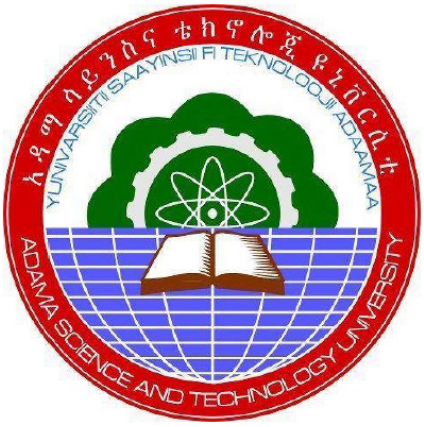
Comparative Analysis of Multicarrier Modulation Techniques with Higher Order QAM for Fifth Generation Wireless Communication



Hise Teferi Dumari

A Thesis Submitted to the Department of Electronics and Communication Engineering
School of Electrical Engineering and Computing
Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Communication Engineering

Office of Graduate Studies
Adama Science and Technology University

June, 2022
Adama, Ethiopia

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ACKNOWLEDGMENT

Firstly I would like to acknowledge the almighty God for the unending grace, favour, perfect health and strength during the entire process of this thesis.

Secondly, I would like to express my deepest gratitude to my, main advisor Dr. Rajeev K.Shakya and co-Advisor Dr. Demissie Jobir Gelmecha, for their guidance, and full support during thesis work. I appreciate their support and patience. I am constantly impressed by their technical intuition, and I have learned a lot from them. They shared me their academic life experiences. Their experiences motivated me to pass different challenges

I would like to express my sincere thanks to Dr. Ram Sewak Singh for his positive feedback and encouragement throughout the completion of this thesis work.

I would like to show my gratitude to Mr. Zewdu Burusa for his valuable support by arranging the work place open for discussion and laboratory experiment works with taking a lot of responsibility.

I would like to thank my all classmates specially Mr. Mustefa Badri, Mr. Zelalem Melak, Mr. Teshome Watro and Mr. Sisahu Tolcha for their patience to support me in every challenges that I faced. I would like to thank Ms.Piniel Mekonnen and her friends for their encouragement and positive support. I would like to thank Ms. Eyerusalem Paulos for her advice and technical support.

I would greatly thanks to Adama Science and Technology University for sponsoring me to take this master's program opportunity.

Finally, I am so grateful to my best friend Ms.Tizita Mulugeta for her prayer, love and advice to be successful. Also I am so grateful to my family who always let me to go to right way and made me strong.

CONTENTS

APPROVAL PAGE OF M.SC THESIS i
APPROVAL OF BOARD OF EXAMINERS ii
DECLARATION iii
RECOMMENDATION iv
ACKNOWLEDGMENT v
LIST OF TABLES ix
LIST OF FIGURES x
LIST OF ACRONYMS xii
ABSTRACT xiv
CHAPTER ONE: INTRODUCTION 1
1.1 Background of the Study 1
1.2 Statement of the Problem 4
1.3 Objective 5
1.3.1 General Objective 5
1.3.2 Specific Objectives 5
1.4 Contribution of the Study 5
1.5 Scope of the Study 6
1.6 Limitation of the Study 6
1.7 Thesis Outline 6
CHAPTER TWO: LITERATURE REVIEW 8
2.1 Chapter Overview 8
2.2 Introduction to 5G Wireless Communications 8
2.3 Use Case of 5G Technology 10
2.3.1 Enhanced Mobile Broadband 11
2.3.2 Massive Machine Type Communications 11
2.3.3 Ultra Reliable and Low Latency Communications 12
2.4 The Requirements of 5G Technology 12
2.5 Key Enabling Technology of 5G and Beyond 13
2.5.1 Millimeter Waves 13
2.5.2 Sub-Millimeter or Terahertz Band 14
2.5.3 Small Cells or Heterogeneous Networks 15
2.5.4 Beamforming 15
2.5.5 Device Centric Architecture 16

2.5.6 Full Duplex Technology 16
2.5.7 Visible Light Communications 17
2.5.8 Massive MIMO 17
2.6 New Air Interfaces 19
2.6.1 Non-orthogonal multiple access (NOMA) 19
2.6.2 Orthogonal multiple access (OMA) 19
2.7 Single Carrier and Multicarrier Modulation Techniques 20
2.8 Review of Related Works 21
CHAPTER THREE: MATERIALS AND METHODS 24
3.1 Introduction 24
3.2 Materials 24
3.3 Methods 24
3.4 Multicarrier Modulation Techniques 24
3.4.1 Orthogonal Frequency Division Multiplexing (OFDM) 25
3.4.2 Filtered- Orthogonal Frequency Division Multiplexing (F-OFDM) 27
3.4.3 Weighted Overlap and Added Orthogonal Frequency Division Multiplexing (WOLA-OFDM) 27
3.4.4 Universal Filter Multicarrier (UFMC) 29
3.4.5 Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM) 31
3.4.6 Proposed Filter Bank Multicarrier with Quadrature Amplitude Modulation (FBMC/QAM) 33
3.5 Prototype Filters 35
3.5.1 Rectangular Filter 35
3.5.2 Raised Cosine Filter 36
3.5.3 Exact Hamming Filter 36
3.5.4 Exact Black Man Filter 36
3.5.5 Root Raised Cosine Filter 36
3.5.6 PHYDYAS Filter 36
3.5.7 Hermite Filter 37
3.6 Simulation Parameters 37
3.6.1 Power Spectral Density 37
3.6.2 Bit Error Rate 37
3.6.3 Spectral Efficiency 38
3.6.4 Computational Complexity 39
3.6.5 Signal to Interference Ratio 40

CHAPTER FOUR: RESULT AND DISCUSSION 41
4.1 Simulation Parameters 41
4.2 Spectral Efficiency Comparison 42
4.3 Power Spectral Density Comparison 43
4.4 Bit Error Rate Comparison 45
4.5 Computational Complexity Comparison 58
4.6 Signal to Interference Ratio Comparison 59
CONCLUSION AND RECOMMENDATION 61
5.1 Conclusion 61
5.2 Recommendation 62
REFERENCES 64

LIST OF TABLES

Table 2.1 Requirements of 5G Technology 13
Table 2.2 Contribution and gap of different related works. 23
Table 3.1 Multiplication of different multi-carrier modulation techniques . . 40
Table 4.1 Parameters for Multi-carrier Modulation Techniques 41
Table 4.2 Power Spectral Density of Different Modulation Schemes at 20, 30, 40 and 50 normalized frequency. 45
Table 4.3 Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Vehicular A channel model. 49
Table 4.4 Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Vehicular B channel model. 53
Table 4.5 Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Pedestrian B channel model. 57
Table 4.6 Power Spectral Density of Different Modulation Schemes at 20, 30, 40 and 50 normalized frequency. 59

LIST OF FIGURES

Figure 2.1 Different application of 5G technology (Chataut & Akl, 2020). . 9
Figure 2.2 Use case diagram of Future IMT (Series, 2015). 10
Figure 2.3 Uplink and Down link structure of Massive MIMO (Chataut & Akl, 2020). 15
Figure 2.4 Full Duplex Technology (Chataut & Akl, 2020). 17
Figure 2.5 Uplink and Down link structure of Massive MIMO (Chataut & Akl, 2020). 18
Figure 3.1 The General System Model for Multicarrier Modulation Techniques (Kassaw et al., 2020). 25
Figure 3.2 Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021). 26
Figure 3.3 Filtered- Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021). 27
Figure 3.4 Weighted Overlap and Added Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021). 28
Figure 3.5 Universal Filter Multicarrier System (Bendimerad et al., 2021). 30
Figure 3.6 Filter Bank Multicarrier with offset QAM System (Jeon et al., 2016). 32
Figure 3.7 Filter Bank Multicarrier with QAM System. 34
Figure 4.1 Spectral Efficiency of Multicarrier Modulation Techniques. . . . 42
Figure 4.2 Power spectral density versus normalized frequency of different prototype Filters for sub-carrier spacing 15kHz, number of sub-carriers 1024 43
Figure 4.3 Power spectral density versus normalized frequency of different multi-carrier modulation techniques for sub-carrier spacing 15kHz, number of sub-carriers 1024. 44
Figure 4.4 Bit Error rate performance of OFDM at M-QAM. 46
Figure 4.5 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 4-QAM. 46
Figure 4.6 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 16-QAM. 47
Figure 4.7 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 64-QAM. 47

Figure 4.8 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 256-QAM. 48
Figure 4.9 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 1024-QAM. 48
Figure 4.10 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 4-QAM. 50
Figure 4.11 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 16-QAM. 50
Figure 4.12 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 64-QAM. 51
Figure 4.13 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 256-QAM. 51
Figure 4.14 Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 1024-QAM. 52
Figure 4.15 Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 4-QAM. 54
Figure 4.16 Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 16-QAM. 54
Figure 4.17 Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 64-QAM. 55
Figure 4.18 Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 256-QAM. 55
Figure 4.19 Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 1024-QAM. . . . 56
Figure 4.20 Computational Complexity of Multicarrier Modulation Techniques. 58
Figure 4.21 Signal to interference ratio versus normalized time offset of Multicarrier Modulation Techniques. 60
Figure 4.22 Signal to interference ratio versus normalized frequency offset of Multicarrier Modulation Techniques. 60

LIST OF ACRONYMS

AMPS	Advanced Mobile Phone System
BER	Bit Error Rate
CDMA	Code Division Multiplexing Access
CP-OFDM	Cyclic Prefix- Orthogonal Frequency Division Multiplexing
DPSK	Differential Phase Shift-Keying
FBMC	Filter Bank Multicarrier
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
F-OFDM	Filtered Orthogonal Frequency Division Multiplexing
GMSK	Gaussian Minimum Shift-Keying
GPRS	General Packet Radio Service
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
ICI	Inter Carrier Interference
IoT	Internet of Things
ISI	Inter Symbol Interference
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Machine to Machine
MATLAB	Matrix-Laboratory
MMS	Multi Media Message Support
NMTS	Nordic Communication System
OFDM	Orthogonal Frequency Division Multiplexing
OoBR	Out of Band Radiation

OoS	Orthogonality of Sub-carriers
PAPR	Peak Average Power Ratio
PSD	Power Spectral Density
QoS	Quality of Service+
SC-OFDM	Single Carrier- Orthogonal Frequency Division Multiplexing
SIR	Signal to Interference Ration
SMS	Short Messaging Service
TACS	Total Access Communication System
TD-LTE	Time Division-Long Term Evolution
TDMA	Time Division Multiple Access
UFMC	Universal Filter Multicarrier
Wi-MAX	Worldwide – Interoperability for Microwave Access
WOLA	Weighted Overlap and Add

ABSTRACT

Currently, a known multi-carrier modulation technique which used in 4G wireless communication technology is Orthogonal Frequency Division Multiplexing. It has several advantages like ease of implementation, immunity to interference, high data rate. However, the rising users demand on wireless communication resulted needs for advancement of wireless communication system. The upcoming wireless communication technology is needed to be a system with low latency, very fast data rates, best quality of service and greater channel capacity. The present OFDM transmission not fulfil the requirements of 5G wireless communication system because of major drawbacks like out of band radiation and usage of cyclic prefix. To overcome the challenges of OFDM different modulation schemes like Filter Bank Multi-carrier with offset-Quadrature-Amplitude Modulation, Filter Bank Multi-carrier with Quadrature-Amplitude Modulation, Universal Filter Multi-carrier, Filtered-OFDM, and Weighted Overlap and Added-OFDM are proposed. In this study, the FBMC with QAM using Hermite prototype filter is proposed to overcome drawbacks of FBMC with QAM using PHYDYAS prototype filter. The performance of each multi-carrier techniques are analyzed based on power spectral density, computational complexity, bit error rate, spectral efficiency and signal to interference ratio. Simulation result shows that the power spectral density of FBMC with QAM using Hermite filter resulted 4.7dB reduction of out of band emission compared to FBMC with QAM using PHYDYAS filter. The bit error rate and the signal to interference ratio of the proposed system outperform than others.

Keywords: FBMC/OQAM, FBMC/QAM, F-OFDM, WOLA-OFDM, UFMC, OFDM.

CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

Wireless communication is the fastest-growing category in today's communication industry. It has attracted the users' interest. The wireless communication industry is currently expanding at the highest rate. The reason for the fast growth of the wireless communication technologies market is the rising number of subscribers(Patil et al., 2012). As a result, cellular networks are required to expand in order to meet the growing demand for wireless communication. In today's world, a cell phone is an essential tool, and its development is accelerating. The increasing load on existing wireless communication networks necessitates the improvement of wireless communication networks' data rates and reliability to cope with the ever-increasing mobile traffic. To satisfy the users need cellular network technologies have evolved from first-generation to fifth-generation and beyond (Chataut & Akl, 2020).

The first-generation wireless communication system was introduced in the early 1980s. Because of the use of analog technology, the signal provided by this system was an analog speech signal. The modulation and multiple access techniques used by the 1G system were frequency modulation (FM) and frequency division multiple access (FDMA). This generation of mobile networks provided data rates of up to 2.4 kbps. Due to excessive interference, the voice quality offered by the 1G technology was poor. Its transmission system was not secure; consequently, this necessitated the second-generation of wireless networks(Patil et al., 2012).

The second-generation wireless communication system emerged in the 1990s. It has been considered as the digital version of the 1G. It enabled short message service (SMS) and low-rate internet data access along with voice services. The multiple accesses used by this generation were Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA), along with Frequency Division Duplexing (FDD). Different modulation techniques were used by different countries. The modulation technique used for 2G in the United States and Japan was Differential Shift Phase Keying (DPSK) with raised cosine filtering, which is a non-constant envelop technique, whereas in Europe, Gaussian Minimum Shift-Keying (GMSK) was used. The data rates offered by this generation were from 14.4kbps up to 64kbps. 2.5G networks were introduced with data rates up to 384 kbps. The 2.5G system includes General Packet Radio Service (GPRS), Enhanced Data GSM Evolution (EDGE), and CDMA2000 (Kassaw et al., 2020).

The third-generation of wireless communication systems was introduced in the 2000s. This generation provided better advantages than the previous one. The services offered by this generation were web browsing on cell phones, integrated with voice, SMS, email, Multimedia Message Support, video downloading, picture sharing, and other smartphone technologies. The multiple access technique used by this generation was Code Division Multiple Access. The data rate provided by this generation was above 384kbps, but the system requires large bandwidth and complex infrastructure. Due to continuous demand for higher data rates, High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) were introduced in 3G networks to increase data rates. These types of networks are referred to as 3.5G networks, and they provide data rates of up to 2Mbps. 3.5G provided a higher data rate, but the implementation and the equipment were costly, and compatibility with 2G was very challenging(Sharma, 2013).

The fourth-generation wireless communication systems were introduced in 2010s. This generation offers data rates near to 100Mbps and can support more data traffic with advanced quality of service (QoS). It provided application such as online gaming, video conferencing and mobile television. This generation includes Wi-MAX, Long Term Evolution (LTE) and Long Term Evolution Advanced (LTE-A) and it has feasible functionality with previous generation networks (Chataut & Akl, 2020).

The fifth-generation wireless communication systems are starting to be implemented and expected as faster than that of current fourth-generation. This generation will provide data rate up to 10Gbps, greater reliability and low latency. It supports Internet of Things-enabled devices and smart vehicles. To meet the ongoing demands of 5G, effective wireless access technology is required that can boost throughput without requiring extra bandwidth or densifying the cell (Zhang et al., 2016).

Single carrier modulations and multi-carrier modulations are the two types of wireless communication systems modulation techniques currently available. Multi-carrier modulation divides the entire frequency channel to sub-carriers, and the high-rate data stream is split into numerous low-rate ones sent in parallel on sub-carriers, whereas single carrier modulation uses only one signal frequency to send data symbols. As a result, the symbol interval in multi-carrier modulations is longer than in single-carrier modulations, giving multi-carrier modulation systems a greater resistance to ISI than single-carrier modulation systems.

Single carrier modulations have some advantages over multi-carrier modulations. In single carrier modulation systems, the peak to average power ratio is very low, which is beneficial for system stability and the use of low-cost equipment in the design of wireless communication systems (Jiang et al., 2017). Single-carrier modulation systems are less

vulnerable to frequency shift and phase noise than multi-carrier modulation systems, making them ideal for communication systems, particularly paroxysmal point-to-point communication systems.

However, single-carrier modulations are less capable of dealing with multi-path fading channels than multi-carrier modulations, resulting in lower spectral efficiency. Higher bandwidths for single-carrier modulation systems indicate smaller symbol intervals, resulting in increased sensitivity to multi-path fading channels, making single-carrier modulation systems sensitive to ISI (Jiang et al., 2017). Complex multi-tap equalizers must be used to overcome the ISI, which adds to the complexity and cost. Multicarrier modulation has the ability to combat multi-path fading channels, which makes it popular.

The current 4G technology uses OFDM as multi-carrier modulation technique. In this modulation scheme a number of orthogonal closely spaced sub-carriers are used as data carrier. Because of the orthogonality of sub-carriers no need to insert guard band between each sub-carriers to avoid inter carrier interference (Kassaw et al., 2020). This modulation scheme uses cyclic prefix to avoid the interference between each symbols in turn reduce the spectral efficiency. This modulation scheme has high PAPR and poor out of band emission. Due to these demerits, OFDM can not be a promising, and capable technique for 5G and beyond wireless communication(Kishore et al., 2017).

5G and beyond technology has special differences compared to current OFDM. It supports internet of things enabled devices, machine to machine communication and smart vehicles, high speed data rate ranging up to 10Gbps and above(Patil et al., 2012).To achieve the requirements of future wireless communication different multi-carrier modulation techniques like Filter Bank Multicarrier (FBMC), Weighted Overlap and Added-OFDM (WOLA-OFDM), Filtered-OFDM (F-OFDM) and Universal Filter Multicarrier (UFMC) are proposed as candidate wave-forms.

Analysis of different multi-carrier modulation techniques are provided in (Kumar & Prasad, 2020; Kundrapu et al., 2019; Kishore et al., 2017). There are different performance metrics that used by different researchers to analyze the performance of multi-carrier modulation schemes like peak average power ratio, bit error rate, power spectral density, spectral efficiency, signal to interference ratio, computational complexity. However, most papers do not consider all performance metrics listed above to draw their conclusion. In this study the detailed analysis of candidate multi-carrier modulation schemes at higher order quadrature amplitude modulation like 64-QAM, 256-QAM and 1024-QAM are discussed.

1.2 Statement of the Problem

The data rate of fifth generation wireless communication system is needed to be faster compared to previous fourth generation to provide better services to subscribers. In the future a system with low energy consumption as well as cost is desired. The fifth-generation should enable machine to machine communication at ultra-low cost and ultra-high reliability while supporting long year of battery life. To enhance the requirement of 5G technologies like spectral efficiency, bandwidth and coverage it is better to research on the enabling technology of 5G technologies. The air interface includes wave-forms, multiplexing schemes, modulation schemes and coding schemes which used to reduce the latency in the air-link and to increase spectral efficiency, throughput, area capacity density and energy efficiency (Kumar & Prasad, 2020).

Currently, single carrier orthogonal frequency division multiplexing used for up-link and multi-carrier OFDM for down link. However, compared with multi-carrier modulations, single-carrier modulations are less capable of dealing with multi-path fading channels, which is a reason for the reduction of spectral efficiency. OFDM possess certain disadvantages like use of CP which costs on spectral efficiency of waveform, large side lobes which limits the utilization of spectrum. Also OFDM requires time synchronization to maintain the orthogonality between different users. Additionally, high peak-to-average ratio is also considered to be one of the biggest hurdles in OFDM which greatly reduce the performance, efficiency of non-linear OFDM amplifier (Mansour Shalaby et al., 2021). Therefore, OFDM is not likely to be considered for the next generation.

The drawbacks of OFDM in 4G wireless communication system should be solved for 5G wireless communication systems. Therefore, various types of modulation schemes have been proposed for 5G wireless communication instead of CP-OFDM. FBMC, UFMC, f-OFDM and WOLA-OFDM are some of proposed candidate modulation schemes for 5G. There is lack of comprehensive and fair comparison among these candidate waveforms. Based on this, we are motivated to study some of proposed candidate modulation schemes like FBMC, f-OFDM, WOLA-OFDM, UFMC. To obtain insightful analysis we will not only introduce the basic principle of the wave-forms but also reveal the characteristics of each waveform. Moreover, performance comparison made in terms of Power spectral density (PSD), Bit error rate (BER), Computational Complexity, Signal to Interference ratio. Performance analysis is validated by computer simulation employing MATLAB.

1.3 Objective

1.3.1 General Objective

The objective of this thesis is comparative analysis of multi-carrier modulation techniques with higher order QAM (F-OFDM, WOLA-OFDM, FBMC, UFMC) for 5G wireless communication system with that of OFDM.

1.3.2 Specific Objectives

Specific objectives of the study are:

1. To study the performance of OFDM technique by applying M-QAM (4-QAM, 16-QAM, 64-QAM, 256-QAM, 1024-QAM).
2. To analyze the Bit Error Rate performance of candidates of 5G multi-carrier modulation techniques by applying M-QAM (4-QAM, 16-QAM, 64-QAM, 256-QAM, 1024-QAM).
3. To improve the bit error rate performance of FBMC using prototype filter
4. To study the complexity of multi-carrier modulation techniques.
5. To analyze the performance of multi-carrier modulation techniques based on PSD, Spectral Efficiency and SIR.

1.4 Contribution of the Study

A well studied and organized research report on enabling technology of fifth-generation wireless communication will provide strong information on how to design a system with those system that fulfill the requirement of 5G standard. This thesis work is done on performance evaluation of candidate modulation schemes of fifth-generation wireless communication system and CP-OFDM also the bit error rate performance of FBMC-QAM is improved by using hermite filter as prototype filter. The candidate multi-carrier modulation techniques are analyzed under different performance metrics like, power spectral density, bit error rate, signal to interference ratio, spectral efficiency and computational complexity. In this work the bit error rate and power spectral density performance of filter bank multi-carrier is improved by adopting hermite as prototype filter of proposed work. Hermite filter not used for FBMC-QAM by any researcher at higher modulation order as per review of related work. Thus, this thesis work is help full to aware and assess the merit and drawbacks of each modulation schemes whether each candidate waveform fulfill the requirement of fifth-generation wireless communication or not and also to give direction for researchers to do more research.

1.5 Scope of the Study

The research area of new generation modulation schemes is broad and still on research by different researchers. The focus area of this study falls on the enabling waveform of fifth-generation, more specifically on new air interfaces which is new modulation schemes. OFDM has its own advantage and drawbacks. Because of the drawback in it, OFDM cannot be the candidate waveform for fifth-generation wireless communication system. To overcome the drawback of OFDM several alternative candidate modulation schemes have been intensively studied.

This thesis provides description of the most popular fifth-generation candidate modulation schemes and block diagram. The comparison of 5G candidate wave-forms done in terms of power spectral density, spectral efficiency, throughput, bit error rate, signal to interference ratio, computational complexity and peak average power ratio is also provided. The bit error rate of FBMC-QAM improved using hermite filter which enhance the system quality of service.

1.6 Limitation of the Study

This thesis limited to simulation of the system which is done using application software called MATLAB and simulation is undertaken on single user scenarios, by assuming all the available resource is used by single user. The implementation of the real system is difficult because of the availability of the component.

The bit error rate analysis of the proposed system is not good under channel model like pedestrian A, Extended vehicular A and Extended vehicular B channel models.

1.7 Thesis Outline

The outline of this thesis is summarized as follows:

Chapter 1 Introduction: This chapter mainly focuses on, background of the study, statement of the problem, objectives, contribution of the study, scope of the study and limitation of the study.

Chapter 2 Literature Review: This chapter mainly focuses on Introduction to 5G wireless communication, use case of 5G technology, requirements of 5G technology, key enabling technology of 5G and beyond, new air interfaces single carrier and multi-carrier modulation techniques and review of related works.

Chapter 3 Materials and Methods: This chapter mainly focuses on materials and methods used to accomplish the research work, multi-carrier modulation techniques, prototype filters and simulation parameters.

Chapter 4 Result and Discussion: This chapter mainly focuses on simulation

parameters, power spectral density comparison, bit error rate comparison, spectral efficiency comparison, computational complexity comparison and signal to interference ratio comparison.

