Performance Evaluation of Candidate Waveforms with Higher Order QAM for Massive MIMO System under Vehicular and Pedestrian Channels

Peniel Mekonnen Mengistu

A Thesis Submitted to the Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

July, 2023

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "**Performance Evaluation of Candidate Waveforms with Higher Order QAM for Massive MIMO System under Vehicular and Pedestrian Channels**" is my original work. That is, it is not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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RECOMMENDATION

We, the advisors of this, hereby certify that we have read the revised version of the thesis entitled *"***Performance Evaluation of Candidate Waveforms with Higher Order QAM for Massive MIMO System under Vehicular and Pedestrian Channels***"* prepared under our guidance by Peniel Mekonnen Mengistu submitted in partial fulfillment of the requirement for the degree of Masters of Science in Communication Engineering. Therefore, we recommend the submission of revised version of the thesis is to the department following the applicable procedures.

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Major Advisor	Signature	Date
______________________	_______________	____________________
Co-advisor	Signature	Date

APPROVAL PAGE of M.Sc. THESIS

We, the advisors of the thesis entitled "**Performance Evaluation of Candidate Waveforms with Higher Order QAM for Massive MIMO System under Vehicular and Pedestrian Channels**" and developed by **Peniel Mekonnen Mengistu** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor	Signature	Date
Co-Advisor	Signature	Date

We, the undersigned, members of the board of Examiners of the thesis by **Peniel Mekonnen Mengistu** have read and evaluated the thesis entitled "**Performance Evaluation of Candidate Waveforms with Higher Order QAM for Massive MIMO System under Vehicular and Pedestrian Channels**" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering.

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Internal Examiner	Signature	Date
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis are contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AoA	Angle of arrival
AoD	Angle of departure
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CP-OFDM	Cyclic Prefix- Orthogonal Frequency Division Multiplexing
FBMC	Filter Bank Multicarrier
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FM	Frequency Modulation
F-OFDM	Filtered Orthogonal Frequency Division Multiplexing
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
LTE	Long Term Evolution
MATLAB	Matrix-Laboratory
MCM	Multicarrier Modulation
MIMO	Multiple Input Multiple Output
m-MIMO	Massive Multiple Input Multiple Output
MMMS	Multi Media Message Support
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak Average Power Ratio
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SC-OFDM	Single Carrier- Orthogonal Frequency Division Multiplexing
SMS	Short Messaging Service

SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UFMC	Universal Filter Multicarrier
3D	Three Dimensions
1G	First Generation
2G	Second Generations
3G	Third Generations
4G	Fourth Generations
5G	Fifth Generations

ABSTRACT

Future wireless technology is expected to come with a great improvement on data rate with best service quality. However, the number of subscribes to the emerging technology is increasing day to day. The capacity of future technologies should support massive number of users to achieve the demand of the subscribers. But the increasing number of customers for the upcoming wireless communication systems is meeting the demand for increasingly higher data rates while maintaining a consistent quality of service across the network. To address this issue, wireless communication systems have been utilizing multicarrier modulation schemes as opposed to single carrier modulation methods. A variety of modulation techniques and multicarrier strategies have been invented and integrated with Multiple Input Multiple Output system which is an essential part of modern cellular wireless networks. Multicarrier modulation techniques can effectively overcome channels that experience fading with several paths. Different multicarrier modulation techniques are proposed by different researchers to handle the customers need and to reduce the drawbacks of the existing system. The most recommended multicarrier modulation techniques are Orthogonal Frequency Division Multiplexing, Fil*tered Orthogonal Frequency Division Multiplexing, Universal Filtered Multi-Carrier and Filter Bank Multi Carrier. The effectiveness of these suggested multicarrier modulation methods is examined in this thesis using a variety of realistic communication channel models, including the Pedestrian A, Pedestrian B, Vehicular A, Vehicular B, Proposed Extended Pedestrian A, and Proposed Extended Vehicular A channel models. The performance metrics used for simulation are, signal to noise ratio versus bit error rate, Normalized frequency offset versus signal to interference ratio and Normalized time offset versus signal to interference ratio. The analysis is done for different higher order Quadrature amplitude modulation schemes like Quadrature amplitude modulation (4, 16, 64, 256, and 1024). According to result, Filter Bank Multi Carrier performs better than all other waveforms. Under those Quadrature amplitude modulation order with the channel model, the error making probability of Filter Bank Multi Carrier is lower. It is concluded that a higher Quadrature amplitude modulation order causes a higher bit error rate value. To accommodate a large number of users and Signal to Noise Ratio, greater Quadrature amplitude modulation order is a solution. The bit error rate value of Filter Bank Multi Carrier falls below* 10^{-4} *for Signal to noise ratio greater than 35dB.*

