Performance Comparison of Waveform Contenders for 5G Physical Layer: OFDM, FBMC, UFMC and GFDM

By

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THESIS ACCEPTANCE CERTIFICATE

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ABSTRACT

5^{th} Generation of mobile communication promises to deliver the data rates and services, which 4G could not deliver. To meet the demands and pre-foreseen requirements a complete new system is required incorporating the merits of the previous generations and subtracting the demerits. Internet of things (IoT's) and machine type communications (MTC) accelerates the keenness to redesign the whole architecture starting from physical layer to higher ones.

This Research work aims to propose a waveform, filter bank multi carrier (FBMC) for the foreseen scenarios of 5^{th} generation of telecommunication and compares the results with 4^{th} Generation OFDM waveform. Filter banks are the advanced forms of multicarrier sub band processing and aims to deliver much better results than OFDM. These filter banks exploit the shortcomings of fast Fourier transforms at the trade-off of adding complexity to the systems i.e. Poly-Phase Filter Networks (PPN). This research work further discusses the waveform contenders for 5G physical layer, which include Universal Filter Bank Multicarrier waveform (UFMC) and Generalized Frequency Division Multiplexing (GFDM). It elaborates the transceiver structures, the modules and filtering techniques involved in the implementation of UFMC and GFDM. By the end of this dissertation, it draws logical and analytical conclusion of the research work.

DEDICATION

This research work is dedicated to my parents

Naseem-ul-Hassan and Shahnaz Akhter

for their endless support, love and encouragement.

ACKNOWLEDGMENTS

I would like to thank my thesis advisor **Col Dr.Adnan Ahmed khan** for his motivation, dedication, critical questioning and thorough understanding of the topic. His mentoring helped me throughout the research process.

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Most importantly, not this research work but my whole MS degree became a reality with the keen, unfailing and continuous support of my family members (Parents and siblings) especially my mother **Mrs. Shahnaz Akhter** without her, I could not even make a semester possible.

Finally, I must express my gratitude to the friends for their unconditional support throughout the process of research and thesis writing, Thank you

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ACRONYMS

This is the list of most important abbreviations in the thesis.

AMPS	AMPS
AR	Augmented Reality
AWGN	Additive white Gaussian Noise
BTS	Base Transceiver Station
BW	Bandwidth
BER	Bit Error Ratio
CCDF	Complementary cumulative distribution function
CDMA	Code Division Multiple Access
CFO	Carrier frequency offset
CP	Cyclic Prefix
DFT	Discrete Fourier Transform
ETSI	European Telecommunications Standards Institute
FBMC	Filter Bank Multicarrier Waveform
FDMA	Frequency Division Multiple access
FFT	Fast Fourier Transform
GFDM	Generalized Filter Bank Multi carrier
GSM	Global System for mobile
GRPS	General Packet Radio Service
ICI	Inter-Carrier Interference
IFFT	Inverse Fast Fourier Transform
IMTS	Improved Mobile telephone system
ISI	Inter symbol Interference
ITU	International Telecommunication Unit
MC	Multi carrier
MIMO	Multiple Input Multiple Output
MS	Mobile Station

NBFM	Narrow band frequency Modulation
OFDM	Orthogonal Frequency Division Multiplexing
OQAM	Offset Quadrature Amplitude Modulation
PAPR	Peak to average power ratio
PPN	Poly Phase Filter Network
Rx	Receiver
PN	Pseudorandom Numbers
QAM	Quadrature Amplitude Modulation
SDMA	Space Division Multiple Access
SER	Symbol Error ratio
SNR	Signal to Noise ratio
TDMA	Time division Multiple Access
TX	Transmitter
LTE	Long-term evolution
UFMC	Universal Filter Bank Multi carrier
VR	Virtual Reality
WBFM	Wide band frequency modulation
WLAN	Wireless Local Area Network

Chapter 1

1 INTRODUCTION

This chapter covers the brief introduction of the research work and problem formulation of the thesis. It also states the scope, significance and methodology adapted to complete the research work.

1.1 Introduction to the Filter Bank Multicarrier Waveform (FBMC)

Cellular world always demands for higher data rates, spectrum efficiency and fidelity to access the spectrum in a flexible way. This is the era of 4^{th} generation in terms of telecommunication heading very fast towards 5G. The research work discusses a new modulation scheme Filter bank multicarrier (FBMC) and its possible usage in the physical layer of the next tentative generation, 5G. The proposed techniques for the 5G physical layer access spectrum includes Filter bank multi carrier (FBMC), universal filter bank multi carrier (UFMC), Generalized frequency division multiplexing (GFDM) and Orthogonal frequency division Multiplexing (OFDM) [1] [2] [3].

FBMC is an evolved form of OFDM and multi carrier (MC) modulation scheme. It uses the blocks of Fast fierier transform (FFT) and inverse Fast Fourier transform (iFFT), adds Polyphase filter (PPN) structure to it and produce more flexible results than already existing 4G multiple access spectrum technology i.e. Orthogonal frequency Division Multiplexing (OFDM). FBMC do not use Cyclic prefix (CP) which adds to its spectrum efficiency. CP is OFDM is used to cater for multi path fading when delay of the symbol is less than the CP. The filter band adds features to FBMC that is band selectivity, low peak to average power ratio (PAPR), low out of band radiation and low sampling rates [4]. Figure: 1-1 gives a rough comparison of the two waveforms, both which will be covered thoroughly in detail in this thesis.

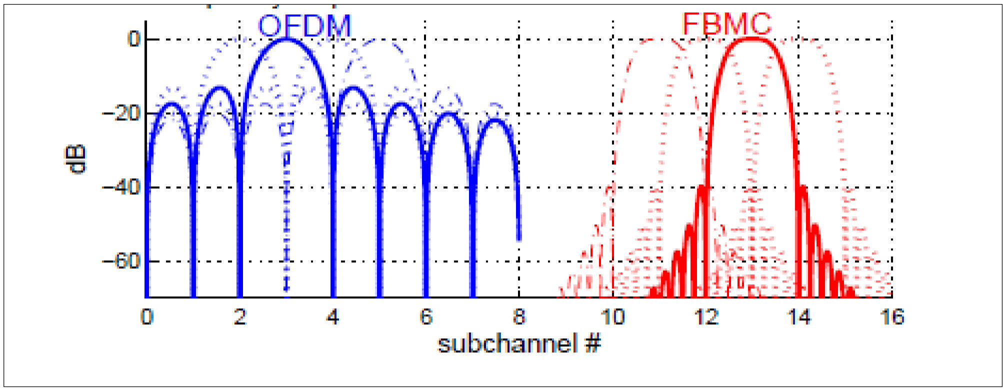


Figure 1-1: Sub Channel Spectra of OFDM and FBMC

Moreover, this research covers the demands and quality of services, which will be needed 10 years ahead in communication keeping in mind what the previous generations have achieved so far and what is next in the bucket. It further discusses the future research work.

1.2 Problem Formulation, Challenges and Requirements for 5G

Challenges are the essential part of research and developments. The mobile generations are always heading towards new user needs and enhancements towards quality and services. Since the last four decades' cellular generation has improved from 1G to 4G. For every generation a new key point index and services are defined and are attached and aroma of a generation. e.g. 1G was the era of Analogue communication, 2G was the era of Digital communication, 3G dealt with pseudorandom codes with the and 4G with the multi carrier frequencies. 5G will cover those aspects which the previous generations have not achieved so far and will introduce more spectral efficiency, high data rates, some killer applications, battery efficient communication, more target oriented services, high capacity to users, low spectrum leakage, self-organizing networks (SON) and much more.

Having said that we have OFDMA in current 4G networks. OFDM technologies have some shortcomings which makes us re-think about ta new flexible technique that can heal those drawbacks. The cyclic prefix is added to the OFDM symbol, which is $1/4^{th}$ of the symbol length itself, it is then added at the beginning of the symbol as shown in the Figure: 1-2. This adds to extra redundancy and hence, reduced spectrum efficiency [5]. The OFDM symbols have higher PAPR and out of band radiations [6] as shown in Fig: 1-2. These shortcomings forced researchers to look for another solution. Filter banks made their way into these problems and offer much better solutions along with FFT/iFFT [4].

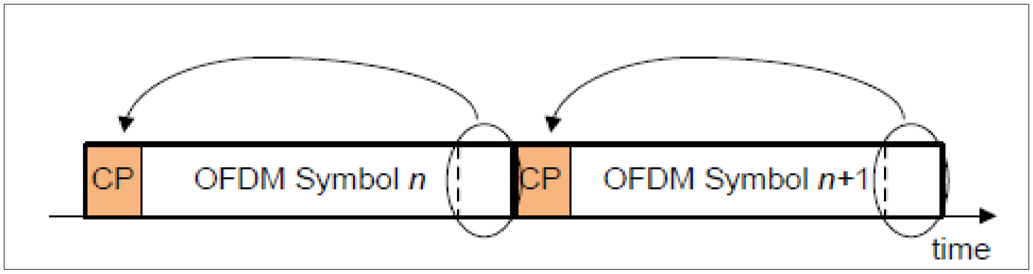


Figure 1-2: CP in OFDM

1.3 Scope of Research work and Deliverables

This research covers the need of FBMC with respect to the new data and spectrum efficiency requirements. It critically mentions the shortcomings from OFDM and try to improve the results by adding filter bank networks to its architecture. FBMC make low out of band radiation due to which the co-channel interference is reduced.

The research work briefly touches the demands of 5G, its key drivers, future endeavors and killer applications. It deals in detail with one of the contenders for the 5G physical waveform access technology i.e. out of the three main contenders FBMC, UFMC and GFDM [7] it deals with FBMC in detail only covering its literature review, transmission model and implementation. Moreover, its critical analysis and quantitative comparison with orthogonal frequency division multiplexing (OFDM) is also covered.

The simulation results include the impulse response of the FBMC and OFDM filters in time and frequency domains, BER performance of FBMC and OFDM in Additive white Gaussian noise channel (AWGN) and Vehicular channel Model A. [Index-A]

In the end, this thesis cites further research work areas in the way of 5G with references. 5G is a huge research area covering new MIMO techniques, self-organizing network techniques, modern channel estimations and aims to improve the legacy networks.

1.4 Significance of Research

This research formulates the fact that 5G is needed and we need to redesign the physical layer waveform to produce better results and flexibility for the 5G's applications i.e. Machine type communication (MTC) and internet of things (IoT's). With the further research areas defined, it starts a healthy discussion on the upcoming generations of telecommunication and future ventures. The beauty of this research lies in the new emerging topics that came out of this specific research work.

1.5 Research Methodology

The research work starts from literature review about the upcoming requirements of new era of communication (5G) worldwide. The literature review is done from different academic and commercial sources. This research then narrows down itself to the physical layer of the OSI model and lists the drawbacks of OFDM and formulates the problem. Then, it discusses a filter bank multi carrier waveform (FBMC) in detail and covers thoroughly FBMC's Literature, design and implementation.

Implementation of the two waveforms OFDM and FBMC is carried out in SystemVue2015 and MATLAB simulation software. Then, there is a critical comparison of the two schemes proposed and a logical conclusion. In the end, there is a full road map for the future research areas in the 5G communication.

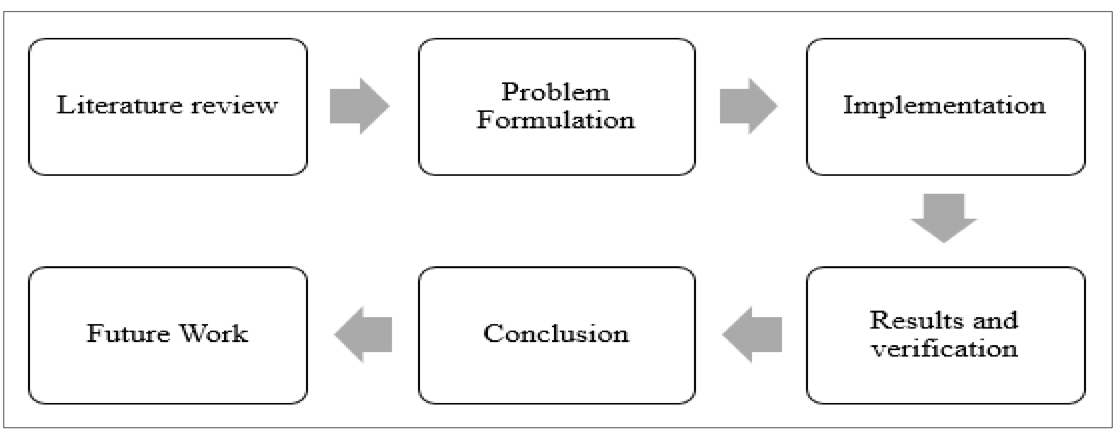


Figure 1-3: Research Work Flow

1.6 Basic Definitions

Waveform:	A waveform is an abstract representation of the signal in a physical medium.
Full Duplex:	Communication in which sender and receiver sends and receives simultaneously.
Half Duplex:	Communication in which sender and receiver sends and receives one at a time.
Bursts:	Signal transmission over a short period.
Uplink:	Communication from Mobile station to BTS.
Downlink:	Communication from BTS to Mobile station.
Coherence Bandwidth:	The bandwidth in which the channel response is considered flat.
FDD:	Frequency division duplex uses same time indifferent frequencies.
TDD:	Time division duplex uses same frequency in different time slots.
Narrow band:	The channel in which Bandwidth of information signal does not exceed coherence BW.
Wide Band:	The channel in which Bandwidth of information signal exceed coherence BW.
Rake Receiver:	A Receiver that is designed to reverse the effects of multipath fading.
Handover:	Shifting of an ongoing call from channel to another, while remain connected to core network.
Transceivers:	Transmitter and receiver combined together makes a transceiver.

1.7 Thesis Outline

Chapter 1	Introduction	It covers the introduction of FBMC, OFDM drawbacks, problem formulation, and scope of research, research methodology, basic definitions, and thesis outline.
Chapter 2	Evolution of Cellular Networks	It lists the cellular evolution from 1G to 5G. 5G's key drivers and a comparison of technologies and services of cellular Generations.
Chapter 3	Literature Review	It covers the Literature review of Multiplex access schemes of physical layers from 1G to 4G. It covers FDMA, TDMA, CDMA and OFDMA in detail. It furthers illuminate the OFDMA advantages over the previous generations and its disadvantages as well.
Chapter 4	Filter Bank Multi Carrier Modulation	It covers the Literature review of FBMC. Its implementation from FFT/iFFT blocks. It further discusses the Polyphase filter banks (PPN) structure in FBMC.
Chapter 5	Universal Filter Bank Multicarrier	It covers the basic Implementation of UFMC. Its modification from FBMC and transceiver structure. It enlists the comparison of UFMC and OFDM from literature and draws conclusion.
Chapter 6	Generalized Filter Bank Multicarrier	It discusses the transceiver of GFDM, Circular convolution and tail biting technique involved in it.
Chapter 7	Implementation and Results	It covers the implementation of OFDM and FBMC in SystemVue and MATLAB, their filter impulse response in time and frequency domain, computational complexity, BER measurements

		in AWGN and more realistic vehicular channel model A.
Chapter 8	Analytical comparison of OFDM, FBMC, UFMC and GFDM	This chapter enlists the differences of OFDM and FBMC transceivers, their implementation and their overall results and impact in multi carrier systems.
Chapter 9	Conclusion and Future work	It writes the conclusion of the research works and further unveils the future research work, which was uncover during the research process.
Bibliography		It states the research papers, books, Journals and Articles refereed ad studied for the completion of thesis.
Appendix		Appendix enlists those details, which are not written in detail between thesis chapters and are touch only. These include Hadamard Matrix, channel vector A.

Chapter 2

2 EVOLUTION OF CELLULAR NETWORKS – A BRIEF OVERVIEW

Evolution of cellular networks puts on light on the continuous growth of the telecommunication systems. It wraps around the data rates, services, modulation schemes and key drivers of the 2G, 3G, 4G and 5G. It overlays the concept that why the world needs 5th Generation of telecommunication by highlighting its key motorists of 5G from Literature already available.

While there is growth in all the sectors of life and so is the evolution in telecommunication as well. Telecommunication systems evolves throughout the years and we can always pre-assume that is an always-evolving process with new technologies meeting the required demands of that particular era [8]. Moreover, not only the telecommunication generations evolve but also the Wi-max standard also glorified with the new ventures and services in telecommunication standards.

Figure: 2-1 explains a thorough evolution starting from 1990 1G to 2020's 5G. The boost in telecommunication started when digital communication made its part. Hardware, which can process digital bits, were developed and new modulation schemes were invented. Initially there were many private companies working separately then the urge for international roaming arise, the private companies merged and form a standard body, which depicts the mutual understanding and globalization of the telecom structure worldwide.

1G gave the smooth voice communication, followed by 2G delivering a better capacity and data. 3G focused on broadband services and gave even better capacity, data rates and services. 4G services include live data streaming, elf organizing networks and higher data rates. 5G is supposed to deliver more than what the previous generations did.

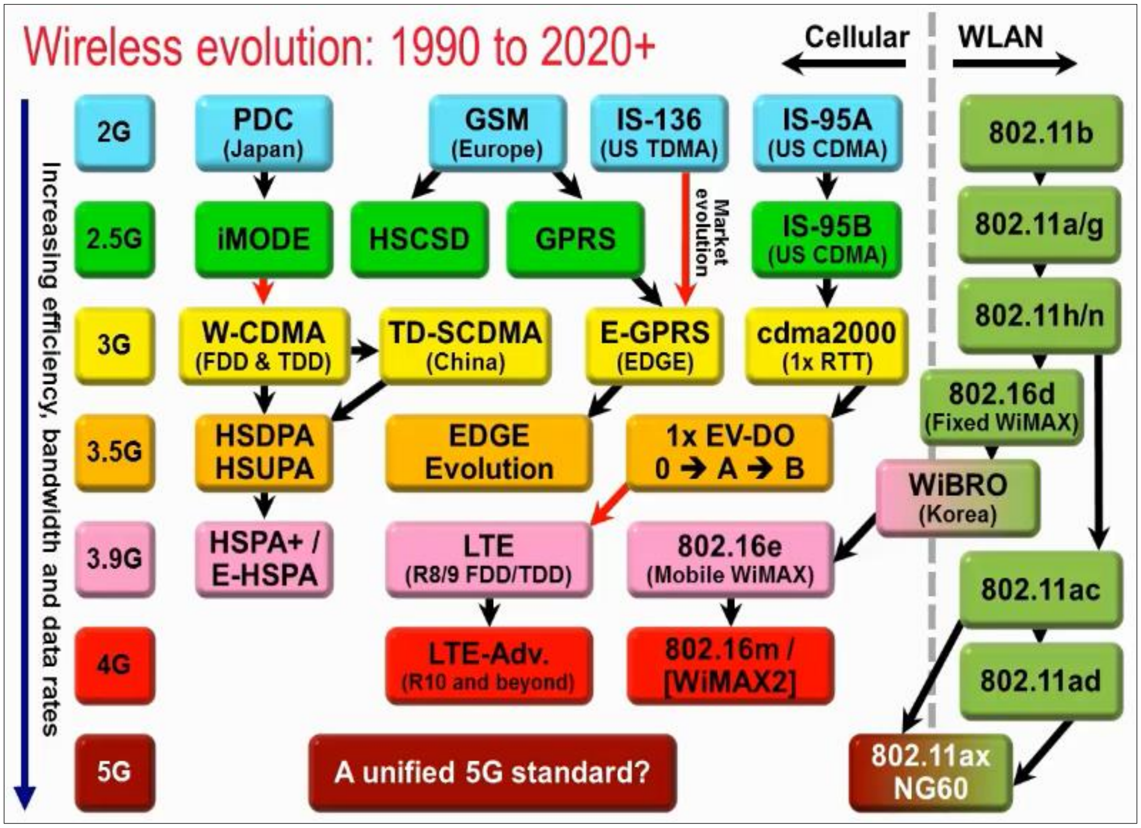


Figure 2-1: Telecom Evolution along with Wi-Fi Standards

2.1 First Generation -- 1G

First generation of communication started when first long distant call was established, it was an analogue call with voice only. AMPS: analogue Mobile phone sets, were the first mobile set used by military communication in early 20th century. 1G also included car-based systems, in 1940 is where a large transmitter was installed on the large building and a mobile car has the receiver installed in it, it was a half-duplex push to talk system.

IMTS, Improved mobile Telephone system in 1960's was introduced for a full-duplex communication. Then, different privet communication companies pledged in and introduced their own systems in 1970's. Out of which few are TACS: Total access mobile communication, NMT: Nordic Mobile Telephone. These two were used in parts of Europe, while J-TACS: Japanese Total access systems were used in parts of Japan and Hong Kong. In 1982 Bell Labs introduced AMPS: Advanced Mobile Phone systems, the key idea was to develop the geographical layer into cells and each cell was served by a base station so that frequency reuse can be implemented. As a result, AMPS could support 5 to 10 times more users than IMTS.

2.1.1 2G drivers

I. Weak security on air interface
II. Full analogue mode of communication
III. No roaming
IV. Limited capacity an scalability

2.2 Second Generation -- 2G

To implement roaming in 1988 all private organizations started working under one umbrella and it was European telecommunication standard institute ETSI, and develop second-generation systems. 2G was launched in Finland in 1991 as a GSM based systems. Second generation of cellular communication was made with the digital communication technologies emergence [9]. SMS was incorporated along with voice and data services were introduced. The data rate initially committed was 9.6 kbps. The goals achieved were voice communication was digitally encrypted, greater mobile communication and more cellular penetration.

2.2.1 2.5G

To further, achieve higher data rates in 1995 a new generation GPRS later on called 2.5G was introduced. It was Packet switch network with GSM. It achieved up to 160kbps speed.

2.2.2 2.75G

After GPRS enhanced data rate i.e. Edge was introduced which uses 8PSK modulation and data rate was enhanced to 500 kbps. In 1998 internet boom.

2.3 Third Generation -- 3G

3GPP introduced 3Gtechnology. Third generation was the era of wireless technologies. Web browsing, email services, downloading activities from web, snaps were introduced in the third generation. 3G should be capable of handling around 2 Megabits per second. It was the wide band using CDMA technique, hence the name W-CDMA. It had so many revisions before falling to 4G LTE.

2.4 Fourth Generation -- 4G

Fourth generation is dealing with high data rates, live video streaming and much more. 4G technologies dealt with multiple phone attachment at a time. 4G Long Term Evolution is a much better and promising version of 4G increasing data rates to higher and up to the pledges made by 4th generation. The physical layer of 4G is of OFDM waveform with the uplink as SC-OFDMA. The uplink of 4G is SC-OFDMA because at the uplink the mobile station is energy constraint s

2.5 Fifth Generation -- 5G

5G is supposed to be standardized in the year 2020. Its applications would be including machine type communication, more of a wireless and asynchronous era. The demands of 5G are more immense and diversified [7].

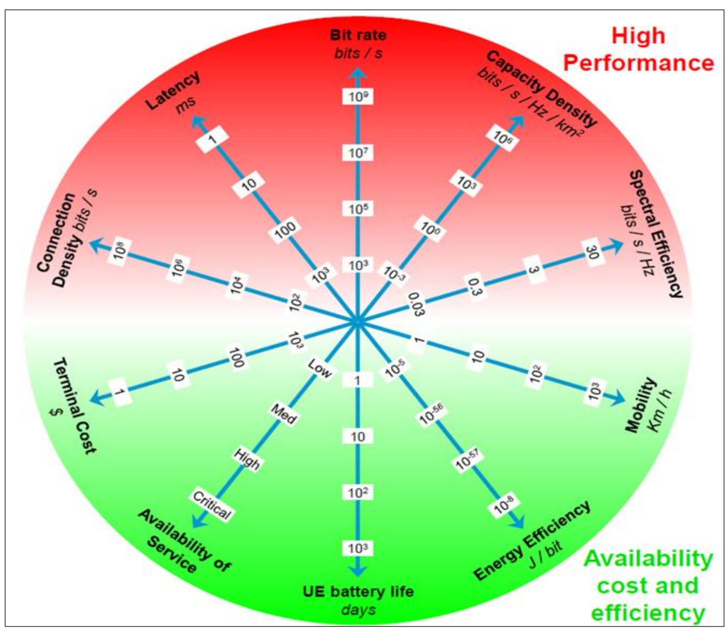


Figure 2-2: Shaping 5G, Performance vs. Availability, Cost and Efficiency

The demands can be interpreted by the wheel structure as shown in the figure. The emerging demands of 5G are far more comprehensive than the previous four generations.

From the wheel given in the Figure: 2-2, it is very clear that the upper half are the demands of the vendor while the lower half are the demands of the customers. Keeping in view all of them this cannot be provided by a single solution.

2.6 5G key Drivers, and Motivation

There are always new points and applications associated with the next generation of communication. With 5G we have the following parameters attached.

2.6.1 Internet of Things

Internet of things is the new era of modern world where all the devices will be inter-connected through internet. On average, it is believed that in UK a single person will be connected to almost 27 devices at a time and 50million devices around the world will be connected at a time. These devices include kitchen holds (refrigerators, microwave, and toasters) to living room gadgets smart TV, telephones fans air conditions etc. With these much of devices interconnected we need a very efficient timings and so a strict synchronized environment is not feasible at all [10].

The present 4G waveform is highly synchronous ad its latency is too high for these type of communications. Moreover, bandwidth efficiency is needed to cater all these devices in place.

Two classes of machine type communication can be derived, one is massive machine type communication and the other is targeted machine type communication [11]

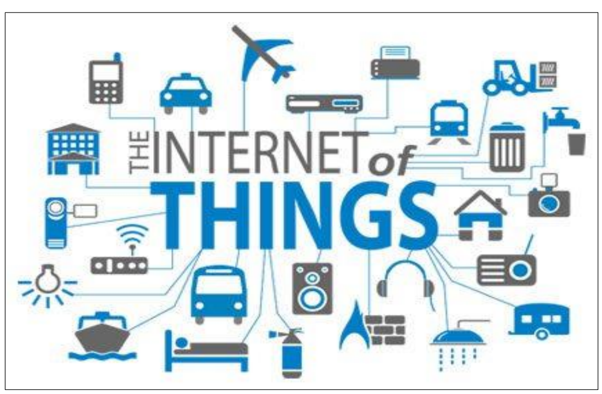


Figure 2-3: Internet of Things

2.6.2 Latency not the Speed

Due to internet of things and multi-player gaming and other applications, 5G will need a very low latency for its applications unlike 4G. It is estimated that 4G video streaming will increase up to 76% with the passage of time and human demands, telecom people admits that the data rate offered by 4G will rather not be enough to cope up with.

2.6.3 Virtual and Augmented Reality

Virtual reality is a computer software oriented objects technology accompanied with hands free hardware set which makes you believe into a composite view along with voices, images and environment. It takes you into an imaginary artificial world. The technique is a gaming and movie innovation. It is improving the tracking technologies and movements. It is being started from early 1950's with a much bigger hardware and now big names such as Facebook, Google, Apple, and amazon have separate working groups working on virtual and augmented reality. This much increase in concern suggest that there is a huge market for this technology in the coming future and hence the network requirements given can be foreseen by the Figure: 2-4.