Conclusion and Recommendation: This section mainly focuses on conclusion and recommendation for future work.

CHAPTER TWO
LITERATURE REVIEW

2.1 Chapter Overview

In this chapter, introduction to 5G wireless communication technologies, use case of 5G wireless communication technologies, requirements of 5G wireless communication technologies, key 5G enabling technologies, new air interfaces, single carrier and multi-carrier modulation techniques and related literatures on candidate waveform of 5G wireless communications that directly related to the objective of this study are reviewed.

2.2 Introduction to 5G Wireless Communications

Wireless communication refers to the transfer of data over a long distance without the need of wires, cables, or other electrical conductors. Wireless communication is a fairly wide term that covers all procedures and ways of connecting and communicating between two or more devices via wireless devices and networks employing a digital connection. It is a reliable and economical way of data and voice exchange (Chataut & Akl, 2020).

Cellular networks should be able to handle increased data traffic even while improving spectrum efficiency (Patil et al., 2012). 5G mobile networks are already being deployed, with the goal of being 100 times faster than current 4G networks. 5G networks will provide data rates of up to 10 Gbps, as well as low latency (measured in milliseconds) and increased reliability. Consider the possibility of downloading a high-definition movie in a fraction of a second (Zhang et al., 2016).

In today's world, there is a growing demand for wireless technological applications. This is increasing the stress on current wireless communication networks, necessitating the enhancement of data rates and reliability of wireless communication networks to cope with the ever-growing mobile traffic. Cellular networks have evolved from the first generation to the fifth generation and beyond to meet the demands of consumers.

The need to meet requirements has pushed each successive generation of mobile technology (Kassaw et al., 2020). The demand for 2G resulted from the need to have a system with high data rate and sufficient data communication than 1G support.[Review on Generation] Transition from 2G to 3G was mainly target to enable mobile internet. The transition from 3.5G to 4G service was offered users to access fast data speeds with lower latency rates.

Live broadcasting, self-driving cars, mobile television, mobile shopping, and other services have all become significant sources of income for service providers. From a resource usage perspective, the capability of 3G and 4G does not support these services (Series, 2015). The number of linked devices is rapidly expanding as a result of numerous new applications. To design a system that handles those devices focusing on increasing data throughput is not enough. As shown in figure 2.1, this technology can support a wide range of Internet of Things (IoT) enabled products and smart cars. To meet the ongoing demands of 5G, efficient wireless access technology that can boost throughput without expanding bandwidth or densifying the cell is needed.

From the combined work of several projects, a system with the best features is developed. The METIS (Mobile and Wireless Communications Enablers for the Twenty-First Information Society) project investigates 5G concepts and discusses the challenges (Zhang et al., 2016). The project 5th Generation Non-Orthogonal Waveforms (5GNOW) is focused with non-orthogonal waveforms for asynchronous signaling. Other 5G projects include Physical Layer Wireless Security (PHYLAWS), CROWD project, 5G project partnership, Samsung, and others (Bhushan et al., 2014).

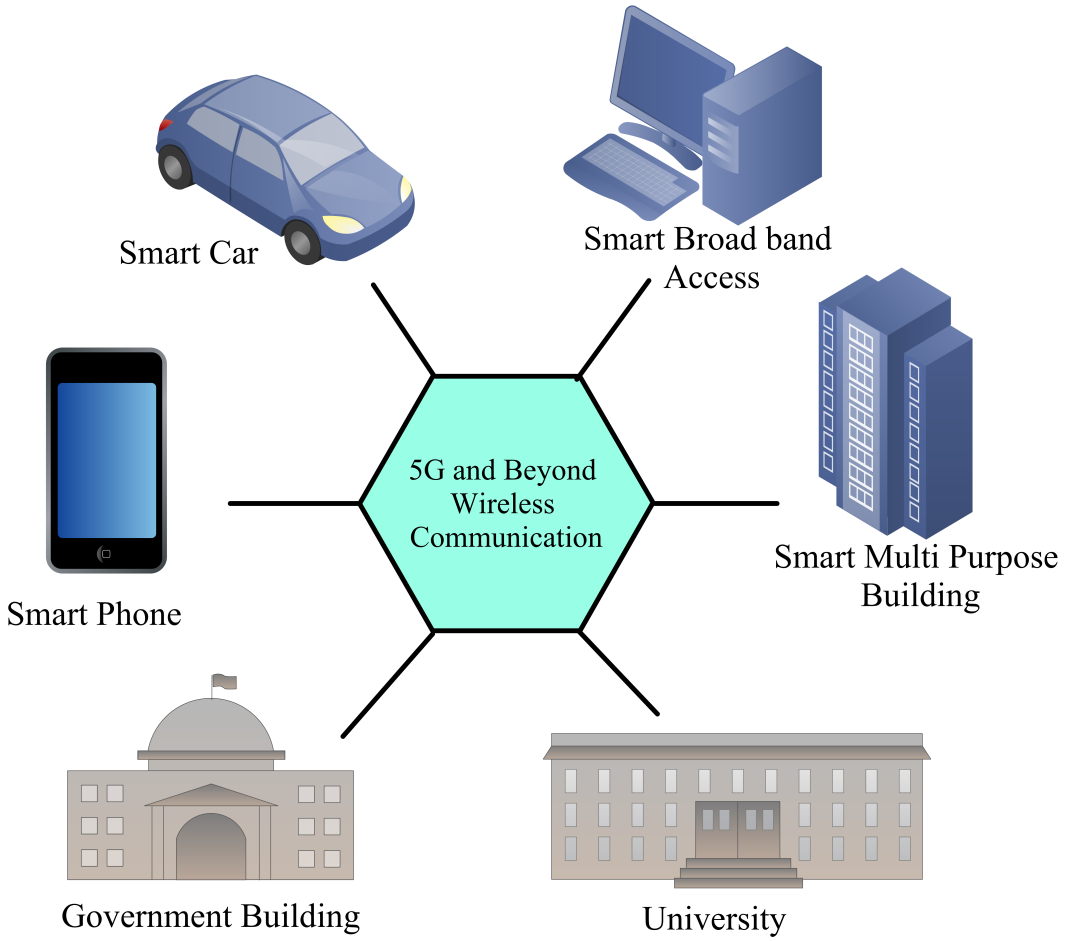

Figure 2.1: Different application of 5G technology (Chataut & Akl, 2020).

Fifth-generation wireless communication technology is the most recent in a series of

cellular network standards. Each generation (1G, 2G, 3G, etc.) is defined by a set of telephone network standards that describe how the system is implemented technologically. Excellent data rates, low latency, efficient signaling, high spectrum efficiency, improved energy economy, long battery life, and pervasive connectivity are just a few of the significant benefits of 5G.

2.3 Use Case of 5G Technology

The International Telecommunication Union (ITU) has developed a use case diagram for 5G technology. Enhanced mobile broadband (EMBB), massive machine type communication (MMTC), and ultra-reliable low latency communication (URLLC) are three of the key application categories of 5G technology, according to the ITU. Additional use cases, that are not currently foreseen, are expected to emerge. Flexibility will be required in the future of IMT in order to adapt to new use cases with a diverse set of criteria. Future IMT systems will provide a wide range of capabilities. Future IMT systems should be constructed in a highly modular fashion, depending on the conditions and various needs in different nations, so that not all functions are required to be included in all networks(Kassaw et al., 2020).

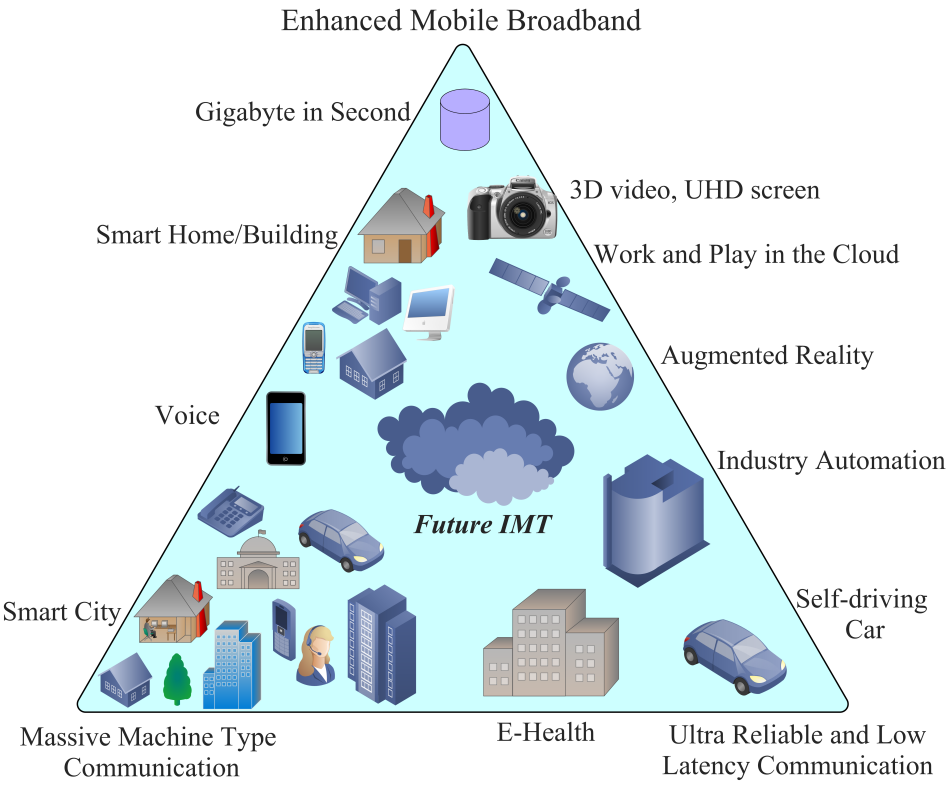

Figure 2.2: Use case diagram of Future IMT (Series, 2015).

The figure shows the use case of 5G like EMBB, MMTC and URLLC. Specific application that 5G technology must support is also provided in the future IMT.

2.3.1 Enhanced Mobile Broadband

Human-centric use cases for multi-media content, services, and data are addressed by Mobile Broadband. The increase in traffic volume is primarily due to the increase in data size and the number of applications that require higher data rates. The demand for mobile broadband will continue to rise (Metis, 2012), resulting in improved mobile broadband. In order to increase speed and provide a more seamless user experience, the EMBB usage scenario will include new application areas and needs in addition to existing mobile broadband apps. This use case includes a variety of scenarios, such as wide-area coverage and hotspot, each with its own set of needs. A large traffic capacity is required in a region with a high user density in case of hotspot. In the case of wide-area coverage, seamless coverage and medium to high mobility are required, as well as a significantly enhanced user data rate as existing rates. However, in comparison to a hotspot, the data rate requirement may be relaxed.

As more devices connect to the internet, different streaming services such as music and video, interactive video and mobile internet connectivity will become more widely used. Many of these applications demand constant connectivity in order to give users with real-time information and notifications (Farhang-Boroujeny, 2011). In addition, cloud storage and applications for mobile communication platforms are rapidly developing. This can be used for both work and pleasure. Based on these factors, 5G is expected to provide EMBB of up to 10,000 times present network capacity and peak throughput of 10 Gbps(Kassaw et al., 2020). EMBB must handle a much larger range of code rates, code lengths, and modulation orders than LTE due to its requirements (Series, 2015).

2.3.2 Massive Machine Type Communications

This use case is composed of a large number of linked devices typically transmitting a low amount of non-delay sensitive data, as the name suggests. It is designed to handle massive-machine networks in order to enable the Internet of Things (IoT) at home and in the workplace. Every device is required to be cost effective i.e. low cost and have very long battery life.

In the last few years, the number of mobile devices such as phones, tablets, and smart watches has grown massively, and at the same time, new applications such as video streaming/downloading and multiplayer gaming that need a considerable amount of bandwidth have emerged. (Luo & Zhang, 2016) In addition, dense wireless sensor networks will be implanted in smart cities and smart houses, frequently referred to as smart society. Household products such as refrigerators, stoves, heating systems, and even clothing are increasingly being developed as ”smart devices” that can communicate with other devices over the internet. Many of these services only necessitate the

transport of a small amount of data among the devices in a big network.

Internet of Things (IoT), are growing by incorporating various types of devices in both household and commercial environments. By 2020, the industry estimates that 50 billion potential IoT devices will be in use (Series, 2015). This type of technology requires very low power consumption, cheap cost, the ability to manage a high number of connections, and good scalability (Luo & Zhang, 2016). The challenge for 5G will be to combine the administration of all of these connected devices.

2.3.3 Ultra Reliable and Low Latency Communications

The most important capabilities for this use case are throughput, latency, and availability. This category comprises innovative services like remote control of vital infrastructure, self-driving vehicles, smart-grid control, industrial automation, drone control and coordination, and others that will transform industries with ultra-reliable/available low-latency communications (Series, 2015). Wireless control of industrial manufacturing or production processes, remote medical surgery, smart grid distribution automation, transportation safety, and so on is some examples.

Wireless mobile communications have become increasingly important for industrial applications in industrial automation. Wires are costly to build and maintain, so the possibility of replacing them with re-configurable wireless links attracts to a wide range of sectors (Kassaw et al., 2020). To achieve this, the wireless connection must have a similar delay, dependability, and capacity to those of cables, as well as be easier to manage. A smart grid can be thought of as an additional network with minimal latency. A smart grid connects sensors that use digital information to automate energy usage and distribution, including gas and heat. Low latency and very low error probabilities are two new objectives that 5G must meet (Huawei, 2015).

2.4 The Requirements of 5G Technology

The use cases and vision of the 5G technology leads to requirements that the future mobile broadband system will need to meet (Series, 2015), (Osseiran et al., 2014) . Some of 5G wireless network requirements are as follows.

Peak Data rate: The maximum theoretically attainable data rate that can be assigned to a single mobile station under error-free conditions when all available radio resources are used for the relevant link is the peak data rate. The minimum peak data rate is 20 Gbps.

Areal Capacity: The 5G radio access network should be able to scale-up system capacity by adding additional cells in a target area, which is estimated to be up to 10 Mbps/m2, in order to support the rapid increase in future mobile data traffic.

Energy Efficiency: The design of 5G radio access technology should aim for improved energy efficiency in order to offset the 100 times increase in device/network energy consumption required for 5G wireless communications compared to 4G.

Massive Connectivity: 5G connectivity is not always limited to mobile devices. Instead, every single unit with a modem function will connect to each other for reasons such as safety, communication, and a more comfortable existence. 5G is estimated to have 10 times more concurrent IoT interconnections than 4G.

Table 2.1: Requirements of 5G Technology

Requirements	**Desired Values**	**Application Example**
Data rate	1-10Gbps	Virtual Reality
Data Volume	9Gbytes/hr in busy period	Dense urban information society
Latency	Less than 5ms	Traffic efficiency and safety
Connected Device	300,000 devices per AP	Massive deployment of devices
Battery Life	One decade	Massive deployment of devices

2.5 Key Enabling Technology of 5G and Beyond

To make 5G and beyond networks a real, many technologies have been developed and explored in recent years. The major key enabling technologies that have been considered for 5G and beyond systems include millimeter waves, small cells, beam forming, device-centric architecture, full-duplex technology, massive MIMO, Terahertz wave, and visible light spectrum (Chataut & Akl, 2020).

2.5.1 Millimeter Waves

Cellular communication occurs at frequencies below 6 GHz, while services such as medical imaging, microwave remote sensing, amateur radio, terahertz computing, and radio astronomy occur at frequencies above that. The radio frequency spectrum has been congested as a result of the tremendous rise in data transmission. As a result, a user's bandwidth is limited, resulting in a slower and less reliable connection. Using a frequency over 6 GHz for wireless communication is one technique to solve this problem. There has been a lot of research into broadcasting millimeter waves at frequencies above 6 GHz, and it has never been used for wireless communication. Millimeter waves have a frequency range of 30 GHz to 300 GHz, and their length varies from 1 to 10 mm, as opposed to the tens of centimeters employed in today's mobile communication systems(Chataut & Akl, 2020).

In the last few years, many aspects of millimeter waves have been documented (Wu et al., 2015; Rangan et al., 2014; Wang et al., 2018). The authors of (CHAKRABORTY et al., 2018), explored the millimeter-wave technology's potentials and problems. The paper by (CHAKRABORTY et al., 2018) discusses the future of the 5G network using millimeter wave technology. The bandwidth of millimeter waves can be ten times that of the entire 4G cellular band. These high-frequency waves have been used in satellite applications, but not for mobile broadband. Millimeter wavelengths are not appropriate for long-range applications because to their reduced wavelength. Another issue with millimeter waves is that they cannot pass through buildings or obstructions and are absorbed by rain.

2.5.2 Sub-Millimeter or Terahertz Band

The wireless market is quickly developing as a result of globalization. With the idea of 6G networks, a greater spectrum will be required for near future. Wireless communication could be carried out at frequencies greater than millimeter-wave (30 GHz–300 GHz). Terahertz refers to the frequency range between 300 GHz and 3 THz. Despite the fact that this concept is still in its infancy, study in this area could be beneficial to the wireless communications industry. Apart from having a larger spectrum, the THz band has other advantages, including interference-free deployment, scalability, better security, green field spectrum availability, and low power consumption, front-haul boost for wireless networks, reduced antenna sizes, and focused beams (Singh et al., 2019).

THz technology could be useful in imaging, spectroscopy, holographic telepresence, industrial, and large-scale communications, among other things. Complex antenna design to accommodate higher antenna gain, access point specification and deployment, sophisticated circuit design, high propagation loss, and complex mobility management are all problems and new fields of research in THz band installations (Singh et al., 2019).

In recent years, the concept of ultra-massive MIMO (UM-MIMO) has evolved, which uses plasmonic materials to build antennas and transceivers to achieve THz band capacity. Nano antennas and transceivers can be made out of materials like graphene and metamaterials. The THz band can be used with these micro antennas and transceivers (Jornet & Akyildiz, 2014).

These small antennas and transceivers can be used in UM-MIMO to increase spatial multiplexing and beamforming. As a result, spatial multiplexing and beamforming can improve data speeds and communication range, respectively. THz UM-MIMO for 5G and future networks will require a significant amount of research. Fabrication of plasmonic nano array antennas, channel estimation, precoding, signal recognition,

beamforming, and beamsteering are some of the problems (Faisal et al., 2020).

2.5.3 Small Cells or Heterogeneous Networks

Small cells are low-power, tiny base stations that may be positioned every 100 meters to cover small geographic areas. In densely populated locations, these low-power base stations keep the signal from dropping. Because tiny cells are light and small, they may be placed almost anyplace. If millimeter waves are used instead of the typical sub-6 GHz spectrum, the small cell can be made much smaller and fitted into increasingly small places (Sudarshan et al., 2006). Small cells will be critical for delivering 5G's high-speed mobile broadband and ultra-low latency. Small cells are further classified into microcells, femtocells, and picocells based on their coverage area and number of users.

2.5.4 Beamforming

The capacity of the base station to adjust the antenna's emission pattern is known as beamforming (Molisch et al., 2017). As shown in Figure 6, beamforming helps the base station in finding an appropriate route to provide data to the user even while reducing interference with other users along the way (Yang et al., 2018). Beamforming provides a number of benefits in 5G networks and beyond. Beamforming technology can be utilized in future networks in a variety of ways, depending on the situation. Beamforming serves to increase spectrum efficiency in massive MIMO systems, and it helps to raise data rate in millimetre waves (Yang et al., 2018).

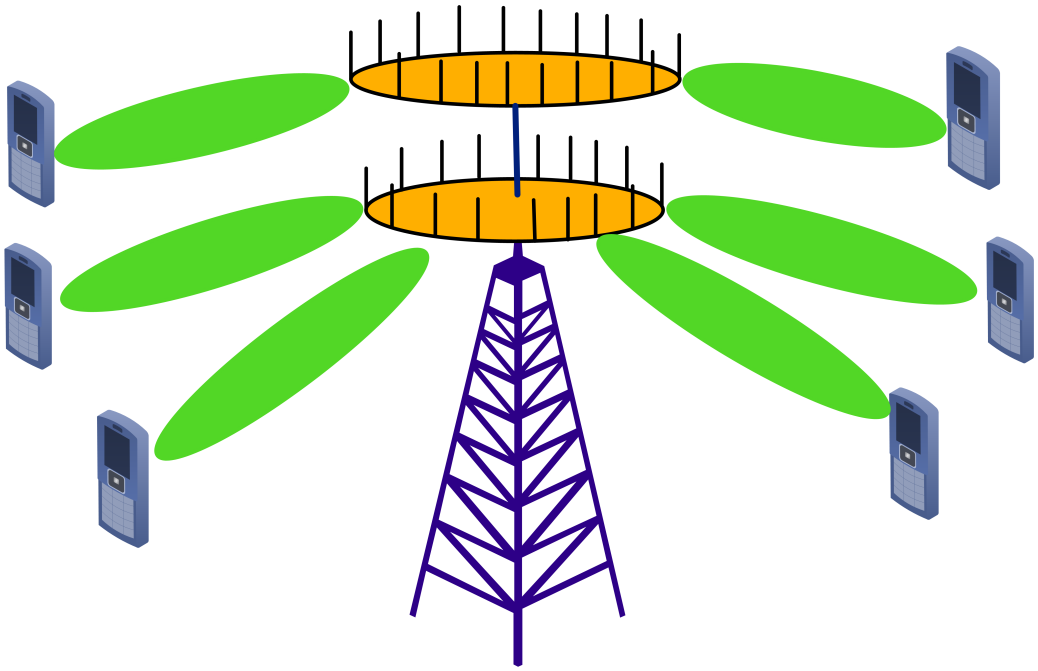

Figure 2.3: Uplink and Down link structure of Massive MIMO (Chataut & Akl, 2020). The base station in massive MIMO systems can provide data to the user over several paths, and beamforming coordinates packet movement and arrival time to allow nu-

merous users to contribute data at the same time. Because millimeter waves are unable to pass through obstacles and do not propagate over long distances due to their shorter wavelength, beamforming is used to direct concentrated beams towards users. As a result, beamforming assists a user in receiving a strong signal while avoiding interference from other users.

2.5.5 Device Centric Architecture

The present 4G system is based on a base station-centric architecture, in which a device obtains services from the base station via downlink and uplink connections, as well as control and data channels. Cell density or base station density is quickly increasing as the number of users grows (Boccardi et al., 2014), and this network densification will necessitate big modifications in the 5G and beyond networks. In addition, the introduction of millimeter waves will allow numerous frequency bands with vastly differing propagation properties to coexist.

To address difficulties such as network densification and increasing frequency bands, a base station-centric architecture may evolve into a device-centric architecture in future networks. A user device would communicate in a device-centric design by transferring information through numerous heterogeneous nodes (Biswash et al., 2014). Reference (Mishra et al., 2016) summarizes many studies on the benefits of device-centric architecture for 5G networks.

2.5.6 Full Duplex Technology

To avoid interference, wireless transmission and reception are usually not done at the same frequency bands. To obtain orthogonal non-interfering signals, every bidirectional system must split the uplink and downlink channels using the time or frequency domain. As seen in Figure 2.4, full duplex refers to simultaneous transmission and reception across the same frequency band and at the same time.

Full-duplex signal transmission will be used in 5G networks to potentially increase network capacity and benefit higher tiers (e.g., MAC layer). Full-duplex technology has the downside of increasing signal interference through troublesome echo (Mahmood et al., 2017). Several research on full-duplex technology and its benefits for 5G networks have been undertaken (Bai et al., 2019).