.

Keywords: Massive Multiple Input Multiple Output, Quadrature amplitude modulation, Candidate Waveforms, Extended Vehicular A, Extended Pedestrian A, Pedestrian A, and Pedestrian B, Vehicular A, Vehicular B

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

The market for wireless communication technology is expanding quickly due to an increase in subscribers. Massive MIMO has been investigated as a component of the basic 5G system and will play a significant role in smart connectivity in 2020 (Sharma, 2013). Cellular networks must therefore grow in order to keep up with the rising Wireless demand communication. A cell phone is a necessary tool in the modern world, and its development is accelerating. In order to handle the ever-growing mobile traffic (Mohammad Abu-Dalbouh, 2019), it is necessary to increase wireless communication networks data speeds and reliability due to their increasing load.

First Generation was analog in nature, similar to a regular radio or an old-style walkie-talkie. Base stations, often known as cell towers, handled the signals instead of end-to-end transmission. Frequency modulation (FM) and frequency division multiple access (FDMA) have been the modulation and access methods employed by the 1G system. This system's service had poor voice quality (Al-Jawhar et al., 2021).

Second Generation represented the transition from analog to digital transmission of voice. So that second-generation wireless networks were initiated due to low transmission rate between the base station and mobile station and the insecurity of the transmission system. These digital, TDMA- or CDMA-based mobile systems are of the second generation. Digital cellular systems, which employ digital modulation, outperform analogue ones in a number of ways, including greater bandwidth utilization, increased privacy, and the addition of error detection and correction (ITU-R, 2015).

Third generation has been made to deal with the shortcomings of 2G and 2.5G. It makes application of a wideband wireless network, which increases communication clarity. In addition to voice, Multimedia Message Support (MMS), SMS, email, video downloading, image sharing, and other smartphone capabilities, this generation also included web browsing on mobile phones. It is employed Code Division Multiple Access as its multiple access method.

The fourth-generation can manage more data traffic while maintaining a higher level of service and delivers data rates of up to 100Mbps. It offered programs like mobile television, internet gaming, and video conferencing. Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying are the digital modulation methods utilized by 4G LTE networks (QPSK). LTE is able to provide faster data speeds due to a better antenna technique like MIMO, bigger bandwidths, and higher QAM modulation orders. Networks in LTE Advanced employ use 256 QAM(X. Zhang et al., 2015).

Fifth Following 1G, 2G, 3G, and 4G networks, generation mobile networks are the newest global wireless standard. With the help of 5G, a brand-new network may be created that connects almost everyone and everything, including machines, objects, and devices. With 5G wireless technology, more users will have access to faster peak data rates of multiple gigabits per second (Gbps), extremely low latency, increased stability, huge network capacity, increased availability, and a more consistent user experience. Greater effectiveness and efficiency enable new user experiences and link new industries.

Modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal (Marian Joseph Jeffery et al., 2020), Single carrier modulations and multicarrier modulations are the two groups into which wireless communication techniques now fall. The modulation in analogue modulation is continually applied in response to the analogue information signal. In digital modulation, a discrete signal modulates an analogue carrier signal. This modulation technique can be divided into single and multicarrier modulation techniques (H. Zhang et al., 2016). Single carrier modulation systems use a single signal frequency to transmit data symbols, as opposed to multicarrier modulation, which divides the entire frequency channel into several sub-carriers and transmits the high-rate data stream in parallel on sub-carriers. Because the symbol interval in multicarrier modulation is wider, multicarrier modulation systems (Abdel-Atty et al., 2020) offer better ISI resistance than single-carrier modulation systems.