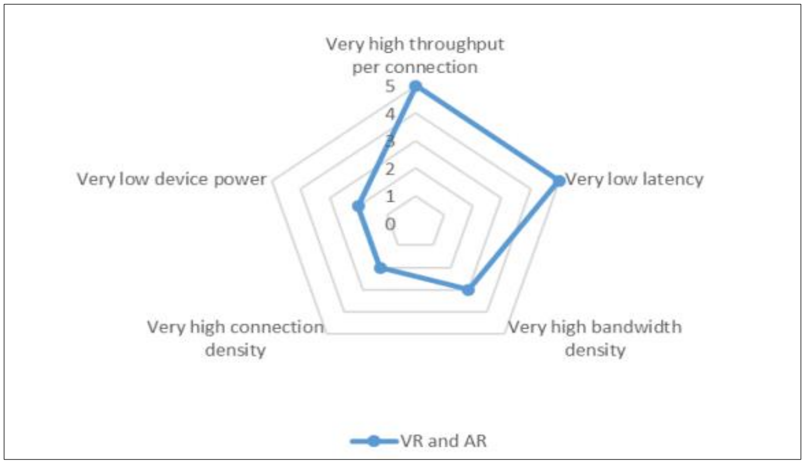


Figure 2-4: Virtual Reality Expected Network Demands

2.6.4 Software based 5th Generation

It is advised to make the new generations of communication software based rather than hardware based in order unlike previous generation, by Professor Sutton during Pocket-lint is so that only software upgrade would be enough to launch into 6G.

2.6.5 Smart Cities

Smart cities is a term used for a sensor based centralized system include traffic management, emergency and health management, weather and networking among all the organizations a buildings, even the devices within the cities. These sensors based networks will demand a cost effective and a flexible networking solution ensuring low latency and huge reliability.

Keeping in mind the above-mentioned goals, 4G band and service are not enough to cope up with the increasing technologies and demands, so 5G is expected to cover all these services with an enhanced capacity and reliability to services.

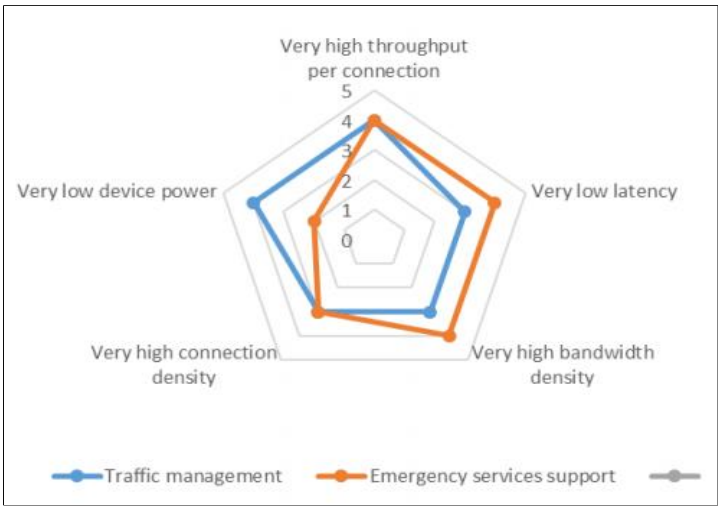


Figure 2-5: Smart Cities Requirements

2.7 Projected 5G Specifications:

At this stage, it is very cumbersome to concretely define the 5G goals and set absolute parameters, however, with the help of industry it was possible to list down some of the parameters in a Table: 2-1and Table: 2-2.

Table 2-1: Key Point Index for 5G

Parameter	Value
Latency in the air link	<1ms
Latency end-to-end (device to core)	<10ms
Connection density	100x compared with LTE
Area capacity density	1Tbit/s/km^2
System spectral efficiency	10bit/s/Hz/cell
Peak throughput (downlink) per connection	10Gbit/s
Energy efficiency	>90% improvement over LTE

5G Mobile Industrial goals may include boundless connectivity network economics, massive IoT's and critical communication, huge capacity and enhanced broadband.

Table 2-2: 5G Required Performance to address for 5G

Parameter	Technology efforts
Latency in the air link	New multiplexing schemes; new coding schemes, shorter transmit time interval (TTI)
Latency end-to-end (device to core)	New network architectures
Connection density	New multiplexing schemes; new coding schemes
Area capacity density	Higher frequency bands; beam-forming antennas; MIMO antennas
System spectral efficiency	New multiplexing schemes; new coding schemes; MIMO antennas
Peak throughput (downlink) per connection	Beam-forming antennas; higher frequency bands; MIMO antennas
Energy efficiency	New multiplexing schemes; new coding schemes, new control channel structures

The key Technologies for 5G include [12] [13] [10].

I. Millimeter wave
II. Massive MMO
III. Internet of things
IV. Machine type communication
V. Doubly selective channel equalization

VI. Compress sensing

VII. 1GB Data rate

VIII. Smart Cities

Table 2-2 writes briefly about the technologies from 1G to 5G, year of start, data rates, modulation techniques and multiple access techniques [14].

Table 2-3: Technologies Comparison of Telecom Generations

Generations	**Year**	**Radio Technology**	**Modulation Technique**	**Multiple Access**	**Data Rates**
1G	1950	Analogue	AM, FM	FDMA	No data
2G	1988	Digital	GMSK	FDMA, TDMA	9.6kbps
2.5G	1995	Digital	8PSK	FDMA, TDMA	115 kbps
2.75G	1998	Digital	8PSK	FDMA, TDMA	473.6 kbps
3G	2001	Digital	QPSK, 16QAM	CDMA, WCDMA TD-SCDMA	21.6Mbps
4G	2011	Digital	QPSK, 16QAM, 64 QAM Adaptive Modulation	DL OFDMA UL SC-FDMA	DL 100Mbps UL 50 Mbps
5G	2020 Proposed	Digital	16QAM, OQAM Adaptive Modulation	FBMC, GFDM, UFMC, CP-OFDM	1Gbps Proposed

Chapter 3

3 REVIEW OF MULTIPLE ACCESS SCHEMES

Literature review covers the physical layer multiple access technologies of the telecom generations with emphasis on multi carrier (MC) multiple access which started with OFDM. It covers in detail OFDM background, how it started, its applications, usage and drawbacks as well.

Multiple access technologies share the spectrum in a most optimized way so that a large number of subscribers can share the spectrum with a good quality of service. As the spectrum is a natural resource and it is limited, we have to share it in such an efficient way so that we may achieve higher spectral efficiency with good quality of service.

3.1 Multiple Access Techniques Evolution

In wireless communication the BTS needs to serve a lot of mobile terminals at once both for uplink and downlink, and mobile station also communicates with the BTS , so chances of interference are very high , to cater for the interference problem, multiple access schemes are introduced. Schemes to allow the channel access includes [15].

1. Frequency division multiple-access (FDMA)
2. Time division multiple-access (TDMA)
3. Spread Spectrum Multiple Access (SSMA)
    I. Frequency hopped multiple access (FHMA)
    II. Code division multiple access (CDMA)
4. Space Division Multiple access (SDMA)
5. Orthogonal Frequency division multiple-access (OFDMA)
6. ***Proposed 5G Techniques (ODFM, FBMC, UFMC, GFDM)*** [10]

FDMA, TDMA, CDMA and OFDMA are most widely used Multiple access techniques. These techniques can further be classified into narrow band and wide band technique depending upon how they are exploited.

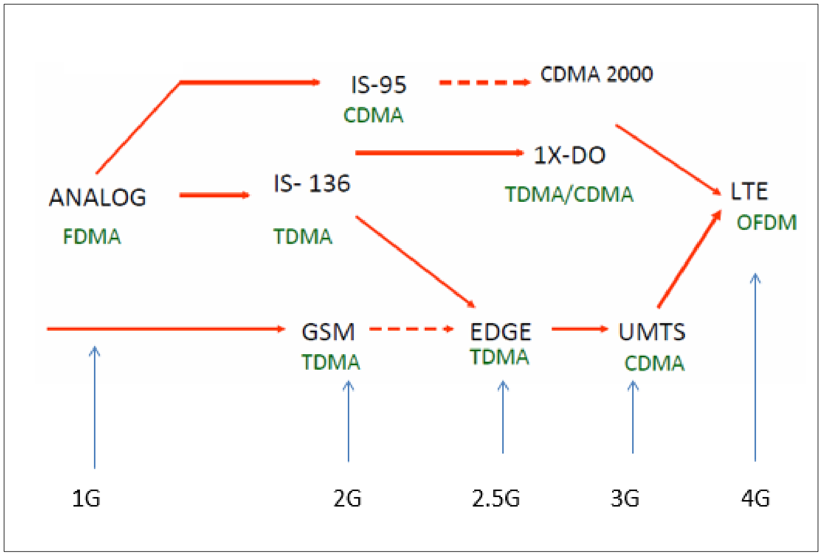


Figure 3-1: Evolution of Multiple Access Techniques in Cellular Networks

3.2 Frequency Division Multiple Access (FDMA)

It is the MA technique in which a user is assigned a frequency or pair of frequencies Fig: 3-2. One is used for the uplink and one for the downlink. The allocated frequency is not used again in the cell or adjacent cells to as to avid interference. Multiple users can use the same frequency provided they call in separate time slots.

3.2.1 FDMA Salient Features

It uses one circuit at a time; if not in use by the subscriber, it is idle. It is usually implemented in a narrow band system. A strong filtering is required to minimize c channel interference. Its Symbol time is larger than the delay time. AMPS /1G mobile systems were based on FDMA/FDD systems. It was a half-duplex mode where a single frequency was assigned to the user, one need to wait during the receive signal. Later on for full duplex, a second channel was also assigned which was 45MHz apart from 1st channel to avid interference.

3.3 Time Division Multiple Access (TDMA)

TDMA came with the digital communication, because in digital communication continuous transmission is not required. Users do not use the allotted spectrum continuously all the time. In TDMA, channels are usually wideband and users are allotted different time slots Fig: 3-2, during those time slots, they can enjoy the full spectrum fidelity.

A huge time synchronization is required in TDMA, number of channels are less as user share in frequency domain, and it uses different time slots for the transmission and reception, which is time division duplex.

3.3.1 TDMA Salient Features

The features of TDMA includes the following: TDMA shares a single carrier frequency with several users where each users makes use of non-overlapping time slots. The number of time slots per frame depends on several factors such as modulation technique, available bandwidth etc. Data transmission in TDMA is not continuous but occurs in bursts. This results in low battery consumption since the subscriber transmitter can be turned OFF when not in use. Because of a discontinuous transmission in TDMA, the handoff process is much simpler for a subscriber unit, since it is able to listen to other base stations during idle time slots. TDMA uses different time slots for transmission and reception thus duplexers are not required. TDMA has an advantage that is possible to allocate different numbers of time slots per frame to different users. Thus, bandwidth can be made available on demand to different users by concatenating or reassigning time slot based on priority.

3.4 Spread Sequence Multiple Access (SSMA)

In SSMA, a narrow band signal is converted into a wide band signal by multiplying the signal with a pseudorandom number. This techniques uses the bandwidth more than minimum required for radio channel transmission in case of single user, but in case of multiple users since all uses the same bandwidth with different PN codes, it becomes bandwidth efficient

There are two main types of spread spectrum techniques, one is code division multiple access and other is frequency hopped multiple access

3.4.1 Frequency Hopped Multiple Access

In FHMA technique the carrier frequency of the user is hopped into multiple frequencies, into pseudorandom way, the data is then transmitted into different carrier frequencies in the form of bursts.

3.4.2 Code Division Multiple Access (CDMA)

It assigns the same bandwidth and frequency to all the users but spreads them into wide band signal using different codes, which are exclusive and uncorrelated to each other. This technique is most commonly used in 3G systems. To achieve orthogonally between the users PN codes CDMA technology uses 64 Walsh-Hadamard codes and an m-sequence. Appendix A. In CDMA technology, the signal suffers a delay due to spread spectrum; this causes a problem in dispreading. Orthogonality became a serious issue; in TDMA and FDMA, we have enough guard bands of time and frequency respectively. To cater these issues hybrid spread spectrum techniques are used like CDMA/FDMA or TCDMA. Time and Code Division Multiple Access. In this TCDMA method, different cells are allocated different spreading codes. In each cell, only one user per cell is allotted a particular time slot. Thus at any time only one user is transmitting in each cell. When a handoff takes place, the spreading code of that user is changed to the code of the new cell. TCDMA also avoids near-far effect, as the number of users transmitting per cell is one.

3.5 Space Division Multiple Access (SDMA)

SDMA increases the transmission capacity over fixed bandwidth. It uses the radio directions of antenna to multiple users. In previous technologies BTS has to send data in all directions and receiver receives all the available signal information including noise too, this reduces the system overall efficiency and wastage of transmitted power too. SDMA uses narrow beam antennas to locate the mobile users and are directional to zones as well. This increases the system performance and reduces the power wastage too. The spot beam antennas may server at the same frequencies. It requires a reasonable inter cell separation and thus limits the cell usage and hence the frequency reuse factor. SDMA uses a timing advance TA feature to locate the MS position and distance and then it uses the power down feature at BTS to lower its power. Thus, it is energy efficient system. In 5^{th} generation, green communication will be a major concern and will use similar kind of feature for the energy saving purpose [16].

With the more focused antennas multiple frequencies can be reused within the same area, however it produce more better results with hybrids like SDMA with FDMA and TDMA.

3.5.1 SDMA Salient Features

Salient Features of SDMA includes:

I. Dictates the radiation energy to every user in space
II. Covers the area with the same frequency
III. Inter-channel frequency is reduced due to directional and narrow beamed antennas
IV. Infinite large antennas needed for directional propagation which affects the overall system cost

The difference in the form of figure is represented in Figure: 3-3.

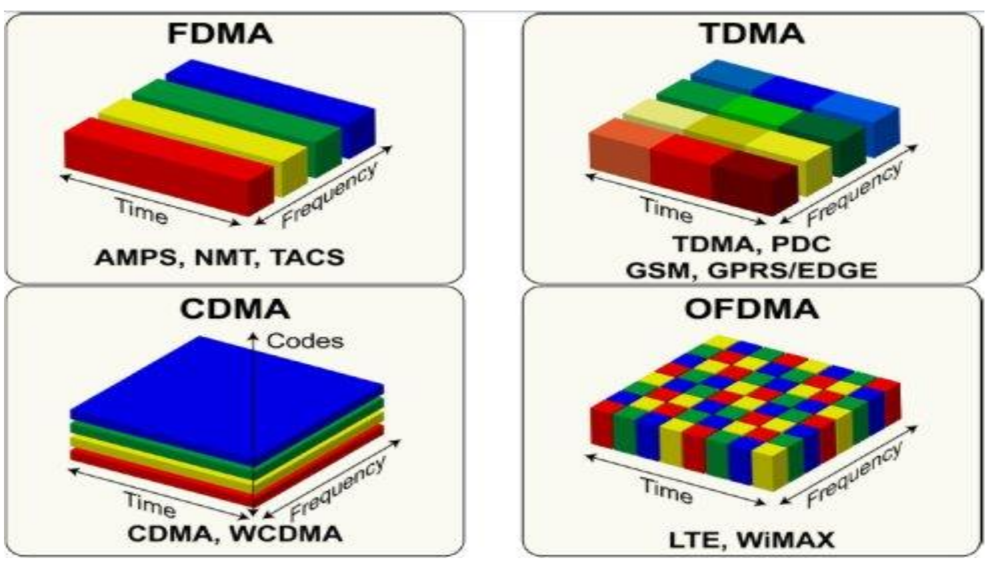


Figure 3-2: FDMA, TDMA, CDMA & OFDMA

Table 3-1: SDMA, CDMA, TDMA and FDMA Comparison

Technique	**FDMA**	**TDMA**	**CDMA**	**SDMA**
Concept	Divide the frequency band into disjoint sub-bands	Divide the time into non-overlapping time slots	Spread the signal with orthogonal codes	Divide the space in to sectors
Active terminals	All terminals active on their specified frequencies	Terminals are active in their specified slot on same frequency	All terminals active on same frequency	Number of terminals per beam depends on FDMA/ TDMA/CDMA
Signal separation	Filtering in frequency	Synchronization in time	Code separation	Spatial separation using smart antennas
Handoff	Hard handoff	Hard handoff	Soft handoff	Hard and soft handoffs
Advantages	Simple and robust	Flexible	Flexible	Very simple, increases system capacity
Disadvantages	Inflexible, available frequencies are fixed, requires guard bands	Requires guard space, synchronization problem	Complex receivers, requires power control to avoid near-far problem	Inflexible, requires network monitoring to avoid intracellular handoffs
Current applications	Radio, TV and analog cellular	GSM and PDC	2.5G and 3G	Satellite systems, other being explored

3.6 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is the multiuser adaptation of the most popular waveform OFDM. It exploits the given spectrum using FFT and divides into multiple subcarriers which are orthogonal to each other so as the avoid interference [17].

3.6.1 Difference Between OFDMA and FDMA

The difference between FDMA and OFDMA lies into the Orthogonality in the later one, which is depicted in the Fig: 3-4 as well. Fig: 3-4 shows that when we divide the given frequency using FFT, we have the same number of subcarriers with very less spectrum usage than FDMA system. This ensures spectrum efficiency. In FDMA there is a guard band between each subcarrier, which is not needed in OFDMA.

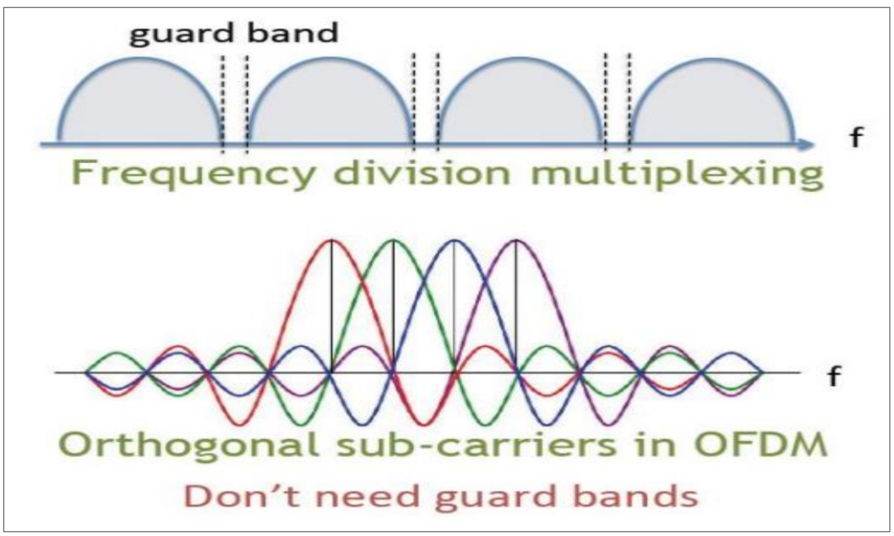


Figure 3-3: Bandwidth in FDMA and OFDMA

3.6.2 How OFDM Works?

Consider Fig: 3-3 of OFDM Transmitter, Data is modulated using any modulation scheme such as QAM starting from BPSK to QAM, 16QAM up to 64 QAM. The data is converted into parallel streams, which are of low data rates. Then the inverse Fourier transform block is inserted and it is for the Orthogonality of the subcarriers.

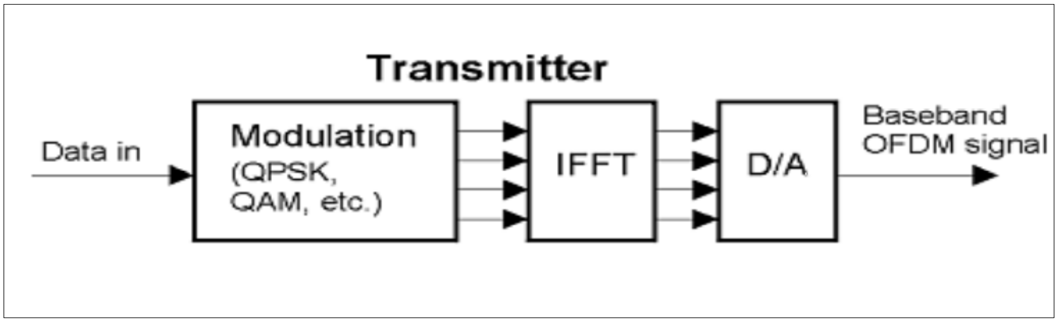


Figure 3-4: OFDM Transmitter

ODFM receiver is exactly the opposite of the OFDM transmitter.

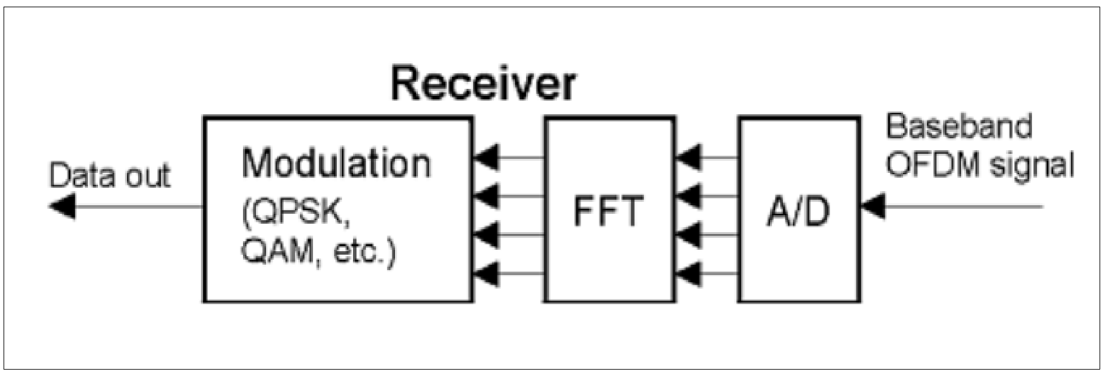


Figure 3-5: OFDM Receiver

IFFT coverts the signal from frequency domain to time domain but here in OFDM by convention it is used for Orthogonality purpose only. Equation 3-1 shows the IFFT operation.

$$X[k] = \frac{1}{N} \sum_{t=N/2}^{N/2-1} x(t) e^{-j2\pi kt/N}$$

Equation 3-1:

Equation 3-2 shows the FFT operation.

$$X[k] = \frac{1}{N} \sum_{t=N/2}^{N/2-1} x(t) e^{-j2\pi kt/N}$$

Equation 3-2:

Orthogonality of the two bins are depicted by Equation 3-3.

$$\sum_{t=N/2}^{N/2-1} e^{-j2\pi kt/N} e^{-j2\pi pt/N} = 0, \forall p \neq k \qquad \text{Equation 3-3:}$$

IFFT result can be seen in the Fig: 3-5.

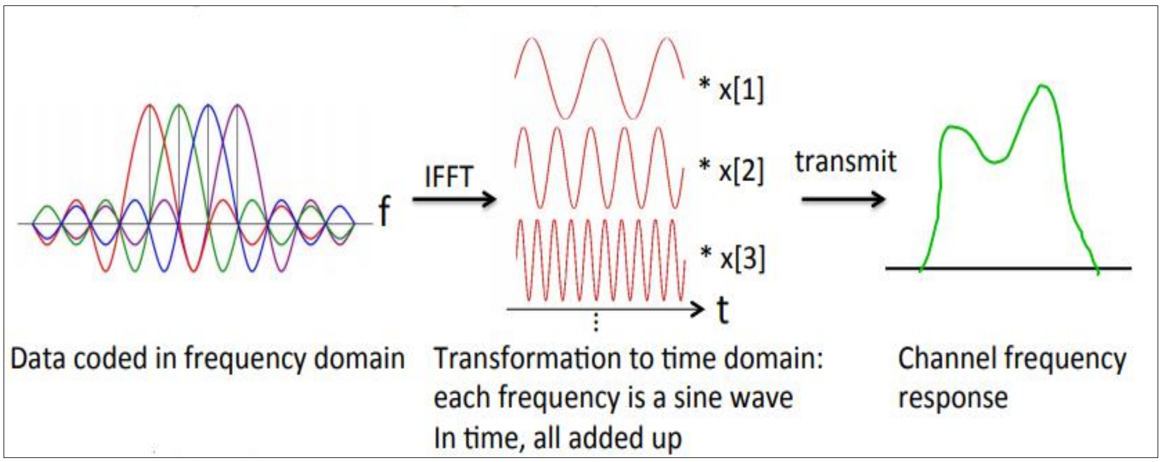


Figure 3-6: IFFT on OFDM Transmitter

FFT result is shown in Fig: 3-6. Each subcarrier is decoded using QAM or respective decoder.

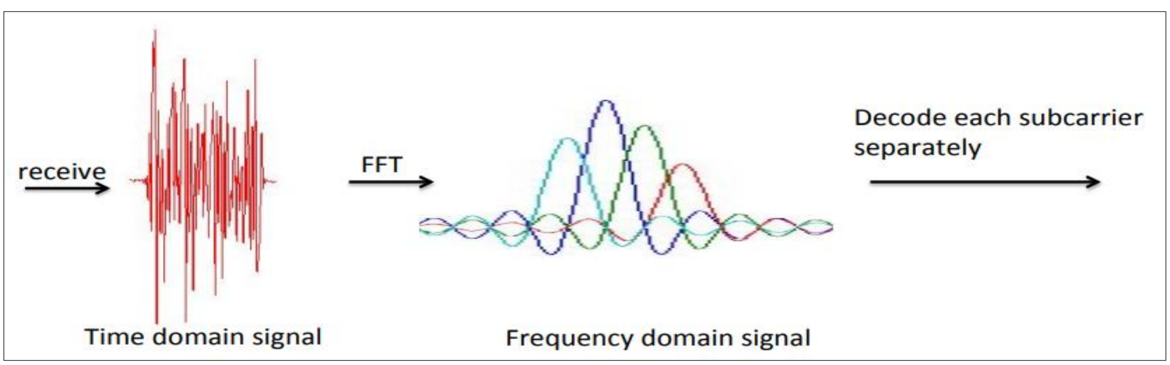


Figure 3-7: FFT at Receiver Side

3.6.3 Inter Symbol Inference (ISI) and Cyclic Prefix (CP) in OFDM

OFDM is highly sensitive to multipath fading affects as the subcarriers are orthogonal to each other, a very small fading affects a lot the Orthogonality of the sub carriers and hence the demodulation of the symbols become difficult [18]. Multipath fading adds inter symbol interference (ISI) to the symbol Fig: 3-7. Due to the multipath fading, delayed version if a symbol overlaps with the previous adjacent symbol, this introduce ISI Fig: 3-8.