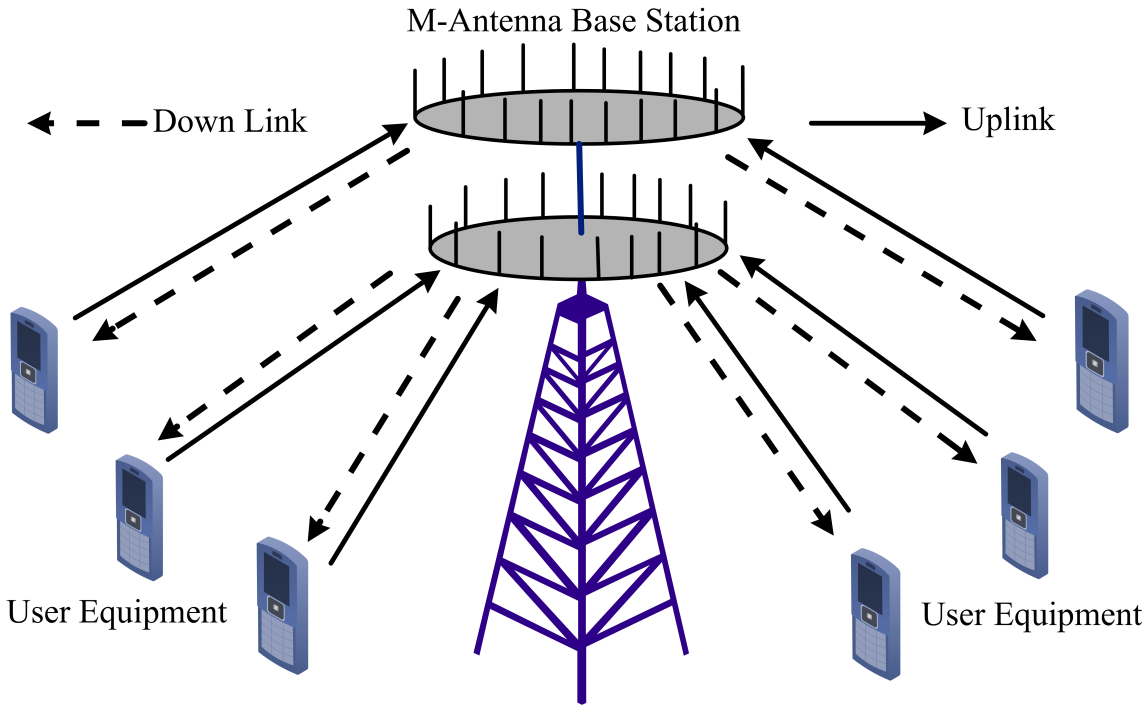

Figure 2.4: Full Duplex Technology (Chataut & Akl, 2020).

2.5.7 Visible Light Communications

For future generation networks, Visible Light Communication (VLC) provides optical fiber-like performance. It transmits the signal across a shorter distance utilizing visible light between 400 and 800 THz, employing both fluorescent lamps and LEDs. VLC can be developed with very low-cost hardware and can use the unlicensed spectrum. VLC does not generate any electromagnetic radiation; hence it is not exposed to it from outside sources. Because this technique necessitates the use of a light source, it is best suited to indoor applications. IEEE 802.15.7 defines a VLC standard, although the 3rd Generation Partnership Project (3GPP) has not examined it for cellular networks (Giordani et al., 2020). VLC has been identified as one of the main enabling technologies for 6G networks, and it would be highly valuable for smart city applications.

2.5.8 Massive MIMO

MIMO systems are an important aspect of today's wireless networks, and they have been employed widely in recent years to attain high spectral and energy efficiency. Prior to the development of MIMO, single-input-single-output systems were often used, which had low throughput and could not reliably accommodate a large number of users.

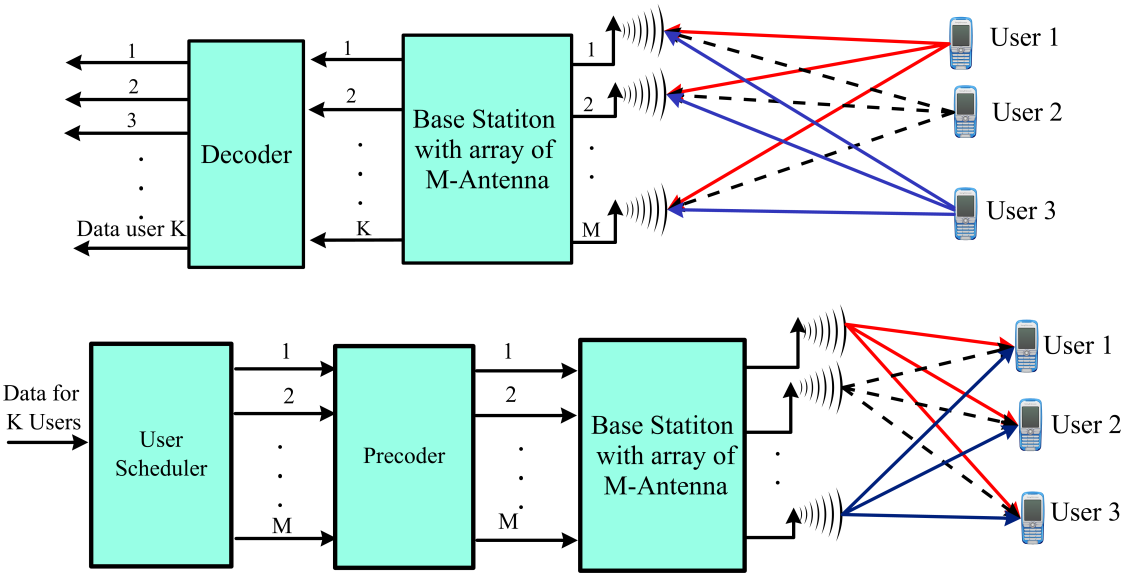

Figure 2.5: Uplink and Down link structure of Massive MIMO (Chataut & Akl, 2020).

Various innovative MIMO technologies, such as single-user MIMO (SU-MIMO) (Adnan et al., 2016), multi-user MIMO (MU-MIMO) (Giordani et al., 2020), and network MIMO (Chataut & Akl, 2020), have been developed to meet this increasing user demand. These new technologies, however, are insufficient to meet the ever-increasing needs. In the last few years, the number of wireless users has exploded, and these users generate trillions of bytes of data that must be handled efficiently and reliably.

There are also billions of Internet of Things (IoT) devices contributing to data traffic, with varied applications in smart health care, smart homes, and smart energy. By the end of 2020, there are expected to be over 50 billion linked devices. Current 4G/LTE MIMO technologies are unable to handle this massive flood of data traffic with greater speed and reliability. As a result, massive MIMO technology is being considered by the 5G network as a possible solution to the problem of large data traffic and users (Giordani et al., 2020). Massive MIMO systems and their benefits have been the subject of several research (Chataut & Akl, 2020).

Massive MIMO is the most exciting wireless access technology for 5G and beyond. Massive MIMO is a development of current MIMO systems used in wireless networks that aggregates hundreds or even thousands of antennas at the base station and serves tens of users at the same time (Paulraj & Kailath, 1994). Massive MIMO's more antennas will help focus radiation into a smaller area of space, improving spectral efficiency and throughput.

Figure 2.5 depicts the massive MIMO down-link and up-link systems. In a massive MIMO system, as the number of antennas rises, the radiated beams get narrower and more spatially concentrated toward the user. Figure 10 depicts the beam patterns for various antenna setups. These spatially concentrated antenna beams boost per-

formance for the intended user while reducing interference for nearby users (Paulraj & Kailath, 1994). Massive MIMO has a number of advantages over standard MIMO systems (Nojima et al., 2012).

2.6 New Air Interfaces

Adaptive waveform, adaptive protocols, adaptive frame structure, adaptive coding and modulation family and adaptive multiple access schemes are among the building elements and configuration mechanisms of the new air interface. The air interface can accept a wide range of user services, spectrum bands, and traffic volumes using these blocks and processes (Huawei, 2015). The novel air interface architecture may significantly improve spectral efficiency, increase connectivity, and minimize latency, allowing for the deployment of customized IoT and high-bandwidth-consuming scenarios like virtual reality. Another essential technology for the 5G network is new multiple access technology, which comprises both orthogonal and non-orthogonal multiple accessing.

2.6.1 Non-orthogonal multiple access (NOMA)

Various NOMA methods have been developed to handle a large number of and significantly varied types of users and applications in 5G networks. NOMA is a multiplexing technique that uses power and/or code domains to accommodate additional users in the same resource block. Proposed power-domain NOMA, code domain NOMA, and NOMA multiplexing in multiple domains are three key types of NOMA that are considered potential MA schemes for 5G networks (Sahin et al., 2013).

Multiple users can share the same time/frequency/code resource block with power-domain NOMA because their power levels are different. In contrast, by allocating various codes to different users, code domain NOMA can enable several transmissions within the same time-frequency resource block. Rather than multiplexing signals in a single domain, multiplexing in various domains, such as the power domain, code domain, and spatial domain, has been proposed (Chen et al., 2016).

2.6.2 Orthogonal multiple access (OMA)

All previous and contemporary wireless networks use OMA as a basic component. The resource blocks in these systems are orthogonally partitioned in time, frequency, or code domains, resulting in minimum interference between adjacent blocks and very simple signal detection. OMA is considered as an enabling technology for 5G with novel modulation methods (Sahin et al., 2013). Pulse shaping, sub-band filtering, precoding, guard interval (GI) shortening, and mapping symbols in the delay-Doppler domain are some of the numerous types of modulation techniques for OMA that are based on diverse principles (Chen et al., 2016).

2.7 Single Carrier and Multicarrier Modulation Techniques

The focus of this thesis is on 5G enabling technologies, notably modulation techniques for the new air interface. Single carrier modulations and multi-carrier modulations are the two types of wireless communication systems modulation techniques currently available (Jiang et al., 2017). Multi-carrier modulation divides the entire frequency channel into many sub-carriers, and the high-rate data stream is divided into numerous low-rate ones transmitted in parallel on sub-carriers, whereas single carrier modulation uses only one signal frequency to send data symbols.

Single – carrier modulation techniques have a long historical background and widely used in many wireless communication systems, including conventional 1G, 2G, 3G wireless communication systems and the uplink of 4G wireless communication system. Single carrier modulation techniques has lower peak average power ratio (PAPR) compared to multi-carrier modulation techniques (Jiang et al., 2017). Having low PAPR is essential for the stability of the system and adoption of low cost devices in the design of wireless communication system. Single carrier modulation techniques are less sensitive to frequency shift and phase noise. This makes them easier for the time and frequency synchronization. Due to these advantages single carrier modulation techniques are still deployed in 4G standard.

However, compared with multi-carrier modulations, single-carrier modulations are less capable of dealing with multipath fading channels, resulting in less spectral efficiency. Wireless communication systems are becoming more and more broadband due to the development of technology. Single carrier modulation becomes less efficient when the bandwidth of communication system is higher, because the symbol interval becomes smaller which leads to higher sensitivity to multipath fading. Multipath fading makes a system with single carrier modulation techniques to be vulnerable to inter symbol interference (ISI). To overcome the ISI complex multi-tap equalizer have to be employed, which leads to high complexity and cost (Jiang et al., 2017).

Currently, multi-carrier modulation systems are attracting more and more attentions due to their ability to fight against multipath fading channel. Multicarrier Modulation (MCM) is an efficient method for transmitting information over a linearly distorted channel. Its basic idea is to divide the channel spectrum into parallel, narrowband sub-channels. Therefore, the symbol interval in multi-carrier modulations is longer than that of single-carrier modulations, which gives multi-carrier modulation systems stronger ability against the ISI than single-carrier modulations. Multicarrier signalling offers the advantages of simpler equalization, immunity to impulse noise and flexibility in allocating sub-channels.

Different multi-carrier modulation techniques have been studding by different researchers. In this thesis we have chosen waveforms that got most attention by different researchers. Those wave forms are OFDM, F-OFDM, WOLA-OFDM, FBMC/OQAM, FBMC/QAM, and UFMC. We have analysed the performance of these wave forms using different performance metrics and also we have improved the performance of FBMC/QAM by using Hermit filter as prototype filter for multi-carrier modulation. The related works of different researchers are provided in next section.

2.8 Review of Related Works

Comparative Analysis of OFDM, FBMC, UFMC and GFDM for 5G Wireless Communications provided in (Kumar & Prasad, 2020). The bases for the comparison were PAPR, BER, OOBR, latency and spectral efficiency. This article review the 5G candidate waveform generations, hardware requirements. They try to address merit and drawbacks of each waveform for better comparison. The evaluated waveform has their own advantages and demerit, consequently research is going on their problems existing in the present day and potential applications in future communications. The study shows the basic principle operation of various MCM system, hardware requirement and comparative analysis of PAPR, BER, OOBR, latency and spectral efficiency for 5G communications. The outcomes of literature survey, clearly shows that existing result partially supported for 5G technology. This paper limited to PAPR, BER, PSD, latency and spectral efficiency but complexity aspect not addressed.

Peak to Average Power Ratio and Bit Error Rate Analysis of MultiCarrier Modulation Techniques is studied in (Jeffery et al., 2020). The multi-carrier modulation techniques that compared in this paper were OFDM, SC-OFDM and FBMC. The Poly-Phase Networking (PPN) filter banks are used in the implementation of FIR filters in FBMC. This in turn decomposes the wideband signals into a narrowband signal, resulting in lower PAPR of the whole system. Parameters like Signal to Noise Ratio (SNR), BER, PAPR are used as performance metrics to analyze OFDM, SC-FDMA and FBMC. Performance Metrics are compared across various channels like Rayleigh, Rician and Double Selective and their influence on the modulation techniques but complexity, signal to interference ratio and spectral efficiency analysis not addressed.

Comparative Performance Analysis of Modulation Formats for 5G Wireless System is provided in (Kassaw et al., 2020). In this research the modulation schemes of 5G wireless system like FBMC, UFMC are compared to that of CP-OFDM. The performance metric used to compare these modulation formats were BER, spectral efficiency, power spectral density and computational complexity. They provided the basic principle of the waveform and also revealed the characteristics of each wave forms. This research

shows some drawback of CP-OFDM and the potential candidate modulation format that overcome the limitation of CP-OFDM. The research is limited to performance metrics like BER, spectral efficiency, PSD and computational complexity and SIR, and the like aspect not addressed and also other modulation formats for 5G.

Characteristic Analysis of OFDM, FBMC and UFMC Modulation Schemes for Next Generation Wireless Communication Network Systems is provided in (Kundrapu et al., 2019). The basis for comparison were spectral efficiency, bit error rate, peak average power ratio by utilizing various sub-carriers and modulation techniques. The results evidently prove that the spectral efficiency is quite insufficient in the case of OFDM. FBMC and UFMC prove to be highly fictional and the drawbacks in the previous case are neutralized by the usage separate filters for each sub-carrier which further increases the PAPR value (Abdel-Atty et al., 2020). On advanced analysis we derive to conclusions that UFMC waveform technique is preferable for 5G on considering the value of PAPR. Optimization will add to the betterment of the situation. They studied the spectral efficiency, power spectral density, Peak to Average Power Ratio and performance in terms of bit error rate in practical senses but signal to interference ratio, complexity aspect not addressed.

Comprehensive analysis of UFMC with OFDM and FBMC is provided in (Kishore et al., 2017) in terms of peak average power ratio by applying different sub-carriers and modulation techniques. They try to address the advantage and drawback of OFDM and proposed FBMC and UFMC are the candidate waveforms that overcome the shortcomings of OFDM. The benefits of UFMC and FBMC are partially presented in it. They proposed UFMC as best choose. In this paper analysis is limited to PAPR but PSD, complexity, BER aspects not addressed.

In (Zayani et al., 2016) WOLA-OFDM: a potential candidate for asynchronous 5G investigated the performance in relaxed synchronization scenario, of a new contender waveform making its appearance recently named Weighted Overlap and Add based OFDM (WOLA-OFDM). In this paper they compared cyclic prefix OFDM with WOLA-OFDM and UFMC. The bases for comparison were power spectral density, bit error rate and mean square error. The study shows that WOLA-OFDM could be a promising candidate wave form, outperforming both CP-OFDM and UFMC in any synchronous scenario. This paper limited to parameter like MSE, BER and PSD but complexity, signal to interference ratio, spectral efficiency aspects are not addressed.

Implementation of a 5G Filtered-OFDM Waveform Candidate and FBMC-New Multicarrier Modulation Technique is provided in (Ramadhan, 2019). OFDM is the basic multi-carrier modulation technique for both wireless and cellular communications. OFDM is a perfect choice for point-to-point communication, which offers minimum

complexity and achieves very high bandwidth. However, it has several challenges such as, limited spectral efficiency and large out of band emissions. In order to overcome these challenges, there are several modulation techniques being developed in these days, among these Filter Bank Multi Carrier (FBMC) is one of the techniques.

These paper describes about PSD and BER of the FBMC, conventional Cyclic Prefix based Orthogonal Frequency Division Multiplexing systems and F-OFDM under Additive White Gaussian Noise channel. FBMC technique has less out of band emissions as a result of less number of side lobes. Meanwhile, the omission of CP improves the bandwidth efficiency of the system.

Table 2.2: Contribution and gap of different related works.

Title	Contribution	Gap
Comprehensive analysis of UFMC with OFDM and FBMC (Kishore et al., 2017)	The analysis is focused on peak to average power ratio by applying different sub-carriers and modulation techniques	PSD, complexity, BER aspects not addressed.
Peak to Average Power Ratio and Bit Error Rate Analysis of MultiCarrier Modulation Techniques (Jeffery et al., 2020).	Performance Metrics are compared across various channels like Rayleigh, Rician and Double Selective and their influence on the modulation techniques	complexity, signal to interference ratio and spectral efficiency analysis not addressed
Characteristic Analysis of OFDM, FBMC and UFMC Modulation Schemes for Next Generation Wireless Communication (Kundrapu et al., 2019)	The analysis is focused on spectral efficiency, bit error rate, peak average power ratio by utilizing various sub-carriers and modulation techniques	The signal to interference ratio and complexity of aspect not addressed.
Comparative Analysis of OFDM, FBMC, UFMC and GFDM for 5G Wireless Communications (Kumar & Prasad, 2020).	The bases for the comparison were PAPR, BER, OOBR, latency and spectral efficiency.	The complexity aspect not addressed.
Implementation of a 5G F-OFDM and FBMC Modulation Techniques (Ramadhan, 2019)	Wave-forms like F-OFDM and FBMC studied	Other wave forms that have comparable performance like WOLA-OFDM, UFMC not addressed

CHAPTER THREE
MATERIALS AND METHODS

3.1 Introduction

This chapter mainly focuses on materials and methods used to accomplish the research work, multi-carrier modulation techniques, prototype filters and simulation parameters.

3.2 Materials

Software materials used in this thesis are MATLAB R2021a, Concept Draw Office, and TeXstudio. Concept Draw Office are used to draw block diagrams, figures. MATLAB R2021a, which is a computing software that consists of Editor, which is used to write a code for entire system. TextStudio, is an integrated writing environment. It is writing tool which is recommended to write mathematical equations.

3.3 Methods

First we reviewed literature and identified the research gap, collected the data that are directly related to the research problem, the collected data are studied and analyzed, then we have tried to understand the concept of the problem clearly and designed the system model, then simulated the designed system on MATLAB. From simulation result we recommended the best solution for particular and specified case according to scientific research method.

3.4 Multicarrier Modulation Techniques

A general block diagram of multi-carrier modulation techniques can be represented as shown in figure 3.1. Multicarrier modulation systems divide the whole frequency band into many sub-carriers and the high-rate data stream is divided into many low rate data streams to transmit in parallel on sub-carriers (Kassaw et al., 2020). Therefore, the symbol interval in multi-carrier modulations is longer than that of single-carrier modulations, which gives multi-carrier modulation systems stronger ability against the ISI than single-carrier modulations.

The information bits arrive at the input are a rate of R bits/s. In the first block, the information bits are collected in group of $\log_2 M$ bits and mapped to symbols from M-QAM constallation and forwarded to the next block at the symbol rate of $R_s = \frac{R}{log_2 M}$ symbols/second (Kassaw et al., 2020). F-OFDM, UFMC, WOLA-OFDM, FBMC/OQAM, FBMC/QAM are the expected future generation modulation techniques.

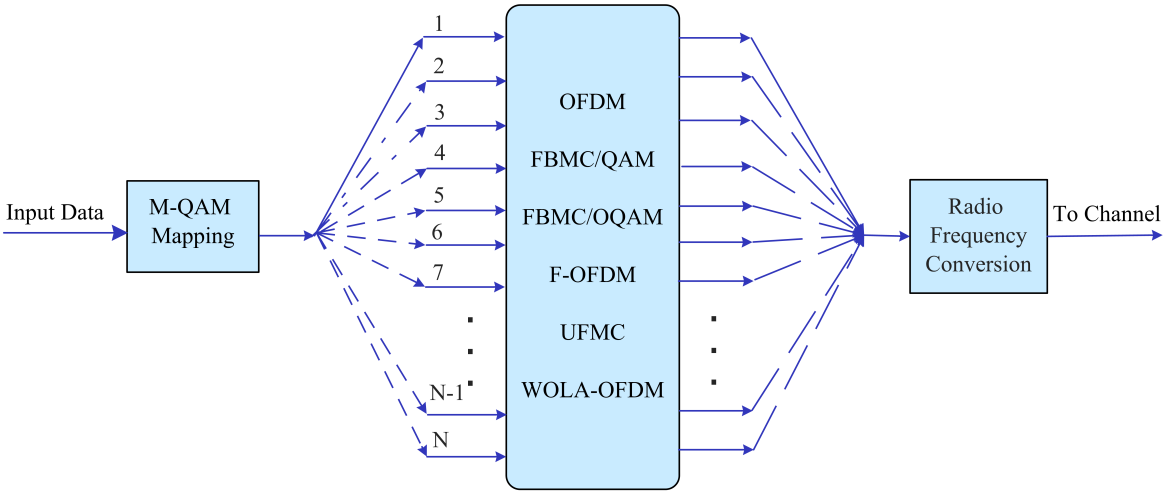

Figure 3.1: The General System Model for Multicarrier Modulation Techniques (Kassaw et al., 2020).

3.4.1 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multicarrier transmission method that divides the frequency band in to a number of sub-channels. It consists of IFFT and FFT block in both transmitter and receiver respectively. The mathematical expression of OFDM signal which obtained from modulated N sub-carriers can be expressed as in (Kassaw et al., 2020)

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

where, $for \;\; 0 \leq t \leq T_s$, d_n is complex data symbol which modulates the N^{th} sub-carrier at the modulation interval, while T_s is the time duration of OFDM symbols which is $T_s = NT_d$ and T_d is the serial symbol duration.The orthogonality of the sub-carrier is ensured, if the distance between neighboring sub-carrier frequencies equal and sub-carriers are located as in (Kassaw et al., 2020)

$$f_n = \frac{n}{T_s} \qquad for \; n = 0, 1, 2, ..., N-1 \tag{3.2}$$

The output of the channel, after radio frequency conversion, is the received signal $r(t)$ obtained from convolution of $s(t)$ with the channel impulse response $h(t)$ and addition of a noise signal $w(t)$ as in (Kassaw et al., 2020)

$$r(t) = \int_{\infty}^{\infty} s(t-\tau)h(\tau, t)d\tau + w(t) \tag{3.3}$$

The discrete time representation of the received signal with noise represented as follows as in (Kassaw et al., 2020)

$$\begin{aligned} r[n] &= h[n] * s[n] + w[n] \\ &= \sum_{u=0}^{T-1} h[\tau] s[n - \tau_u] + w[n] \end{aligned}$$

The output of the FFT is the multi-carrier demodulated sequence N complex valued symbols (Bendimerad et al., 2021)

$$d_n = \sum_{k=0}^{N-1} r_k e^{-(\frac{j2\pi nm}{N})} \qquad for\ n = 0, 1, 2, ..., N-1 \tag{3.4}$$

Generally time domain expression of OFDM is given as in (Bendimerad et al., 2021)

$$X_{OFDM}(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \times \Pi(n) \times e^{-(\frac{j2\pi nm}{N})} \qquad for\ n = 0, 1, 2, ..., N-1 \tag{3.5}$$

where, x_k denoted the complex symbols that emanate from a given constellation,$\Pi(t)$ denote the rectangular waveform filter and N the number of sub-carriers.

