful symbol. The zero prefix of UFMC is assumed of same length as OFDM CP. Table 5.3 summarizes the computational complexity overhead of each waveforms per information symbol for different system setups.

As the result show in Table 5.3, both UFMC and FBMC yields higher complexity than OFDM. By considering optimized implementation, FBMC requires three point six times more real number of multiplications than OFDM to transmit the same amount of data symbols. This resulted due to addition of filtering operation and increasing of length of equalizer to mitigate frequency selectivity of channel. Efficient implementation of UFMC is around five point five (5.5) times more complex than OFDM.

Table 5.3: Number of multiplication and additions of multicarrier signal processing for 2 different configuration

Multicarrier Waves	**Real Number of**	**Case I**	**Case II**
OFDM	Multiplication	21,800	22,024
	Addition	59,032	59,144
UFMC	Multiplication	122,376	122,376
	Addition	354,052	354,052
FBMC	Multiplication	67,600	79,888
	Addition	138,256	150,544

5.5 Result Discussions

As a result, shows the best OoB emission is obtained with FBMC with an overlapping factor $K = 4$. The reason why they have different spectrum leakages, to a large extent, depends on the type of filter used. FBMC have lower spectral sidelobes due to the use of the pulse-shaping filters instead of rectangular windows employed in OFDM system. The lower OoB emission enables the transmitter to fill more subcarriers with data, which increasing the spectral efficiency of 5G user scenarios. Also it implies that the waveforms will not need large guard bands to avoid adjacent channel interference (ACI). Cognitive radio (CR) is one of application of 5G which require strict ACI. The lesser side lobes of FBMC reveals to be almost insensitive to multiuser interference. UFMC, due to the block filtering, performs a lower OoB leakage compared to OFDM, but is outperformed by FBMC.

Another performance considered is the spectral efficiency comparison of modulation schemes by computing their time-modulation efficiency. The time-efficiency of each modulation schemes is described in Figure 5.2. The result shows that, when the transmission time gets longer, the spectral efficiency of FBMC is outperforms both OFDM and UFMC. The efficiency tends to modulation efficiency due the fact that lack of CP and ZP. Although, for transmitting short bursts data. FBMC suffers from its long filter tails, which outperform by both UFMC and OFDM. Even if it is better spectrally, UFMC is outperformed by OFDM due to its filter tail additional with the guard interval. Also for multicarrier modulations there is a gain of spectral efficiency by increasing the number of bits in each subcarrier. But this should be considered on the bit error rate of transmission. This can be mitigating by different mechanisms.

The other result from the simulation was BER vs SNR. For the three of the modulations, the less the BER result is the higher the SNR and the better communication quality. Despite the fact that higher Doppler frequency (leads to faster variation of channel), the BER performance of the modulation schemes became degraded. The result shows that under a several fading environment, waveforms with sufficient guard interval has the best performance, almost the ISI caused by the multipath can been canceled. However, the addition of guard interval cost their spectral efficiency. Since fast-fading channel is difficult to be estimated, their performance decreased significantly. They provide related result on robustness against fast-fading channels. Additional channel mitigation techniques are needed. Also higher-order modulations are considered for wave forms. Compared to lower-order modulation, the BER performance in each waveform is significantly degraded.

Computational complexity is another critical metric of the waveform design which depends on the number of operation required at transmitter and receiver. At last, we also showed that new candidates numerical complexity overhead on two propagation channel with medium and higher delay spread. The complexity of PPN base FBMC is more than double to that of OFDM, mainly due to filtering operation and the multi tap equalizers to mitigate channel interference. Also when transmitted symbol became higher, the computational complexity of UFMC systems seems much larger than the conventional OFDM and FBMC. This resulted from the, mainly each resource block operates one FFT. When it comes in LTE, there are 100 resource blocks to be modulate, the overhead complexity will reach higher order than OFDM. Issues are arising to minimizing the complexity of UFMC. One of this is applying the different and lower size of FFT for resource blocks, which is analyzed (lower size of FFT) in above section.

Chapter 6

Conclusion

6.1 Conclusion

OFDM is a robust and mature technology used in several communication systems indeed, which is the core technology of 4G systems. In 5G rather than improving the existing data rate, also there are new services such as M2M, IoT etc. The very stringent requirements of 5G network has pushed researchers to look for other solutions. To maximize spectral efficiency, the 5G air interface technology will need to be flexible and capable of mapping various services. Therefore, flexibility and good frequency localization of modulation schemes are key requirements.

In this thesis, performance comparison of 5G candidate modulation schemes is proposed under common frame work. FBMC and UFMC were selected and compared with CP-OFDM in terms of power spectral density, BER, spectral efficiency and computational complexity. In each cases the transmitted data had the same parameters and the signal were propagating through the same channel. The result reveal advantages and drawbacks for each modulation schemes.

It was notice that the PSD performance was much better after using that of FBMC compared with that of CP-OFDM and UFMC scheme. This characteristic let them to perform better in asynchronous transmission. The BER performance of UFMC and OFDM schemes approximate to that of FBMC with cost of their spectral efficiency. According to the gain of spectral efficiency, FBMC is able to achieve full time efficiency through holds only in case of symbol sequences with infinite length. This will not prefer for scenarios like machine-type communications, where the packets to be transmitted are expected to be rather short. UFMC is more suitable for short burst asynchronous transmissions as compared with the two.

Beside transceiver performance evaluation of modulation schemes, comparison of numerical evaluation also held. Computational complexity is critical on scenarios like IoT, to meet extreme low area. Accordingly, OFDM has an easy implementation, but with high level of OoB emission. The schemes UFMC and FBMC perform lower OoB emission but higher complexity. On account of, UFMC performs higher computational complexity than FBMC-PPN.

UFMC modulation scheme is an interesting option. The pulse shaping function gives robustness to access with relax synchronization compared to OFDM. UFMC also preserves backward compatibility with OFDM algorithms. On the other hand, the well localized frequency response of FBMC-OQAM results for the use of fragmented spectrum with minor interference on adjacent bands. But this waveform may difficult to adapt to short packet size transmission because the loss of its spectral efficiency. Although, the absence of guard periods and guard bands gives FBMC an efficient gain for larger packet size. On the last the complexity of transceiver design of UFMC is higher also to that of FBMC compared to OFDM transceiver.

6.2 Recommendations for Future work

In this thesis, modulation techniques for 5G networks were discussed. These techniques can be used deal with OOB leakage, BER and spectral efficiency in 5G. However, there are still many open issues in this area.

1. In this thesis, the waveform design is assumed to be performed at baseband. On the other hand, one of the potential of 5G communication technologies under consideration is the use of millimeter wave frequencies. In this way, signals allocate more bandwidths to faster transmission. To identify the performances of modulation schemes further analysis on higher frequency could be helpful.

2. When we compared them, it is assumed that all systems are perfectly synchronized. What if when there is synchronization problem in the environment?

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