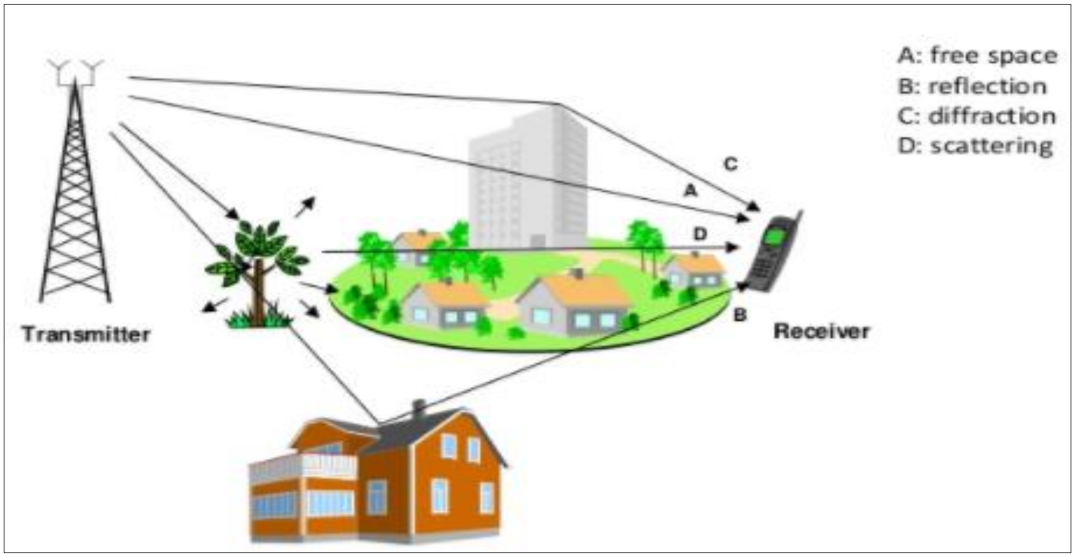


Figure 3-8: Multipath Fading

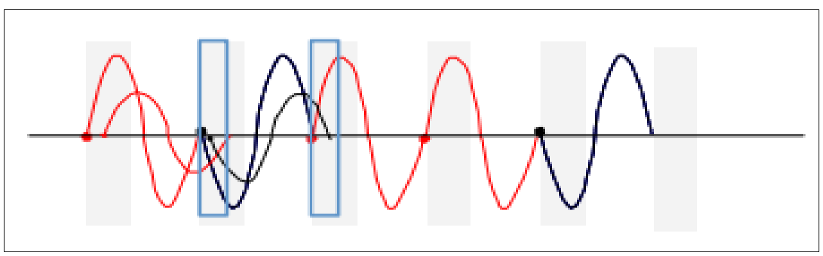


Figure 3-9: Inter Symbol Interference

To counter the effect of Multipath fading a guard band can be introduced in OFDM as shown in Fig: 3-9.

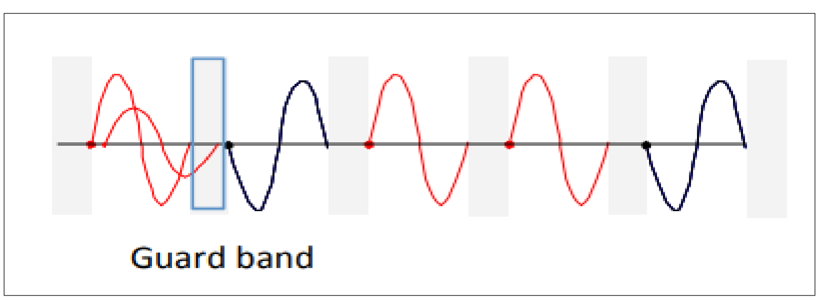


Figure 3-10: Guard Band

There are two problems in adding guard band to the symbols directly.

I. Empty signal cannot be sent as the transceiver's hardware structure do not allow it.

II. The exact delay spread is not known

To minimize the above two problems a copy of the symbol is replicated and added to OFDM symbol. In 802.11 standard CP is 1:4 of the original symbol.

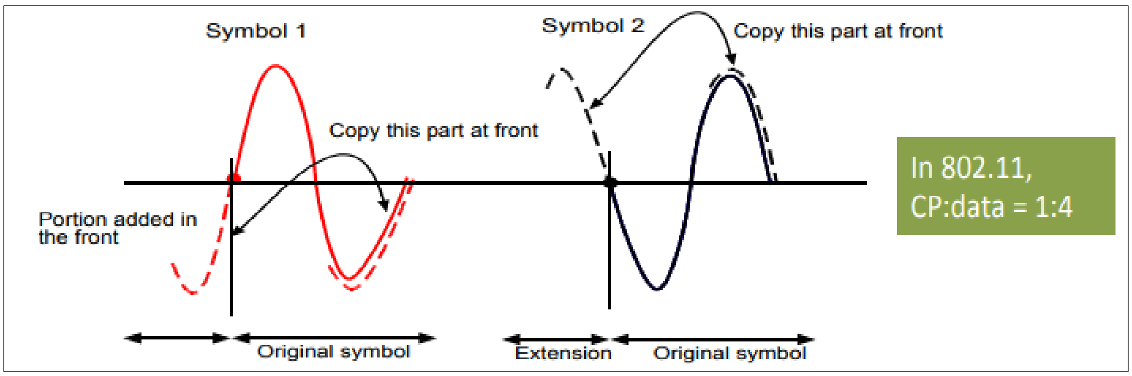


Figure 3-11: CP Addition

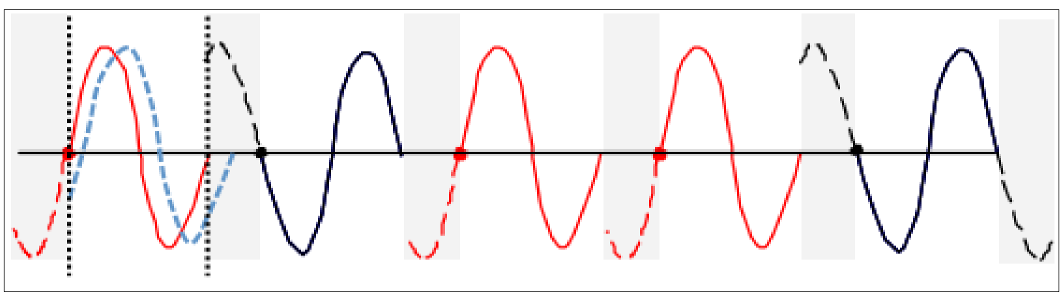
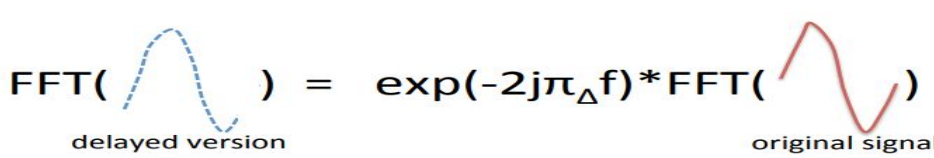


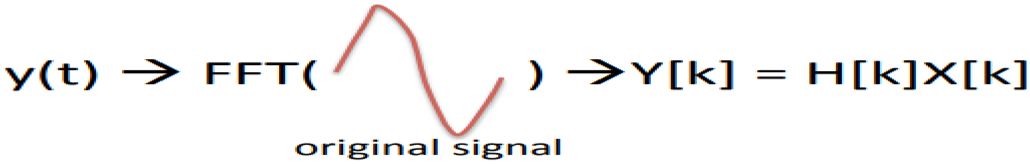
Figure 3-12: After CP Addition

The signal is periodic because of the usage of FFT, so we assume it as



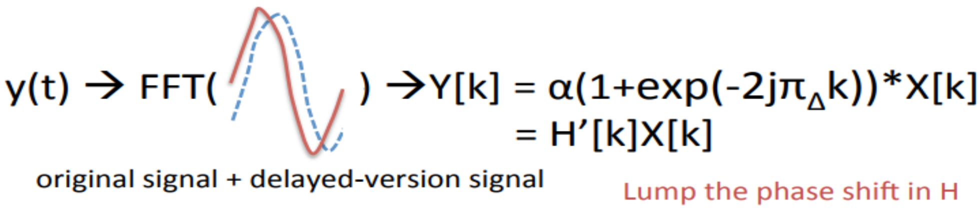
Equation 3-4

Delay in time division means rotation in frequency domain, so the correct signal is obtained by anti-rotation in frequency domain. Now without Multipath rotation is shown in Equation: 3-5



Equation 3-5

Equation: 3-6 shows the behavior without Multipath



Equation 3-6

Now, OFDM transmitter and receiver after adding CP is shown in Figure: 3-12

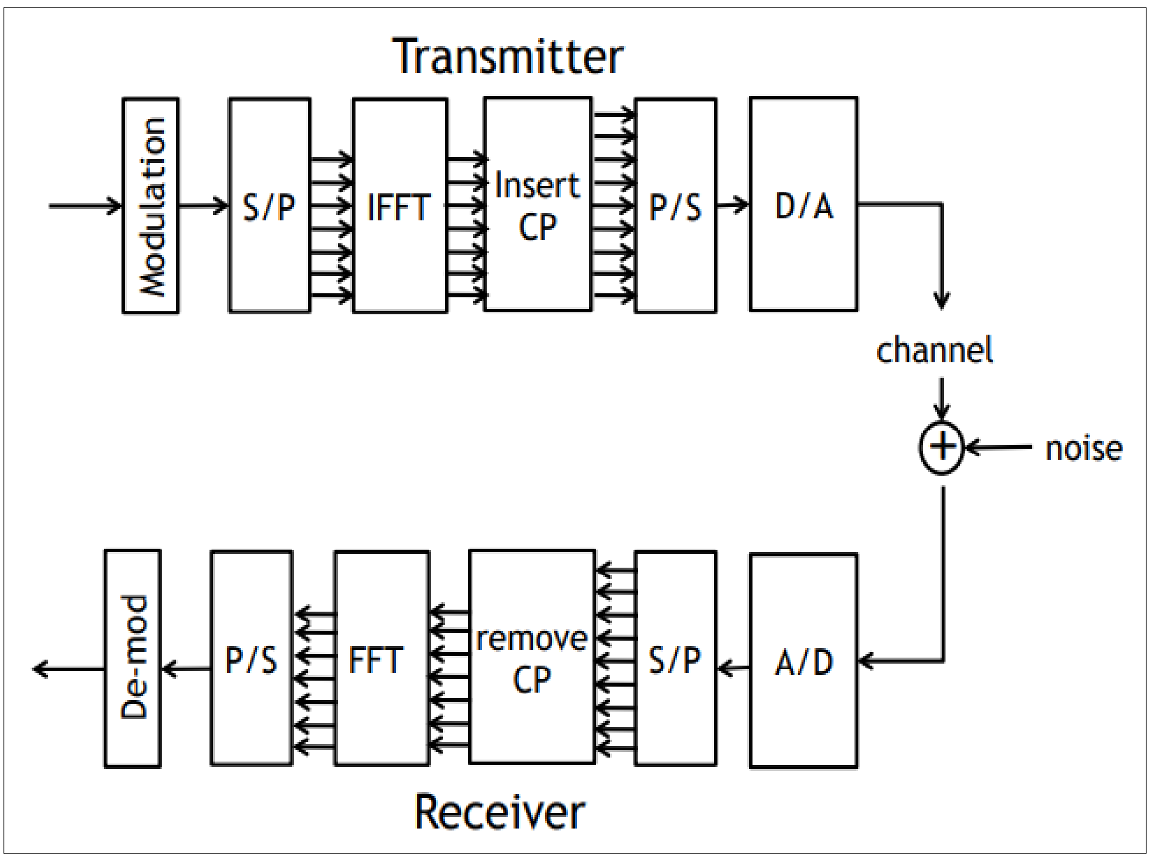


Figure 3-13: OFDM Tx and Rx after CP Addition

3.6.4 Advantages of OFDM

OFDM has several advantages over traditional waveforms.

3.6.4.1 Easy Implementation and Spectrum Efficiency

It has orthogonal subcarriers, which do not overlap at zero axis Fig 3-4. This increases the spectrum efficiency. With the addition of modules FFT and iFFT its implementation becomes easy.

3.6.4.2 Immunity Against Frequency Selective Fading

OFDM is more immune to frequency selective fading [19]. The subcarriers are divided into narrow bands due to which frequency selective fading effect some of the sub-carriers not the whole data symbol Figure: 3-14.

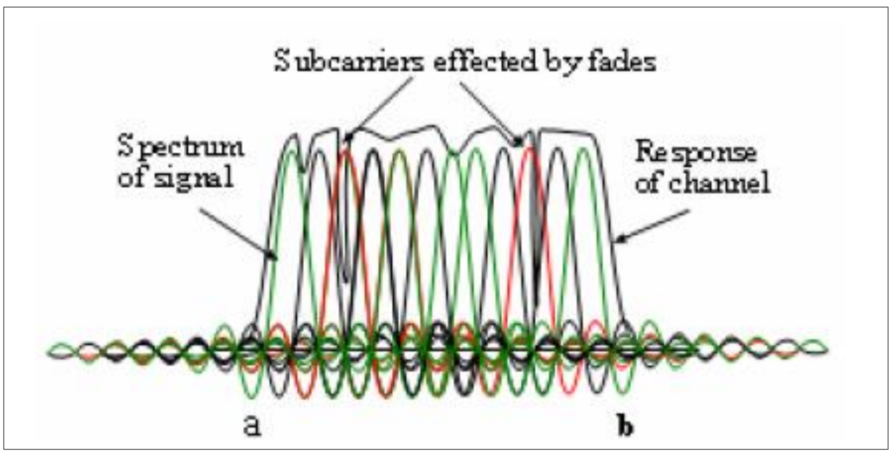


Figure 3-14: OFDM Response to Frequency Selective fading

3.6.4.3 Reduced Multipath Fading Effects

Due to addition of Cyclic prefix (CP), multipath fading is greatly reduced Figure: 3-12.

3.6.4.4 Easy Equalization at Receiver

The addition of FFT and IFFT modules have made easy to receive the signals and demodulate them at receiver Figure: 3-13, in case of CDMA it was difficult to equalize the channel response.

3.6.5 Disadvantages of OFDM

Disadvantages of OFDM includes Inter-Carrier Interference (ICI), Peak to average power ratio (PAPR) and higher out of band emission (OOB).

3.6.5.1 Sensitivity to Carrier Offset

A small frequency offset results in Inter-carrier Interference (ICI). Single carrier systems are less sensitive to frequency and drift offsets.

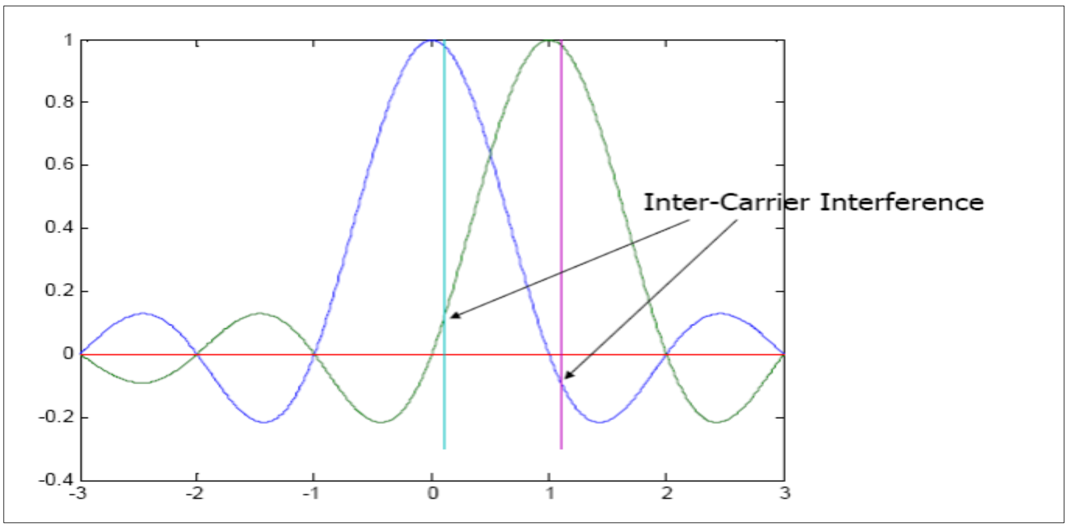


Figure 3-15: ICI in OFDM

3.6.5.2 Peak to Average Power Ratio (PAPR)

PAPR is the ratio of the maximum power of the transmission system to the average power [20] Equation: 3-7. The amplifier of the OFDM must behave in the linear regions in order to avoid saturation. The output of the iFFT at the transmitter becomes uneven and maximum power remains with some of the subcarrier instead of being uniform.

$$PAPR = \frac{\max|x(t)|^2}{E\left[|x(t)|^2\right]}$$ *Equation 3-7*

To compensate the effects of PAPR many techniques have been introduce which include clipping, windowing, interleaving and block coding techniques [21] [22].

3.6.5.3 Out of Band Radiation (OOB)

The side lobes of the sub carriers after modulation in OFDM have very high side lobes in case of OFDM [23]. Out of band is the data transferred outside the main lobe Figure: 5-3.

3.6.5.4 Reduced Spectrum Efficiency due to CP

Cyclic prefix is added at the cost of bandwidth, although its addition reduces multipath fading but it also adds to reduced spectrum efficiency.

3.7 Time to Redesign the Multiple Access Scheme

Considering the above all disadvantages of OFDM and maintaining a list of the 5G demands and key drivers from Chapter 2 , it makes the world think about the redesign of the multiple access scheme which ensures spectrum efficiency, higher data rates, low latency and also to be able to meet the demands for the IoT’s and MTC. Several new modulation schemes as well as customized OFDM solutions are being studied and are still under research by the research and development community of telecommunication.

The new waveform contenders for 5G physical layer include Filter bank multi carrier system (FBMC), Universal filter bank multi carrier system (UFMC), Generalized frequency division multiple access (GFDM) and Single carrier Orthogonal frequency division multiplexing (SC-OFDM) [24].

Filter bank multicarrier applies the filter property to every subcarrier before it is transmitted; this reduces the out of band radiation to several folds. Universal filter bank multicarrier applies the filter properties to the whole symbol after being modulated and added [25] while in generalized filter multiple access (GFDM) a tail biting technique for CP is added [26]. All these techniques contribute to low PAPR as compared to OFDM.

3.8 Conclusion of Chapter

In this chapter, multicarrier modulation techniques from 1G to 4G are cited with details, and their pros and cons are discussed. Furthermore, OFDM is studied thoroughly and cited. Its advantages and disadvantages are stated. In the end, new waveform contenders by the telecommunication research community are listed and touched upon. This chapter conclude with the fact that a new waveform is required to meet the demands of the 5G technology and to compensate the disadvantages of OFDM.

Chapter 4

4 FILTER BANK MULTICARRIER MODULATION

Filter bank multi carrier is proposed by Salzburg, which provide a better wave shaping of subcarriers as compared to OFDM. In filter bank multicarrier waveform equalization is easy and without cyclic prefix therefore a loose synchronization is ensured which leads to time efficiency in accordance with 5G device requirements [27].

In this chapter FBMC is covered in detail, its transceivers structure, modulation and implementation method is also cited. Moreover, the theory behind the filter banks is covered along with mathematical proofs.

4.1 Implementing FFT on Multi Carrier Systems

Fast Fourier transform was applied on multi carrier systems, but its limitation does exist. It leaks Spectrum. To avoid spectrum leakage time window is extended in which the symbols overlap with each other. The extension is solely done based on Nyquist criteria. Sampling theorem is a tunnel between the analogue and digital signals, it makes sure that no information is lost during the conversion process of signals.

Polyphase filter bank multi carrier is just a way to produce the same results using less computation. When we combine OQAM with Filter bank multicarrier, maximum bit rate is achieved without the need of a cyclic prefix, which is required in OFDM modulation. All the distortions either phase, frequency or time are handles at sub channel level in FBMC [28].

Since FBMC Is a modification of OFDM, both can exist side by side after initial synchronization, moreover FBMC can be used in cognitive radios

4.2 Fast Fourier Transform

Inverse fast Fourier transform is applied at the input to generate orthogonal subcarriers and the reverse of it is applied for demodulating the signal. M is the size of Inverse fast Fourier transform and fast Fourier transform. Di (mM) is the input to the modulator and (m+1) M is the output of Fast Fourier Transform.

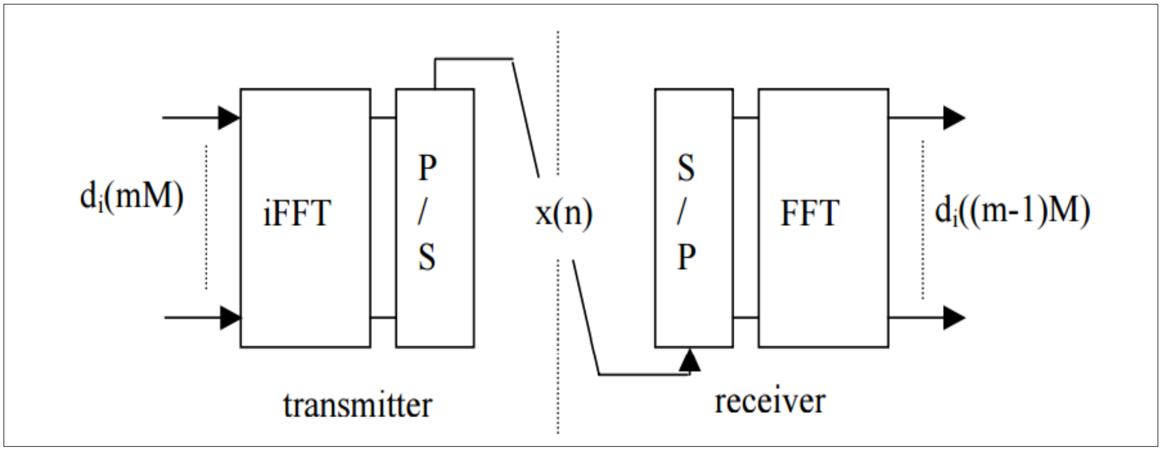


Figure 4-1: FFT Transmitter and Receiver

A parallel to serial converter is present at the modulator and serial to parallel at the Demodulator. The sampling frequency is, it shows that the two symbols do not overlap each other.

$$x(n) = \sum_{i=0}^{M-1} d_i(mM) e^{j2\pi \frac{i(n-mM)}{M}} \qquad \text{Equation 4-1}$$

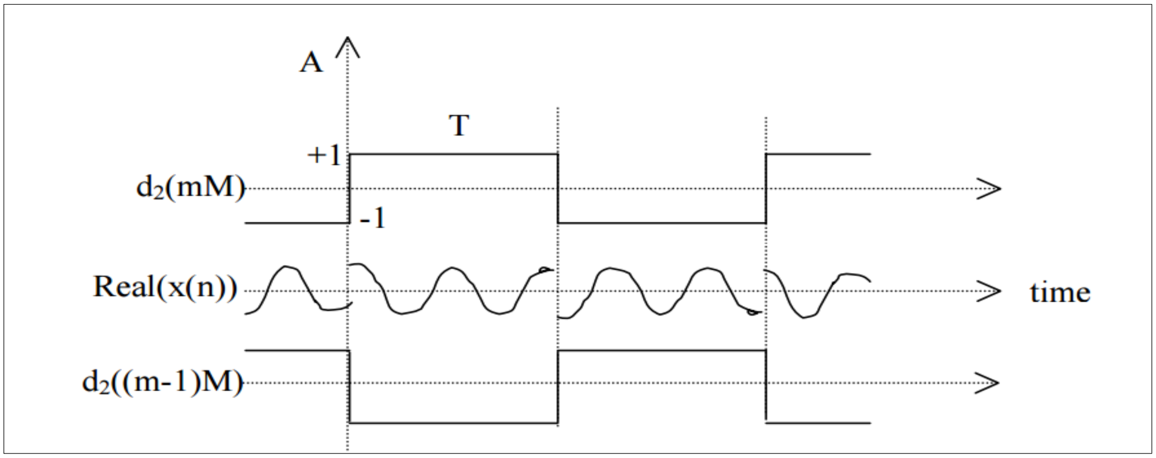


Figure 4-2: Data and Respected Transmitted Signal

Consider the figure above now, sine wave is being transmitted in the duration of T d2 (mM) is the input and d2 (m-1) M is the receiver signals, clearly it can be seen that orthogonally is the only condition for recovering data. The data is recovered by the following equations.

$$d_i(mM) = \frac{1}{M} \sum_{n=mM}^{mM+M-1} x(n) e^{-j2\pi \frac{i(n-mM)}{M}} \qquad \text{Equation 4-2}$$

We can notice the act that due to the presence of serial to parallel and parallel to serial there is a delay of one symbol.