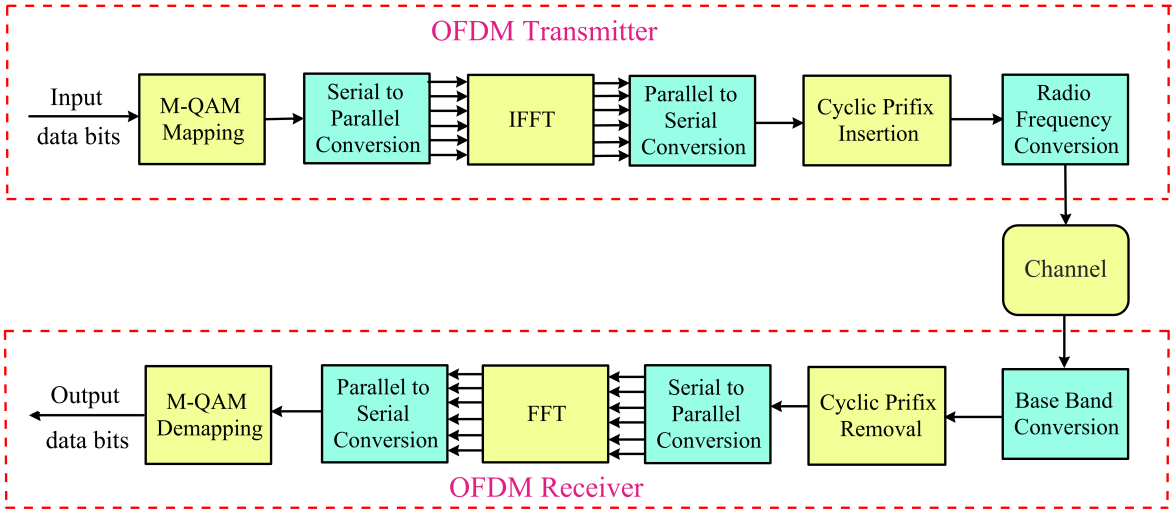

Figure 3.2: Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021).

Figure 3.2 shows that the digital data bits are mapped to complex symbols QAM. These data symbols are converted to N streams which correspond to sub –carrier frequencies by serial to parallel convertor. Then it passes through IFFT to produce time sequence of the streams. In OFDM signal, the complex values modulating sub-carriers in each symbol period are statistically independent of each other which are orthogonal. Orthogonality of sub-carriers prevents inter carrier interference (Kassaw

et al., 2020). Cyclic prefix is added at transmitter and removed at receiver. It used to avoid inter symbol interference between different symbols.

3.4.2 Filtered- Orthogonal Frequency Division Multiplexing (F-OFDM)

The Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is a spectrum shaping mechanism using filter process. The prototype filter used in this candidate waveform is a rectangular pulse mask of OFDM symbol, again also cyclic prefix. Generally time domain expression of F-OFDM is given as (Bendimerad et al., 2021)

$$X_{F-OFDM}(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \times f(n) \times e^{-(\frac{j2\pi nm}{N})} \tag{3.6}$$

where, $for\ n = 0, 1, 2, ..., N-1$, $f(n) = p(n).w(n)$, $p(n)$: is the ideal band pass filter and $w(n)$: is the Hanning window.

Filtering is very essential to reduce side lobes leakages. F-OFDM is multicarrier modulation technique that introduces filtering operation to overcome the weakness of OFDM (Ramadhan, 2019).

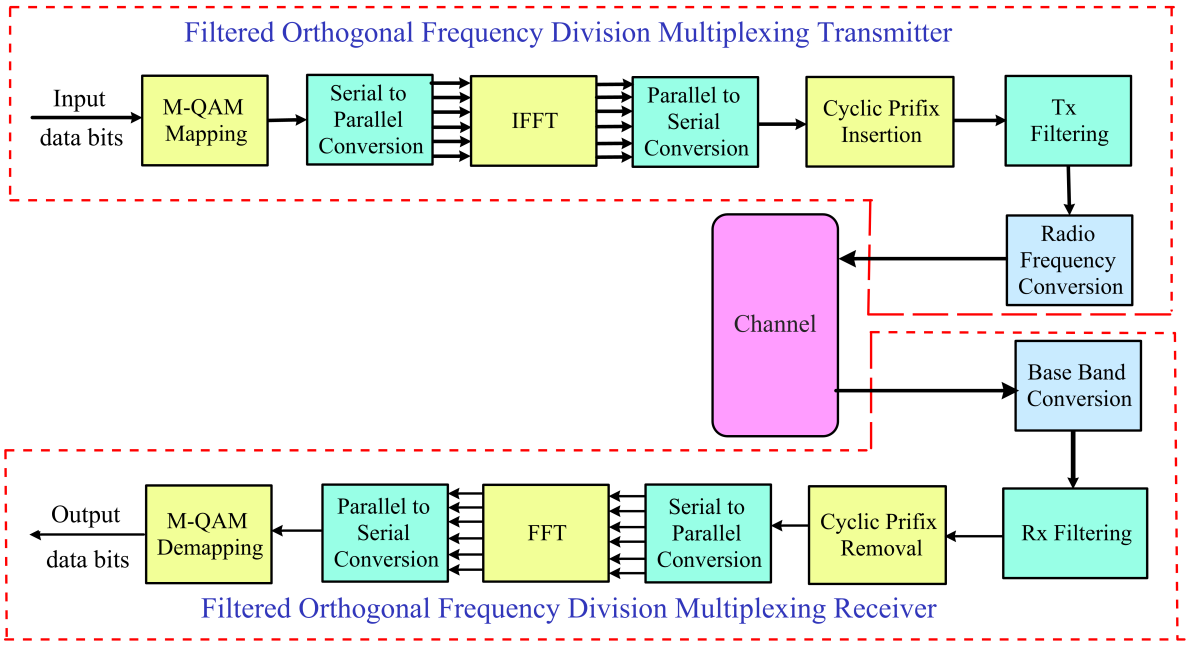

Figure 3.3: Filtered- Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021).

3.4.3 Weighted Overlap and Added Orthogonal Frequency Division Multiplexing (WOLA-OFDM)

Weighted Overlap and Add based OFDM (WOLA-OFDM) is a candidate waveform for future wireless communication. In it, the conventional usage of rectangular pulse

shape is avoided and a pulse with soft edges is used instead. These soft edges are added to the cyclic extension by a time domain windowing. This results in a better spectral containment. The smooth transition between the last sample of a given symbol and the first sample of the next symbol is provided with point-to-point multiplication of the windowing function and the OFDM symbol with cyclic prefix and cyclic suffix (Zayani et al., 2016).

To create the cyclic prefix we copy and append the CP+W samples from the last part of a given symbol and first W samples of a given symbol to its end. Thus, the WOLA-OFDM time domain symbol is cyclically extended from N samples to $N + CP + 2W$. In WOLA-OFDM after cyclic extension a window of length $L = N+CP+2W$ samples is applied (Zayani et al., 2016). Many windowing functions are studied and compared in terms of enhancing side lobe suppression. The Meyer Root Raised Cosine considered as best windowing for WOLA-OFDM. WOLA-OFDM is good to suppress inter user interference.

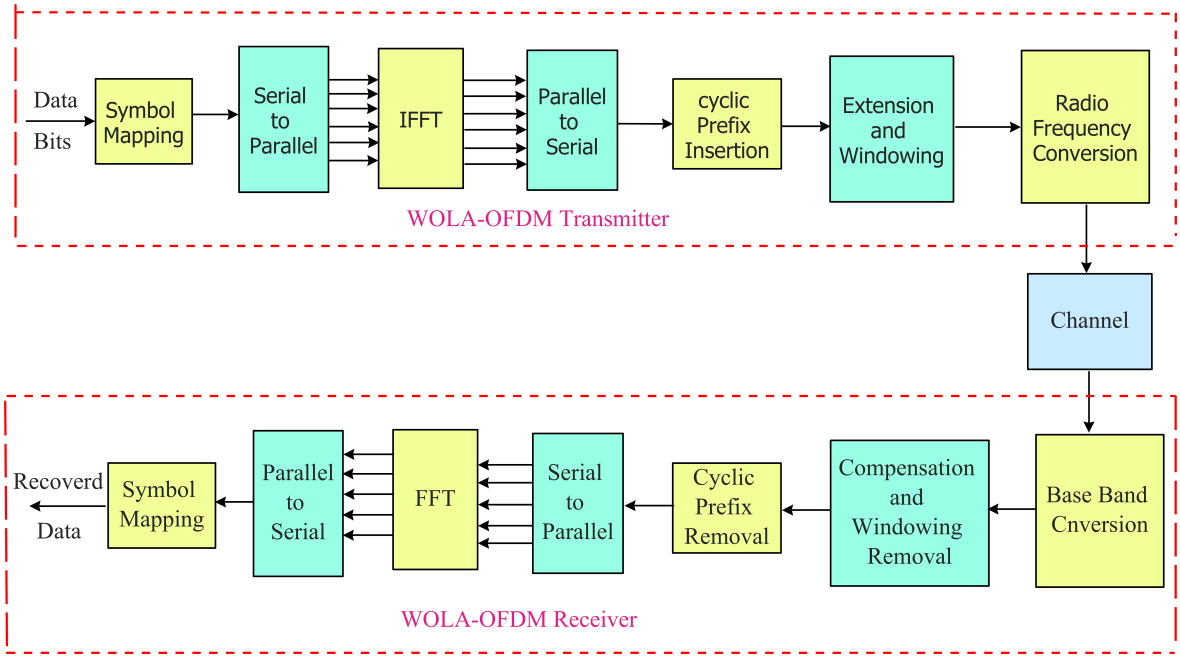

Figure 3.4: Weighted Overlap and Added Orthogonal Frequency Division Multiplexing System (Bendimerad et al., 2021).

Generally time domain expression of WOLA-OFDM is given as in (Zayani et al., 2016)

$$X_{WOLA-OFDM}(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_k \times W(n) \times e^{-(\frac{j2\pi nm}{N})} \tag{3.7}$$

where, $n = 0, 1, 2, ..., N-1$ and $W(n)$, is the discrete time domain representation of

raised cosine window function can be written as in (Zayani et al., 2016).

$$W[n] = \begin{cases} \cos^2\left[\frac{n+N_g+1}{N_w-1}\frac{\pi}{2}\right], & -N_g - N_w \leq n \leq -N_g - 1 \\ 1, & -N_g \leq n \leq N-1 \\ \cos^2\left[\frac{n-N}{N_w-1}\frac{\pi}{2}\right], & N \leq n \leq N + N_w - 1 \end{cases} \tag{3.8}$$

where, N_g is cyclic prefix length, N_w is window length and N represents number of symbols.

3.4.4 Universal Filter Multicarrier (UFMC)

Universal filtered multi-carrier (UFMC) technique can be considered as a derivative of OFDM with sub band filtering operation. This post filtering process leads to a lower out of band leakage than for OFDM. The orthogonality between sub-carriers in each sub-band unit is maintained. UFMC is a technique that combines the benefits of both OFDM and FBMC. Rather than filtering each carrier individually like in FBMC, a group of sub-carriers (called sub-bands) are filtered (Kumar & Prasad, 2020). The filter parameters and number of carriers per sub-band are typically common, which prevents aliasing. Nonetheless, non-contiguous sub-bands are possible to allow flexible utilization of the available spectrum. Therefore, UFMC can be considered as a compromise between OFDM and FBMC.

Let assume that the UFMC transmit signal consist of N sub-carriers and is divided in to B sub-bands. Each sub-bands containing N/B sub-carriers. The input to the UFMC waveform generator block is a set of constellation QAM mapped symbols S. The symbols S are divided into frequency blocks S where each frequency block is made up of p sub-carriers. If B is number of frequency blocks, then B data vectors are processed with IFFT sub-matrix (each of dimension NxP) respectively (Kumar & Prasad, 2020). Then each sub-band is filtered by a sub-band filter of length L and response from the different sub-band is summed.

The discrete base-band UFMC signal is expressed mathematically as in (Bendimerad et al., 2021):

$$x_{UFMC}(n) = \sum_{k=0}^{K-1} S_k(n) * f_k(n) \tag{3.9}$$

where, K is the number of sub-bands, $f_k(n)$ shows the filter coefficients in sub-band of order k and $S_k(n)$ refers to the equivalent OFDM modulated signal over sub-band of

order k expressed as in (Bendimerad et al., 2021):

$$S_k(n) = \sum_{k=0}^{M-1} s_{k,m}(n - m(N + N_g)) \tag{3.10}$$

where, M denotes the number of OFDM symbol blocks, and N_g is the length of the zero padding added to each symbol as in (Bendimerad et al., 2021).

$$s_{k,m} = \sum_{l=(k-1)L}^{kL-1} A_{l,k,m} \times e^{j\frac{2\pi ln}{N}} \tag{3.11}$$

where, $A_{l,m,k}$ represents the data transmitted over l^{th} sub-carrier, the m^{th} temporal symbol block and the k^{th} sub-band. For UFMC the filter chosen is Chebysheve filter which is given as in (Bendimerad et al., 2021)

$$f_k(n) = \frac{\cos(L\cos^{-1}[\beta\cos(\frac{\pi n}{L})])}{\cosh[L\cosh^{-1}(\beta)]]} \qquad for\ n = 0, 1, 2, ..., N-1 \tag{3.12}$$

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

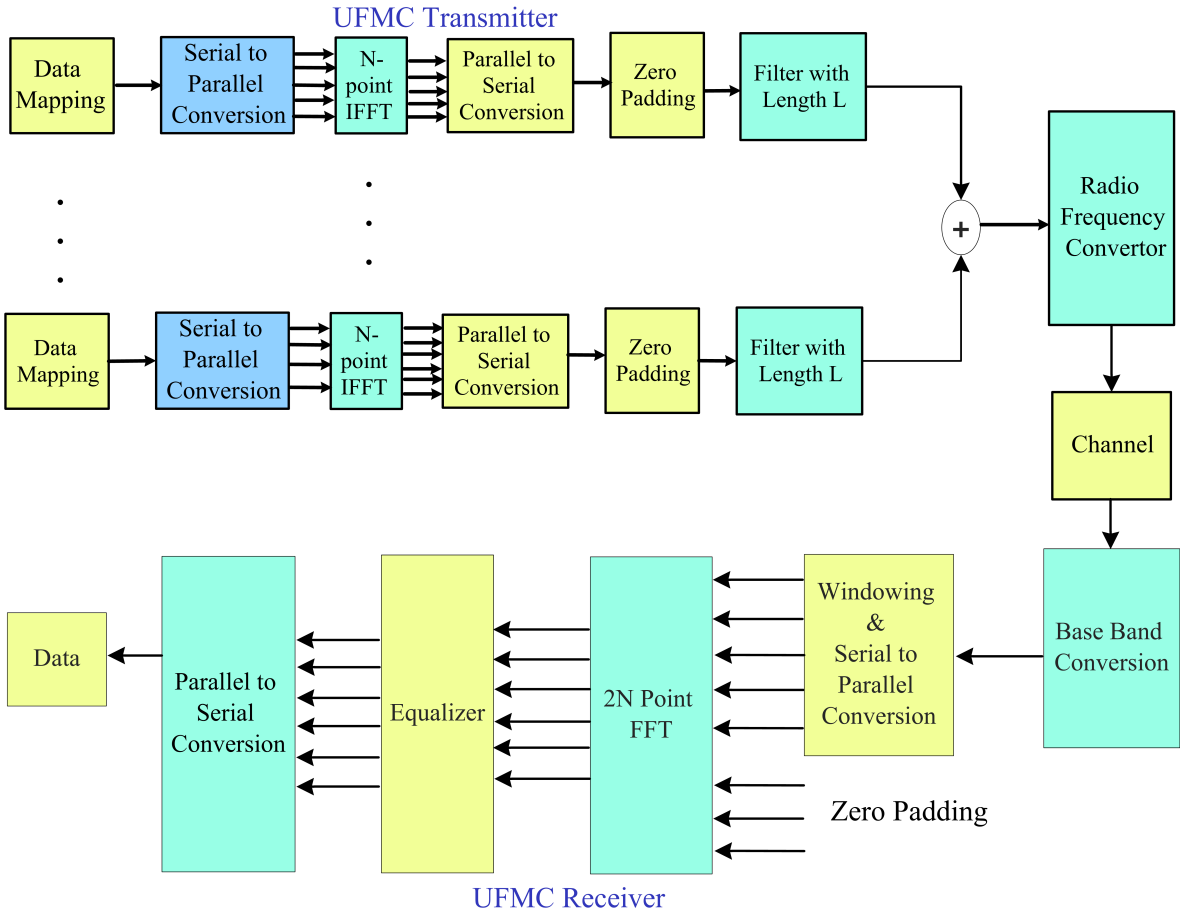

Figure 3.5: Universal Filter Multicarrier System (Bendimerad et al., 2021).

3.4.5 Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM)

FBMC-OQAM is based on real valued symbol transmission and reception. There is OQAM pre-processing and OQAM post-processing to convert complex to real and real to complex values respectively(Abdel-Atty et al., 2020). The orthogonality of FBMC-OQAM is maintained by the pulse shape of the prototype filter and the real value detection of OQAM. The real and imaginary part of complex data is transmitted via single prototype filter called PHYDYAS in this case. The transmitted signal of a discrete time FBMC-OQAM system is expressed in (Jeon et al., 2016) as.

$$s(n) = \sum_{-\infty}^{\infty} \sum_{m=0}^{M-1} d_{m,k} \theta_{m,k} f[n - k\frac{M}{2}] e^{j\frac{2\pi}{M}m(n-D)} \tag{3.13}$$

where, n indicates the time index, m represents the subcarrier index, k indicate symbol index, $d_{m,k}$ represents the real valued symbol, M represent the number of sub-carriers and $f(n)$ shows the synthesis impulse response which maps $d_{m,k}$ in to the signal space. $\theta_{m,k} = j^{k+m}$ is additional phase term.The filter delay which represented by D appears to generate a causal discrete time prototype filter $f(n)$, and it is fixed $D = \frac{(L-1)}{2}$ with filter length equal to L as in (Jeon et al., 2016).

The demodulated symbol at the receiver on the m' sub-carrier at k' time instant can be expressed as in (Jeon et al., 2016)

$$\begin{aligned} \hat{d}_{m',k'} &= \sum_{-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \sum_{m=0}^{M-1} d_{m,k} \gamma_{m,k}[n] \gamma^*_{m',k'}[n] \\ &= d_{m',k'} + \sum_{m \neq m'} \sum_{k \neq k'} d_{m,k} \sum_{n=-\infty}^{\infty} \gamma_{m,k}[n] \gamma^*_{m',k'}[n] \end{aligned} \tag{3.14}$$

where $\gamma_{m,k}[n] = f[n - k\frac{M}{2}] e^{j\frac{2\pi}{M}m(n-D)}$

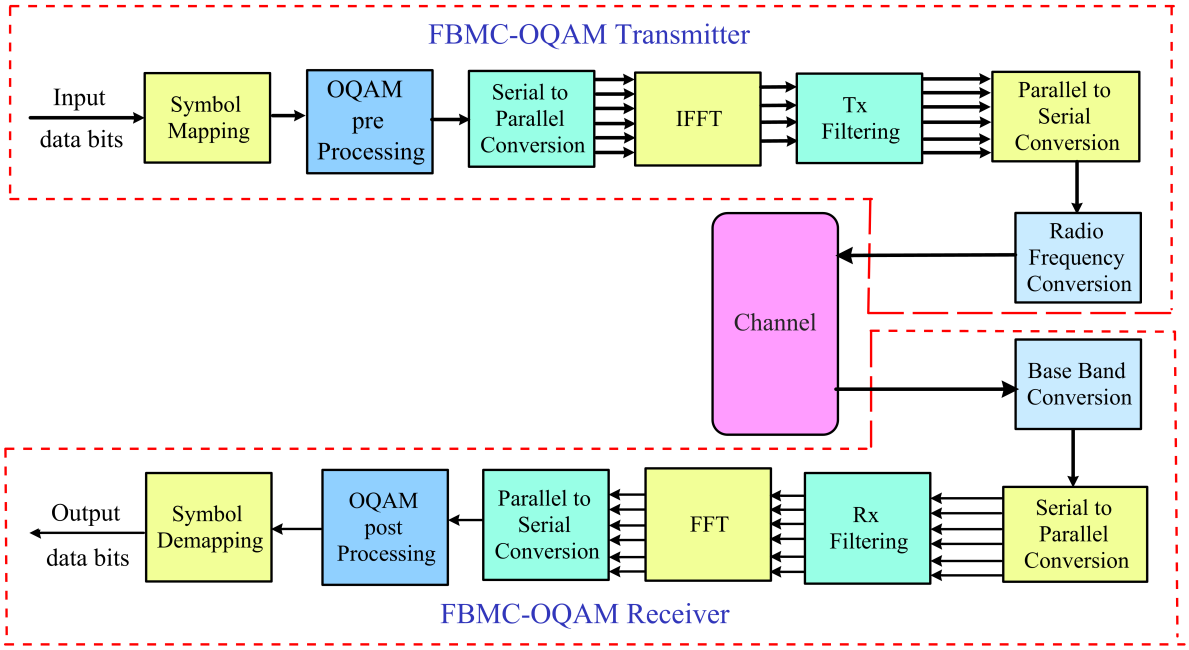

Figure 3.6: Filter Bank Multicarrier with offset QAM System (Jeon et al., 2016).

Over multi-path fading channel $h[n]$ and Additive White Gaussian Noise (AWGN) $w[n]$, the received signal is given by as in (Jeon et al., 2016):

$$\begin{aligned} y[n] &= h[n] * s[n] + w[n] \\ &= \sum_{u=0}^{T-1} h[\tau] s[n - \tau_u] + w[n] \end{aligned} \tag{3.15}$$

where, τ_u is the multi-path delay and T is the number of multi-path delays.On the m' sub-carrier at k' time instant, the demodulated symbol can be represented as in (Jeon et al., 2016)

$$\begin{aligned} r_{m',k'} &= \left\langle y[n], \gamma^*_{m',k'} \right\rangle \\ &= \sum_{n=-\infty}^{\infty} y[n] \theta^*_{m',k'} f[n - k' \frac{M}{2}] e^{j\frac{2\pi}{M} m'(n-D)} \\ &= H_{m'} \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \sum_{m=0}^{M-1} (d_{m,k} \theta_{m,k} \theta^*_{m',k'} f_{m,k}[n - \tau_u] f^*_{m',k'}[n]) + z_{m',k'}[n] \end{aligned} \tag{3.16}$$

where, $\left\langle y[n], \gamma^*_{m',k'} \right\rangle$ is the inner product of $y[n]$ and $\gamma^*_{m',k'}$, $H_{m'}$ denotes the channel frequency response of $h[n]$ on $\frac{2\pi}{M} m'$ that is $H_{m'} = \sum_{u=0}^{T-1} h[\tau_u] e^{-j\frac{2\pi}{M} m' \tau_u}$, $f_{m,n}[n] = f[n - k\frac{M}{2}] e^{j\frac{2\pi}{M} m(n-D)}$ and $z_{m',n'}[n] = \sum_{n=-\infty}^{\infty} w[n] f^*_{m',n'}[n]$

3.4.6 Proposed Filter Bank Multicarrier with Quadrature Amplitude Modulation (FBMC/QAM)

FBMC-QAM transmits complex symbols using two different prototype filters, which is termed as even and odd filters to deliver even and odd subcarriers respectively. The orthogonality of FBMC-QAM is maintained by the pulse shapes of two prototype filters. In baseband discrete-time model, FBMC-QAM signal at transmitter side is written as in (Jeon et al., 2016):

$$s(n) = \sum_{-\infty}^{\infty} \left(\sum_{p} a_{p,k} g^{e}[n - kM] e^{j\frac{2\pi}{M}m(n-D)} + \sum_{p} a_{p,k} g^{o}[n - kM] e^{j\frac{2\pi}{M}m(n-D)} \right) \quad (3.17)$$

where, $g^{e}[n]$ represent even filter, $g^{o}[n]$ represents odd filter and $a_{p,k}$ represents a complex data symbol in terms of QAM constellation. In this study we propose a PHYDYAS Filter as a prototype filter in both transmitter and receiver as even and odd filter to improve the out of band emission and the bit error performance of FBMC-QAM.