1.2. Statement of the Problem

It is projected that compared to the 4G wireless communication system, the 5G wireless communication system will provide services that are hundreds of times more abundant. Future systems should have low costs and energy consumption. It is better to explore the supporting technologies of 5G technologies in order to improve the requirements of 5G technologies such as spectrum efficiency, signaling efficiency, bandwidth, and coverage. In order to decrease air-link latency and boost spectrum efficiency, throughput, area capacity density, and energy efficiency, the air interference uses waveforms, multiplexing systems, modulation schemes (candidate waveforms), and coding schemes. Orthogonal frequency division multiplexing with a single carrier is now employed for up-link and multicarrier OFDM for down-link. However, single-carrier modulations are less able to handle multipath fading channels than multicarrier modulations, which contribute to the decline in spectral efficiency (Zayani et al., 2018). In order to maintain the orthogonally across multiple users, OFDM also needs time synchronization. High peak-to-average ratio is also regarded as one of the main obstacles in OFDM, which significantly lowers the effectiveness and performance of nonlinear OFDM amplifiers. For 5G wireless communication systems, the shortcomings of OFDM in 4G wireless communication systems need to be addressed. As a result, a number of modulation methods other than CP-OFDM have been suggested for use in 5G wireless communication. Some of the suggested possible modulation methods for 5G include FBMC, UFMC, and F-OFDM. These waveforms (OFDM, FBMC, and UFMC) have not been thoroughly compared based on the channel uncertainty specifically on vehicular and pedestrian channel models. This gives us motivation to research some of the prospective candidate waveforms that have been offered, such as FBMC, f-OFDM, and UFMC. Performance will also be analyzed in terms of Bit Error Rate (BER), and Signal to Interference Ratio.

1.3. Objectives

1.3.1. General Objective

The main objective of this thesis is to analyze the performance of existing OFDM and Proposed 5G and beyond candidate waveforms with higher order QAM for massive MIMO under Vehicular and Pedestrian channel models.

1.3.2. Specific Objectives

Specific objectives of the study are:

1. To analyze the bit error rate performance of candidate waveforms based on the channel models for Pedestrian A, Pedestrian B, Vehicular A, and Vehicular B channel models.
2. To illustrate the Signal to Interference Ratio of the candidate waveforms in Pedestrian A, Pedestrian B, Vehicular A, and Vehicular B channel models.
3. To estimate how well waveforms, perform over the AWGN channel.
4. To evaluate the performance of modulation techniques in 5G and beyond in Extended Pedestrian and Vehicular A channel model.

1.4. Significance of the Study

Strong guidance on how to construct a system will be provided by a well-researched and arranged research paper on fifth-generation wireless communication's underlying technology. This thesis focuses on the performance assessment of potential OFDM and fifth-generation wireless communication system modulation techniques in the presence of channel uncertainty. As a result, this thesis work is extremely helpful in understanding how various waveforms perform when there is channel uncertainty. It also greatly aids in understanding and evaluating the benefits and drawbacks of each candidate waveform, determining whether or not each candidate waveform satisfies the requirements of Massive MIMO wireless communication, and providing guidance for upcoming research.

1.5. Scope of the Study

This research focuses on modulation techniques which are the supporting technologies for fifth generation wireless communication and beyond. OFDM offers benefits and disadvantages of its own. Due to its flaw, beyond the fifth generation, OFDM is not a viable waveform for wireless communication systems. To solve the drawback of OFDM, numerous alternative candidate waveforms have received in-depth research. However, there is a lack of a detailed and objective evaluation of these alternative waveforms based on channel uncertainty. The most prominent fifth generation candidate waveforms are analyzed in this research, mainly performance analysis for a variety of channels, including Extended Vehicular A, Extended Vehicular B, Pedestrian A, Pedestrian B.