Therefore, for the proper functioning of a system we need some extra modification otherwise demodulating the signal would not produce any significant results. Moreover, in the situation when we do have multi path channel propagation, this will go even worst. Therefore, to cater the effect we have two ways to go

I. OFDM in which we have a guard band and we extend the time periods of a symbol and demodulate with the same fast Fourier transform

II. If we do not want to extend our symbol duration, keep the symbol time constant and do some modifications to the fast Fourier transform block, this technique is called filter bank multi carrier technique FBMC

4.3 Fast Fourier Transform as a Filter

Considering the input of the figure one and output, we can relate them mathematically as

$$y_0(n) = \frac{1}{M}[x(n-M)+....+x(n-1)] = \frac{1}{M}\sum_{i=1}^{M} x(n-i)$$ *Equation 4-3*

This is a low pass filter equation with M co-efficient.

$$I(f) = \frac{\sin \pi fM}{M \sin \pi f}$$ *Equation 4-4*

This is the plotted form of the above equation; the x-axis is scaled to 1/M

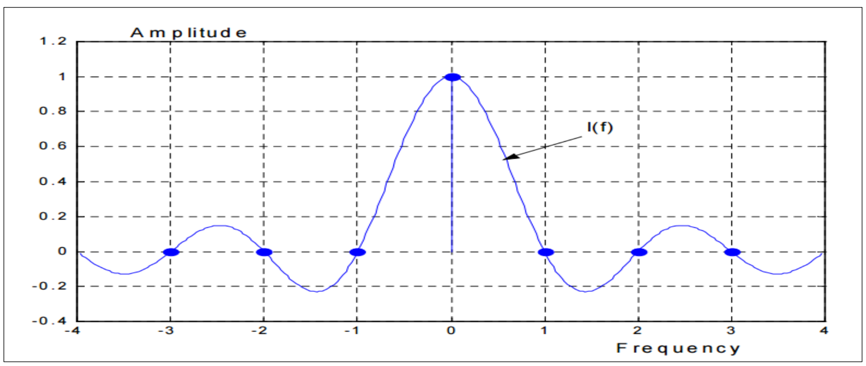


Figure 4-3: Frequency Response of Fast Fourier Transform

Similarly, the output is formulated by the following equation

$$y_k(n) = \frac{1}{M}\sum_{i=0}^{M-1} x(n-M+i)e^{-j2\pi ki/M}$$ *Equation 4-5*

Another expression is given in Equation: 4-7 when change i with M-i

$$y_k(n) = \frac{1}{M}\sum_{i=1}^{M} x(n-i)e^{j2\pi ki/M}$$ *Equation 4-6*

In the above expression, it can be seen that the co-efficient of filter are multiplied with an exponential term, with K/M as the frequency response. At the zero crossing's we can see the orthogonally

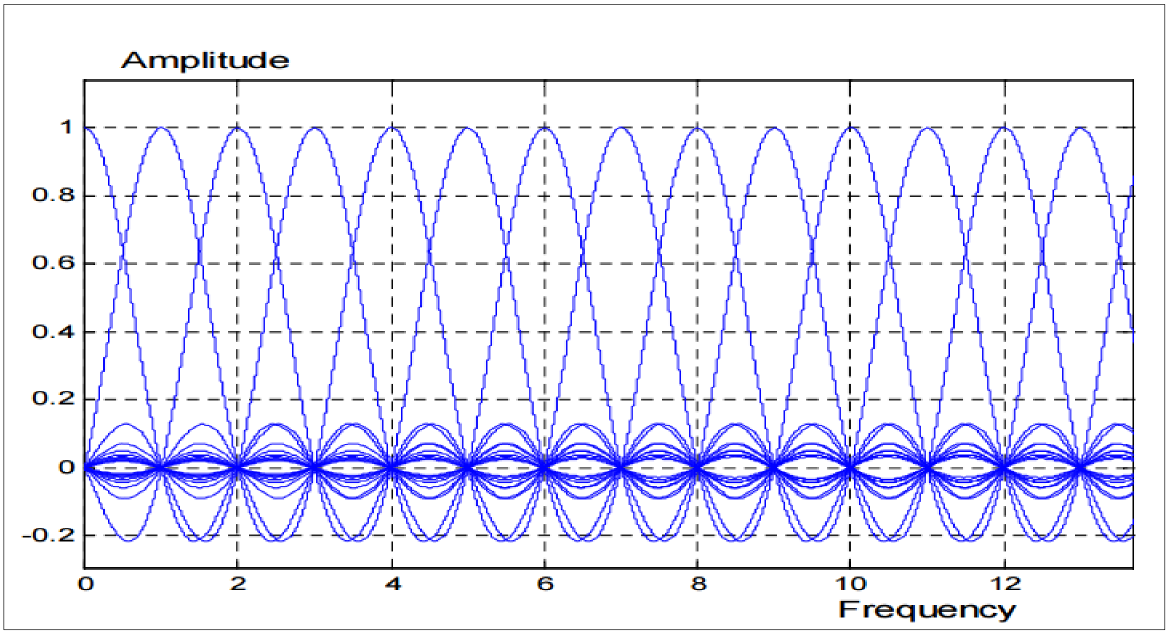


Figure 4-4: Filter Bank Fast Fourier Transform

We design filters based on the co-efficient in time domain or frequency domain, discrete fast Fourier transform relate these co-efficient. Single carrier impulse response is shown in figure 1. Now from the fundamental impulse response we will move to file bank multicarrier as concatenating these filters we will form a bank of filters.

In Fig: 4-4 we can clearly see the out of band response, we surely want to remove that out of band ripples. For this, we need to add extra co-efficient to our time domain as well as frequency domain. Time domain symbols will exceed the multicarrier symbol length and frequency domain symbols will add extra padding and control over the filter impulse response.

4.4 Prototype Filter Design with Overlapping Factor K

The prototype filter, which is also called as fundamental filter, is attributed by an overlapping factor K

$$K = \frac{\text{impulse response duration}}{\text{multicarrier symbol period } T}$$

Equation 4-7

Where K is an integer. Our target is the design a filter where no inter-symbol interference occurs.

4.4.1 Nyquist Criteria

Prototype filter is based on Nyquist criteria rule indicates a graphical condition in which no two symbol interferes and a system is maintained.

The impulse response crosses the zero axis at the integral times multiples of symbol period. In frequency domain it is being translated as the cut off frequency and it is ½ of the symbol rate if the signal. Now as per this we can form the fact that Nyquist filter meet the symmetric condition and a cut-off frequency is there so we half of it in the transmitter side and half of it in the receiver sides as per this criterion we can take the squares of the frequency to formulate our co-efficient. See the table below for the results.

Table 4-1: Prototype Filter co-efficient

K	H_0	H_1	H_2	H_3	σ^2 (dB)
2	1	$\sqrt{2}/2$	-	-	-35
3	1	0.911438	0.411438	-	-44
4	1	0.971960	$\sqrt{2}/2$	0.235147	-65

Filter response in frequency consist of 2K-1, and the continuation of which is obtained through the interpolation formula and the upcoming graph

$$H(f)=\sum_{k=-(K-1)}^{K-1} H_k \frac{\sin(\pi(f-\frac{k}{MK})MK)}{MK\sin(\pi(f-\frac{k}{MK}))}$$ *Equation 4-8*

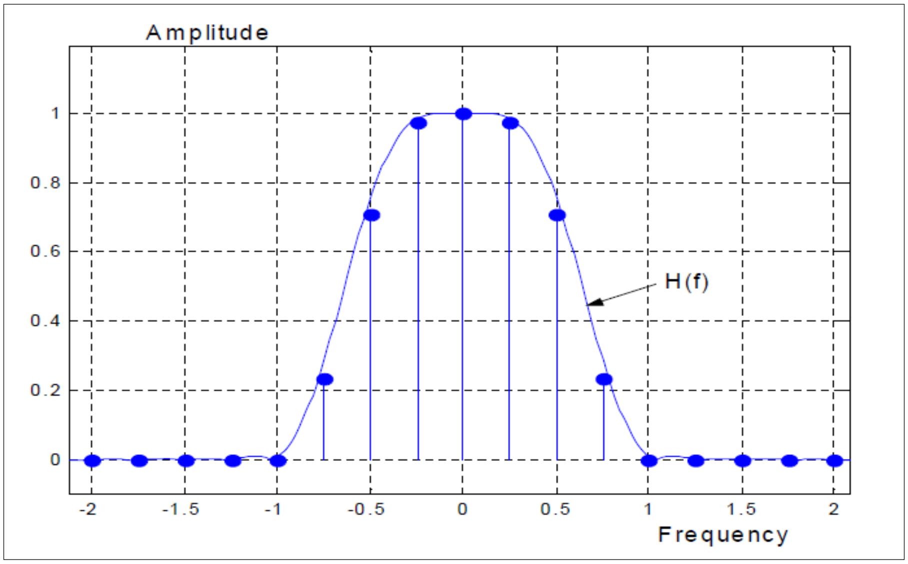


Figure 4-5: Prototype Filter with Frequency Response K=4

The IFFT shows the impulse response by the equation and graph

$$h(t)=1+2\sum_{k=1}^{K-1} H_k \cos(2\pi\frac{kt}{KT})$$ *Equation 4-9*

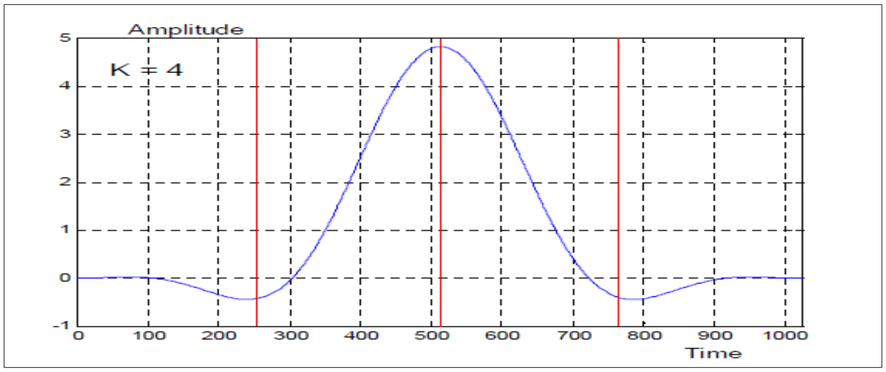


Figure 4-6: Impulse Response of the fundamental Filter for K=4

Now we want a bank of Polyphase filter so we want to concatenate it by giving frequency shifts in it K/M times the exponential term as discussed earlier too. Bank of filter can visualize below. The odd indexes do not overlap which is seen in the graph as well.

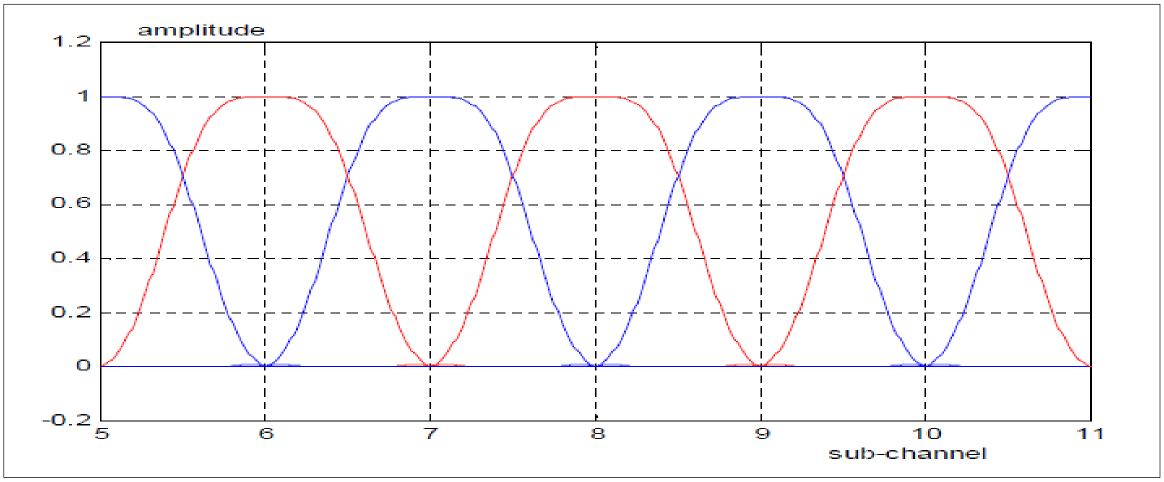


Figure 4-7: Bank of Polyphase Filters with K=4

4.5 Determination of Modulation Scheme

Now we have to determine the modulation scheme for Polyphase filter banks, for which the inter sub channel interference plays the key role. As shown in the immediate previous graph that overlap occurs when the transmitter filter and receiver filter at immediate neighboring frequencies. Now keep in mind the interpolation formula

$$G(f) = \sum_{k=1}^{3} G_k \frac{\sin(\pi(f - \frac{k}{MK})MK)}{MK \sin(\pi(f - \frac{k}{MK}))}$$ *Equation 4-10*

The coefficients of the interference filter are

$$G_k = H_k H_{K-k} \quad ; \quad k = 1, \ldots\ldots, K-1$$ *Equation 4-11*

The frequency response of the sub channel filter and interference filter is shown below in figure below for K = 4

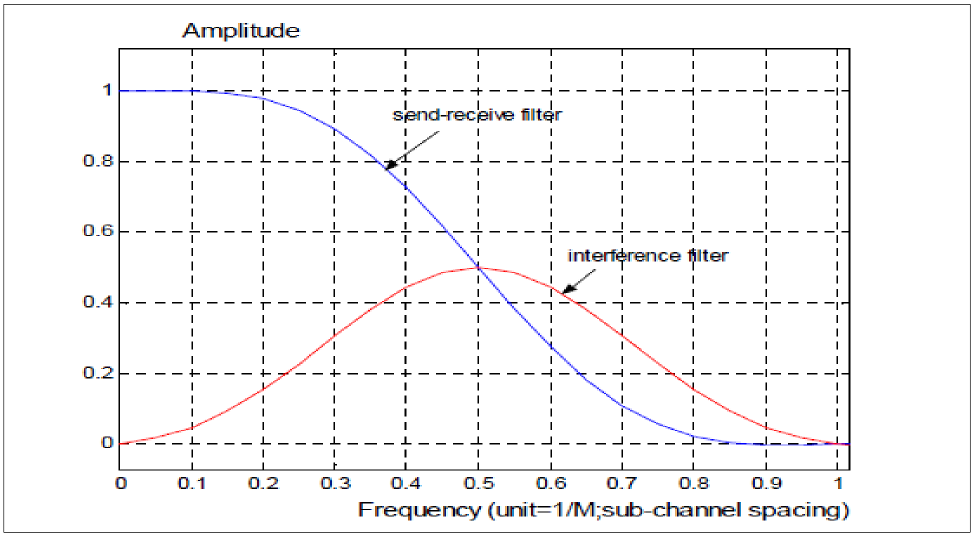


Figure 4-8: Frequency Response of the sub channel and interference Filters

The time domain representation of the above graph is shown by the equation below

$$g(t) = \left[\ G_2 + 2G_1 \cos(2\pi \frac{t}{KT})\ \right]\ e^{j2\pi \frac{t}{2T}} \qquad \text{Equation 4-12}$$

This is a very critical result to mitigate interface, the symmetry is already shown and the latter part of the equation also represents it, and due to this factor, the imaginary part of g (t) crosses the zero axis at the integral multiple of symbol period T and the real part at odd multiples of T/2. This makes us to consider OQAM modulation into consideration.

4.5.1 OQAM Modulation

OQAM is Offset quadrature amplitude modulation. It modulates information signal with the two carrier signals, which are 90 degrees apart, thus maintaining orthogonally. By 90 degrees out of phase carriers, it is highly compatible with orthogonal frequency division multiplexing. In digital/quantized environment, the digits are usually placed in a square grid.

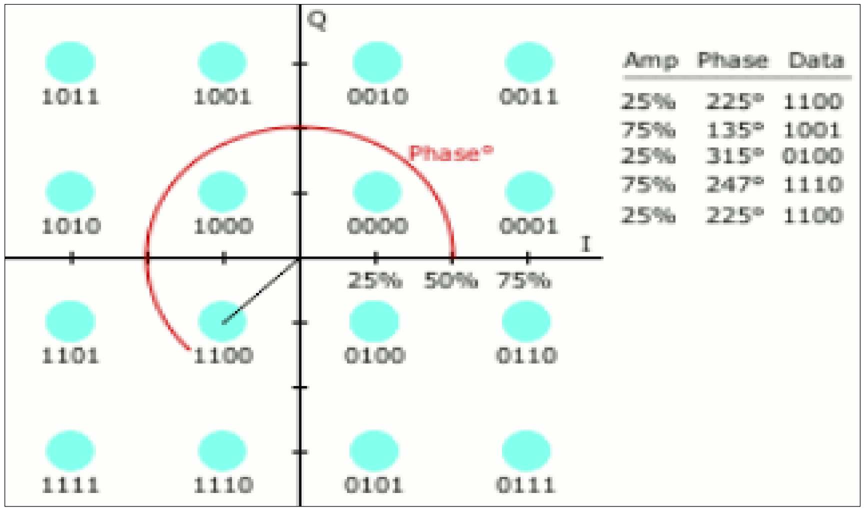


Figure 4-9: Digital QAM

OQAM the symbols are 45 degrees apart [29], while QAM is least resistive to frequency offset by the transmission OQAM does the part and therefore is compatible with the coded OFDM signals, and pulse shaping is relatively more close to OFDM in case of OQAM unlike QAM, though both ensures orthogonally.

In the figure it is shown that QAM constellation real and imaginary data takes the same place, while in OQAM they are 45 degree apart, this is compatible with our filter bank results a derived in the previous section we have made a strong conclusion that OQAM modulation is suitable in case of FBMC. The diversity in OQAM ensures high data rates as well.

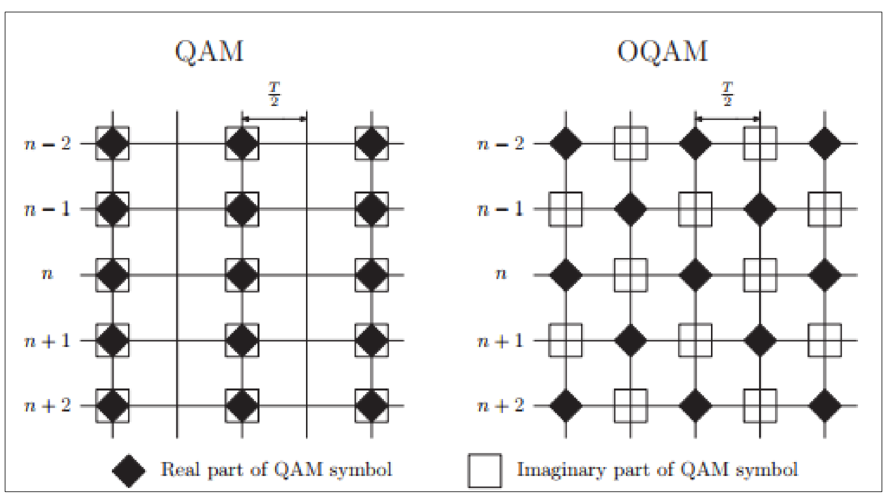


Figure 4-10: QAM and OQAM Constellation

4.6 Final Design Equation

After taking into account all our discussion, we have reached the conclusion that this equation is the final equation of the system.

$$h_2(t) = 1 + 2\sum_{k=1}^{K-1} H_k^2 \cos(2\pi \frac{kt}{KT})$$

Equation 4-13:

Final Equation in time domain

$$H_2(f) = \sum_{k=-(K-1)}^{K-1} H_k^2 \frac{\sin(\pi(f - \frac{k}{MK})MK)}{MK \sin(\pi(f - \frac{k}{MK}))}$$

Equation 4-14:

Final Equation in frequency domain

A crucial parameter would be background noise, it is because outside the neighboring sub channels there is non-Orthogonality, this is mentioned in Table 2-1. This is important because it affects the loading of system and the spectrum sensing capability.

4.7 Extension of Fast Fourier Transform to Filter Banks

As we have formulated our design and now, we are moving to modify our transmitter and receiver designs accordingly.

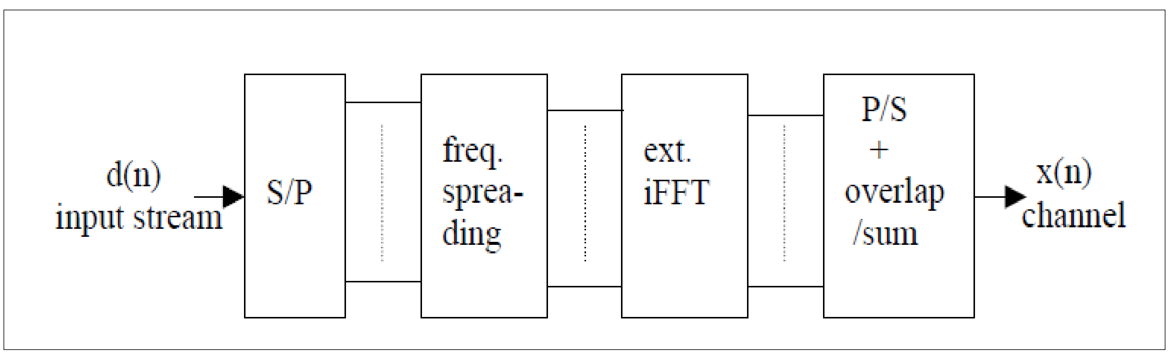


Figure 4-11: Modified Transmitter for Filter Bank Multicarrier

1) In this particular TX we have d(n) as input digital data stream
2) Serial to parallel converted received in a time domain to process multiple data elements simultaneously

3) Frequency spreading to spread the time domain data into frequency domain in order to further process by iFFT
4) An iFFT block to generate carrier, its size is KM, when a data inputs at iFFT block its multiplied by the filter frequency coefficients
5) It's actually a multiplication and summation operation, to be transmitted at the channel

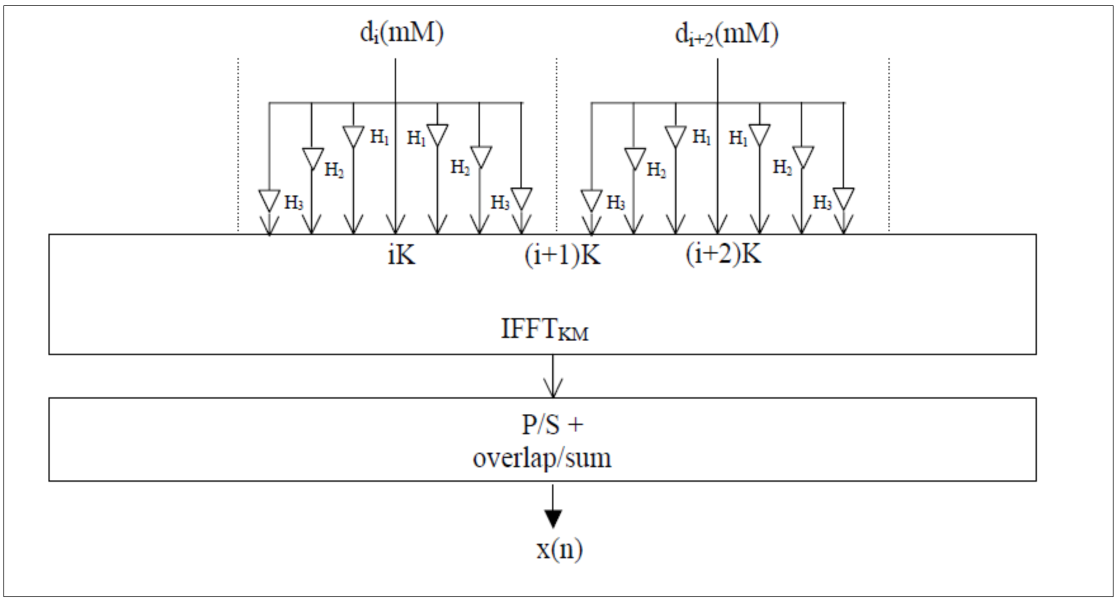


Figure 4-12: Extended iFFT TX Representation

It is clear that I and i+2 do not overlap each other while 1+1 does overlap. We can now apply our previous theory here that use real part of iFFT for i and imaginary part of iFFT for i+1.

TX and RX are connected back to back, so the latency in the system is KM symbols transmitted. As compared to original FFT, modulator and demodulator figure, it is cleared that it has more blocks KM as compared to or original FFT blocks, which were M only, so to reduce this extra redundancy we can move to a bank of filters which will be filter bank multi carrier.

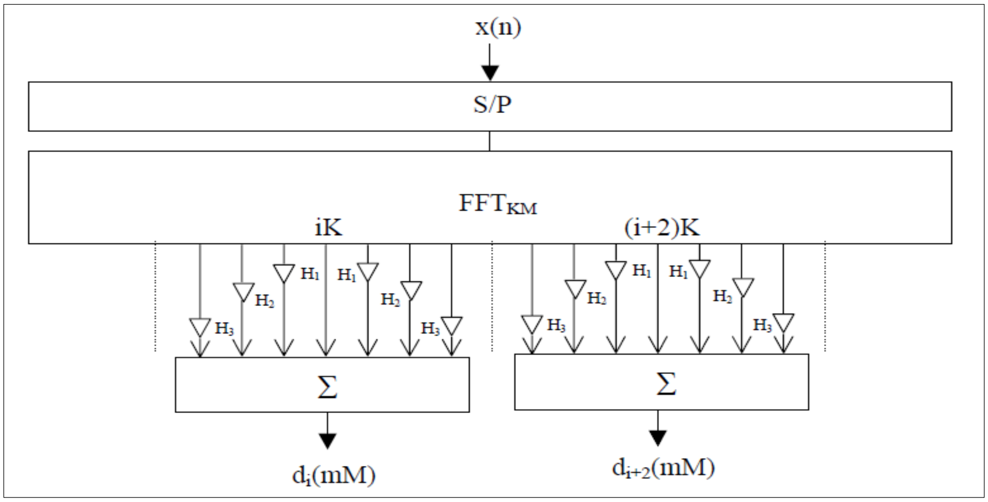


Figure 4-13: Extended iFFT Rx Representation

4.8 Polyphase Filter Networks (PPN-FFT)

Until now we have seen the filter design in frequency domains, now assume that in time domain and move further, it will be clear that size of the filter can be kept to M instead of KM a with some processing added to it called as poly phase filter bank.

The given equation 2-14 is the time domain representation of the signal and it can be represented by the z transform in the later equation. It is within the unit circle

$$y(n) = \sum_{i=0}^{L-1} h_i x(n-i)$$ *Equation 4-15*

$$H(Z) = \sum_{i=0}^{L-1} h_i Z^{-i}$$ *Equation 4-16*

To remove the KM redundancy consider the z-transform as the following equation

$$H(Z) = \sum_{p=0}^{M-1} H_p(Z^M) Z^{-p}$$ *Equation 4-17*

We can formulate the fact that fundamental filter to bank of filter each filter has a frequency response of a shifter, so we can easily pursue t as Polyphase filter network assuming

$$H_p(Z^M) = \sum_{k=0}^{K-1} h_{kM+p} Z^{-kM}$$ *Equation 4-18*

frequency response to each filter. The final equation and the corresponding matrix obtained looks like

$$B_1(Z) = \sum_{p=0}^{M-1} e^{j\frac{2\pi}{M}p} Z^{-p} H_p(Z^M)$$ *Equation 4-19*

$$\begin{bmatrix} B_0(Z) \\ B_1(Z) \\ . \\ . \\ B_{M-1}(Z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & . & . & 1 \\ 1 & W^{-1} & . & . & W^{-M+1} \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & W^{-M+1} & . & . & W^{-(M-1)^2} \end{bmatrix} \begin{bmatrix} H_0(Z^M) \\ Z^{-1}H_1(Z^M) \\ . \\ . \\ Z^{-(M-1)}H_{M-1}(Z^M) \end{bmatrix}$$ *Equation 4-20*

In addition, the structure looks like the following

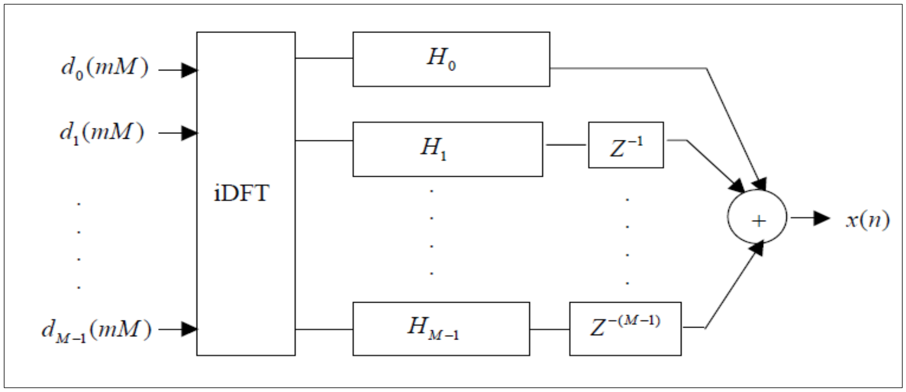


Figure 4-14: Filter Bank TX side PPN

Similarly the receiver ha the inverse of it, iFFT is replaced by DFT, -1/M is the frequency shift multiplier instead of 1/M. In block diagram it is shown by the following figure.