For the ideal channel, demodulated even symbol at the receiver on the m' sub-carrier at k' time instant can be expressed as in (Jeon et al., 2016):

$$\begin{aligned} \hat{a}^{even}_{p',k'} &= \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left(\sum_{p} a_{p,k} g^{e}_{p,k} g^{e*}_{p',k'} + \sum_{q} a_{p,k} g^{o}_{p,k} g^{o*}_{p',k'} \right) \\ &= a_{p',k'} + \sum_{k \neq k'} \left(\sum_{p \neq p'} a_{p,k} g^{e}_{p,k} g^{e*}_{p',k'} + \sum_{q} a_{p,k} g^{o}_{p,k} g^{o*}_{p',k'} \right) \end{aligned} \quad (3.18)$$

For the ideal channel, demodulated odd symbol at the receiver on the m' sub-carrier at k' time instant can be expressed as in (Jeon et al., 2016):

$$\begin{aligned} \hat{a}^{odd}_{p',k'} &= \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left(\sum_{q} a_{p,k} g^{o}_{p,k} g^{o*}_{p',k'} + \sum_{p} a_{p,k} g^{e}_{p,k} g^{o*}_{p',k'} \right) \\ &= a_{p',k'} + \sum_{k \neq k'} \left(\sum_{q \neq q'} a_{p,k} g^{o}_{p,k} g^{o*}_{p',k'} + \sum_{p} a_{p,k} g^{e}_{p,k} g^{o*}_{p',k'} \right) \end{aligned} \quad (3.19)$$

where, $g^{e}_{p,k}[n] = g^{e}[n - kM] e^{j\frac{2\pi}{M}p(n-D)}$ and $g^{e}_{q,k}[n] = g^{o}[n - kM] o^{j\frac{2\pi}{M}q(n-D)}$

In existing system PHYDYAS filter is used as prototype filter. The side lob constraint of PHYDYAS filter is not good compared to that of Hermite filter. The side lobes of Hermite decays faster than that of PHYDYAS filter. Therefore we supposed to choose Hermite filter as prototype filter to improve the power spectral density, bit error rate and signal to interference ratio of FBMC-QAM. The even and odd filter that used for

the proposed system is $g_p^e[n] = p_{hermite}$ and $g_q^o[n] = p_{hermite}$ respectively.

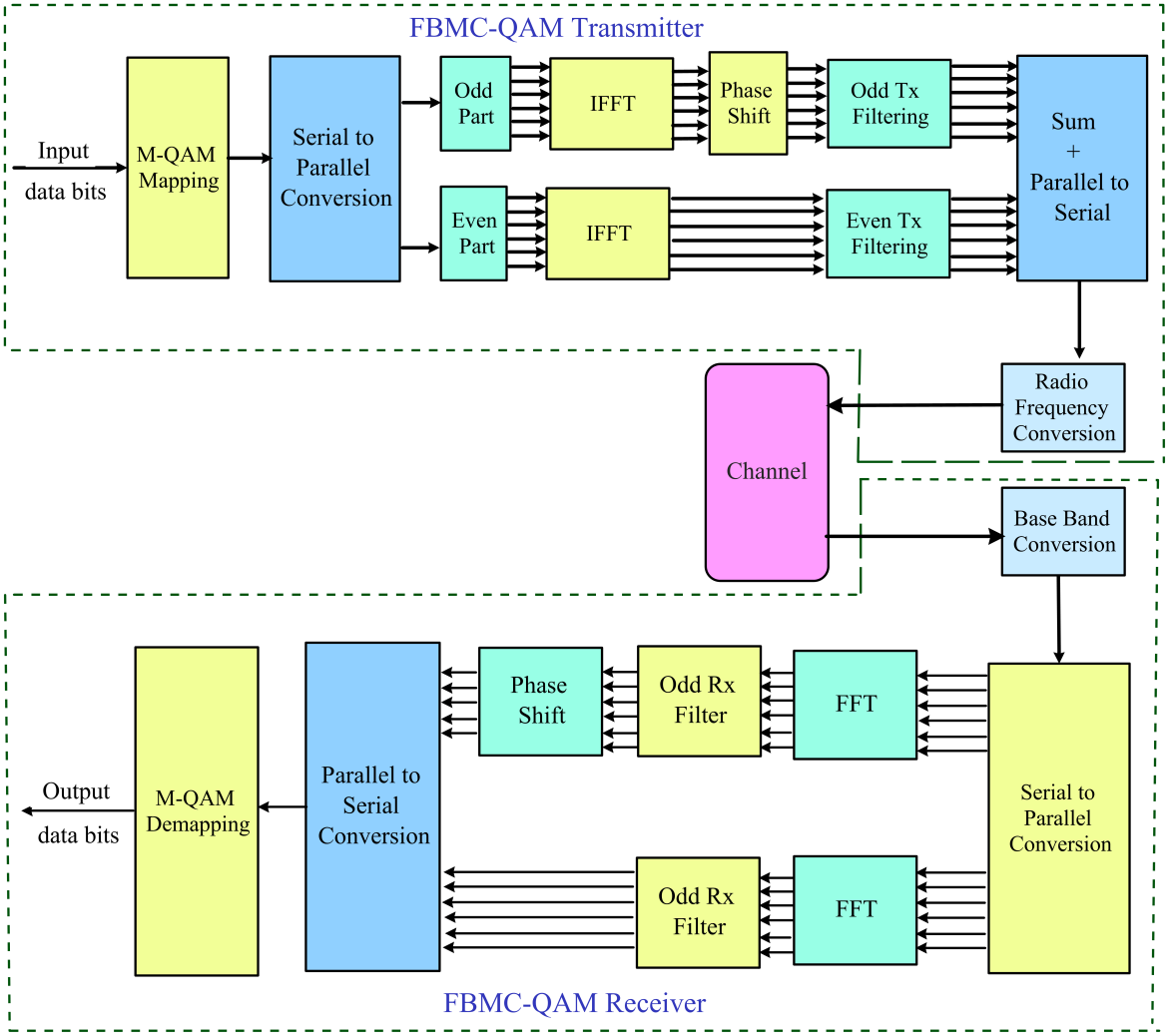

Figure 3.7: Filter Bank Multicarrier with QAM System.

For a multi-path fading channel the received signal of FBMC-QAM $y[n]$ is represented in the same manner as that of FBMC-OQAM. However, because of even and odd sub-carrier associated, the demodulated data symbol is classified in to even and odd symbol demodulations. The even symbol demodulation is represented as in (Jeon et al., 2016):

$$\begin{aligned}
\hat{r}_{p',k'}^{even} &= \left\langle y[n], g_{p',k'}^{e*} \right\rangle \\
&= \sum_{n=-\infty}^{\infty} y[n] g^e \left[n - k' \frac{M}{2} \right] e^{-j\frac{2\pi}{M}p'(n-D)} \\
&= H_{p'} \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left(\sum_p a_{p,k} g_{p,k}^e[n-\tau_u] g_{p',k'}^{e*}[n] \right) \\
&\quad + H_{p'} \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left(\sum_q a_{q,k} g_{q,k}^o[n-\tau_u] g_{p',k'}^{e*}[n] \right) + z_{p',k'}[n] \qquad (3.20)
\end{aligned}$$

If there is no intrinsic interference, or intrinsic interference is sufficiently small, the

demodulated even symbol is obtained by equalization as $\hat{a}_{p',k'} = r^{even}_{p',k'}/H'_p$. In the same manner, the odd symbol demodulation is given as in (Jeon et al., 2016):

$$\begin{aligned}\hat{r}^{odd}_{q',k'} &= \left\langle y[n], g^{o*}_{q',k'} \right\rangle \\ &= \sum_{n=-\infty}^{\infty} y[n] g^{o}\left[n - k'\frac{M}{2}\right] e^{-j\frac{2\pi}{M}q'(n-D)} \\ &= H_{q'} \sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty}\left(\sum_{q} a_{q,k} g^{o}_{q,k}[n-\tau_u] g^{o*}_{q',k'}[n]\right) \\ &\quad + H_{q'} \sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty}\left(\sum_{p} a_{p,k} g^{o}_{p,k}[n-\tau_u] g^{e*}_{q',k'}[n]\right) + z_{q',k'}[n] \end{aligned} \tag{3.21}$$

The demodulated odd symbol obtained as $\hat{a}_{q',k'} = r^{odd}_{q',k'}/H'_q$. For practical application of FBMC-QAM it is important to consider the side lob constraint of prototype filter because a smaller side lobe energy leads to a reduction of the guard band among the channels which is significantly related to spectral efficiency. FBMC-QAM symbol associated complex valued symbols, and the interference from adjacent pulses is exhibited inherently because of the overlap among the pulses and the oversampling in frequency domain and also the inter symbol interferences caused by the overlap/sum procedure completely removed by chosen best reception filter.

3.5 Prototype Filters

In multicarrier transmission system, each channel occupies a relatively narrow frequency band. Therefore, the filter that create lower side lobe is required to avoid the spectral overlap of the channel to drop inter channel interference. However, higher signaling rate can be achieved if the spectral overlap is permitted.

3.5.1 Rectangular Filter

The rectangular function is the prototype filter used for the conventional OFDM transmission scheme. This filter distributes uniformly the energy carried by a symbol through the time domain. At the transmitter its duration can be enlarged so it can effectively combat inter symbol interference and inter carrier interference in time variant multi-path channels. Its analytical expression is (Bendimerad et al., 2021):

$$p(t) = \begin{cases} 1, & |t| \leq \frac{1}{2} \\ 0, & elsewhere \end{cases} \tag{3.22}$$

The characteristics of rectangular filter play a significant role in determining the resulting frequency response of the OFDM system. Specifically, the convolution with rectangular function has the effect of smoothing the signal (Bendimerad et al., 2021).

3.5.2 Raised Cosine Filter

The function itself and its first derivative are continuous. The impulse response of Raised Cosine Filter is given in (Bendimerad et al., 2021) as:

$$p(t) = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos(2\pi t), & |t| \leq \frac{1}{2} \\ 0, & elsewhere \end{cases} \tag{3.23}$$

3.5.3 Exact Hamming Filter

The impulse response of Exact Hamming Filter is given in (Bendimerad et al., 2021) as:

$$p(t) = \begin{cases} \frac{25}{46} + \frac{21}{46}\cos(2\pi t), & |t| \leq \frac{1}{2} \\ 0, & elsewhere \end{cases} \tag{3.24}$$

3.5.4 Exact Black Man Filter

The impulse response of Exact Black-man Filter is given in (Bendimerad et al., 2021) as:

$$p(t) = \begin{cases} \frac{7938}{18608} + \frac{9240}{18608}\cos(2\pi t) + \frac{1430}{18608}\cos(4\pi t), & |t| \leq \frac{1}{2} \\ 0, & elsewhere \end{cases} \tag{3.25}$$

3.5.5 Root Raised Cosine Filter

The impulse response of Raised Cosine Filter is given in (Bendimerad et al., 2021) as:

$$p(t) = \begin{cases} 1 - \alpha + 4\frac{\alpha}{\pi}, & t = 0 \\ \frac{\alpha}{\sqrt{2}}[(1 + \frac{2}{\pi})\sin(\frac{\pi}{4\alpha}) + (1 - \frac{2}{\pi})\cos(\frac{\pi}{4\alpha})], & t = \pm\frac{1}{4\alpha} \\ \frac{\sin((1-\alpha)\pi t) + 4\alpha t\cos((1+\alpha)\pi t)}{\pi t(1-16\alpha^2 t^2)}, & otherwiese \end{cases} \tag{3.26}$$

3.5.6 PHYDYAS Filter

The design of the PHYDYAS prototype filter is based on a frequency sampling technique. The Nyquist theory imposes that the impulse response of the transmission filter must cross the zero axis at all the integer multiples of the symbol period. In frequency domain, this translates to a symmetry condition about the cutoff frequency. So the design is based on considering the frequency coefficients while imposing symmetry condition. The impulse response for PHYDYAS Filter is given in (Jeon et al., 2016)

as:

$$p_{phydyas} = 1 + 2\sum_{k=1}^{K-1} H_k \cos(2\pi \frac{kt}{KT}) \tag{3.27}$$

where, K represents the overlapping factor and K=2,3,4

3.5.7 Hermite Filter

The Hermite pulse shaping filter is given form the linearly combining of the function of the Hermite Gaussian which achieves the Nyquist-I criterion (Bendimerad et al., 2021). Thereby, the Hermite prototype filter coefficients are given by Hermite polynomials in (Bendimerad et al., 2021). The Hermite filter impulse response can be described by :

$$p_{hermite}(t) = \frac{1}{\sqrt{T_o}} exp(-2\pi(\frac{t}{T_o})^2) \times \sum a_i H_i(2\sqrt{\pi}\frac{t}{T_o}) \tag{3.28}$$

where, i=0,4,8,16,20

3.6 Simulation Parameters

This thesis work mainly focus on measuring the performance of multi-carrier modulation techniques with higher order QAM using different performance metrics like power spectral density, bit error rate, spectral efficiency, signal to interference ratio and computational complexity. In this section the concept of each performance metrics that we are going to use are explained in detail.

3.6.1 Power Spectral Density

Power Spectral Density shows the strength of the variation of energy as a function of frequency. The power spectral density (PSD) or power spectrum provides a way of representing the distribution of signal frequency components which is easier to interpret visually than the complex DFT. As the term suggests, it represents the proportion of the total signal power contributed by each frequency component of a voltage signal.

PSD is an important factor that indicates out of band radiation's level and the ability of a given waveform to reuse the spectrum and support coexistence of different services. A lower out of band enables users to access network in an asynchronous mode and to incarnate a high mobility.

3.6.2 Bit Error Rate

There is a chance that mistakes will be introduced into the system when data is transmitted across the channel. If errors are introduced into the data, the system's integrity may be affected. As a result, the system's overall BER's performance must be evaluated. BER measures a performance of this system, including the transmitter, receiver,

and the medium that connects them. The rate at which errors occur in a transmission system is known as the BER. Noise and multi-path propagation channels, which are random in nature, are the primary causes of transmission channel degradation and BER (Kassaw et al., 2020).

The transmitted signal in a multi-path channel arrives at the receiver as a series of pulses. A transmitted signal travels to the receiver along various paths that may have varied durations and thus different related time delays since a multi-path channel reflects signals at multiple locations. When signals flowing down various pathways interfere with each other, fading occurs. We used the Vehicular A, Vehicular B, and Pedestrian B channel models for our BER simulation. It is a viable model for signal propagation in densely populated metropolitan areas where there is no direct line of sight between transmitter and receiver.

3.6.3 Spectral Efficiency

The information rate that can be sent over a given bandwidth in a communication system is referred to as spectrum efficiency, spectrum efficiency, or bandwidth efficiency. It's a metric for how well the physical layer protocol, and sometimes the media access control, uses a limited frequency spectrum. To fulfill excessive data rate requirements, spectral efficiency is critical. In the literature, spectral efficiency is given in a variety of ways. We used the definition suggested by (Doré et al., 2017) for our spectral efficiency analysis since it is more applicable to multi-carrier modulations. The spectrum efficiency is calculated as the product of time efficiency and modulation efficiency (Kassaw et al., 2020).

$$\eta_{mc} = \eta_t * \eta \tag{3.29}$$

where, time η_t and η are time and modulation efficiency of multi-carrier modulation schemes. The efficiency of modulation is determined by the modulation order, the number of active resource blocks, and the coding rate. We only consider the modulation order in this simulation, which is directly connected to the number of loaded bits in each sub-carrier.The time efficiency measures time overhead introduced in transmission. It is defined similar to (Schaich et al., 2014) as:

$$\eta_t = \frac{D_L}{D_L + T_{overhead}} \tag{3.30}$$

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

ber of transmitted multi-carrier symbols in a burst and N is FFT size as shown in (Bendimerad et al., 2021).

$$OFDM, \quad T_{overhead} = \beta L_{cp} \tag{3.31}$$

where β is the number of transmitted multi-carrier symbol in burst and L_{CP} is sample length of Cyclic prefix as shown in (Bendimerad et al., 2021).

$$FBMC, \quad T_{overhead} = N(K - \frac{1}{2}) \tag{3.32}$$

where N is the size of FFT and K is overlapping factor of filters as shown in (Bendimerad et al., 2021).

$$UFMC, \quad T_{overhead} = \beta * (L_{ZP} + L_{UFMC} - 1) \tag{3.33}$$

where β is the number of transmitted multicarrier symbol in burst and L_{UFMC} is filter length as shown in (Bendimerad et al., 2021).

$$F - OFDM, \quad T_{overhead} = \beta L_{cp} \tag{3.34}$$

where β is the number of transmitted multi-carrier symbol in burst and L_{CP} is sample length of Cyclic prefix.

$$WOLA - OFDM, \quad T_{overhead} = \beta(L_{cp} + W_L) \tag{3.35}$$

where β is the number of transmitted multi-carrier symbol in burst and L_{CP} is sample length of Cyclic prefix, W_L as shown in (Zayani et al., 2016).

3.6.4 Computational Complexity

Computational complexity is a computer science concept concerned with the amount of computing resources required for specific tasks(Kassaw et al., 2020). The computational complexity of Multicarrier modulation is measured in terms of the number of real multiplications and additions required to compute the modulation. The computational complexity of a waveform is an important metric for determining how well it can be executed by computers.

To understand the formulas that are given in above table we have to know the multiplication complexity formula for $FFT/IFFT$. For FFT, the number of real multiplication of $N - point\ FFT/IFFT$ using split-radix algorithm as in (Kassaw et al.,

2020) is given by:

$$M_{FFT} = N \log_2 N - 3N + 4, \quad multiplications \tag{3.36}$$

The complexity shown here is only a small part of the full system complexity; RF digital pre-processing and encoders take a significant amount of resources. The number of real multiplications per multi-carrier sign is used to calculate the complexity. This is a modulator complexity metric.To transmit one block of OFDM symbol, the number of real valued multiplication as shown in table:

Table 3.1: Multiplication of different multi-carrier modulation techniques

Candidate Waveforms	**Number of Complex Multiplication**
OFDM (Kassaw et al., 2020)	$2M_{FFT}(N) + 4(N + L_{cp})$
F-OFDM (Bendimerad et al., 2021)	$2(NM \log_2(N) - 6N + 8 + 2(N + T_{cp}L_F) + 2NL_F)$
UFMC (Bendimerad et al., 2021)	$B[M_{IFFT}(N) + M_{FFT}(2N) + 8N] + 2M_{FFT}(2N) + 8N$
WOLA-OFDM (Zayani et al., 2016)	$2(N \log_2(N) - 3N + 4) + 4 * N(N + l_{cp}) * W_L + 4 * W_L$
FBMC/OQAM (Kassaw et al., 2020)	$4M_{FFT}(N) + 8NK + 4N_o(1 + L_{eq})$
FBMC/QAM	$2N \log_2(N/2) + 2(N \log_2(N)) - 9N + 16 + 8(NK + 1)$

3.6.5 Signal to Interference Ratio

The SIR may be used to evaluate the point where interference starts to overtake noise. The SIR used to assess the point where interference begins to overtake unwanted signal. Multicarrier modulation schemes are sensitive to synchronization offset (Li et al., 2018). Time offset and carrier frequency offset can destroy the orthogonality of sub-carriers and also this results ISI and ICI. Time offset is resulted by non-perfect arrangement of samples in time, which occurs due to channel propagation delay. There are two frequency offsets namely carrier frequency offset and sampling frequency offset. Carrier frequency offset caused by the frequency of the received signal and the frequency of the local oscillator at the receiver. Sampling frequency offset caused by sampling effect.

CHAPTER FOUR
RESULT AND DISCUSSION

In this section the performance of candidate multi-carrier modulation techniques are compared with the existing OFDM systems. The comparison is based on key performance indicators like power spectral density, bit error rate, spectral efficiency and computational complexity. The performance of different multi-carrier modulation techniques are assessed in terms of their potential to fill the major requirements of new communication networks. The simulation parameters are taken keeping ITU standard.

4.1 Simulation Parameters

Table 4.1: Parameters for Multi-carrier Modulation Techniques

General Parameters	
Sub-carrier Spacing	15KHz
Sampling Frequency	15.36MHz
Number of Sub-carriers	1024
QAM Modulation Order	64/256/1024
Number of Symbols	512

F-OFDM		**OFDM**	
Filter Type	Windowed Sinc	Length of Cyclic Prefix	72

UFMC		**FBMC/OQAM**	
Chebyshev filter length	73	Overlapping factor	4
Sub-band size	12	Prototype Filter	Hermite Filter
Guard interval length	72	Prototype Filter	PHYDYAS Filter
Side-lobe attenuation	40dB		

WOLA-OFDM		**FBMC/QAM**	
Cyclic Prefix	72	Overlapping factor	4
Windowing	Meyer-RRC	Prototype Filter	Hermite Filter
Windowing length	32	Prototype Filter	PHYDYAS Filter

4.2 Spectral Efficiency Comparison

In this section, each multi-carrier modulations spectral efficiency is assessed in terms of time and modulation efficiency, which represented in bit/second/hertz versus the number of transmitted multi-carrier symbol. It represents the number of bits transmitted over a time frequency unit. It is the product of frequency efficiency and time efficiency. Frequency efficiency represents the localization and a given wave-form spectrum containment in the frequency domain whereas time efficiency represents time overhead introduced to the given data symbol.

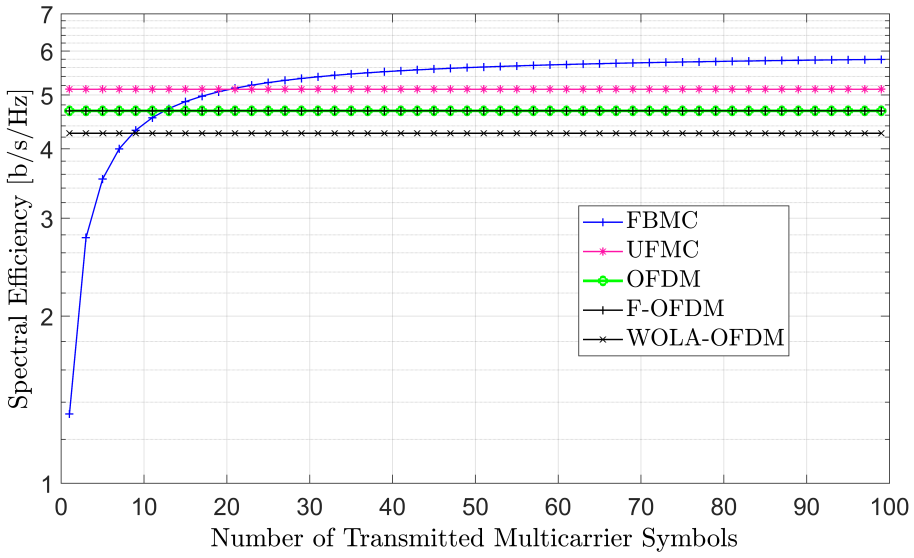

Figure 4.1: Spectral Efficiency of Multicarrier Modulation Techniques.

Figure 4.1 shows the spectral efficiency of different multi-carrier modulation techniques. Spectral efficiency of FBMC depends on the variation of number of transmitted symbol. For higher number of transmitted multi-carrier symbol FBMC has better spectral efficiency than all other multi-carrier modulation schemes. From the result it can be seen that the spectral efficiency of all other wave-form dose not depends on the variation of number of transmitted multi-carrier symbols.

Generally FBMC has better spectral efficiency than all other wave-forms. Filter bank multi-carrier modulation technique has slightly better spectral efficiency than other wave forms because it uses filter for each sub-carriers. The probability of error occurrence and like inter symbol interference and inter carrier interference effect is less compared to all other wave form. Therefore it is better to focus on FBMC to improve the drawback like out of band emission to further support co-existence of multiple services.

4.3 Power Spectral Density Comparison

Normalization is a means to have a measure for a signals in the same, fixed, easy to use range. Normalized frequency is a quantity having dimension of frequency expressed in units of cycle per sample. It is equals $f_n = \frac{f}{f_s}$where f is an ordinary frequency quantity and f_s is the sampling rate.