1.6. Limitation of the Study

This thesis is only concerned with system analysis, which is carried out using the MATLAB application program under the assumption that a single user will use all of the system's resources. The availability of the component makes it challenging to create the genuine system.

1.7. Thesis Outline

There are five chapters in this thesis. These chapters give summaries of many subjects. The background of the study, the problem statement, the aims, the significance of the investigation, the scope of the study, and the study's limitations were all briefly discussed in the first chapter. The second chapter is devoted to reviews of the literature on the vehicular network, as well as the various channel models, transmission techniques, and frequency bands employed in this network.

The overall system model, including the scenario model, blockage model, transmission model, channel model, channel and interference model, and other system model components, is described in the third chapter. The simulation results and research discussion are covered in the fourth chapter. The fifth chapter concludes by summarizing the research's contributions, drawing a conclusion, and outlining its future directions.

CHAPTER TWO

2. LITRATURE REVIEW

2.1. Chapter Overview

This chapter mainly focuses on vehicular communication, wireless networks stochastic geometric model, cooperative transmission, multipath fading models, frequency bands, general performance metrics, and related works.

2.2. Wireless Communication System

A wireless communication system is a type of communication system that transmits data over a wireless medium, such as radio waves, microwaves, or infrared radiation. Without the use of physical wires or cables, it is used to send and receive information over long distances. Mobile phones, Wi-Fi, Bluetooth, satellite communication, radio and television transmission, and other wireless communication systems are utilised in a wide range of applications (Chataut & Akl, 2020). Typically, these systems are made up of a transmitter and a receiver that speak to one another wirelessly. Data is transformed into a signal that may be broadcast via a wireless medium by the transmitter (Devamalar et al., 2020). The receiver then takes in the signal and transforms it back into the original data.

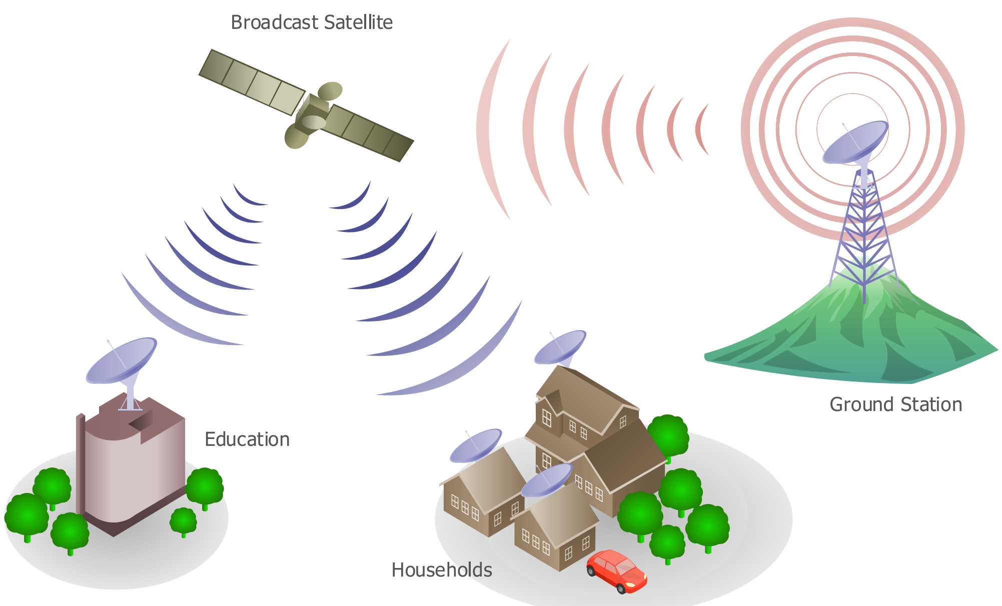

Figure 2. 1 Wireless Communication Medium (X. Zhang et al., 2016)

One of the main advantages of wireless communication systems is their flexibility and convenience. They allow users to communicate from almost anywhere, without the need for physical connections. This makes them ideal for applications such as mobile phones and Wi-Fi, where users need to be able to communicate on the move (Tazeb & Kassaw, 2019). Wireless communication systems also offer a high degree of scalability, allowing them to be used in a range of different applications, from small personal devices to large-scale networks.