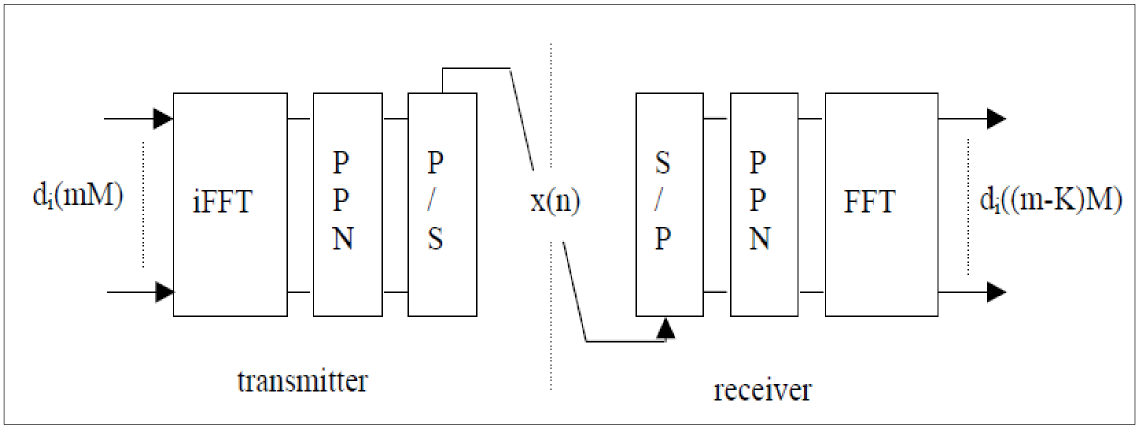


Figure 4-15: Transceivers Using PPN

Moreover, the following block diagram can represent the Polyphase filter structure

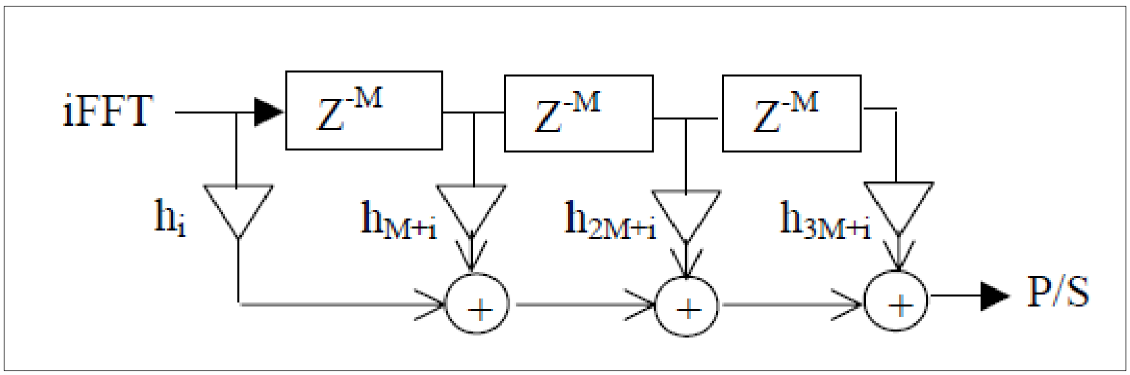


Figure 4-16: PPN Section Only

Until now, TX is generating a real signal, to enhance the data rate the iFFT needs to be doubled.

4.9 OQAM with PPN Network

As discussed earlier, we need to enhance the data rates and exploit the immediate sub channels we need OQAM modulation. Now we will see the OQAM modulation w.r.t to the PPN networks. Usually OQAM modulation I used in single carrier system to cater for the peak rates, here QAM and OQAM will produce the same data rates but OQAM will reduce the interference. Therefore, IFFT is run at double rate and two PPN structures are needed to cater for the OQAM modulation.

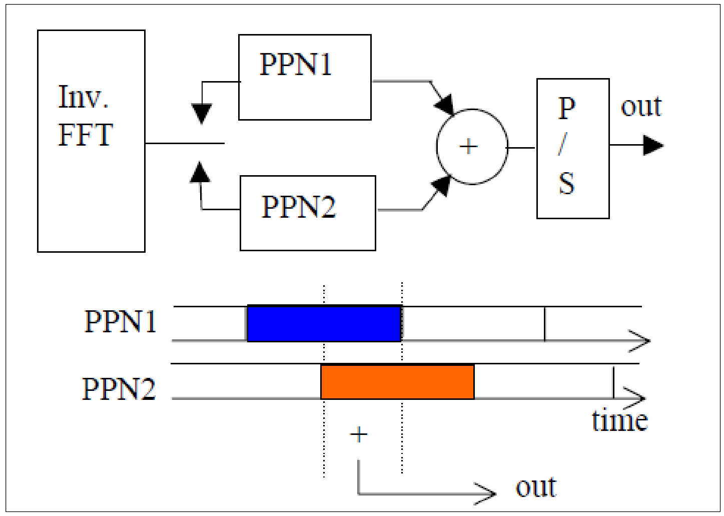


Figure 4-17: OQAM with PPN, TX

Chapter 5

5 UNIVERSAL FREQUENCY DIVISION MULTIPLEXING (UFMC)

This chapter covers the introduction of Universal Filter Bank Multicarrier waveform (UFMC), its transceiver structure along with equations.

5.1 Introduction to Universal Filter Bank Multicarrier (UFMC)

UFMC is another waveform contender for 5G physical Layer. In the previous chapter, FBMC was discussed. It was seen that filters are applied to each sub carrier in FBMC, while in UFMC filters are applied to each sub band; the difference can be seen in the figure.

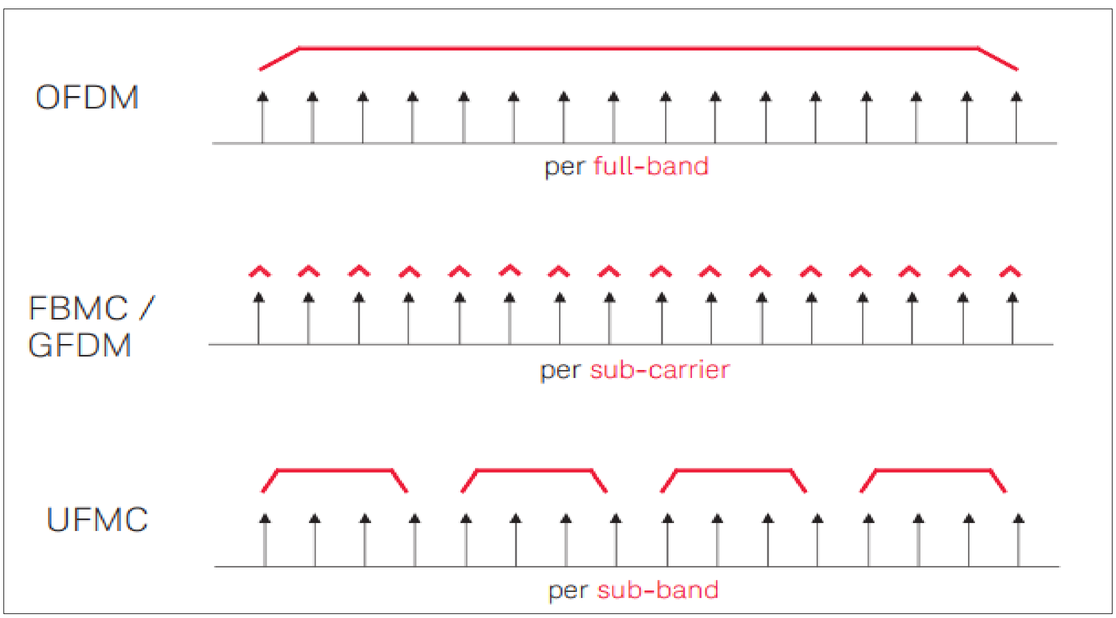


Figure 5-1: Different Filtering methods of OFDM, FBMC and UFMC.

Filtering sub band reduces the complexity in the transceiver design. UFMC is better than FBMC in case of short bursts transmission. UFMC combines the advantages of OFDM and FBMC and tries to discard the disadvantages of both of them.

5.2 UFMC Transceiver Structure

Consider the diagram below to visualize UFMC transmitter structure. Here the operation is performed in such a way that the symbols are generated and converted into parallel streams, blocks of data streams are made and pass through the iFFT block, the output of the iFFT is then converted from parallel to serial lines. A filter with length L is applied to the iFFT processed data streams; these processed data then passed through the base band modulator and converted into analogue for transmission.

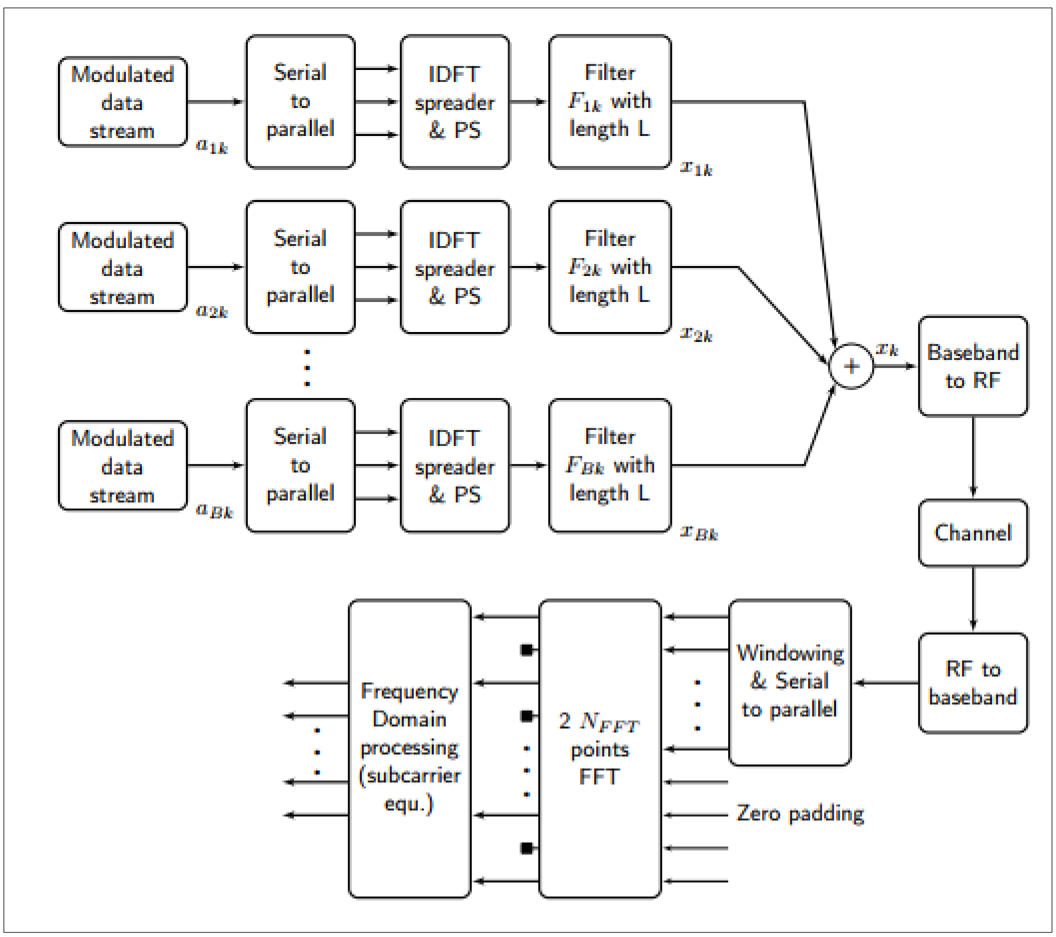


Figure 5-2: UFMC Transceiver

UFMC receiver structure performs exactly opposite of the transmitter side, analogue signals are converted into digital, then time domain windowing is done to remove interference, FFT operation is performed and de-mapping is carried out.

The length of UFM filter is dictated by the size of sub bands , the frequency response can be observed by the figure.

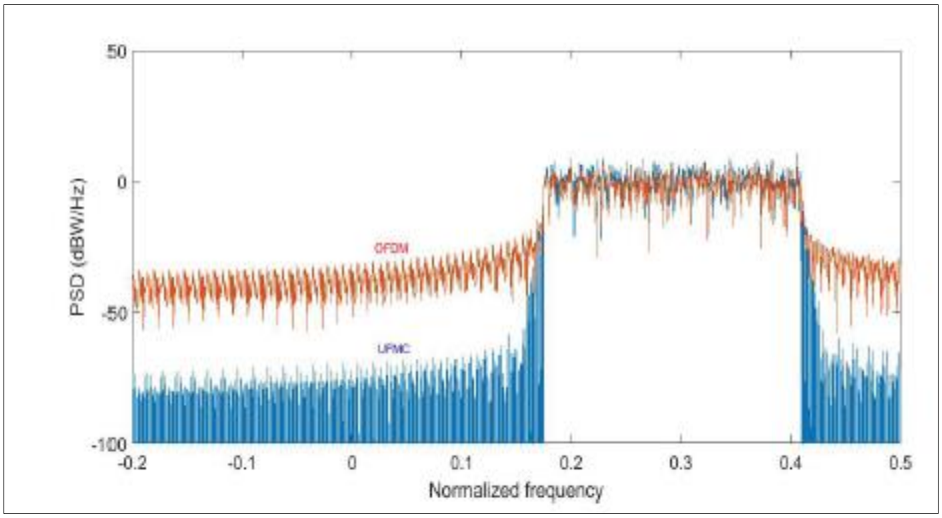


Figure 5-3: OFDM and UFMC frequency response

5.3 SER Analysis of UFMC and OFDM

Symbol Error Ratio (SER) analysis of UFMC and OFDM is shown in Figure 5-5, it is clear that UFMC performs a little better than OFDM in case of higher SER values. But the results show a drastic change when carrier frequency offset (CFO) is introduced [30].

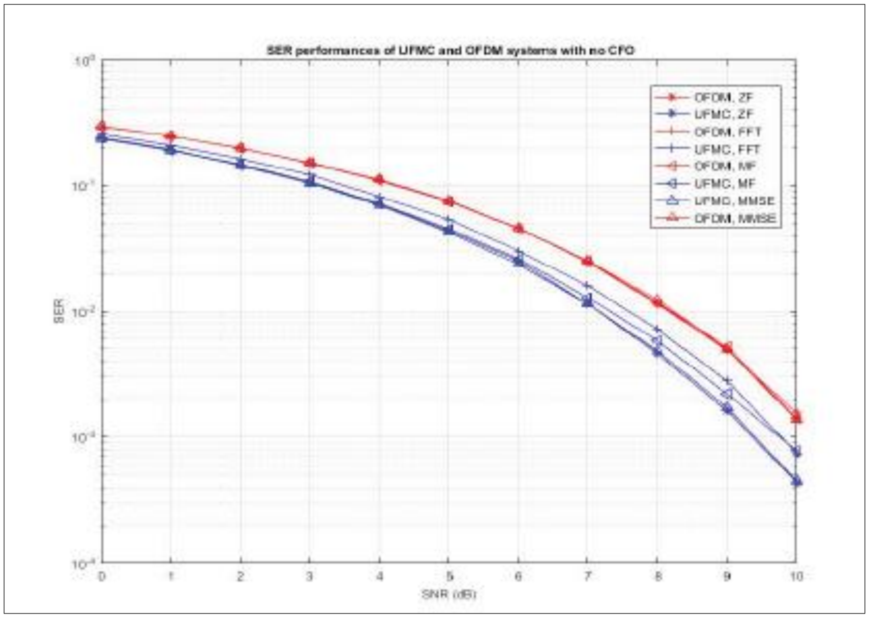


Figure 5-4: SER of UFMC and OFDM

When Carrier frequency offset is introduced, UFMC show less sensitivity to carrier frequency offset (CFO) then OFDM.

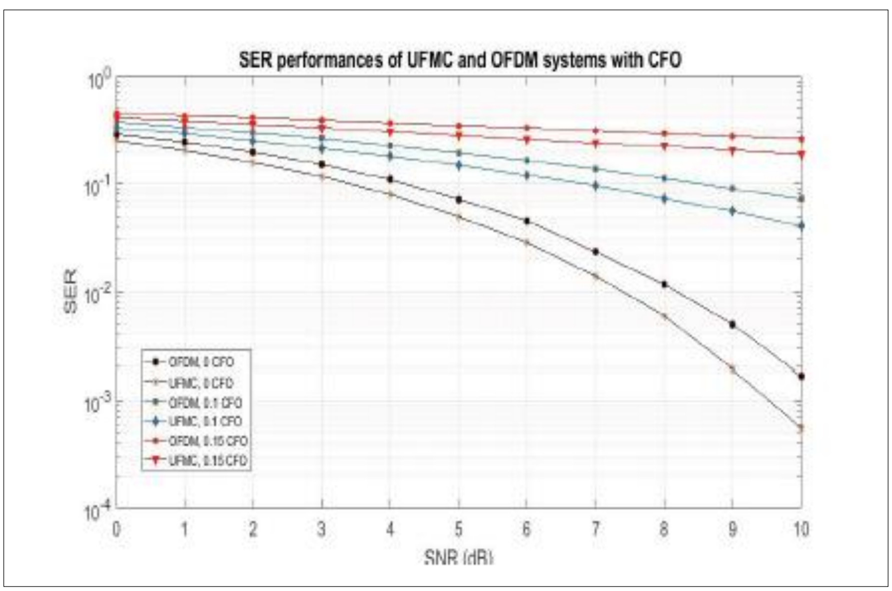


Figure 5-5: SER with CFO

5.4 PAPR of UFMC and OFDM

UFMC performs better than OFDM in case of filters, but on the other hand, UFMC also suffers from PAPR, because its linear region is very less to operate,

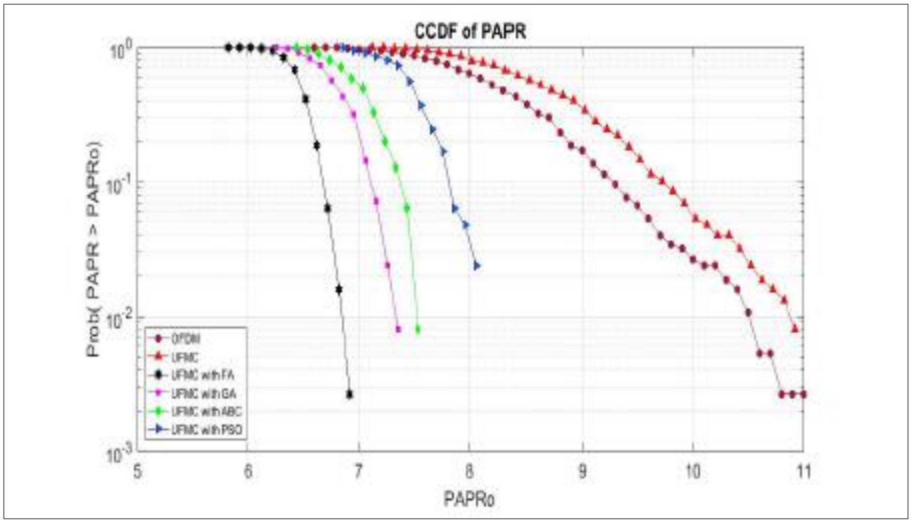


Figure 5-6: CCDF of PAPR, UFMC OFDM

Complementary cumulative distribution function shows the time a signal takes greater then the average power [31]. Ideally, PAPR is not the deciding factor for 5G physical Layer waveform selection, as PAPR can be reduced by other operations as well, windowing, and better filter co efficient implementation. Some of the techniques to reduce PAPR are listed in previous chapters too.

5.5 Conclusion of Chapter

UFMC is another potential waveform showing better results than OFDM in case of SER, PAPR can be reduced using better scrambling techniques.

Chapter 6

6 GENERAIZED FREQUENCY DIVISION MULTIPLEXING (GFDM)

This chapter covers the introduction and transceiver design of GFDM. Moreover, it compares the basic and operational differences of GFDM with OFDM. At the end, the chapter concludes with logical remarks.

6.1 Introduction to GFDM

GFDM is a potential waveform contender for 5G Physical Layer [1]. Its key strength is its flexibility. It modifies the already existing structure of OFDM to utilize the white spaces in the spectrum . GFDM uses spectrum fragmentation to utilize the spectrum efficiently. Some of the new techniques have been added to GFDM to help outperform OFDM such as CP tail biting, circular convolution, which are being discussed later on in this chapter.

6.1.1 GFDM Transmitter

The data is input to the transmitter, it is compressed and sub carrier modulation is done. Sub carrier is modulated using any form of QAM, 16QAM/64QAM. Data up sampling is done to visualize what the signal would suffer of data rate is increased. Then circular convolution is performed. Up conversion is done to shift the carrier frequency to Intermediate frequency so that receiver need not to be re tuned for the upcoming frequency and mixed channel response.

GFDM's one of the key features is the tail biting technique for cyclic prefix (CP), which increases the spectrum efficiency than OFDM [32]. Cyclic prefix (CP) is added to the block of sub carriers for easy equalization at the receiver. It uses the cyclic prefix (CP) per block for the synchronization.

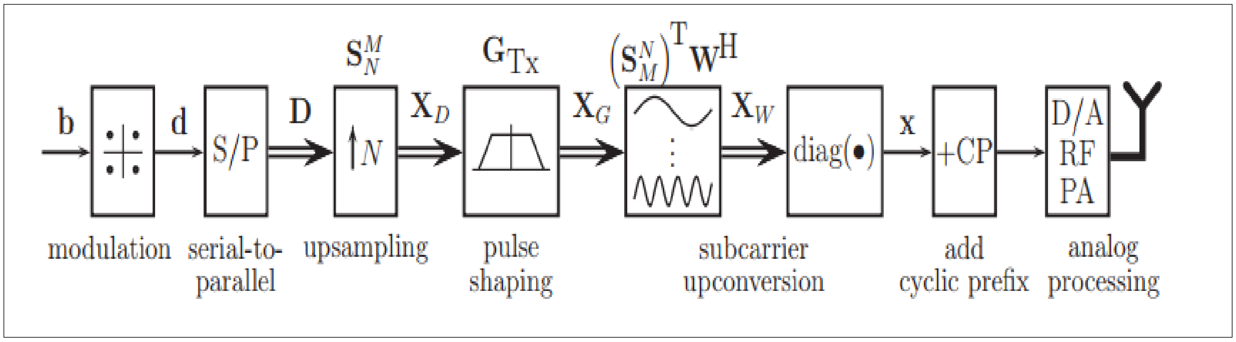


Figure 6-1: GFDM Transmitter

6.1.2 Circular Convolution in GFDM

When signal pass through some medium, medium gives some response to it, we perform convolution in order to check the response. Circular convolution is used instead of linear convolution when the signals are periodic.

Mandatory condition for circular convolution are

1. Periodicity in signals
2. Signals must be of same length

Periodic signals repeat themselves, periodic signals are infinite signals. Unlike linear convolution circular convolution, produce the results of the same length as that of input signals or period length of the signal. Circular convolution can be done in two ways, one in concentric circular method and other is matrix multiplication method. DFT based convolution is circular convolution, because of the periodicity involved in it. In case of DFT based convolution.

Circular convolution = Linear convolution + Aliasing

6.1.3 Up Sampling in GFDM

GFDM uses up sampling , then performs circular convolution, up sampling is performed to increase the time sampling of the signal, it is done to forecast how the signal if it has been up sampled at higher data rate.

6.1.4 GFDM Receiver

GFDM receiver is exactly opposite of the transmitter. Analogue to digital conversion is done, CP is removed, sub carrier down sampling is performed, circular convolution followed down sampling and parallel to derail conversion is done [33].

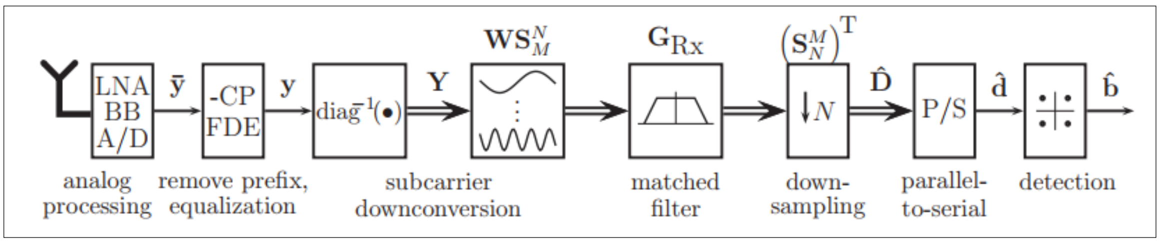


Figure 6-2: GFDM Receiver

Reception at the receiver may take different methods. Circular convolution at the receiver is compulsory for tail biting.

6.2 Supported Equations

Baseband is the real frequency of the data or signal, baseband signal is modulated. Serial to parallel conversion is done. Up sampling is followed by pulse shaping filter. Up conversion is applied to shift frequency to the Intermediate frequency in order to equalize on the receiver.

$$x[n] = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} d_{m,k} g_{\mathrm{Tx}}[n - mN] e^{j2\pi \frac{kn}{N}}, \qquad \textit{Equation 6-1}$$

Equation 6-1 shows the transmitted signal, after all the operation. It is the weighted and added sample after all the sub carriers are ready by the operations. Circular convolution is used as pulse shaping filter in order to aid tail-biting technique at the end.