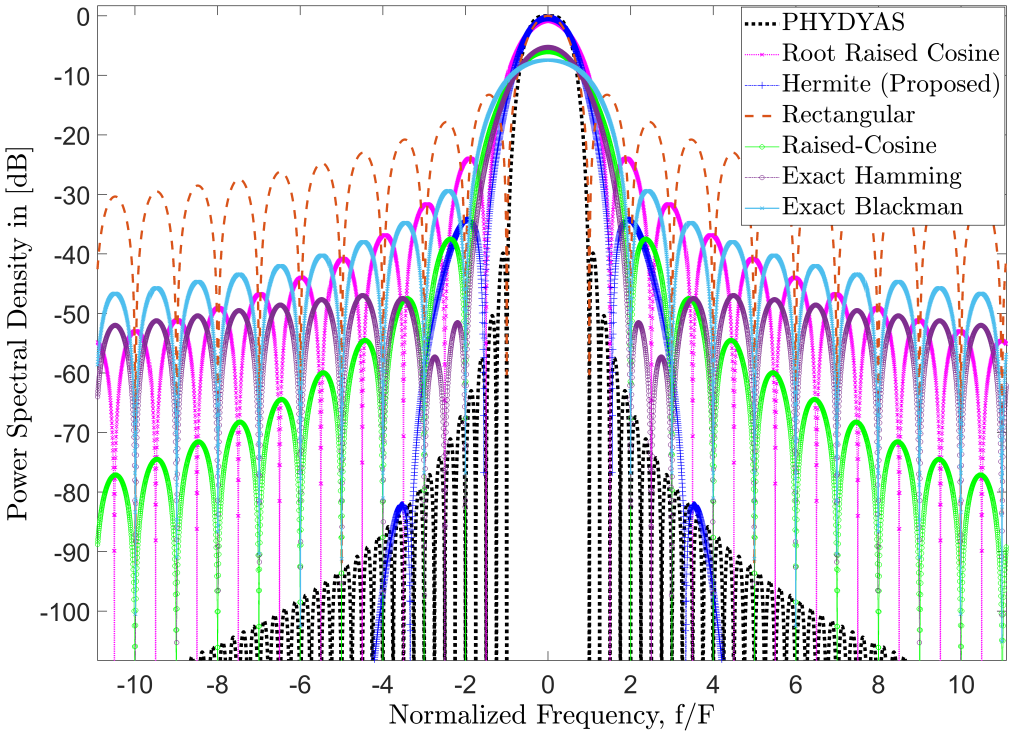

Figure 4.2: Power spectral density versus normalized frequency of different prototype Filters for sub-carrier spacing 15kHz, number of sub-carriers 1024

Figure 4.2 shows the power spectral density versus normalized frequency of different prototype filters in frequency domain. Filters can affect the out of band emission of multi-carriers modulation techniques. To have better multi-carrier modulation technique with minimum out of band emission the filter with small side lobe required. The PSD versus normalized frequency of different prototype filters for sub-carrier spacing 15kHz, number of sub-carriers 1024 shows that Hermite decays faster than all other filters as it can be seen from figure 4.2.

By using hermite filter as prototype filter in filter bank multi-carrier with quadrature amplitude modulation techniques the out of band emission of filter bank multi-carrier with quadrature amplitude modulation improved in some amount. As it can be seen from the power spectral density versus normalized frequency plot of each prototype filter from figure 4.2 all filters side lobe decays after normalized frequency -6 and 6 left hand side and right hand side to normalized frequency zero respectively. Out of

band emission of multi-carrier modulation techniques depends on the power spectral distribution of filters. The main requirement to choose a better filter is choosing a filter with smaller side lobe.

There are a number of filters that are recommended to improve the out of band emission of multi-carrier modulation techniques. But analysis of this study is limited to phydyas filter, root raised cosine filter, hermite filter, rectangular filter, raised cosine filter, exact hamming filter and exact blackman filter. Because most researchers recommended those filters to improve the performance of different multi-carrier modulation techniques. Generally the power spectral density decay rate of Hermite prototype filter is better in some amount than all other filters. Based on this reason hermite filter is chosen as best prototype filter to improve the performance of FBMC-QAM.

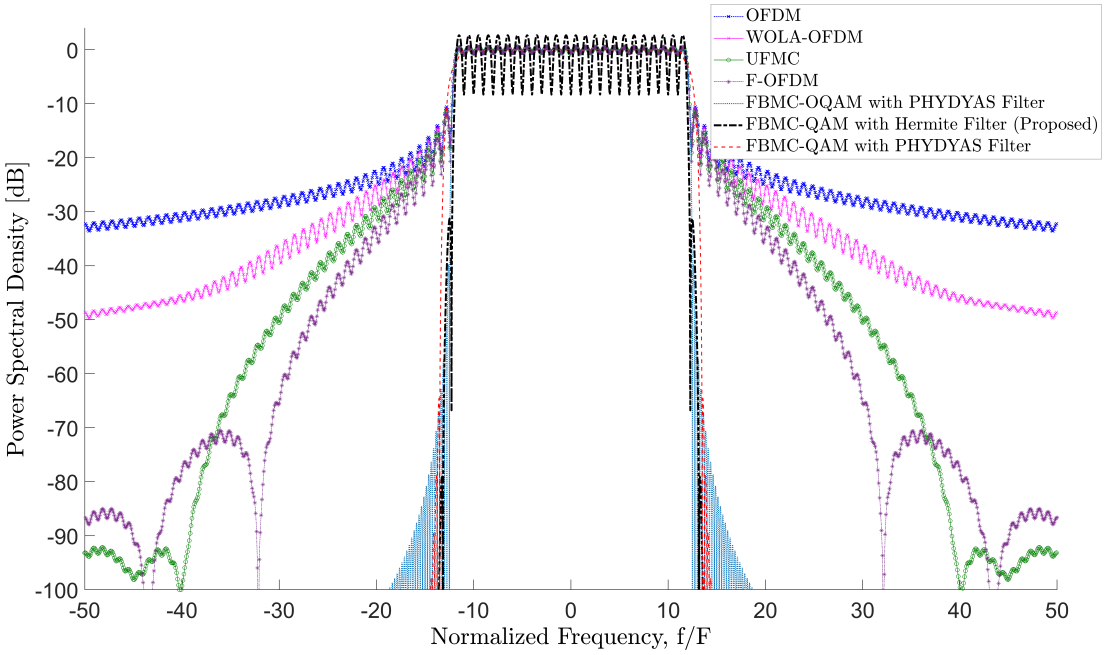

Figure 4.3: Power spectral density versus normalized frequency of different multi-carrier modulation techniques for sub-carrier spacing 15kHz, number of sub-carriers 1024.

Figure 4.3 is a result that simulated for 1024 number of sub-carriers by taking overlapping factor of 4. Overlapping 4 chosen for better side lobe. Number of sub-carrier spacing is chosen 15KHz the same as long term evolution standard (LTE).

Let as consider the power spectral density of multi-carrier modulation techniques at normalized frequency of 30. The PSD of OFDM becomes -29.05dB, the PSD of WOLA-OFDM becomes -37.45dB, the PSD of UFMC becomes -50.51dB, the PSD of F-OFDM becomes -65.5dB, the PSD of FBMC-OQAM using PHYDYAS filter becomes -121dB and the PSD of FBMC-QAM using PHYDYAS becomes -221dB and the PSD of FBMC-QAM using Hermite filter becomes -323dB. From the result it can be conclude that FBMC-QAM with Hermite filter has smallest out of band emission because of hermite

filter a filter which has a small side lobe. The side lobe created by FBMC- QAM with using Hermite filter is smallest which helps to support the coexistence of different services.

Table 4.2: Power Spectral Density of Different Modulation Schemes at 20, 30, 40 and 50 normalized frequency.

Waveforms		Normalized Frequency			
		20	30	40	50
OFDM	Power Spectral Density in dB	-22.06	-29.05	-31.2	-33.27
F-OFDM		-33.94	-65.5	-78.01	-86.65
WOLA-OFDM		-25.61	-37.45	-45.69	-48.66
UFMC		-29.65	-50.51	-90.92	-93.2
FBMC/OQAM with Phydyas		-111.1	-121	-144.5	-151.2
FBMC/QAM with Phydyas		-180.7	-221	-214.4	-215.7
FBMC/QAM with Hermite (Proposed)		-319.5	-323	-323.2	-315.8

Generally because of the adoption of Hermite filter in filter bank multi-carrier with quadrature amplitude modulation certain amount of improvement achieved. To understand the amount of improvement PSD in dB converted in to linear scale. When we compare the PSD of FBMC-QAM using PHYDYAS filter and FBMC-QAM using Hermite filter in linear scale and convert their difference in to dB scale for normalized frequency 30, 4.7dB improvement observed.

4.4 Bit Error Rate Comparison

Bit error rate comparison is another performance metrics to compare the performance of multi-carrier modulation techniques in communication system. Figure 4.4 shows the bit error rate versus signal to noise ration comparison at M-QAM (4-QAM, 16-QAM, 64-QAM, 256-QAM, 1024-QAM) according to specific objective stated in thesis proposal Figure 4.4 simulated number of symbol transmitted 1000 using Rayleigh fading channel. From figure 4.4 we conclude that as signal to noise ration increase the bit error rate decrease. Also as the order of QAM increase the bit error performance increase. However, lower QAM order can not support the large signal to noise ratio. To support massive communication in future we are supposed to use higher order QAM.

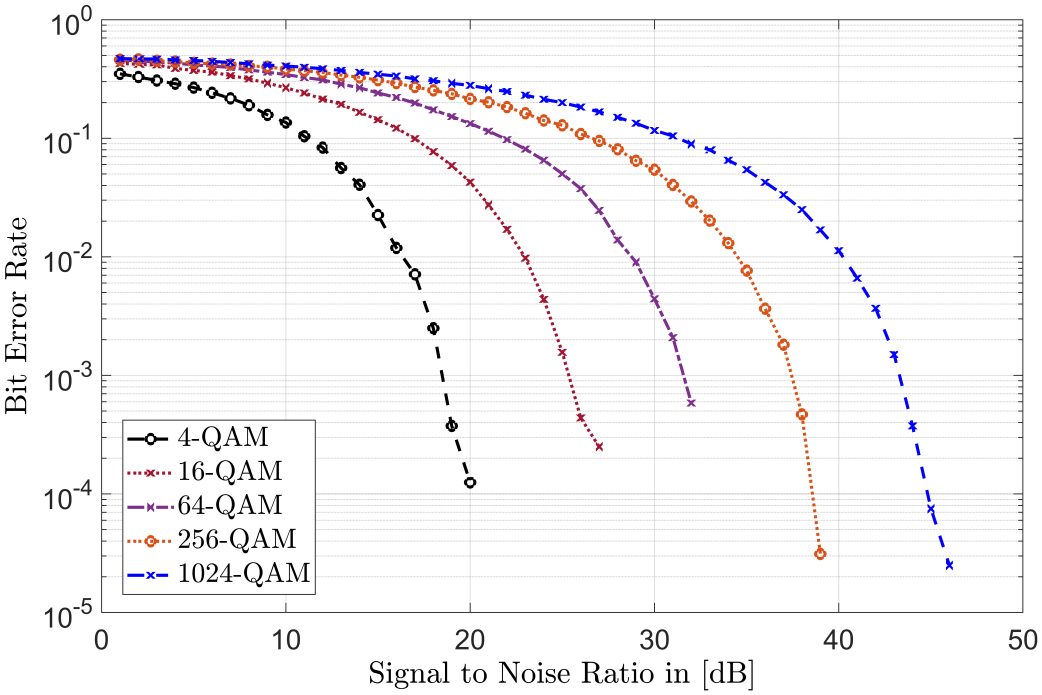

Figure 4.4: Bit Error rate performance of OFDM at M-QAM.

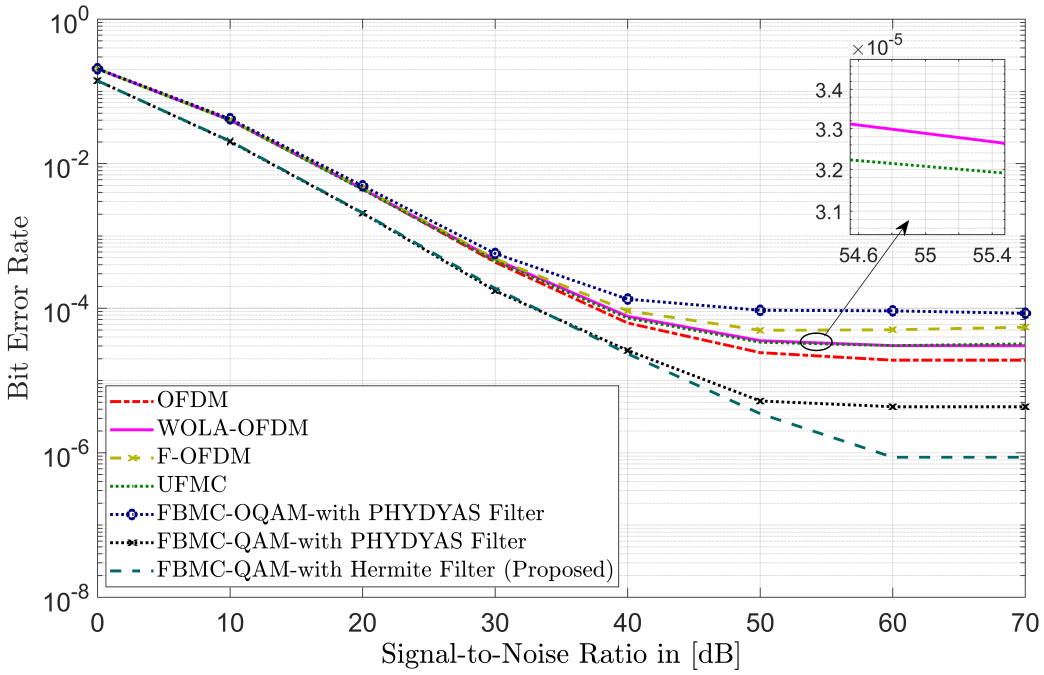

Figure 4.5: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 4-QAM.

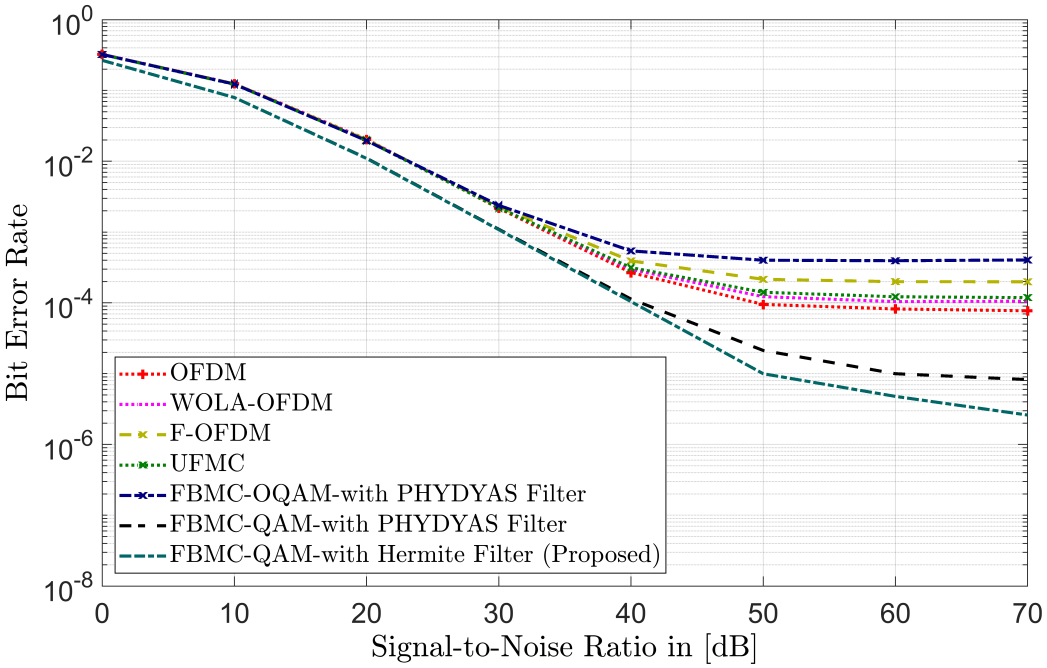

Figure 4.6: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 16-QAM.

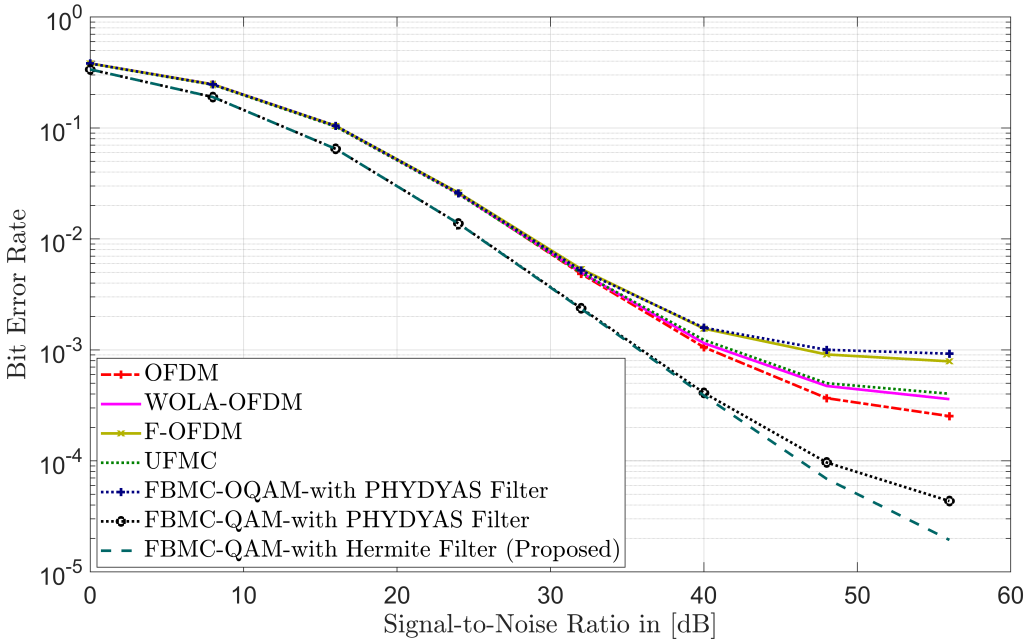

Figure 4.7: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 64-QAM.

Figure 4.5, figure 4.6 and figure 4.7 shows the bit error rate versus signal to noise ration of different multi-carrier modulation techniques. From the results it can be conclude that as the order of QAM increase the bit error rate performance also increase. And also as signal to noise ration of multi-carrier modulation techniques increase the the bit error

performance decrease.In figure 4.5, figure 4.6 and figure 4.7 the bit error performance of FBMC-QAM with hermite filter out performs than all other techniques.

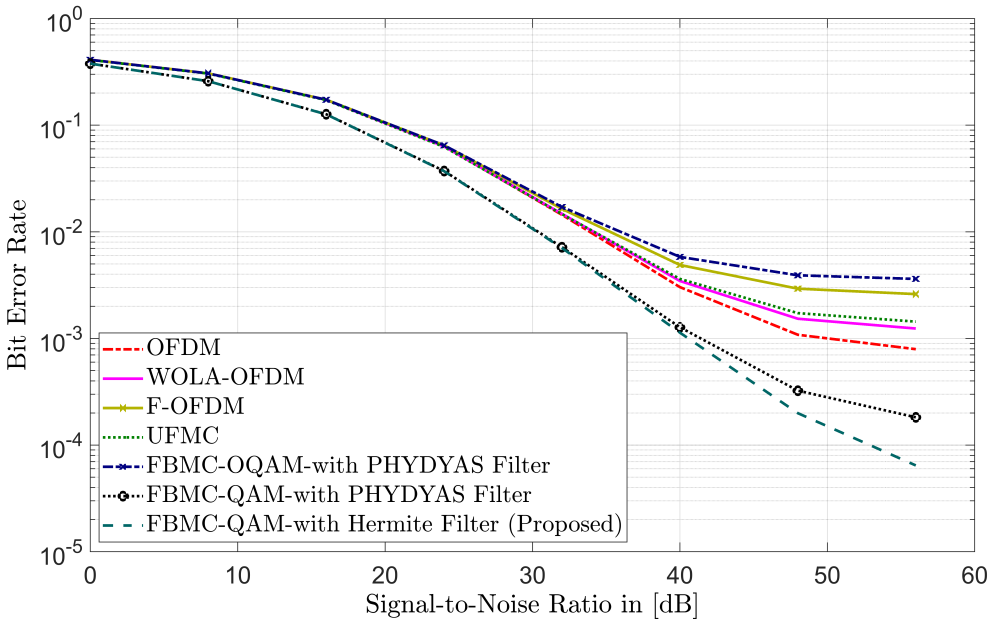

Figure 4.8: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 256-QAM.

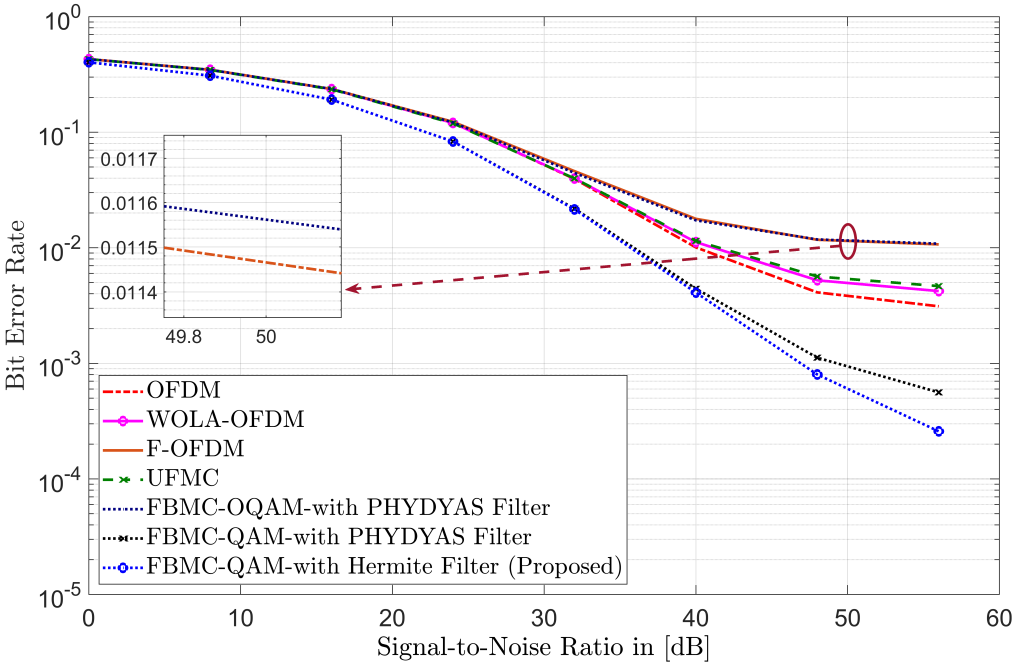

Figure 4.9: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular A channel model at 1024-QAM.

Figure 4.8 and figure 4.9 shows the bit error rate and signal to noise ration relationship. Generally higher order QAM can support large signal to noise ration. The proposed multi-carrier modulation techniques outperforms than all other.

Table 4.3: Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Vehicular A channel model.