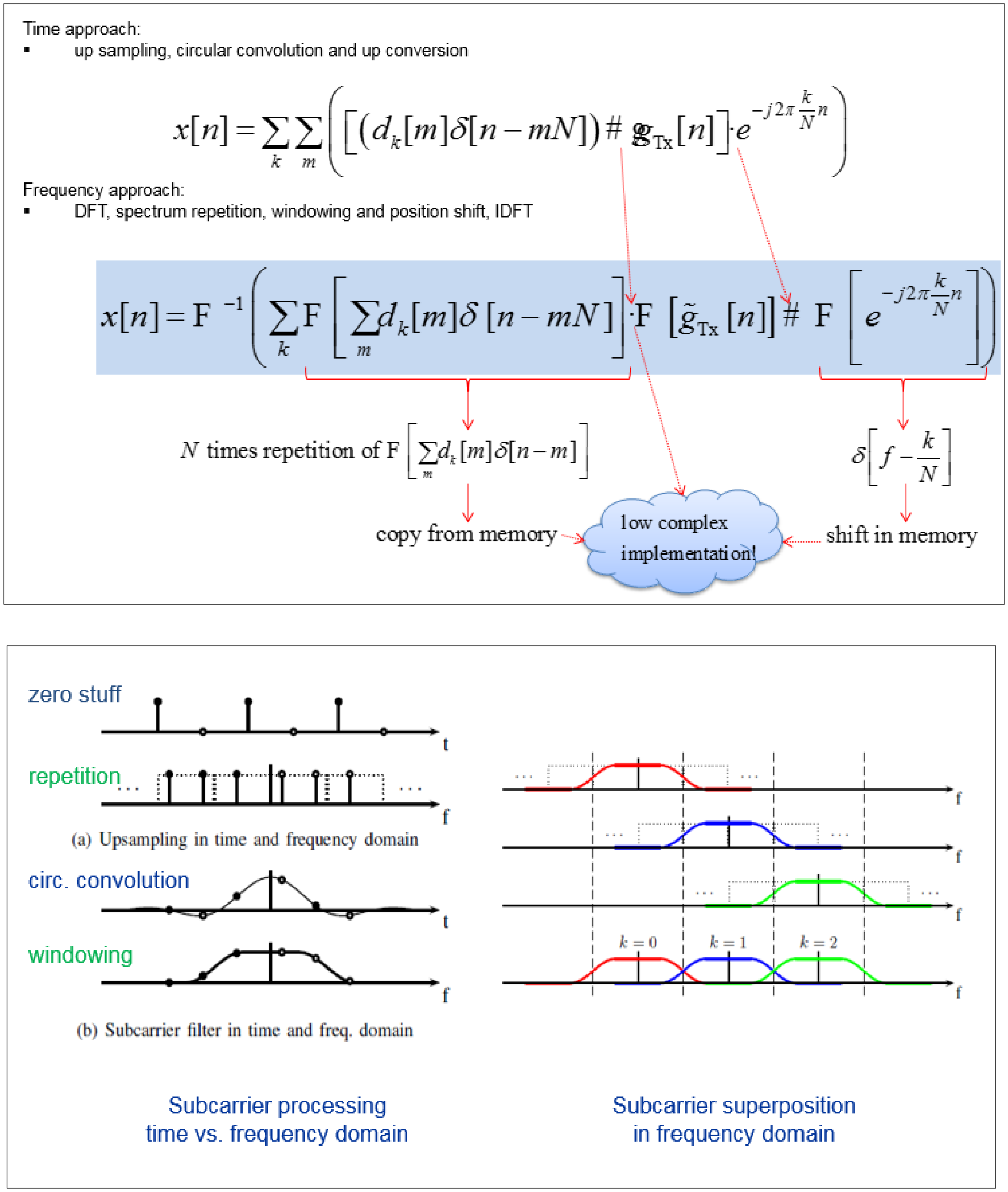
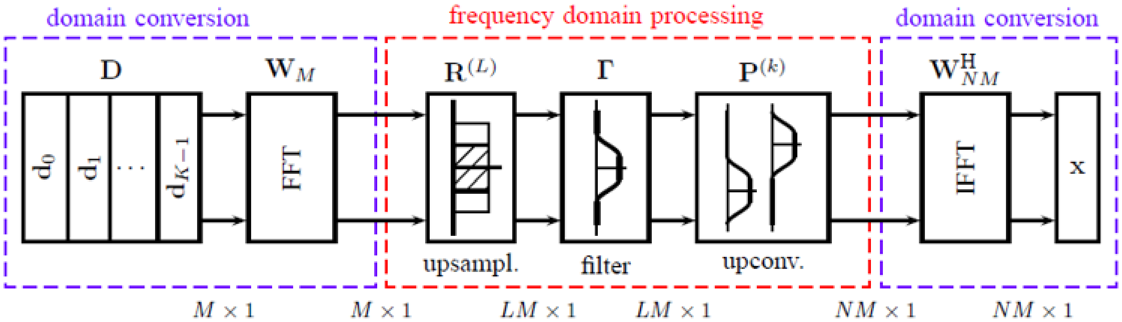


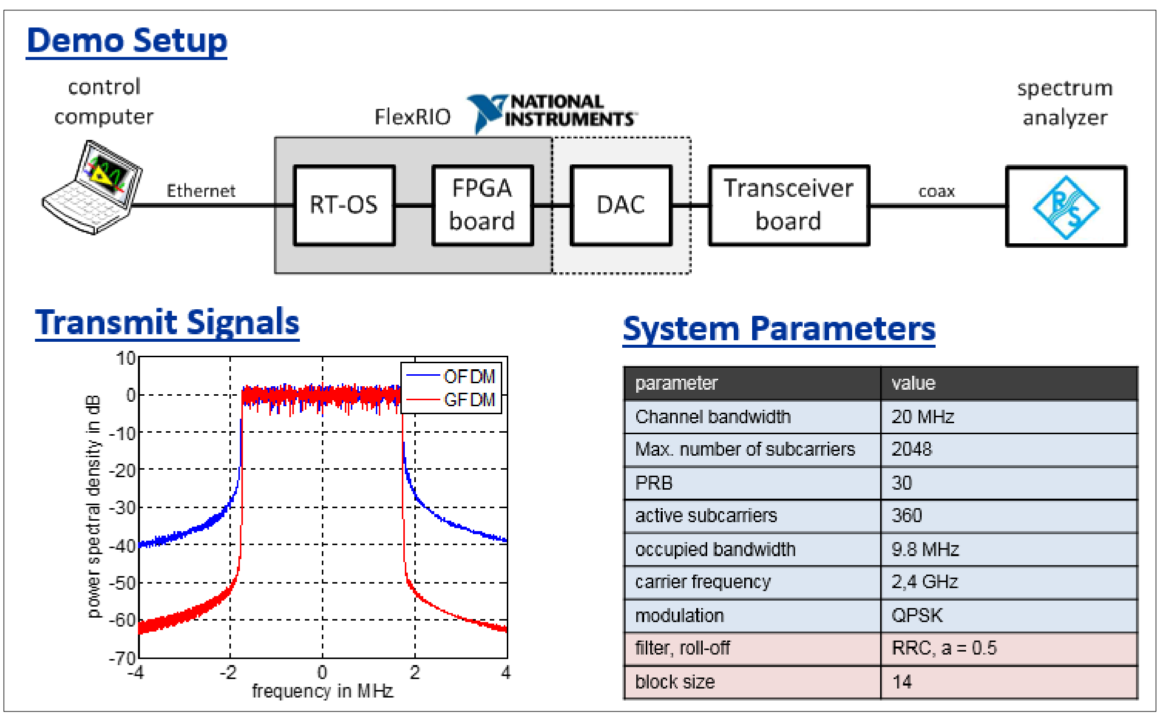
Figure 6-3: Sub Carrier Processing

$$\mathbf{x} = \mathbf{W}_{NM}^{\mathrm{H}} \sum_{k} \mathbf{P}^{(k)} \boldsymbol{\Gamma} \mathbf{R}^{(L)} \mathbf{W}_{M} \mathbf{d}_{k}$$



$$\begin{aligned} C_{\mathrm{GFDM,FFT}} &= KM \log_2 M + KLM + MN \log_2 MN \\ &= \underbrace{MN \log_2 N}_{\text{OFDM complexity}} + \underbrace{(K+N)M \log_2 M + KLM}_{\text{GFDM overhead}} \end{aligned}$$

6.3 Results in Literature Comparing OFDM and GFDM



parameter	value
Channel bandwidth	20 MHz
Max. number of subcarriers	2048
PRB	30
active subcarriers	360
occupied bandwidth	9.8 MHz
carrier frequency	2,4 GHz
modulation	QPSK
filter, roll-off	RRC, a = 0.5
block size	14

Figure 6-4: SystemVue Setup and PSD

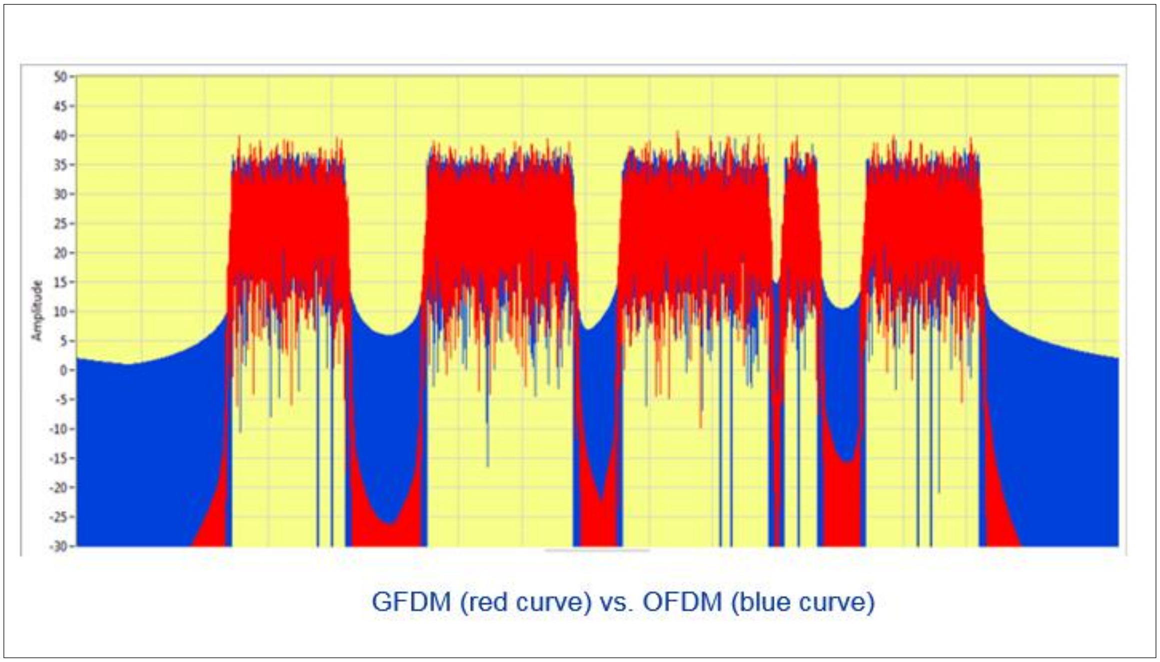


Figure 6-5: OOB GFDM and OFDM

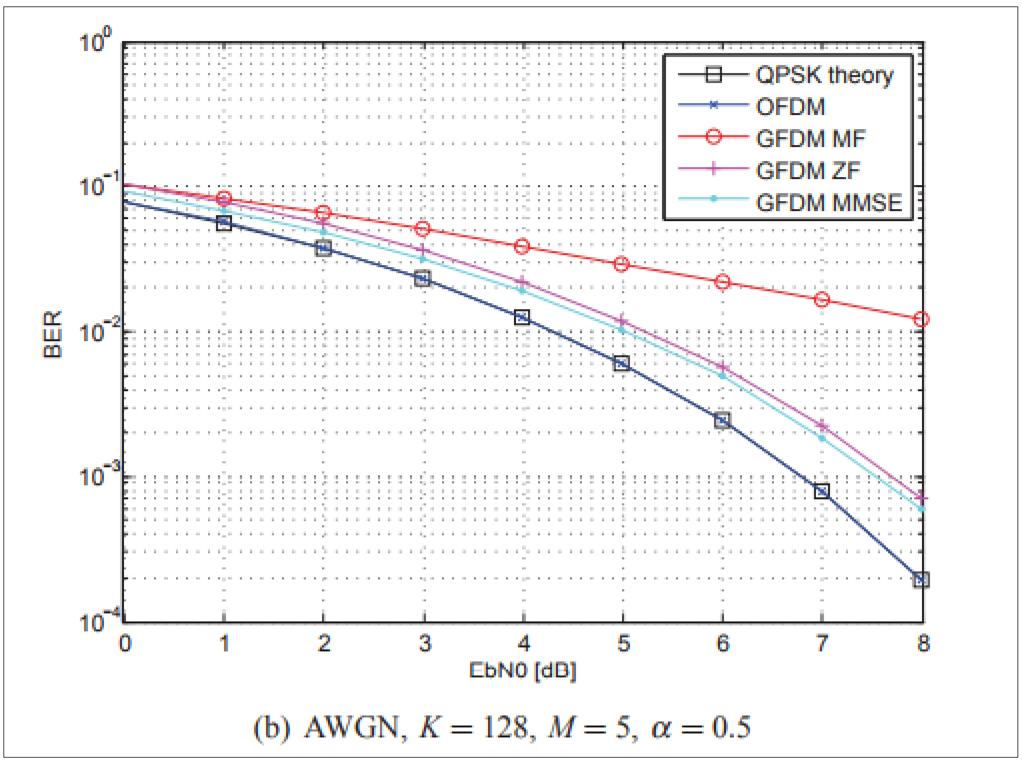


Figure 6-6: BER OFDM and GFDM

6.4 Conclusion of Chapter

Pulse shaped subcarriers can be achieved in GFDM at reasonable computational cost

Out of band radiation in GFDM can outperform OFDM by several orders of magnitude

Chapter 7

7 IMPLEMENTATION AND RESULTS

In this chapter OFDM and FBMC are implemented in SystemVue 2015.01 and MATLAB 2015. SystemVue and MATLAB are simulation softwares enriched in 4G and 5G communication libraries.

7.1 MATLAB Simulations

The Impulse response of the Prototype filter of FBMC and OFDM is implemented in MATLAB 2015. The results is in accordance with the literature discussed earlier.

7.1.1 Filters Comparison

OFDM and FBMC filters are simulated, both time domain and frequency domain. The coefficients values used for the PHYDAS filters are taken from Table 1 of FBMC: A Primer which is the fundamental document for FBMC Model [34]. For the filter comparison the parameter channel number, M is kept 24,(much lower than the coming simulations) to visualize the difference between the side lobes of the two filters, if M is taken the same as that in the next simulations the side lobes difference would not be clear. Figure 4 shows the OFDM window filter and FBMC PHYDAS filter in time domain. Figure 5 shows the comparison of filters in frequency domain, it is clear that side lobes of FBMC filter are much lower than OFDM filter.

Table 7-1: Parameters for Filter Comparison

Parameters	**OFDM**	**FBMC**
M	24	24
Modulation	QAM	OQAM
Modulation Order	64	64
Sub carriers	7	7
K	NA	4

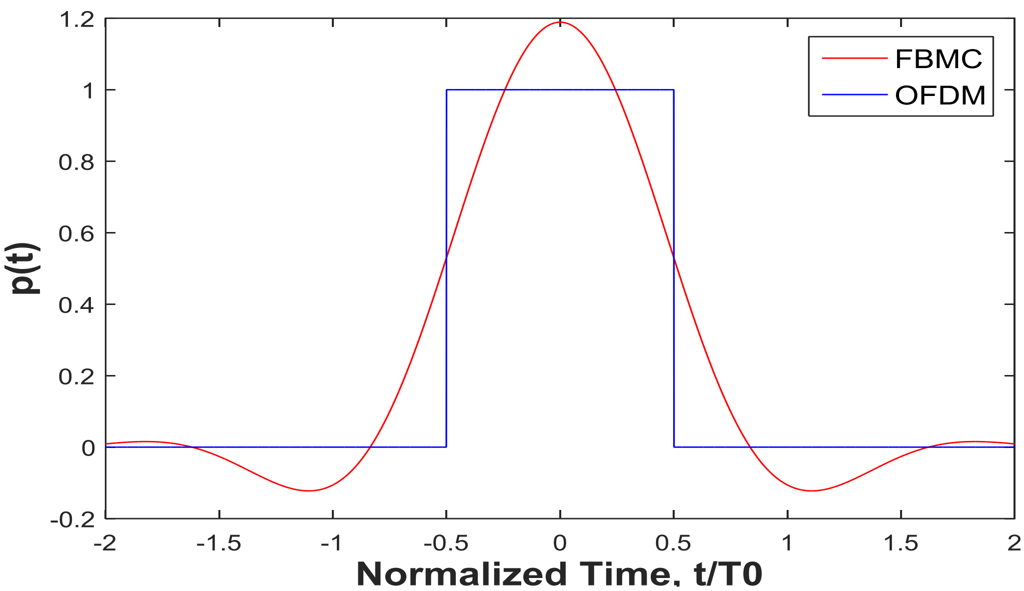


Figure 7-1: Filters in Time Domain

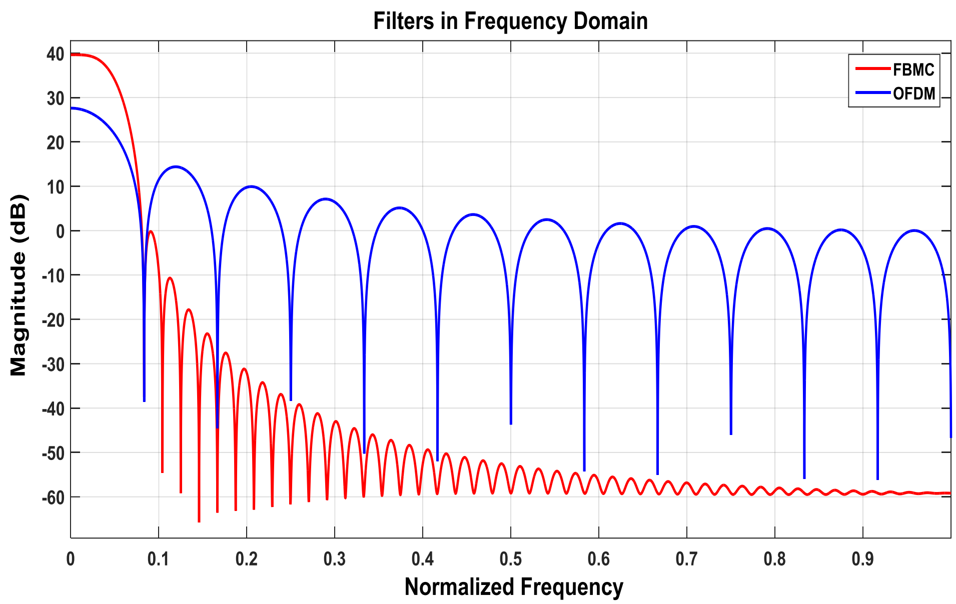


Figure 7-2: Filters In Frequency Domain

Next is the prototype simulation of PHYDAS filter using values of coefficient filter, k = 2, 3, 4 as described in the table 3-1. These graph shows as we increase the overlapping filter value, our out of band radiation decrease.

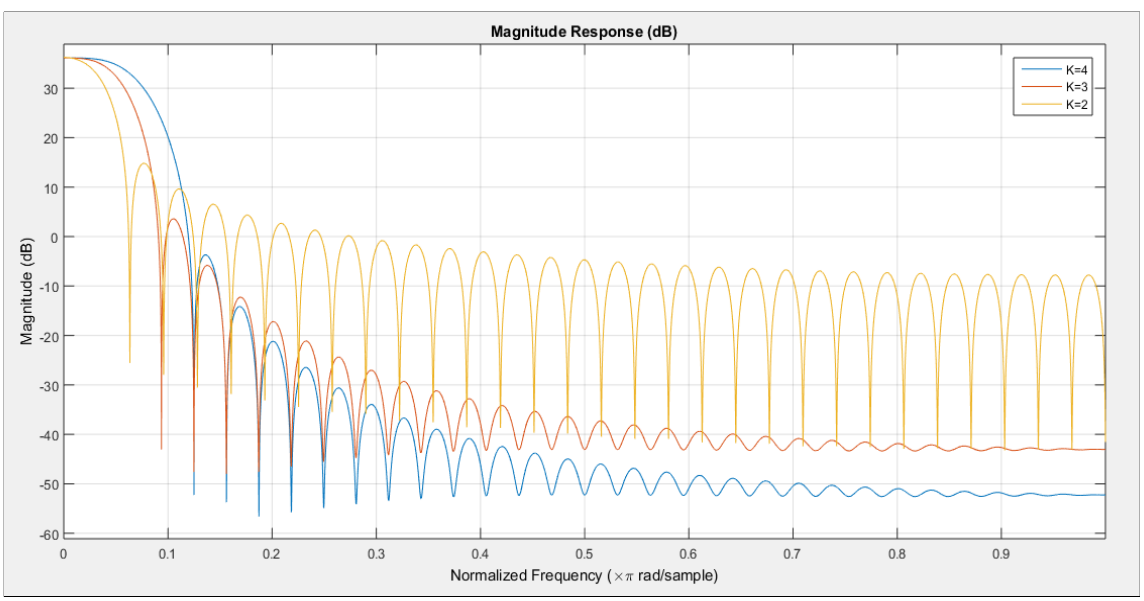


Figure 7-3: Magnitude Response of FBMC Filter with K=2, 3, 4

7.1.2 Sub Carriers Comparison

The sub carriers of the two contenders are simulated using the same parameters as in filters comparison, the x-axis represents the normalized frequency and y- axis is the power spectral density (PSD). The Inter Carrier Interference (ICI) in OFDM is greater than FBMC. Moreover, the PSD curve of both of the sub carriers show that the side lobes of the OFDM bear much greater PSD in comparison to the side lobes of FBMC. For an energy efficient system the side lobes must possess very small PSD.

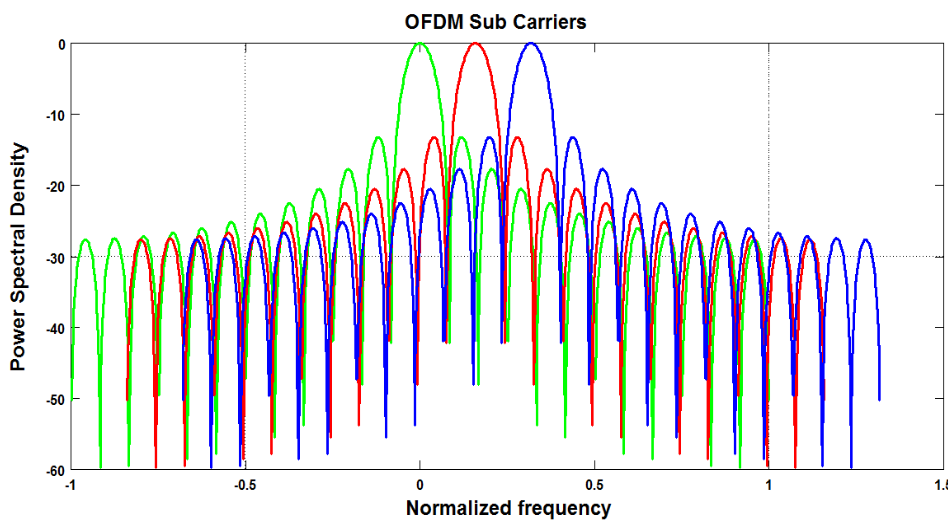


Figure 7-4: OFDM subcarriers

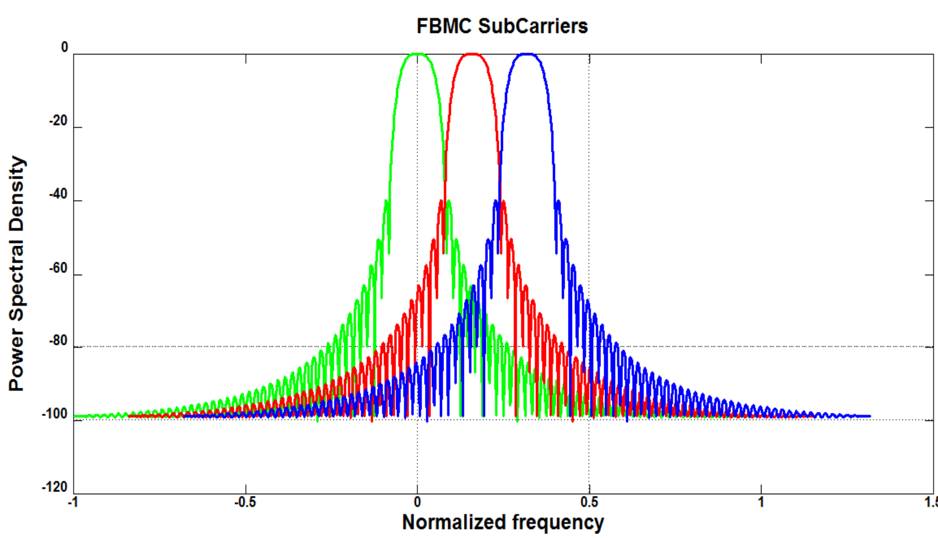


Figure 7-5: FBMC subcarriers

Figure 7-6 shows a power spectral density difference of FBMC and OFDM. The curve shows a visible difference in the PSD of the two waveforms.

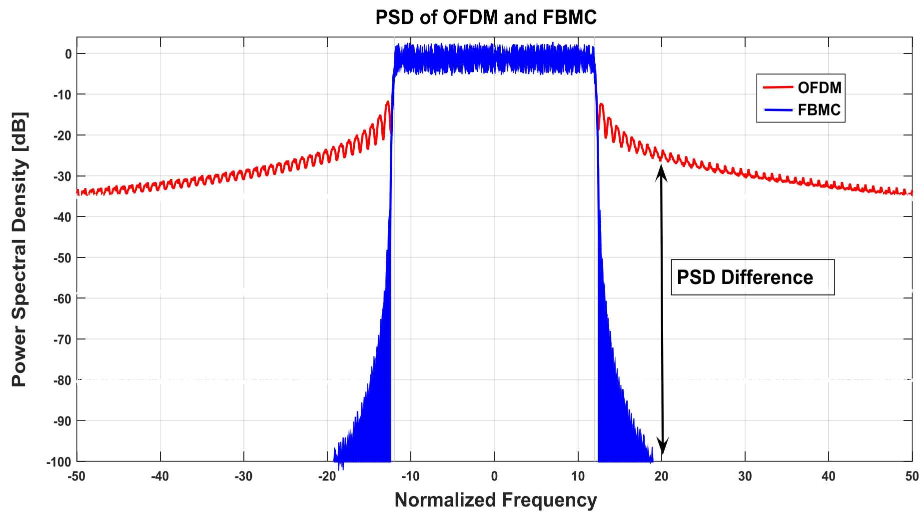


Figure 7-6: PSD of OFDM and FBMC

7.1.3 Computational Complexity at transmitter

The computational complexity of OFDM and FBMC at the transmitter side can be derived easily from the transceiver model of OFDM and FBMC. In multicarrier modulation scheme the complexity lies in the number of multiplications and additions required for the waveforms. The overall complexity of system can be calculated keeping the channel parameters in consideration as well and it's different for every channel model. At the transmitter side, the computations can be easily calculated as for FFT the computational complexity is already derived in Split-radix FFT algorithm [35].

In ODFM only FFT blocks adds to the computations, while in FBMC computational complexity is increased with the addition of overlapping factor K at the transmitter as described earlier in the paper.

The computational complexity of FS-FBMC and PPN-FBMC is different. FS-FBMC is more complex and has more computations than PPN-FBMC.

The Computational complexity of the DFT and IDFT is given below respectively.

I. $C_{DFT\ (Comp)} = M(log_2(M - 3) + 4$

II. $C_{IDFT\ (Comp)} = 3M(log_2(M - 1) + 4$

Now, as we use IDFT at the transmitter side of OFDM and FBMC, we will take into account the IDFT computational Complexity only while calculating the complexity of OFDM at the receiver. The complexity of OFDM is the same as of IDFT at TX.

$$C_{OFDM\ (Comp)} = 3M(log_2(M - 1) + 4 \qquad (7\text{-}1)$$

Filters are added to the TX side of FBMC with the tradeoff of for the bandwidth. The addition of filters with IDFT blocks adds to the computational complexity of the system Model. As the two models are discussed previously, the computations for FS-FBMC and PPN-FBMC are different.

$$C_{PPN-FBMC\ (Comp)} = M(log_2(M) - 3) + 4) + KM \qquad (7\text{-}2)$$

In Equation 14, the addition of KM accounts for the additional multiplications for FBMC. Now comes FS-FBMC, in PPN-FBMC as in FS- FBMC a prototype filter is multiplied with all IDFT blocks and in the end they are added, the computations is huge. It can be expressed in the form as in Equation: 15.

$$C_{FS-PPN\ (Comp)} = 4(M).KM \qquad (7\text{-}3)$$

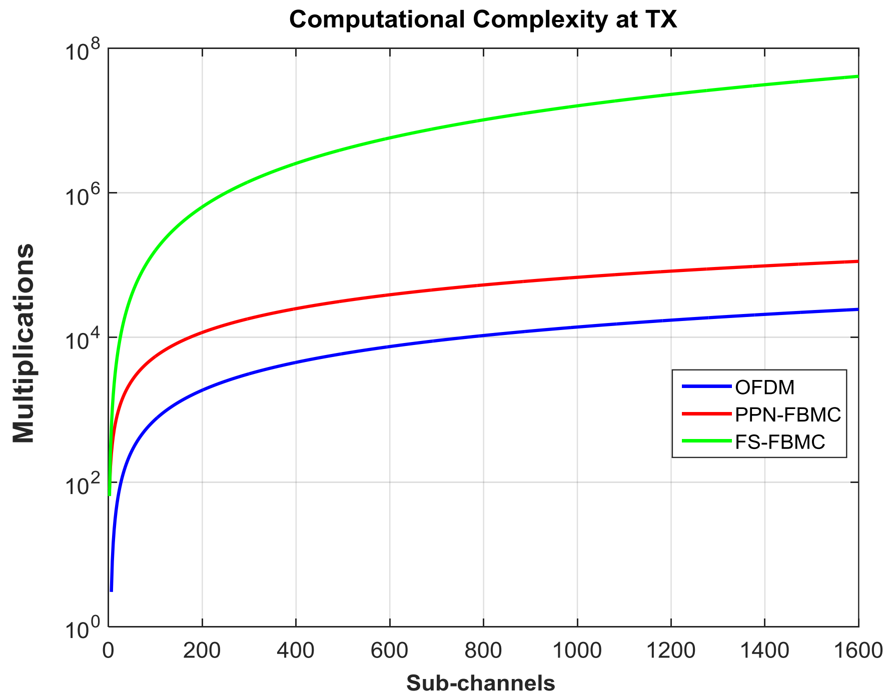


Figure 7-7: Computational Complexity

7.1.4 BER of OFDM and FBMC in AWGN Channel

In AWGN channel, OFDM is simulated without Cyclic Prefix, as AWGN channel has no multi path fading effects so CP is no longer required in this channel. BER expressions for AWGN channel are taken from 9th International ITG proceedings [36]. In Additive white Gaussian Noise channel distribution, OFDM and FBMC shows almost the same BER, because it's the CP which caters for the multi path fading effects, its no longer required in AWGN channel. P_b is the probability of error. The parameters for the BER simulations are given in Table: 7. The parameters for the earlier comparisons ate different to as to clarify the curves and results.

$$P_b \approx \frac{\sqrt{I}-1}{\sqrt{I}log_2\sqrt{I}}\ erfc\left[\sqrt{\frac{3log_2 I\ E_b}{2(I-1)N_0}}\right] \tag{7-4}$$

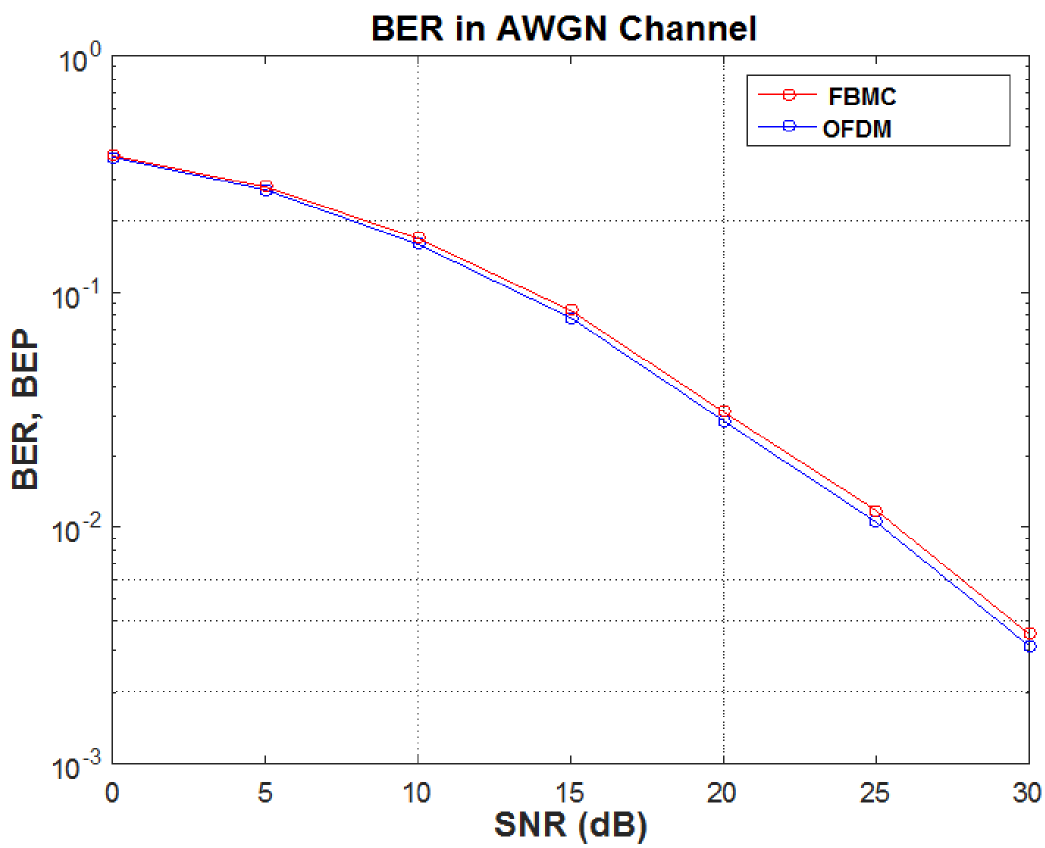


Figure 7-8: BER in AWGN channel

7.1.5 BEP of OFDM and FBMC in Vehicular channel Model A

The parameters followed for Bit Error Probability under Vehicular channel Model A are the same as for AWGN. The Bit Error Probability is now simulated using CP for OFDM and without CP as well. The channel Model is defined by the ITU standard Table: 3 [37] and its object is present in MATLAB under 802.11g libraries. Bit error propagation equations are taken from IEEE letter [38].

Table 7-2: ITU parameters for Vehicular Channel Model A

Tap	**Vehicular Channel Model A**	
	Relative Delay (ns)	**Average Power (db)**
1	0	0
2	310	-1
3	710	-9
4	1090	-10
5	1730	-15
6	2510	-20

Table 7-3: Parameters for BER simulation

Parameters	**OFDM**	**FBMC**
M	32	32
Modulation	QAM	OQAM
Modulation Order	64	64
CP	¼ (sub carrier spacing)	NA (0)
Symbols	3	7
K	NA	6
Carrier Frequency (same as in LTE)	2.5 GHz	2.5 GHz
Sub Carrier Spacing	15kHz	15kHz

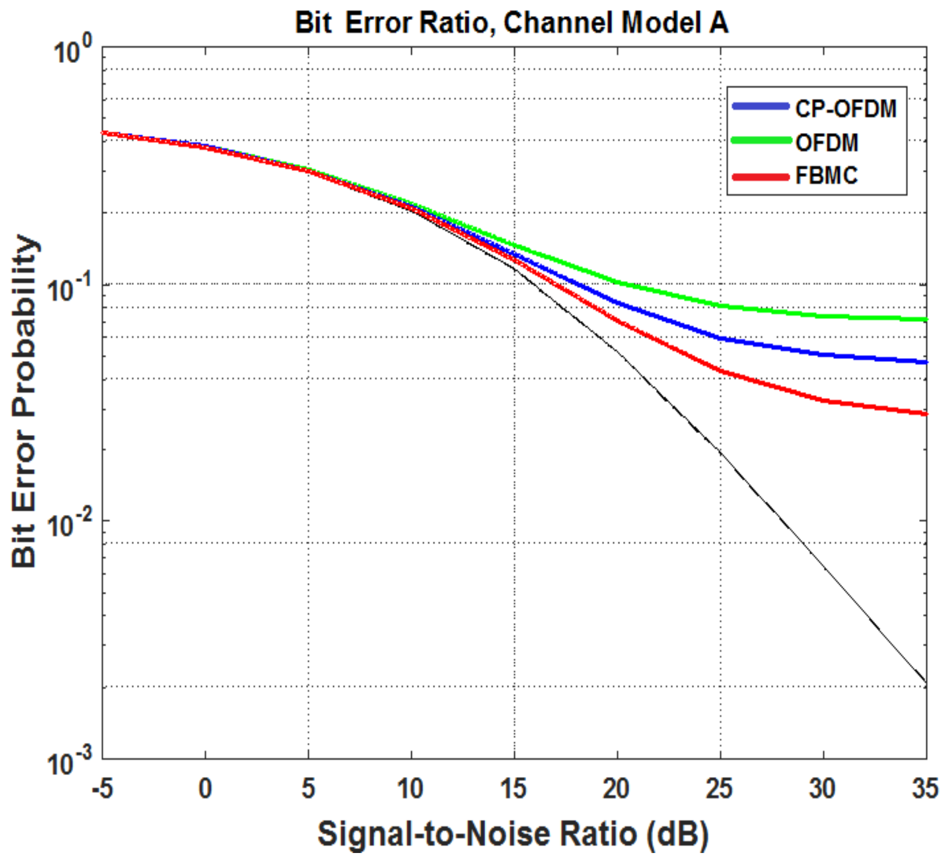


Figure 7-9: BEP in Vehicular Channel Model A

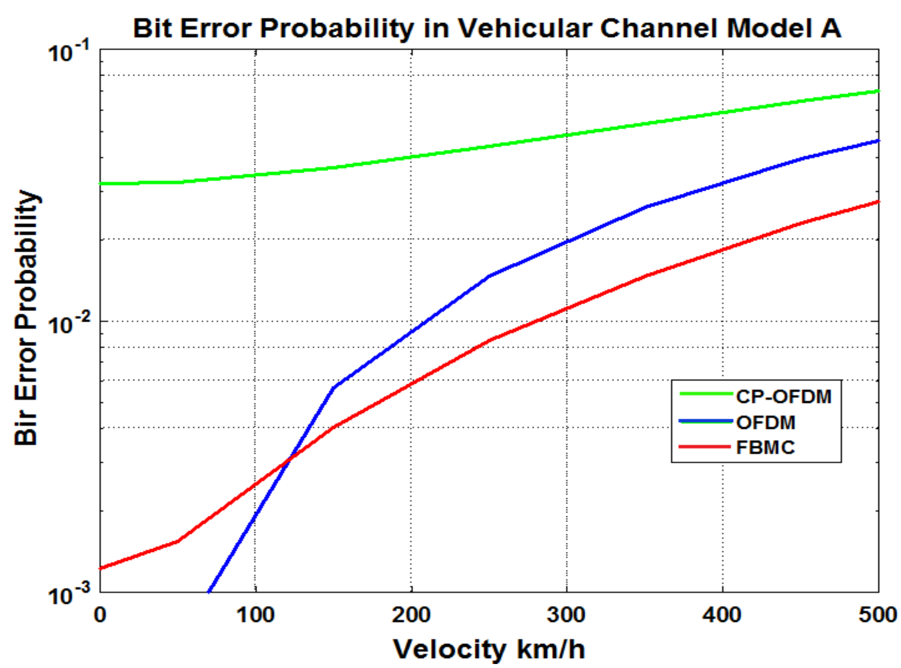


Figure 7-10: BER vs Velocity in Vehicular Channel Model A

Figure 7-10 and Figure 7-11 is the same except that in Fig 11 BEP is plotted with SNR and in Fig 12 BEP is plotted against Velocity. The results indicates that PPN-FBMC is better than OFDM, CP-OFDM in mobile channel. CP-OFDM performs better than FBMC in lower velocity but in higher velocities FBMC takes the lead.

7.2 SystemVue 2015 Simulations

SystemVue is an automation environment in which different electronic devices and communication modules are already present. It eases to design the system and use our own algorithm to get the respective results in a wireless or wired communication system physical layer.

7.2.1 FBMC and OFDM Simulation in SystemVue 2015

This example workspace demonstrates spectrum performance for a FBMC system in AWGN (Additive White Gaussian Noise) channel. Performance of FBMC system is compared with that of OFDM system. Two implementations are given for FBMC system. The number of FFT points is extended to implement the filter bank and PPN_FFT is also provided to reduce computational complexity. OQAM is adopted in the FBMC system. The frame of FBMC is composed of preamble symbols and data symbols. Preamble is consist of two superimposed ZC (Zadoff-Chu) sequence.

Narrow band FBMC source and wideband FBMC source are provided in this example. A simple EVM model is provided to measure the EVM. SNR could be set in the Equations. An amplifier is added to wideband FBMC source to simulate the performance result from wideband transmission system in mm wave. This amplifier could also be replaced with other RF transmit model designed by user.

7.2.2 Step by Step Simulation Methodology for FBMC TX

I. Set the 'NumSubcarriers' parameter to define the number of total subcarriers.
II. The 'ActiveSubcAlloc' parameter defined the allocation of active subcarriers. This parameter is an array, the first row of the array is the beginning allocation of active subcarriers, and the second row is the end allocation of active subcarriers. The range

of the array is from -NumSubc/2 to NumSubc/2-1. According to "ActiveSubcAlloc", the 'NumActiveSubc' parameter acting as active subcarriers number is given in the equations.

III. The 'FilterOverlapFactor' parameter is the overlapping factor of prototype filter used in FBMC system and three options of 'FilterOverlapFactor' is provided in the example with corresponding frequency coefficients in frequency domain defined as paramount 'FilterCoef'. Parameter 'FilterCoef' is defined as a column vector, the elements in odd row are negative, and the elements in even row are positive. The three cases of 'FilterOverlapFactor' in 5G_FBMC_Source is 2, 3 and 4. Correspondingly the parameter 'FilterCoef' should be changed to [1,-sqrt (2)/2], [1,-0.911438, 0.411438] and [1,-0.971960, sqrt (2)/2,-0.235147].

IV. The 'NumPreambleSyms' and 'NumDataSyms' define the number of preamble symbols and data symbols in one frame. In order to make repeat structure in preamble, 'NumPreambleSyms' should be no less than 'FilterOverlapFactor'+2.

V. In order to see attenuation of the spectrum, the 'OversampleRatio' parameter is used to define oversample ratio.

VI. The 'FilterBankStructure' is used to choose the implementation of FBMC. Extended IFFT and PPN_IFFT is provided.

VII. Pilot is also offered. The 'PilotsEnable' is defined to use pilot or not. If pilot is used, the 'Pilot Index' parameter defined the subcarriers that allocated to pilot and the 'Pilot Sequence' is the value of pilot. The number of 'Pilot Index' should be equal to the number of data in 'PilotSquence.'

VIII. Parameter 'Preamble Enable' is provided in FBMC_Source to generate FBMC signal with/without preamble. Make sure 'Preamble Enable' is set to 'YES' when FBMC_Receiver is used. FBMC_Receiver is used in FBMC_EVM too.

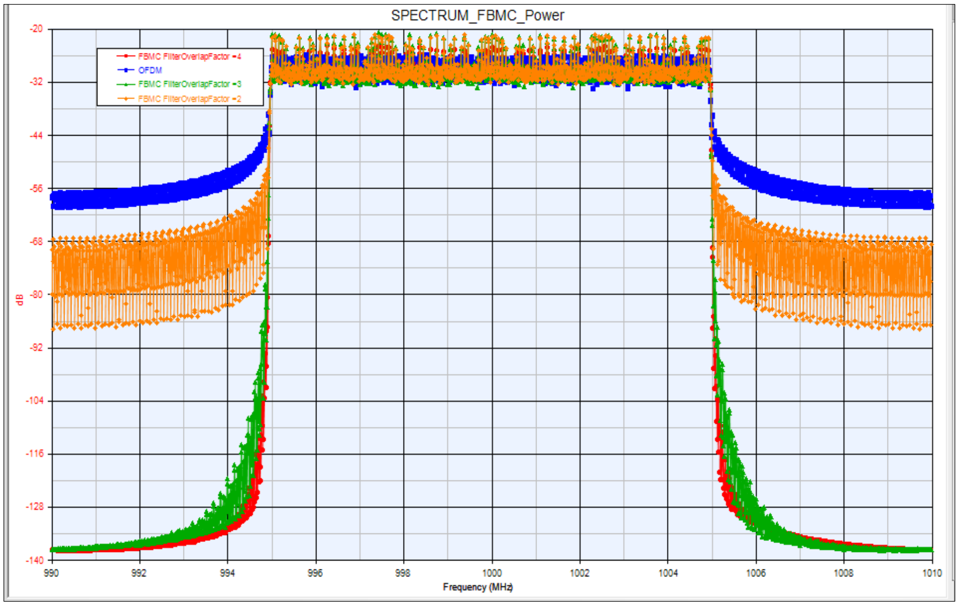


Figure 7-11: FBMC Spectrum Narrow Band

7.2.3 FBMC and OFDM BER Measurement in AWGN Channel

This simulation demonstrates BER vs. SNR measurements and spectrum performance for a FBMC system in AWGN (Additive White Gaussian Noise) channel and fading channel. Performance of FBMC system is compared with that of ideal synchronized and ideal channel estimation OFDM system. Two implementations are given for FBMC system. The number of FFT points is extended to implement the filter bank and PPN_FFT is provided to reduce computational complexity. OQAM is adopted in the FBMC system. The frame of FBMC is composed of preamble symbols and data symbols. Preamble is consist of two superimposed ZC (Zadoff-Chu) sequence. Time & Frequency synchronization, channel estimation and equalization is done in the receiver.

7.2.3.1 Step by Step Simulation Methodology for BER Measurement of FBMC

I. Set the 'NumSubcarriers' parameter to define the number of total subcarriers.

II. The 'ActiveSubcAlloc' parameter defined the allocation of active subcarriers. This parameter is an array, the first row of the array is the beginning allocation of active subcarriers, and the second row is the end allocation of active subcarriers. The range of the array is from -NumSubc/2 to NumSubc/2-1. According to

"ActiveSubcAlloc", the 'NumActiveSubc' parameter acting as active subcarriers number is given in the equations.

III. The 'FilterOverlapFactor' parameter is the overlapping factor of prototype filter used in FBMC system and three options of 'FilterOverlapFactor' is provided in the example with corresponding frequency coefficients in frequency domain defined as parament 'FilterCoef'. Parament 'FilterCoef' is defined as a column vector, the elements in odd row are negative, and the elements in even row are positive. 'FilterOverlapFactor' can be set to 2, 3 and 4. Correspondingly the parameter 'FilterCoef' should be changed to [1,-sqrt (2)/2], [1,-0.911438, 0.411438] and [1,-0.971960, sqrt (2)/2,-0.235147].

IV. The 'NumPreambleSyms' and 'NumDataSyms' define the number of preamble symbols and data symbols in one frame.

V. In order to see attenuation of the spectrum, the 'OversampleRatio' parameter is used to define oversample ratio.

VI. The 'FilterBankStructure' is used to choose the implementation of FBMC. Extended IFFT and PPN_IFFT is provided.

VII. Pilots are also offered. The 'PilotsEnable' is defined to use pilot or not. If pilot is used, the 'PilotIndex' parameter defined the subcarriers that allocated to pilot and the 'PilotSquence' is the value of pilot. The number of 'PilotIndex' should be equal to the number of data in 'PilotSquence.'

VIII. Ideal synchronized FBMC system also can be gotten by set the parameter 'Ideal Sync' of FBMC_Receiver to be 'YES', 'PhaseTrackingEnable' to be 'NO', 'Tmax' should be set to '1/Sample Rate' and 'Fmax' should be set to '0'. In addition, ideal synchronization information such as fractional frequency offset, integral frequency offset and frame timing should be set in the parameter of FBMC_Receiver in this case. To considering the influence of cycle prefix (CP), the performance figure should be rewritten by Eb/N0.

IX. Parameter 'Tmax' and 'Fmax' are used for channel estimation. Parameter 'Tmax' defines the maximum delay of multipath. If 'Tmax' were much bigger than the maximum delay, much noise would be introduced. Therefore, in AWGN channel there is no multipath, 'Tmax' should be set not much bigger than

'1/BaseSampleRate' to get better channel estimation performance. In fading channel, the value of 'Tmax' should be depends on the maximum delay. It is the same case for 'Fmax'.

X. Parameter 'PreambleEnable' is provided in FBMC_Source to generate FBMC signal with/without preamble. Make sure 'PreambleEnable' is set to 'YES' when FBMC_Receiver is used.

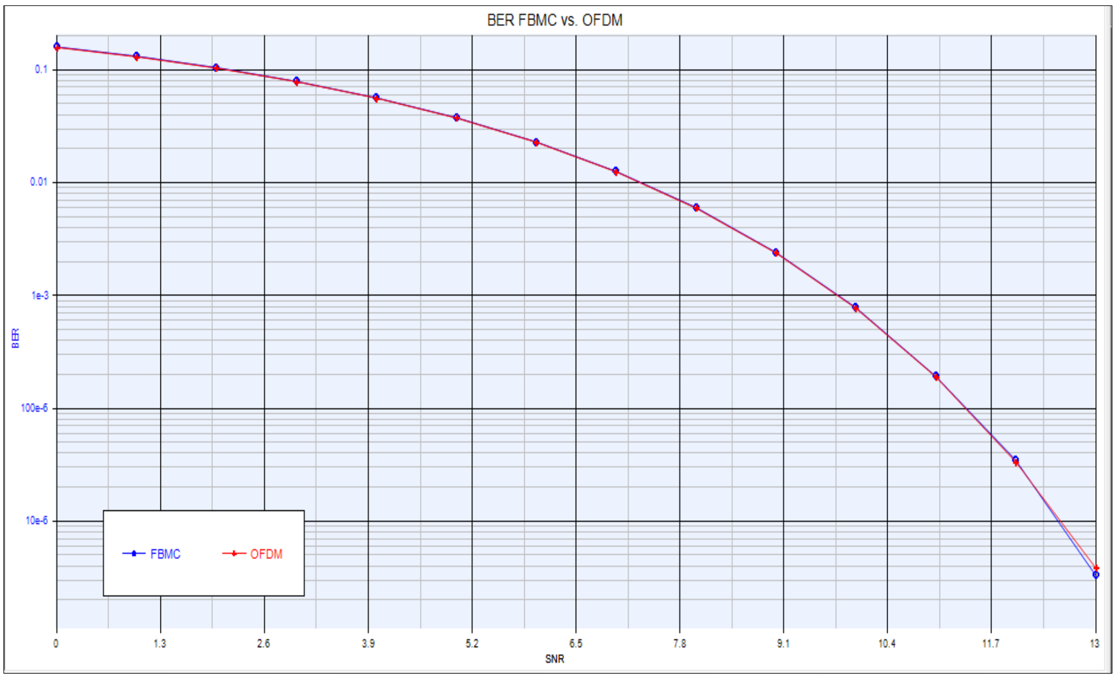


Figure 7-12: BER Measurement of OFDM and FBMC in AWGN Channel

This result is in accordance with the literature provided in the paper. [39]

7.3 Conclusion

In this chapter we simulated the ODFM and FBMC filters both in time and frequency domain, derived and simulated the computational complexity at the transmitter side. For the Bit Error Probability simulations we used the AWGN channel and a multipath fading channel Vehicular Model A. The results show that FBMC has much lower out of band radiations , higher computational complexity at the transmitter side, almost comparable BER in AWGN channel and a very good BER in fading channel Model A. This makes FBMC as an ideal candidate waveform for 5G subject to its further performance and testing in more complex and diverse environments like MIMO, Massive MIMO and IoT's.

8 ANALYTICAL COMPARISON BETWEEN OFDM, FBMC, UFMC AND GFDM

This chapter covers in detail the differences of OFDM and FBMC and draw some radical and concrete culminations for all four waveform contender waveforms and thesis. It starts from OFDM and FBMC and extends to UFMS and GFDM.

8.1 OFDM and FBMC Comparison

FBMC is a customized form of OFDM, using already existing FFT/iFFT block, adding filters to it , and produce much better results as compared to OFDM at the cost of complexity which can be seen in the transceiver blocks.