Waveforms	QAM Order		Signal to Noise Ratio		
			20dB	30dB	40dB
OFDM	4-QAM	Bit Error Rate	4.500×10^{-3}	4.30×10^{-4}	6.200×10^{-5}
	16-QAM		2.040×10^{-2}	2.100×10^{-3}	2.600×10^{-4}
	64-QAM		2.580×10^{-2}	4.800×10^{-3}	1.050×10^{-3}
	256-QAM		6.340×10^{-2}	1.440×10^{-2}	3.000×10^{-3}
	1024-QAM		1.205×10^{-1}	3.940×10^{-2}	1.010×10^{-2}
F-OFDM	4-QAM		4.600×10^{-3}	4.800×10^{-4}	9.200×10^{-5}
	16-QAM		2.010×10^{-2}	2.030×10^{-3}	3.900×10^{-4}
	64-QAM		2.610×10^{-2}	5.400×10^{-3}	1.550×10^{-3}
	256-QAM		6.470×10^{-2}	1.640×10^{-2}	4.900×10^{-3}
	1024-QAM		1.230×10^{-1}	4.610×10^{-2}	1.780×10^{-2}
WOLA-OFDM	4-QAM		4.400×10^{-3}	4.700×10^{-4}	7.700×10^{-5}
	16-QAM		2.010×10^{-2}	2.200×10^{-3}	2.900×10^{-4}
	64-QAM		2.570×10^{-2}	5.000×10^{-3}	1.150×10^{-3}
	256-QAM		6.310×10^{-2}	1.480×10^{-2}	3.500×10^{-3}
	1024-QAM		1.201×10^{-2}	3.980×10^{-2}	1.120×10^{-2}
UFMC	4-QAM		4.300×10^{-3}	4.500×10^{-4}	7.300×10^{-5}
	16-QAM		1.970×10^{-2}	2.220×10^{-2}	3.100×10^{-4}
	64-QAM		2.540×10^{-2}	4.900×10^{-3}	5.700×10^{-2}
	256-QAM		6.250×10^{-2}	1.460×10^{-2}	3.600×10^{-3}
	1024-QAM		1.193×10^{-2}	3.980×10^{-2}	1.140×10^{-2}
FBMC/OQAM with Phydyas	4-QAM		4.900×10^{-3}	5.700×10^{-4}	1.300×10^{-4}
	16-QAM		1.970×10^{-2}	2.400×10^{-3}	5.400×10^{-4}
	64-QAM		2.590×10^{-2}	5.200×10^{-3}	1.580×10^{-3}
	256-QAM		6.460×10^{-2}	1.710×10^{-2}	5.800×10^{-3}
	1024-QAM		1.215×10^{-1}	4.450×10^{-2}	1.730×10^{-2}
FBMC/QAM with Phydyas	4-QAM		2.100×10^{-3}	1.900×10^{-4}	2.600×10^{-5}
	16-QAM		1.110×10^{-2}	1.090×10^{-3}	1.100×10^{-4}
	64-QAM		1.380×10^{-2}	2.400×10^{-3}	4.100×10^{-4}
	256-QAM		3.710×10^{-2}	7.200×10^{-3}	1.200×10^{-3}
	1024-QAM		8.310×10^{-2}	2.180×10^{-2}	4.400×10^{-3}
FBMC/QAM with Hermite	4-QAM		2.000×10^{-3}	1.700×10^{-4}	2.300×10^{-5}
	16-QAM		1.090×10^{-2}	1.080×10^{-3}	1.000×10^{-4}
	64-QAM		1.376×10^{-2}	2.340×10^{-3}	3.800×10^{-4}
	256-QAM		3.700×10^{-2}	7.000×10^{-3}	1.130×10^{-3}
	1024-QAM		8.310×10^{-2}	2.150×10^{-2}	4.000×10^{-3}

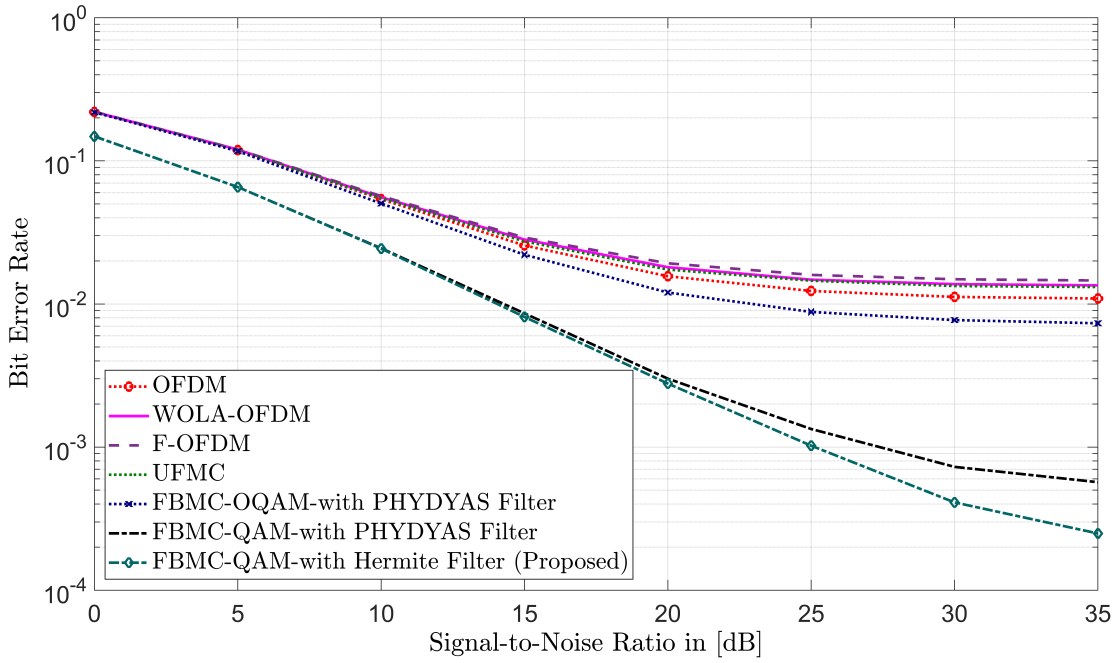

Figure 4.10: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 4-QAM.

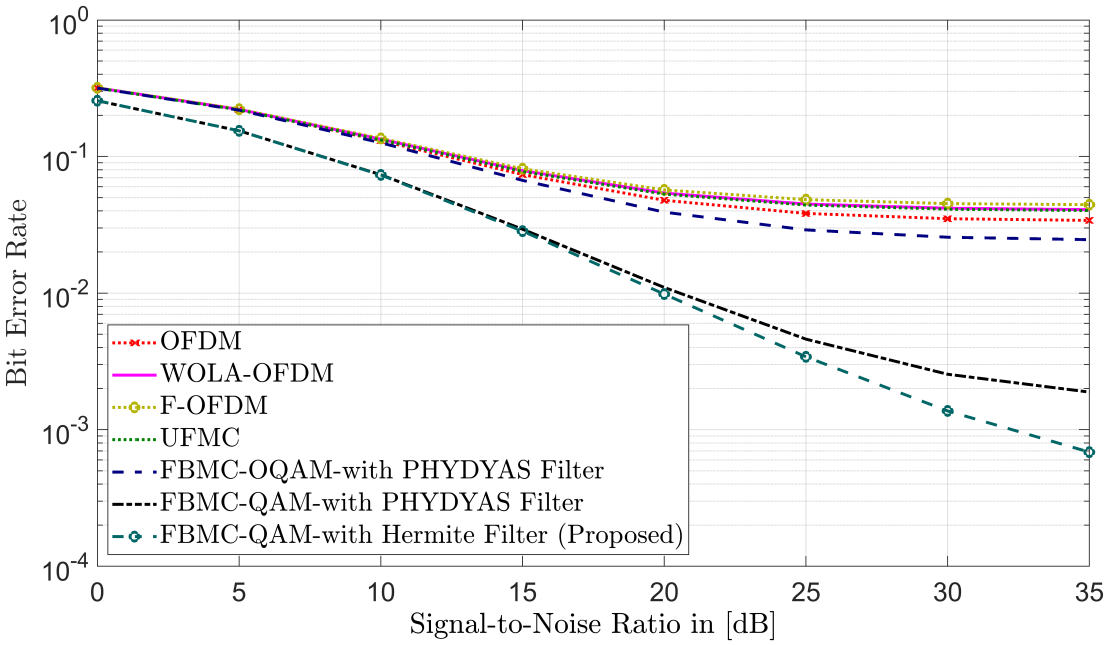

Figure 4.11: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 16-QAM.

Figure 4.10 and figure 4.11 shows the bit error rate versus signal to noise ration analysis. The analysis is done for Vehicular B channel model. In both figures FBMC-QAM with hermite filter outperform than all other multi-carrier modulation techniques.

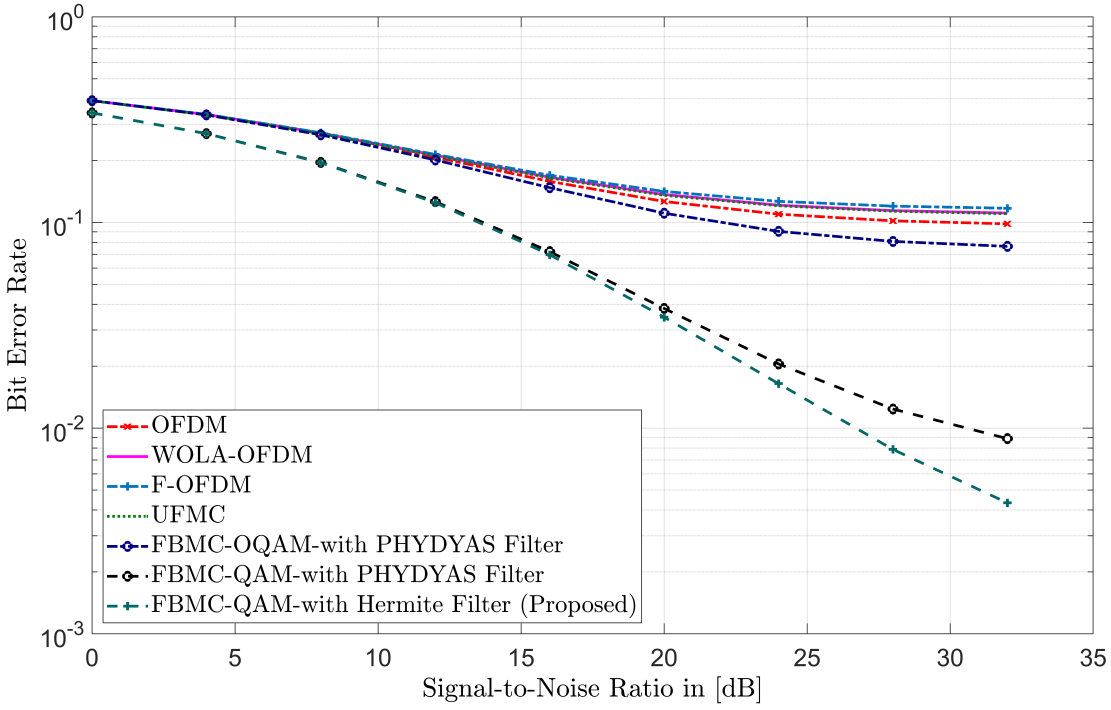

Figure 4.12: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 64-QAM.

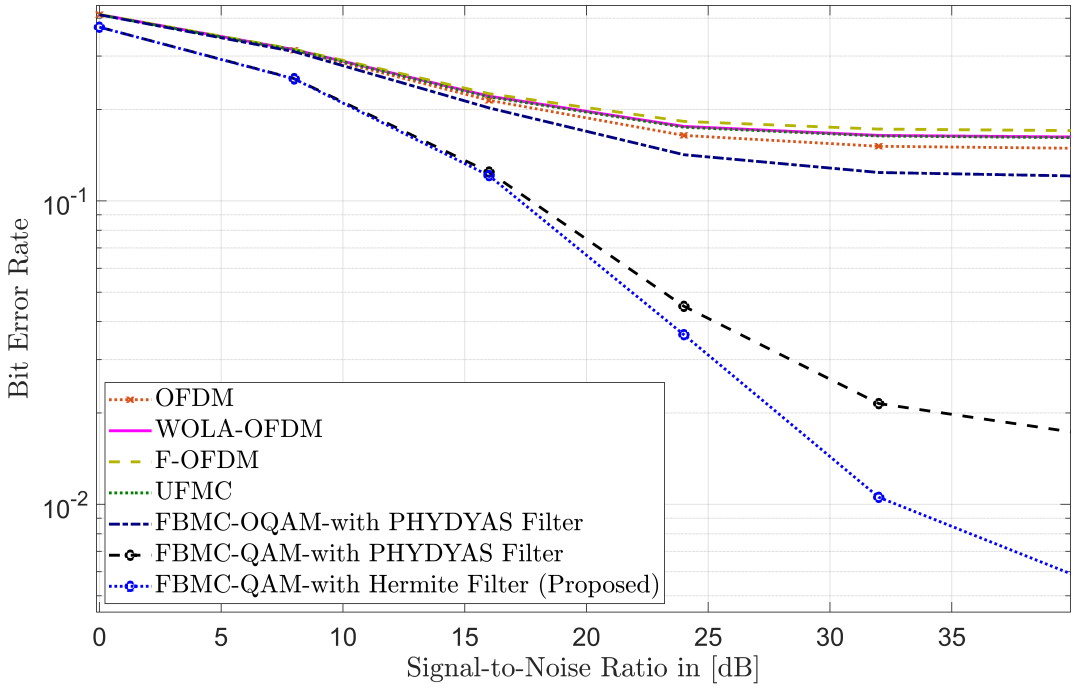

Figure 4.13: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 256-QAM.

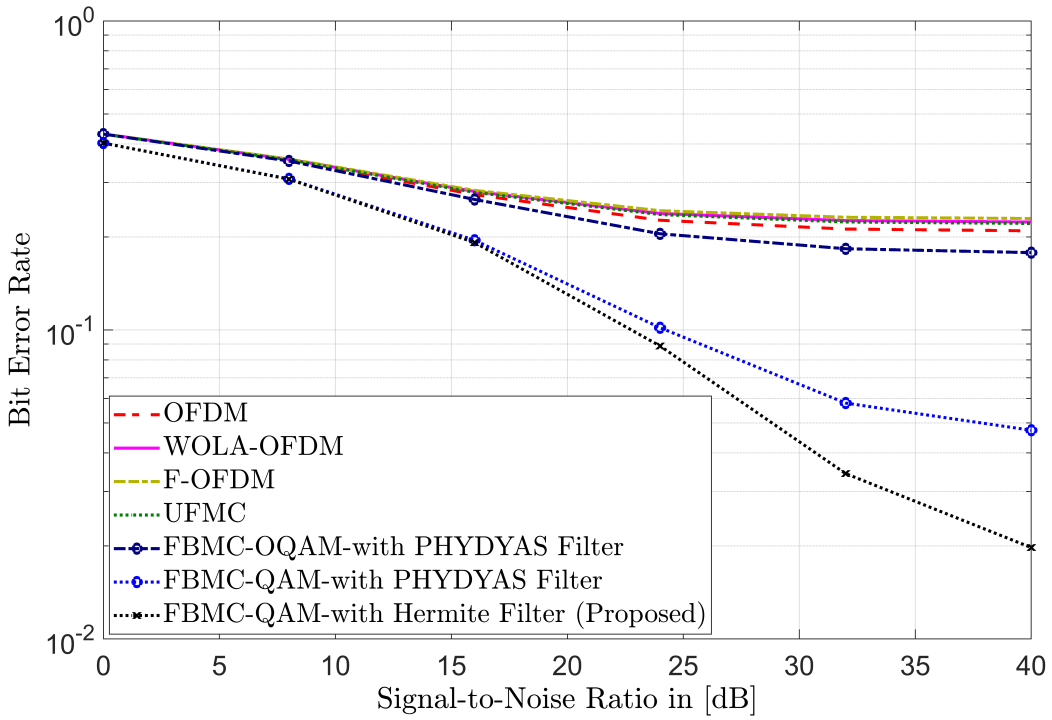

Figure 4.14: Bit Error rate performance of Different Multicarrier Modulation Techniques for Vehicular B channel model at 1024-QAM.

From table 4.4 it can observed that at signal to noise ration 30dB and 64-QAM the bit error rate of orthogonal frequency division multiplexing is 0.09847, the bit error rate of FBMC-QAM with phydyas filter is 0.008895 and the bit error of proposed multi-carrier FBMC-QAM with Hermite filter is 0.004334. When both OFDM and proposed method compared its deference becomes 0.094136. This shows the proposed method reduce the bit error by 95.598% of OFDM. When the bit error rate of FBMC-QAM with phydyas and FBMC-QAM with Hermite filter compared its difference becomes 0.004561. This shows FBMC-QAM with Hermite filter reduce the bit error rate by 51.276% of FBMC-QAM with phydyas.

General when the bit error performance for Vehicular A and Vehicular B channel model observed the bit error performance for Vehicular A channel model is comparably good. From over all view of those channel model as signal to noise ration increase the bit error rate decrease but as QAM order increase the bit error rate decrease. To support large signal to noise ration value higher order QAM is recommended because higher order QAM increase the spectral efficiency of the system. As it can be seen from the result of both Vehicular A and Vehicular B channel model the FBMC-QAM with hermite filter outperforms better than all other wave forms.

Table 4.4: Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Vehicular B channel model.

Waveforms	QAM Order		Signal to Noise Ratio		
			15dB	20dB	30dB
OFDM	4-QAM	Bit Error Rate	2.565×10^{-2}	1.563×10^{-2}	1.121×10^{-2}
	16-QAM		7.370×10^{-2}	4.779×10^{-2}	3.504×10^{-2}
	64-QAM		1.584×10^{-1}	1.265×10^{-1}	9.847×10^{-2}
	256-QAM		2.145×10^{-1}	1.643×10^{-1}	1.513×10^{-1}
	1024-QAM		2.742×10^{-1}	2.265×10^{-1}	2.121×10^{-1}
F-OFDM	4-QAM		2.912×10^{-2}	1.925×10^{-2}	1.489×10^{-2}
	16-QAM		8.132×10^{-2}	5.694×10^{-2}	4.519×10^{-2}
	64-QAM		1.696×10^{-1}	1.416×10^{-1}	1.172×10^{-1}
	256-QAM		2.256×10^{-1}	1.828×10^{-1}	1.724×10^{-1}
	1024-QAM		2.830×10^{-1}	2.431×10^{-1}	2.315×10^{-1}
WOLA-OFDM	4-QAM		2.912×10^{-2}	1.803×10^{-2}	1.376×10^{-2}
	16-QAM		7.887×10^{-2}	5.398×10^{-2}	4.181×10^{-2}
	64-QAM		1.658×10^{-1}	1.368×10^{-1}	1.112×10^{-1}
	256-QAM		2.214×10^{-1}	1.760×10^{-1}	1.644×10^{-1}
	1024-QAM		2.806×10^{-1}	2.382×10^{-1}	2.259×10^{-1}
UFMC	4-QAM		2.738×10^{-2}	1.740×10^{-2}	1.336×10^{-2}
	16-QAM		7.752×10^{-2}	5.304×10^{-2}	4.112×10^{-2}
	64-QAM		1.647×10^{-1}	1.355×10^{-1}	1.103×10^{-1}
	256-QAM		2.201×10^{-1}	1.748×10^{-1}	1.636×10^{-1}
	1024-QAM		2.788×10^{-1}	2.362×10^{-1}	2.235×10^{-1}
FBMC/OQAM with Pydyas	4-QAM		2.208×10^{-2}	1.203×10^{-2}	7.710×10^{-3}
	16-QAM		6.685×10^{-2}	3.913×10^{-2}	2.564×10^{-2}
	64-QAM		1.476×10^{-1}	1.110×10^{-1}	7.654×10^{-1}
	256-QAM		2.025×10^{-1}	1.419×10^{-1}	1.240×10^{-1}
	1024-QAM		2.644×10^{-1}	2.047×10^{-1}	1.831×10^{-1}
FBMC/QAM with Pydyas	4-QAM		8.600×10^{-3}	3.010×10^{-3}	7.200×10^{-3}
	16-QAM		2.936×10^{-2}	1.100×10^{-2}	2.550×10^{-3}
	64-QAM		7.214×10^{-2}	3.821×10^{-2}	8.895×10^{-2}
	256-QAM		7.214×10^{-2}	3.821×10^{-2}	2.149×10^{-2}
	1024-QAM		1.951×10^{-1}	1.017×10^{-1}	5.799×10^{-2}
FBMC/QAM with Hermite	4-QAM		8.110×10^{-3}	2.770×10^{-3}	4.100×10^{-4}
	16-QAM		2.842×10^{-2}	9.832×10^{-3}	1.370×10^{-3}
	64-QAM		6.974×10^{-2}	3.465×10^{-2}	4.334×10^{-3}
	256-QAM		1.211×10^{-1}	3.622×10^{-2}	1.055×10^{-2}
	1024-QAM		1.918×10^{-1}	8.870×10^{-2}	3.420×10^{-2}

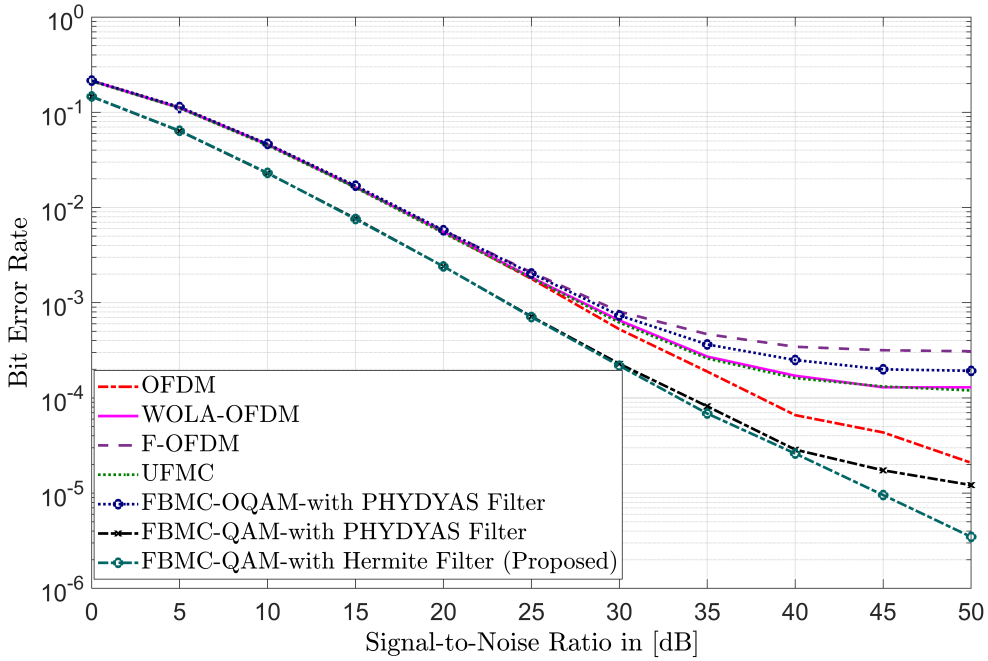

Figure 4.15: Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 4-QAM.

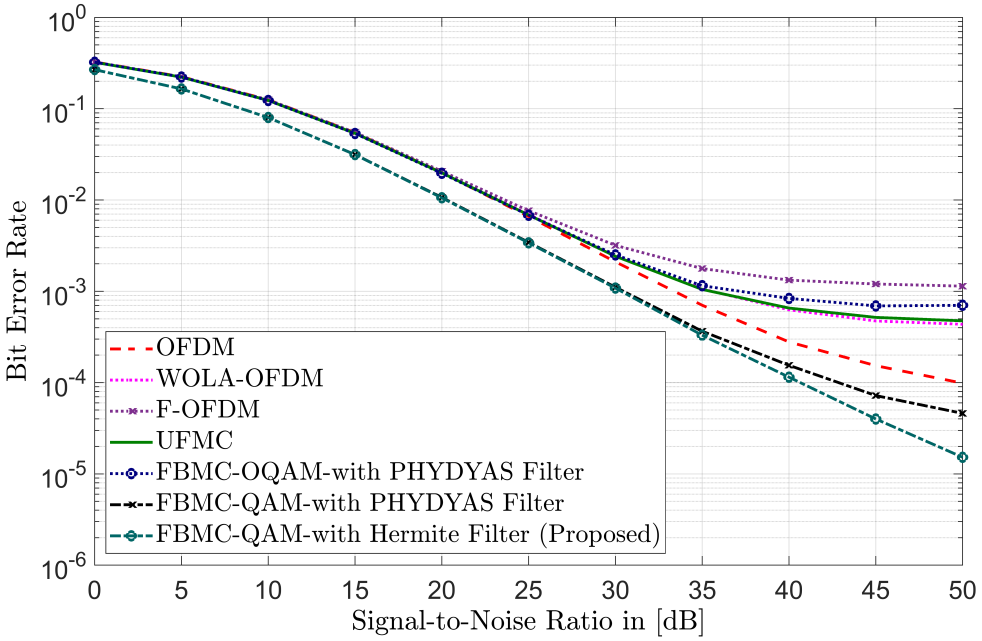

Figure 4.16: Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 16-QAM.