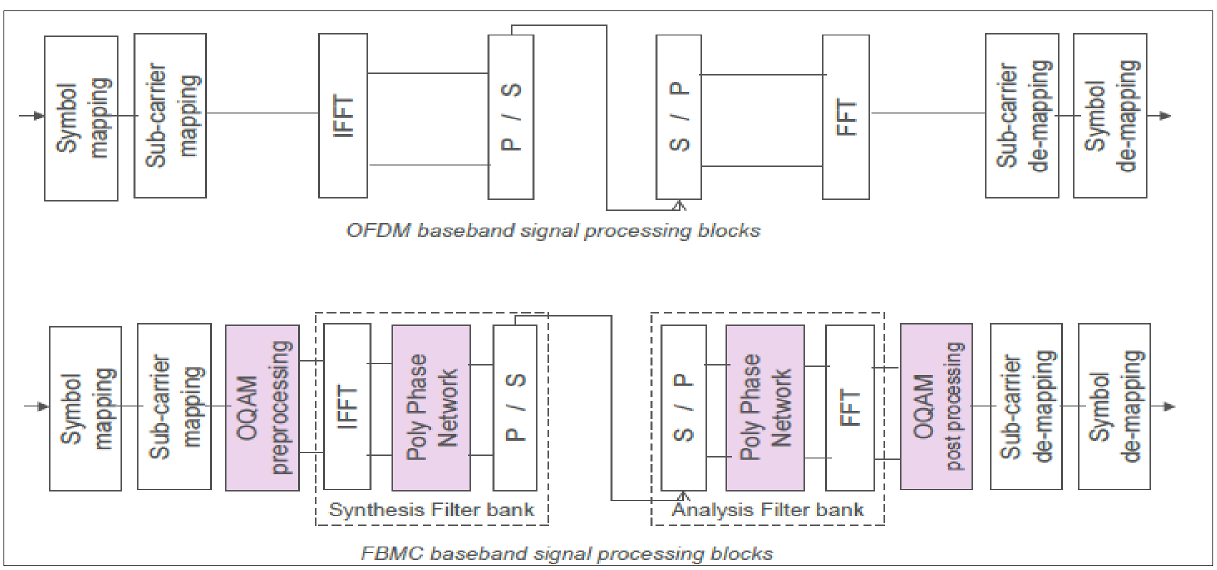


Figure 8-1: OFDM and FBMC Transceiver comparison

8.2 FBMC, UFMC and GFDM Transceivers Comparison Altogether

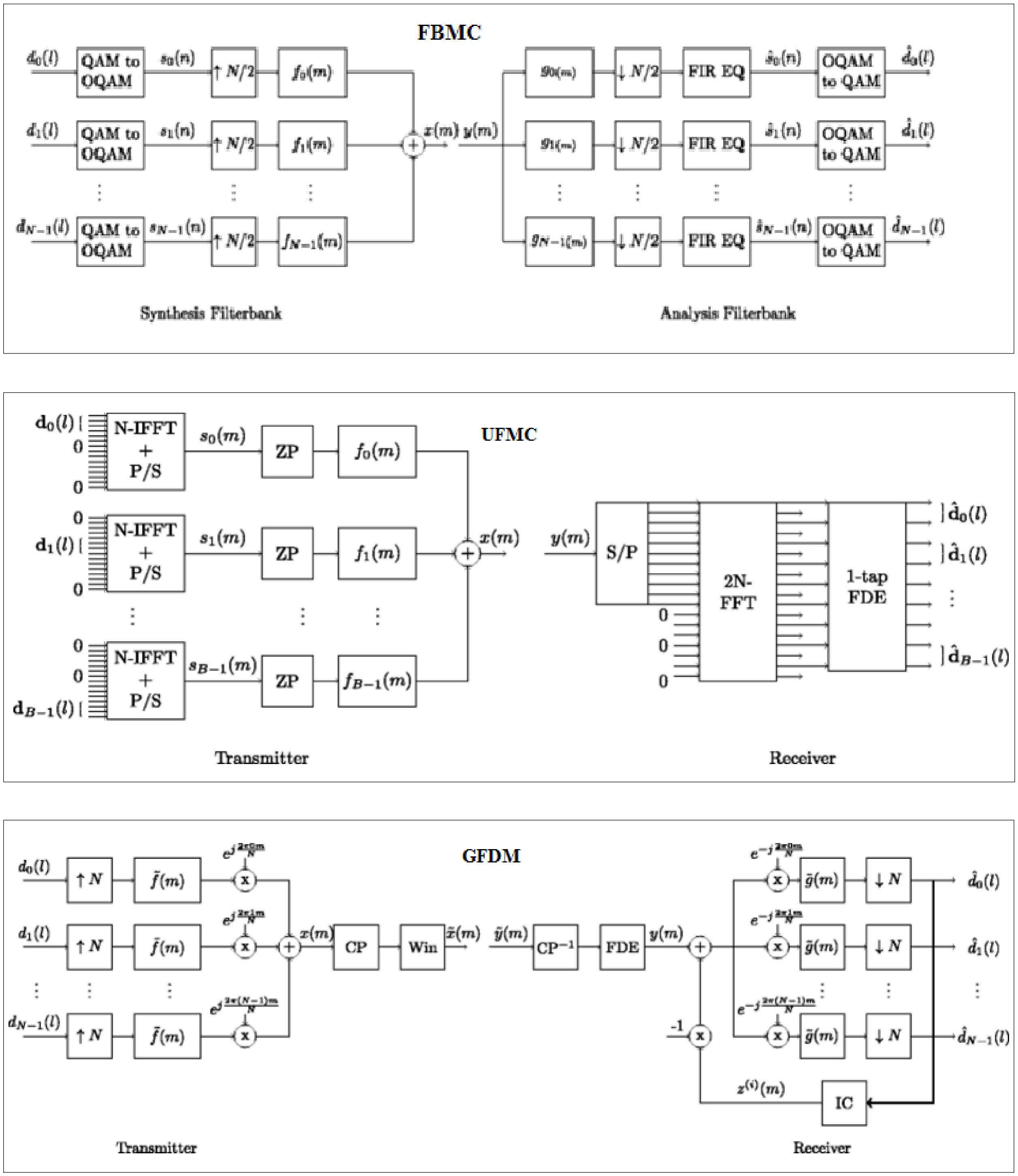


Figure 8-2: FBMC, UFMC and GFDM Transceivers Comparison

Table 8-1: OFDM and FBMC Comparison

OFDM	FBMC
It requires orthogonally in subcarriers	It requires Orthogonality in sub channels only
It divides the given frequency into number of **sub carriers**	It divides the given frequency into number of **sub channels**
Adaptive Modulation i.e. QAM, 16QAM, 64 QAM	**OQAM** modulation is adapted to maintain orthogonally between these sub channels
CP required	No CP required

8.3 Performance Parameters and the Results

The performance matrix over which the world has categorized the waveform contenders for 5G physical layer include BER, Bursts transmission, SER, PAPR, Complexity, OOB [40].

8.3.1 Bursts Transmission

PPN network in FBMC significantly reduce the OOB radiation than OFDM. However, FBMC show poor spectral efficiency in short bursts transmission. GFDM is better in Bursts transmission due to circular convolution. 5th Generation and MTC need more flexibility for bursts transmission.

8.3.2 MIMO

GFDM offers much lower interference than others in MIMO scenarios. However, several techniques are under development to help reduce internal interference in case of MIMO and this interference and compatibility problem can be mitigated.

8.3.3 Complexity in Mathematical Form

Complexity of the contenders are measured mathematically by the Equation 8-1

$$r_{C,w} = \frac{C_w}{C_{\text{OFDM}}}$$ ***Equation 8-1***

And the complexity is depicted by the following Figure. FBMC and GFDM performs 5 times better than the other two waveforms.

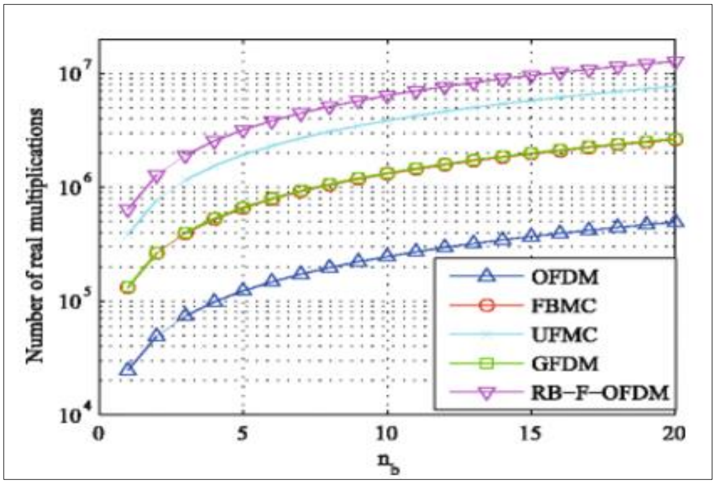


Figure 8-3: Complexity Comparison of Contender Waveform

8.3.4 PAPR

PAPR is one of the biggest performance matrix for evaluation of waveform contenders for 5G. For a 3ms burst the performance is almost the same [41]. However, in [42] its mentioned that only that PAPR result is not enough.

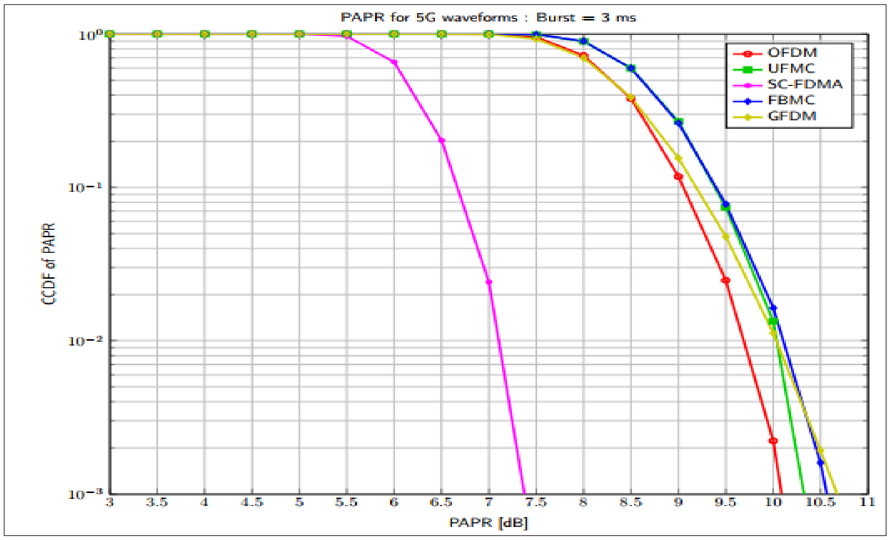


Figure 8-4: PAPR of Waveform Contenders

8.3.5 Complexity

The waveforms have another figure of merit and this is complexity, complexity of the waveforms is equal to complexity of the receiver + complexity of the transmitter. In [43] Mathieu Van Eeckhaute, André Bourdoux,, Philippe De Doncker and François Horlin have derived the mathematical expressions for the performance comparison of the candidate waveforms. They are listed as

For OFDM

$$C_{\text{OFDM}} = n_b \left[2N \log_2 N + 4N \right]$$

Equation 8-2

For FBMC

$$\begin{aligned} C_{\text{FBMC, TX}} &= 2 \times n_b \left[2KN + N \log_2 N \right] \\ C_{\text{FBMC, RX}} &= 2 \times n_b \left[2KN + N \log_2 N \right. \\ &\quad \left. + 4(2K-1)N \right] \\ C_{\text{FBMC}} &= C_{\text{FBMC, TX}} + C_{\text{FBMC, RX}} \end{aligned}$$

Equation 8-3

For UFMC

$$\begin{aligned} C_{\text{UFMC, TX}} &= n_b \Big[2N \log_2 2N + B(N_{\text{ifft}} \log_2 N_{\text{ifft}} \\ &\quad + 2N_{\text{ifft}} \log_2 2N_{\text{ifft}} + 4 \times 2N_{\text{ifft}}) \Big] \\ C_{\text{UFMC, RX}} &= n_b \left[2N \log_2 2N + 4N \right] \end{aligned}$$

Equation 8-4

For GFDM

$$\begin{aligned} C_{\text{GFDM, TX}} =& n_{b,\text{GFDM}} [N (M \log_2 M \\ &+ 2M \times 2) + MN \log_2 MN] \\ C_{\text{GFDM, RX}} =& n_{b,\text{GFDM}} [MN \log_2 MN \\ &+ N(M \log_2 M + 4M \times 2) \\ &+ (2MN \log_2 MN + 4MN) \\ &+ J(2NM \log_2 M + 2MN)] \end{aligned}$$

Equation 8-5

8.4 Performance Comparison of OFDM, FBMC, UFMC and GFDM

Now here is enlisted in a summarized form the very concrete differences between the waveforms [42]. This is in fact the crux of the whole research work.

Table 8-2: Performance Comparison of OFDM, FBMC, UFMC and GFDM

PARAMETERS	**COMPETITORS**			
	OFDM	**FBMC**	**UFMC**	**GFDM**
MULTI USER	Yes	Yes	Yes	Yes
CP	Yes (in Multipath channels)	No (AWGN as well as Multipath channels)	Yes (in Multipath channels)	Yes In Multipath channels (Per block) with Tail Biting Block
FILTERS	Window Filter	PPN Filter Bank	Universal Filter	Adjustable Pulse shaping filters with circular convolution
FFT/IFFT BLOCKS	Yes	Modified FFT	Yes	Yes

PAPR	Very high	Low as compared to OFDM	High at higher voltages	Comparable to FBMC
ADJACENT CHANNEL LEAKAGE (ACL) [44] **FIG: 8:3**	Highest because of high synchronization	Best Location among all four	Lower than GFDM	Comparable to UFMC
OOB [44]	Highest (4^{th})	Lowest (1^{st})	Better than GFDM (3^{rd})	Better than OFDM (2^{nd})
SPECTRAL EFFICIENCY (SE) (BITS/SEC) [44]	$\eta_{OFDM} = \frac{m \times N_{FFT}}{N_{FFT}+N_{CP}}$	$\eta_{FBMC} = \frac{m \times S}{S+K-\frac{1}{2}}$	$\eta_{UFMC} = \frac{m \times N_{FFT}}{N_{FFT}+L-1}$	$\eta_{GFDM} = \frac{m \times P \times M}{P \times M+N_{CP}}$
SE DEPENDS ON	CP and FFT block	Bursts duration	Length of filter	Block size
MODULATION SCHEME	QAM	OQAM	Any QAM, Adaptive	Any QAM, Adaptive
COMPLEXITY (TX)	$C_{OFDM} = n_b\left[2N\log_2 N + 4N\right]$	$C_{FBMC,TX} = 2 \times n_b\left[2KN + N\log_2 N\right]$	$C_{UFMC,TX} = n_b\left[2N\log_2 2N + B(N_{ifft}\log_2 N_{ifft} + 2N_{ifft}\log_2 2N_{ifft} + 4 \times 2N_{ifft})\right]$	$C_{GFDM,TX} = n_{b,GFDM}\left[N(M\log_2 M + 2M \times 2) + MN\log_2 MN\right]$
COMPLEXITY (RX)	$C_{OFDM} = n_b\left[2N\log_2 N + 4N\right]$	$C_{FBMC,RX} = 2 \times n_b\left[2KN + N\log_2 N + 4(2K-1)N\right]$	$C_{UFMC,RX} = n_b\left[2N\log_2 2N + 4N\right]$	$C_{GFDM,RX} = n_{b,GFDM}\left[MN\log_2 MN + N(M\log_2 M + 4M \times 2) + (2MN\log_2 MN + 4MN) + J(2NM\log_2 M + 2MN)\right]$
OVERHEAD SAMPLES	$T_{L,OFDM} = n_b \times CP$	$T_{L,FBMC} = N \times (K - 1/2)$	$T_{L,UFMC} = n_b \times (ZP_L + L_{UFMC} - 1)$	$T_{L,GFDM} = n_{b,GFDM}\frac{GS + M}{M} \times (N \times GS + CP_L)$

SHORT BURSTS	Good Spectral efficiency	Bad spectral Efficiency	Better than FBMC	Better than all 3 others
MIMO COMPATIBILTY	Average	Very Poor	Better than FBMC and GFDM	Better than GFDM
ORTHOGONALITY	Follows strict Orthogonality	Loose Orthogonality	Better than FBMC	Compromised when variable pulse shaping filters are used
SYNCHRONIATION	Strictly required	Loose synchronization required	Strict than FBMC	Loose than GFDM
CLOSENESS TO OFDM	OFDM	2nd in ranking	Closest to OFDM	Farthest of OFDM between FBMC, UFMC and GFDM
COMPLEXITY OVERHEAD [42]	20	5.33	15.64	5.42

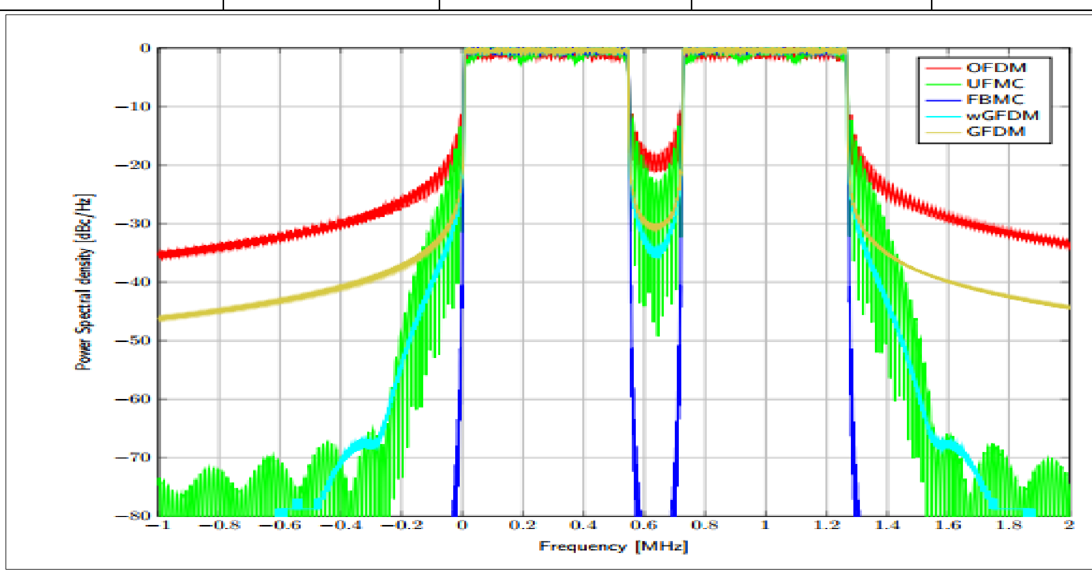


Figure 8-5: PSD of OFDM, UFMC, FBMC, GFDM

8.5 Conclusion

GFDM is better and more flexible than all the three other waveforms, it reduces the out of band (OOB) radiation and its highly compatible with MIMO technology. UFMC is another adaptive technique of OFDM and FBMC but under performs than FBMC. FBMC significantly reduce the OOB radiation but it’s very poor in MIMO technique and also shows very less spectral efficiency when short bursts are transmitted.

The standard for 5G physical layer will be standardized in 2020, however the research and development is still in process to check and conclude the best one from the contenders.

Chapter 9

9 CONCLUSION AND FUTURE WORK

This chapter gives the radical closure of the research work. It enlists the harvest of the simulation and paper work.

Furthermore, it embodies the future work, which can be done by the upcoming researchers. Some new ventures related to 5G were discovered during the research, which are catalogued here.

9.1 Culmination

With the research done during the thesis we have reached the following logical conclusions

I. FBMC has a reduced PAPR as compared to OFDM
II. FBMC and OFDM performs the same in case of AWGN channel
III. FBMC outperforms OFDM in case of more realistic channels such as vehicular channel model A at the cost of more computational complexity
IV. FBMC is not suitable for MIMO with OQAM modulation
V. In case of MIMO FMBC is to be considered with modulation scheme other than OQAM or customized OQAM
VI. FBMC is a strong waveform contender for 5G physical layer along with UFBM, GFDM and CP-OFDM
VII. UFMC is better than FBMC for short bursts transmission
VIII. GFDM is flexible for short bursts transmission unlike FBMC
IX. GFDM is more prone to time and frequency offsets because of its variable circular convolution filters
X. Spectral Efficiency of GFDM is highest among all waveform contender discussed in the dissertation

9.2 Future Work

While researching and prototyping waveform contenders for 5G physical layer, which are listed below, several new ventures and challenging research works are discovered.

I. UFMC – Universal filter bank multicarrier waveform
II. GFDM – Generalized frequency division multiplexing
III. UFMC – Universal filter bank multi carrier
IV. SC-OFDM – Single carrier orthogonal frequency division multiplexing

The 5G challenges cannot be more beautifully explained than the figure below

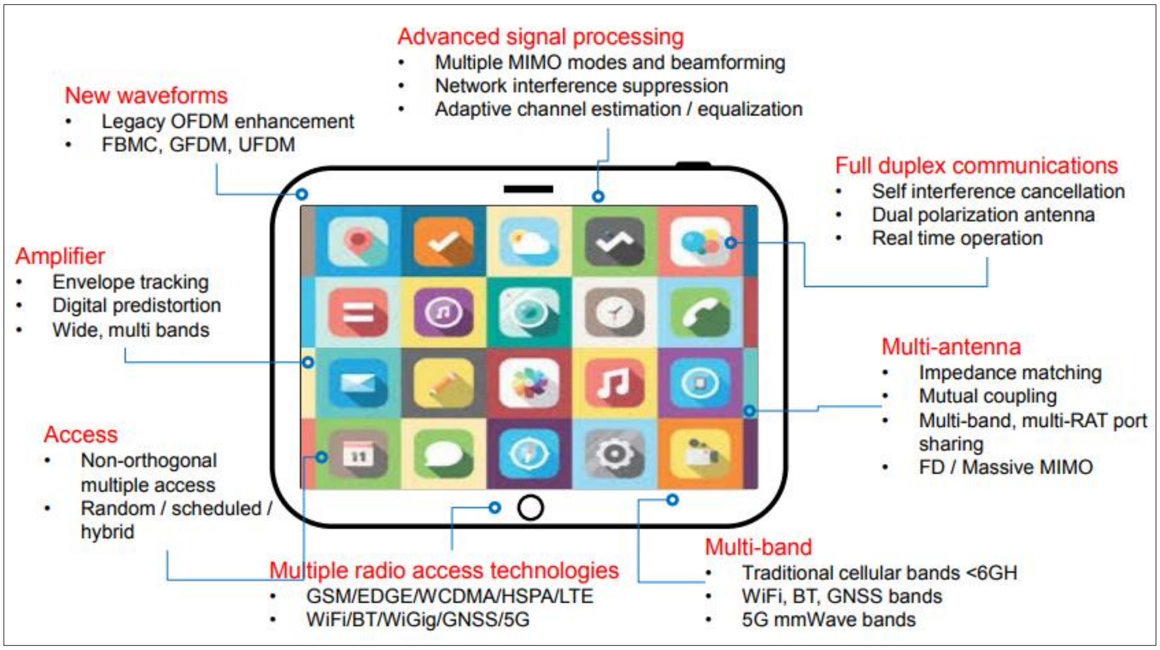


Figure 9-1: 5G Research working Areas

The general areas include 5G waveform, MIMO and multiplex access techniques, amplifier design, multi antenna systems, exploiting microwave and cognitive spectrum analysis and white band usage. The specific areas incudes

I. Removing intrinsic interference from FBMC
II. Customizing FBMC for MIMO technology

III. Security in IoT’s
IV. Prevention of zero day attack in MTC
V. Coordinated MIMO, millimeter MIMO and Massive MIMO
VI. SON—Self organizing Networks

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APPENDIX

[APPENDIX A]

Hadamard matrices

Consider the following:

$$H_1 = \begin{bmatrix} 1 \end{bmatrix} \qquad H_2 = \begin{bmatrix} 1 & 1 \\ 1 & - \end{bmatrix} \qquad H_4 = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & - & 1 & - \\ 1 & 1 & - & - \\ 1 & - & - & 1 \end{bmatrix}$$

These are examples of **Hadamard** matrices, which have the property that they are ± 1 matrices such that

$$H_n H_n^T = nI.$$

Hadamard matrices exist of orders 1,2, 4, or a multiple of 4. Hadamard matrices are of interest because we can define codes based on the rows of the Hadamard matrix.

There are two known ways of making Hadamard matrices. One way is as follows:

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & -H_n \end{bmatrix}$$

This is the **Sylvester** construction. The second construction, the **Paley** construction, is somewhat more subtle. We begin with a discussion of quadratic residues.

Suppose we wanted (for some strange reason) to know for which values of x the following quadratic equation has a solution:

$$y^2 \equiv x \pmod{p}$$

[APPENDIX B]

A.1 Basic Concepts

A.1.1 Channel

The term channel refers to the medium between the transmitting antenna and the receiving antenna as shown in Figure A.1.1

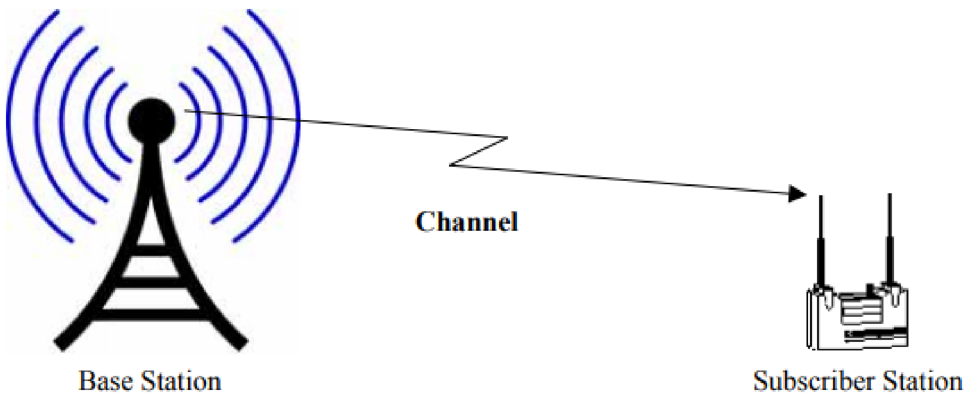

Figure A.1.1: Channel

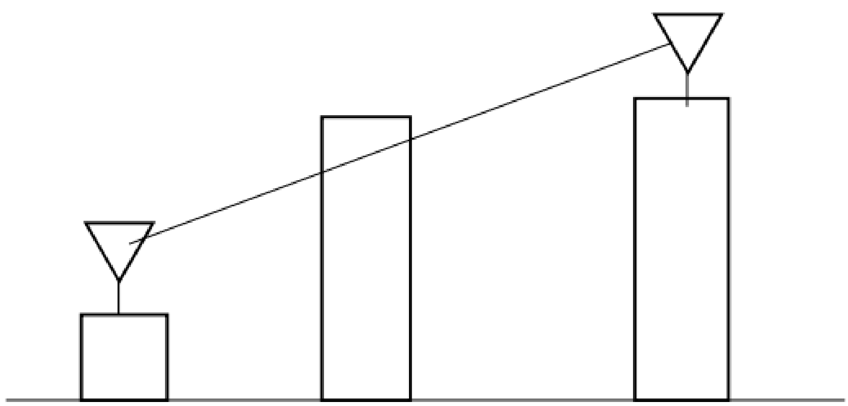

Figure A.1.2: Shadowing

The net path loss becomes:

$$PL(d)\,dB = \overline{PL}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + \chi$$

The objects located around the path of the wireless signal reflect the signal. Some of these reflected waves are also received at the receiver. Since each of these reflected signals takes a different path, it has a different amplitude and phase.

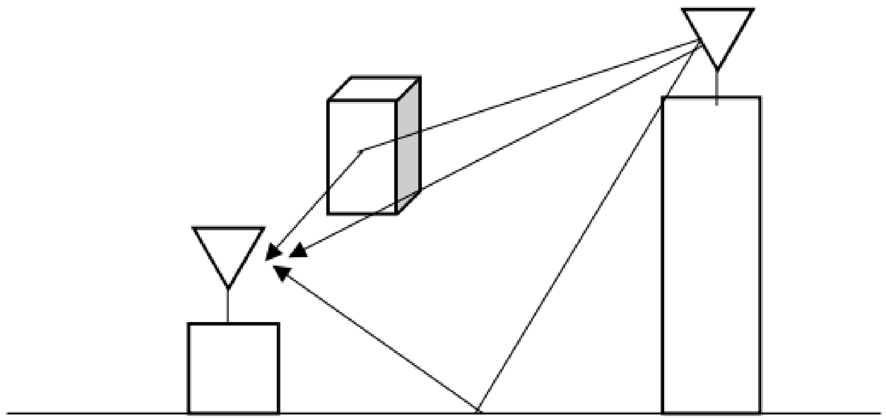

Figure A.1.3: Multipath

Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0	0	0	Flat
2	50	–3.0	100	–3.6	Flat
3	110	–10.0	200	–7.2	Flat
4	170	–18.0	300	–10.8	Flat
5	290	–26.0	500	–18.0	Flat
6	310	–32.0	700	–25.2	Flat