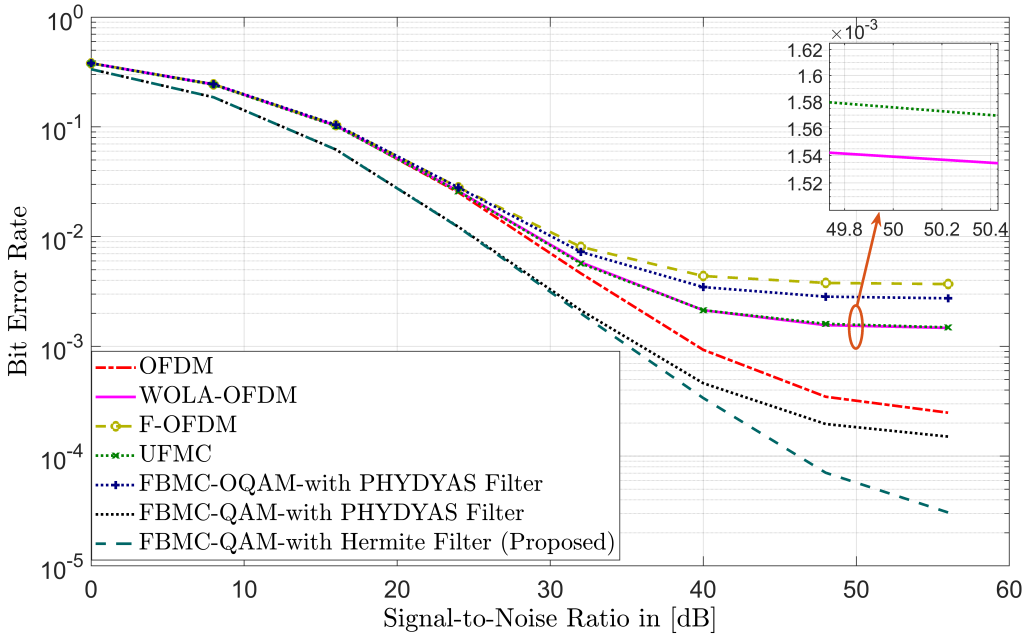

Figure 4.17: Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 64-QAM.

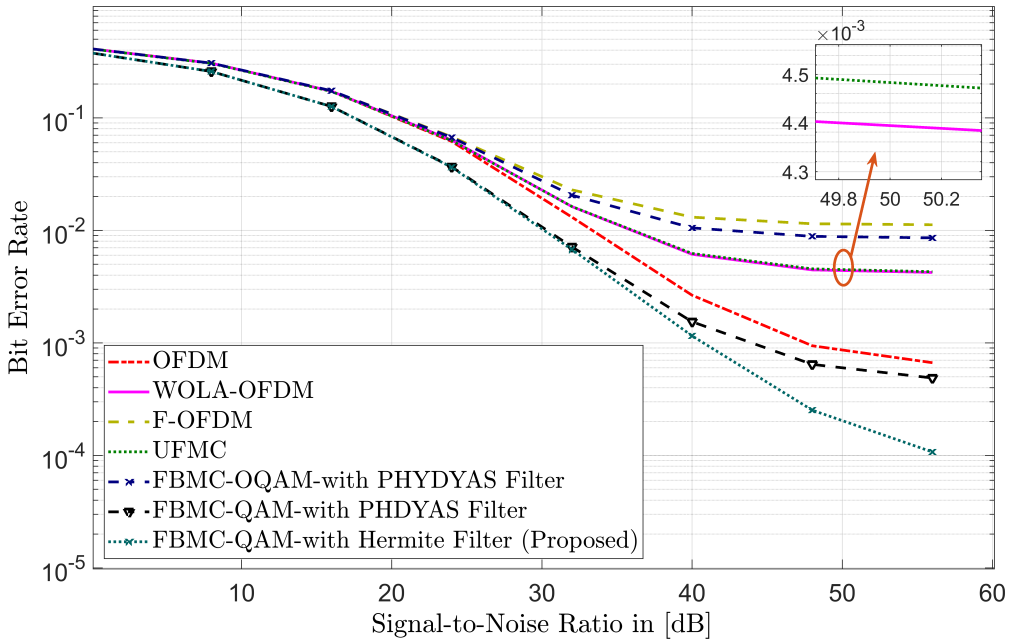

Figure 4.18: Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 256-QAM.

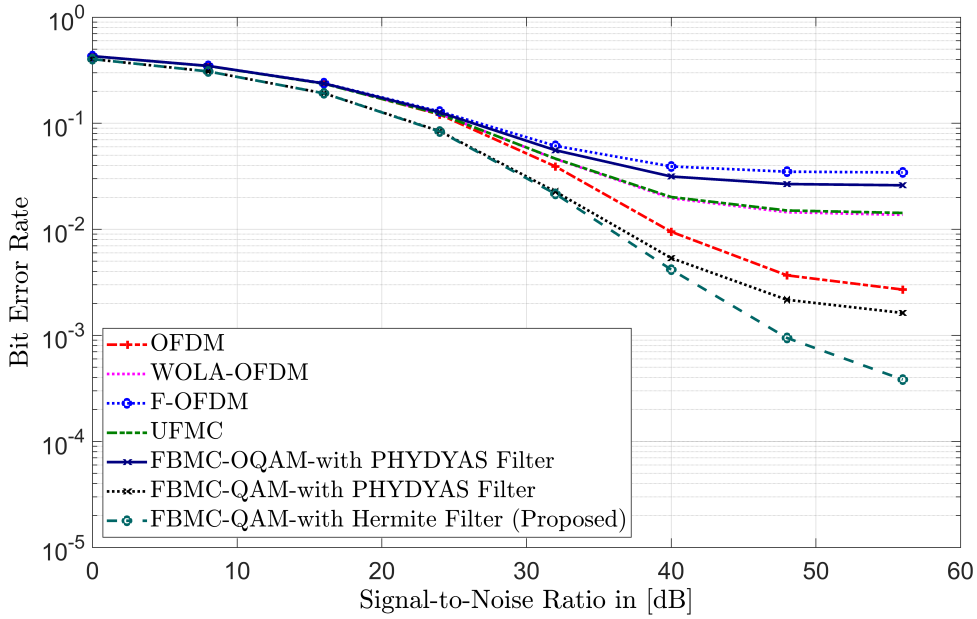

Figure 4.19: Bit Error rate performance of Different Multicarrier Modulation Techniques for Pedestrian B channel model at 1024-QAM.

From table 4.5 we see that at signal to noise ration 40dB and 64-QAM the bit error rate of orthogonal frequency division multiplexing is 0.0046, the bit error rate of FBMC-QAM with phydyas filter is 0.0021 and the bit error of proposed multi-carrier FBMC-QAM with Hermite filter is 0.0003385. When both OFDM and proposed method compared its deference becomes 0.0.0025. This shows the proposed method reduce the bit error by 54.35% of OFDM. When we compare the bit error rate of FBMC-QAM with phydyas and FBMC-QAM with Hermite filter its difference becomes 0.004561. This shows FBMC-QAM with Hermite filter reduce the bit error rate by 92.64% of FBMC-QAM with phydyas.

Generally when the bit error performance for Vehicular A, Vehicular B and Pedestrian B channel models seen the bit error performance for Pedestrian B channel model is better. From over all view of those channel models as signal to noise ration increase the bit error rate decrease but as QAM order increase the bit error rate decrease. To support large signal to noise ration value higher order QAM is recommended because higher order QAM increase the spectral efficiency of the system. As it can be observed from the result of Vehicular A and Vehicular B and Pedestrian B channel models the FBMC-QAM with hermite filter outperforms better than all other wave forms.

Table 4.5: Bit error rate performance of multi-carrier modulation techniques with 4-QAM, 16-QAM, 64-QAM, 256-QAM and 1024-QAM for Pedestrian B channel model.

Waveforms	QAM Order		Signal to Noise Ratio		
			20dB	30dB	40dB
OFDM	4-QAM	Bit Error Rate	5.526×10^{-3}	5.270×10^{-4}	6.500×10^{-5}
	16-QAM		1.992×10^{-2}	2.103×10^{-3}	2.786×10^{-4}
	64-QAM		1.029×10^{-1}	2.530×10^{-2}	4.600×10^{-3}
	256-QAM		1.724×10^{-1}	6.160×10^{-2}	1.310×10^{-2}
	1024-QAM		2.372×10^{-1}	1.209×10^{-1}	3.910×10^{-2}
F-OFDM	4-QAM		5.713×10^{-3}	8.080×10^{-4}	3.446×10^{-4}
	16-QAM		2.067×10^{-2}	3.600×10^{-3}	1.326×10^{-3}
	64-QAM		1.038×10^{-1}	2.820×10^{-2}	8.100×10^{-2}
	256-QAM		1.737×10^{-1}	6.780×10^{-2}	2.290×10^{-2}
	1024-QAM		2.385×10^{-1}	1.292×10^{-1}	6.120×10^{-2}
WOLA-OFDM	4-QAM		5.567×10^{-3}	6.52×10^{-4}	1.710×10^{-4}
	16-QAM		2.000×10^{-2}	2.460×10^{-3}	6.627×10^{-3}
	64-QAM		1.026×10^{-1}	2.590×10^{-2}	5.800×10^{-3}
	256-QAM		1.724×10^{-1}	6.330×10^{-2}	1.630×10^{-2}
	1024-QAM		2.372×10^{-1}	1.228×10^{-1}	4.600×10^{-2}
UFMC	4-QAM		5.392×10^{-3}	6.180×10^{-4}	1.615×10^{-4}
	16-QAM		1.982×10^{-2}	2.420×10^{-3}	6.540×10^{-4}
	64-QAM		1.016×10^{-1}	2.580×10^{-2}	5.700×10^{-2}
	256-QAM		1.714×10^{-1}	6.270×10^{-2}	1.630×10^{-2}
	1024-QAM		2.360×10^{-1}	1.222×10^{-1}	4.63×10^{-2}
FBMC/QAM with Phydyas	4-QAM		5.780×10^{-3}	7.360×10^{-4}	2.500×10^{-4}
	16-QAM		1.959×10^{-2}	2.500×10^{-3}	8.360×10^{-4}
	64-QAM		1.046×10^{-1}	2.810×10^{-2}	7.300×10^{-3}
	256-QAM		1.741×10^{-1}	6.690×10^{-2}	2.050×10^{-2}
	1024-QAM		2.375×10^{-1}	1.267×10^{-1}	5.570×10^{-2}
FBMC/QAM with Phydyas	4-QAM		2.407×10^{-3}	2.280×10^{-4}	2.900×10^{-5}
	16-QAM		1.067×10^{-2}	1.109×10^{-3}	1.545×10^{-4}
	64-QAM		6.210×10^{-2}	1.230×10^{-2}	2.100×10^{-3}
	256-QAM		1.261×10^{-1}	3.670×10^{-2}	7.1×10^{-3}
	1024-QAM		1.917×10^{-1}	8.420×10^{-2}	2.260×10^{-2}
FBMC/QAM with Hermite	4-QAM		2.407×10^{-3}	2.170×10^{-4}	2.600×10^{-5}
	16-QAM		1.057×10^{-2}	1.084×10^{-3}	1.146×10^{-4}
	64-QAM		1.221×10^{-2}	1.998×10^{-3}	3.385×10^{-4}
	256-QAM		3.636×10^{-2}	6.765×10^{-3}	1.153×10^{-3}
	1024-QAM		8.364×10^{-2}	2.157×10^{-2}	4.165×10^{-3}

4.5 Computational Complexity Comparison

Computational complexity analysis of different 5G candidate wave-forms are discussed in this section. It is an essential parameter to assess how the processor executes each multi-carrier modulation techniques. In this section we have evaluated complexity in terms of the number of real multiplications in each multi-carrier symbol.

The main block which creates complexity is IFFT and FFT in both transmitter and receiver respectively. The split-radix algorithm for IFFT and FFT implementation is used for complexity analysis. According to split-radix algorithm the number of real multiplication for N-Point FFT/IFFT is given as $M_{FFT/IFFT} = N \log_2 N - 3N + 4$, *multiplications*. For simulation different parameters were considered. And also the number of sub-channels taken 1024 for all wave-forms, cyclic-prefix as 72 for OFDM which is the same as 4G LTE, overlapping factor 4 for all wave-forms which has better side lobe,filter length 43 for UFMC, filter length 32 for WOLA-OFDM according to different literature.

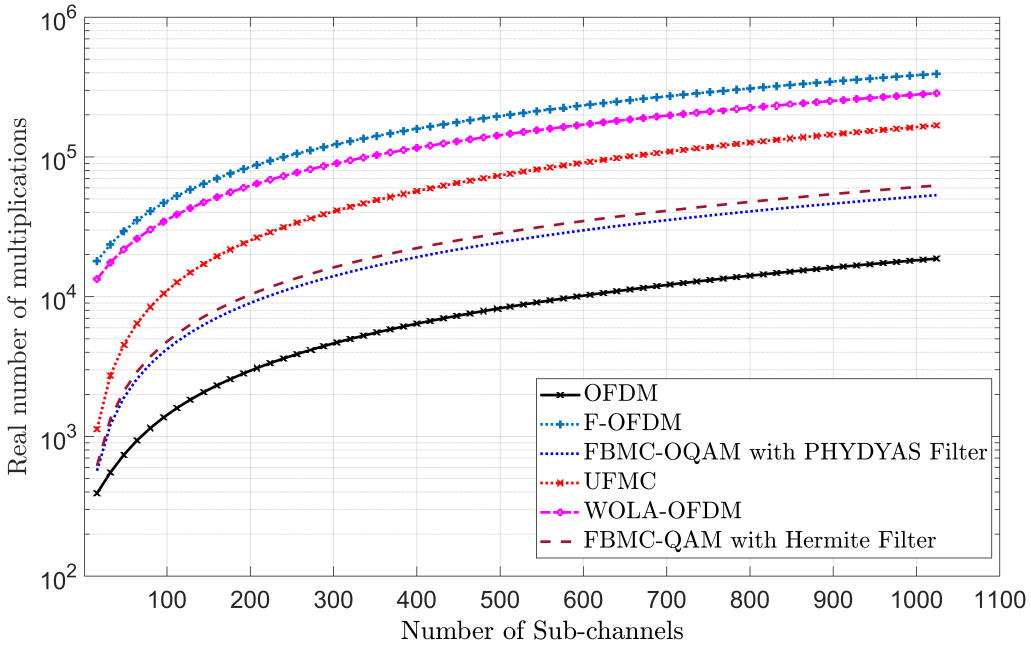

Figure 4.20: Computational Complexity of Multicarrier Modulation Techniques.

Figure 4.20 shows that increasing the number of sub-channel can increase the number of real multiplication. The complexity of OFDM is small compared to all other multi-carrier modulations. However, OFDM has several draw back. FBMC/OQAM and FBMC/QAM has comparable complexity but the PSD and BER performance of FBMC/QAM comes over FBMC/OQAM. However, the complexity of the proposed system requires further improvement.

Table 4.6: Power Spectral Density of Different Modulation Schemes at 20, 30, 40 and 50 normalized frequency.

Waveforms		Number of Sub-channels			
		96	192	384	560
OFDM	Number of Multiplication	1368	2825	6121	9401
F-OFDM		46800	81970	153100	218800
WOLA-OFDM		34490	60140	111800	159400
UFMC		10540	24110	54320	84080
FBMC/OQAM with Phydyas		4032	8617	18360	27680
FBMC/QAM with Hermite (Proposed)		4569	9881	21270	32230

Table 4.6 shows the multiplication complexity of multi-carrier modulation techniques for 96, 192, 384 and 560 sub-channels. When we compare the computational complexity of multi-carrier modulation techniques it is observed that OFDM has least complexity. The proposed system has little bit higher complexity than the the existing FBMC with OQAM with PHYDYAS filter.

4.6 Signal to Interference Ratio Comparison

The simulation result shows the signal to interference ration performance in the presence of both time offset and frequency offset using the parameter like overlapping factor 4, number of sub-carriers 1024 and number of sub-carrier spacing 15KHz. Figure 4.21 shows the signal to interference ratio in dB versus normalized time offset. From the result it can be concluded that signal to interference ratio of FBMC-QAM using PHYDYAS filter has slightly more signal to interference ratio compared to other wave forms. This shows the orthogonality of sub-carrier maintained using FBMC-QAM using Hermite filter in good way than all other waveform.The sensitivity of communication systems to a carrier frequency offset is an important issue because it can result in inter carrier interference (ICI).

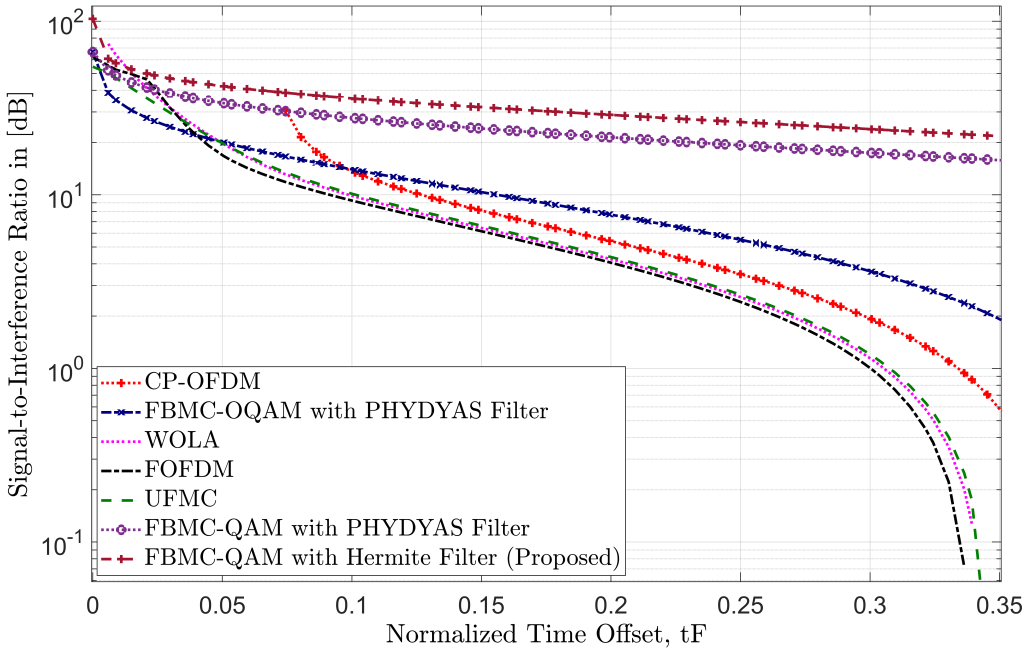

Figure 4.21: Signal to interference ratio versus normalized time offset of Multicarrier Modulation Techniques.

Figure 4.22 show that the signal to interference ratio of multi-carrier modulation schemes versus normalized carrier frequency offset. From the figure the signal to interference ratio of FBMC/QAM with PHYDYAS filter is higher compared to all other waveform.

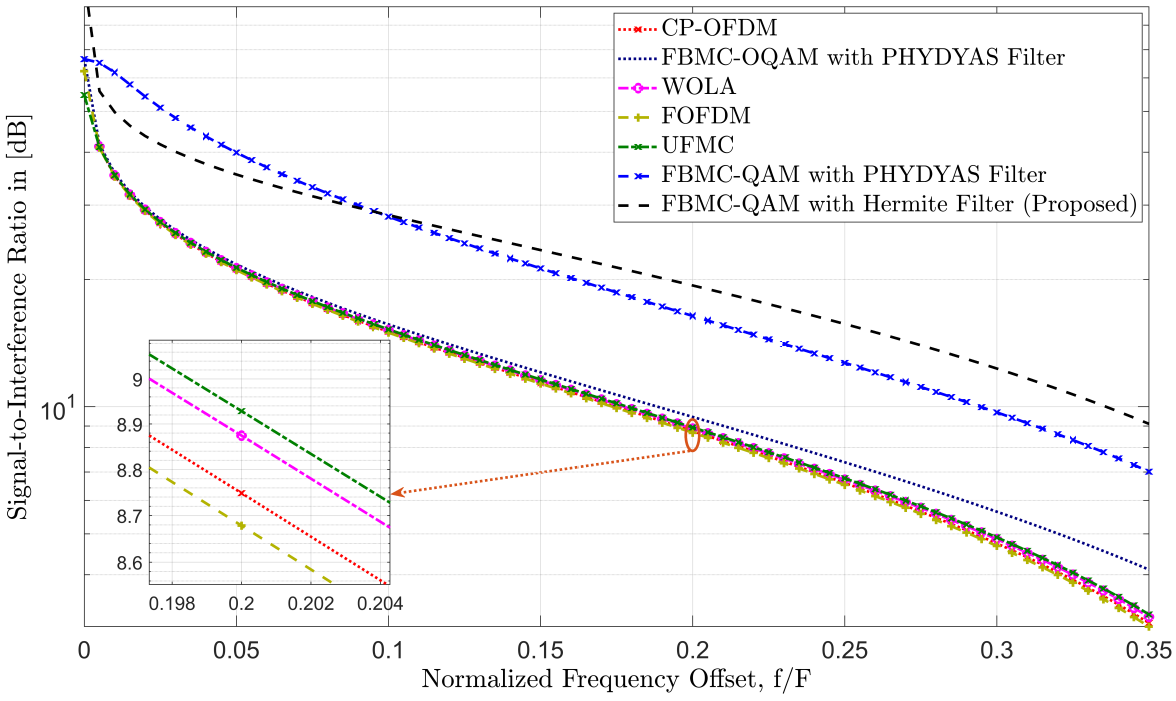

Figure 4.22: Signal to interference ratio versus normalized frequency offset of Multicarrier Modulation Techniques.

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study the performance of multi-carrier modulation techniques like F-OFDM, WOLA-OFDM, UFMC, FBMC with OQAM using PHYDYAS filter, FBMC with QAM using PHYDYAS filter and FBMC with QAM using Hermite filter are compared to that of existing OFDM. The analysis is carried out based on power spectral density, bit error rate, computational complexity, spectral efficiency and signal to interference ratio.

The Power spectral density versus normalized frequency analysis shows that the smaller out of band emission of FBMC-QAM using Hermite filter compared to than all other wave-forms. Let as consider normalized frequency of 30. The power spectral density of OFDM, FBMC with QAM using PHYDYAS filter and FBMC with QAM using Hermite filter is -29.05dB, -221dB, and -323 dB respectively. Difference in dB between FBMC-QAM using PHYDYAS filter and FBMC-QAM using Hermite filter (proposed) is 4.7 which shows that the out of band emission reduction amount and this helps for coexistence of different services.

The bit error rate analysis is carried for Vehicular A, Vehicular B and Pedestrian B channel models at different M-QAM orders like 4-QAM, 16-AM, 64-QAM, 256-QAM and 1024-QAM. The simulation result shows the bit error rate of FBMC with QAM using Hermite filter is better than all other wave-forms in these three channel models. Generally the bit error rate performance of multi-carrier modulation techniques is better in Pedestrian B channel model. As the value of signal to noise ration increase the bit error rate of multi-carrier modulation techniques decrease. As the order of QAM increase the bit error rate also increase.

The spectral efficiency analysis of Filter bank multi-carrier is better compared to other wave-forms. From signal to interference ratio analysis the FBMC with QAM using Hermite filter has greater signal to interference ratio. This shows FBMC with QAM using Hermite filter is good solution among existing wave-forms to maintain orthogonality between sub-carriers which avoids inter symbol interference (ISI) and inter carrier interference (ICI). It is observed that the BER performance of FBMC with QAM using Hermite filter reduced the bit error for Vehicular A, Vehicular B, and Pedestrian B ITU (International Telecommunication Union) standard channel model at 64-QAM. Generally, from analysis it can be concluded that FBMC with QAM using Hermite

filter is the best multi-carrier modulation technique that fits the requirement of 5G wireless communication and beyond compared to all other wave-forms.

5.2 Recommendation

In this thesis comparative analysis of multi-carrier modulation techniques with higher order QAM for fifth generation wireless communication carried. The analysis is carried using performance metrics like power spectral density, bit error rate, spectral efficiency, computational complexity and signal to interference ratio. The multi-carrier carrier modulation techniques chosen for comparison are OFDM, F-OFDM, WOLA-OFDM, UFMC, FBMC with OQAM using PHYDYAS filter, FBMC with QAM using PHYDYAS filter.

Some points that recommended for future works are:

1. The analysis in this thesis is carried using single transmitting and receiving antenna. In the future it is recommend to analyze the system massive MIMO antenna because it enhance the spectral efficiency.
2. The prototype filter used in this research work is Hermite filter. The out of band emission of multi-carrier modulation technique depends on the filter property. It is recommend to chose and design the filter that gives better out of band emission.
3. The analysis in this study is done for fading channel. The channel model considered is ITU standard Vehicular A, Vehicular B and Pedestrian B channel models. It is recommend to do further on other ITU standard channel model.
4. The computational complexity reduction of multi- carrier also recommended

RESEARCH FUND ACKNOWLEDGMENT

This research project is funded byb Adama Science and Technology University under grant number ASTU/SM-R/401/22, Adama, Ethiopia

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