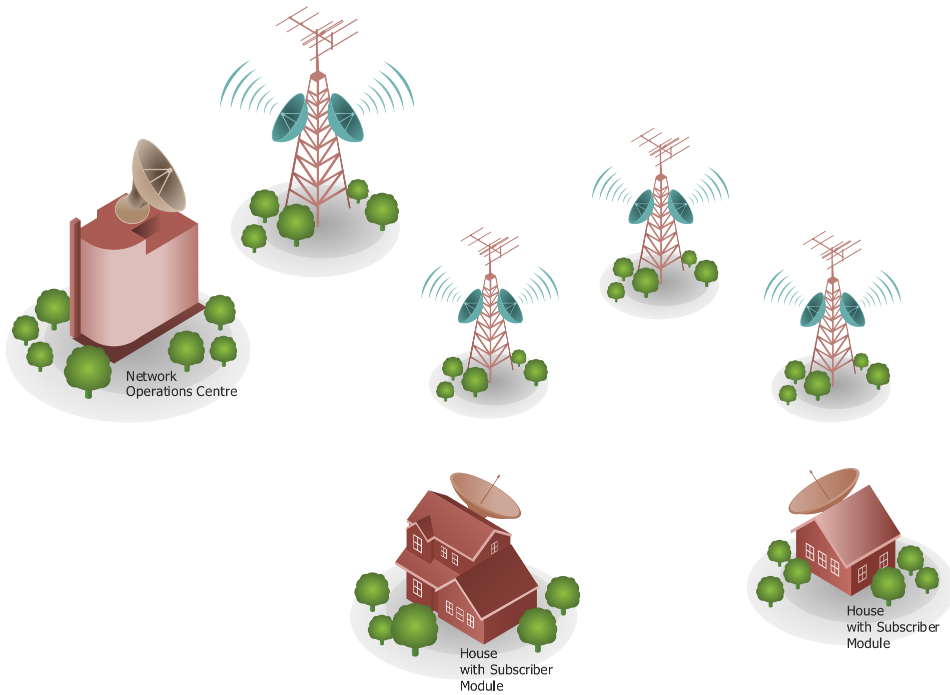

Figure 2. 2 Wireless Broadband Network Layout (Chataut & Akl, 2020)

However, wireless communication systems also have some limitations. One of the main challenges is interference, which can occur when multiple wireless signals are transmitted in the same frequency band. This can lead to degraded signal quality or even complete loss of communication. To overcome this challenge, Beam forming, spread spectrum, and frequency hopping are just a few of the methods that are employed (Wang, 2020). These techniques allow wireless communication systems to operate in environments with high levels of interference, such as in crowded urban areas or in the presence of other electronic devices.

In addition to interference, wireless communication systems also face security challenges, such as eavesdropping and hacking. To address these challenges, various encryption and authentication techniques are used to protect the data transmitted over the wireless medium.

In general, wireless communication systems are a vital component of modern communication infrastructure, allowing users to communicate over a distance without the need for physical wires or cables (X. Zhang et al., 2015). They offer flexibility, scalability, and convenience, but also face challenges such as interference and security threats. Wireless communication technologies will continue to play a significant role in our daily lives as technology develops.

2.3. Basics for Future Wireless Communication System Existence

Significant breakthroughs in wireless communication systems' speed, capacity, and reliability are predicted for the future. Future wireless communication systems must be developed in order to meet society's needs, given the rise in linked devices and the desire for high-speed data transmission. Future wireless communication networks will be developed using a number of major technologies, one of which being 5G (Tazeb & Kassaw, 2019). The fifth generation of wireless communication technology, or 5G, promises a considerable increase in network capacity, lower latency, and quicker data transfer rates. It is anticipated to open the door to new applications including augmented and virtual reality, self-driving cars, and the Internet of Things (IoT).

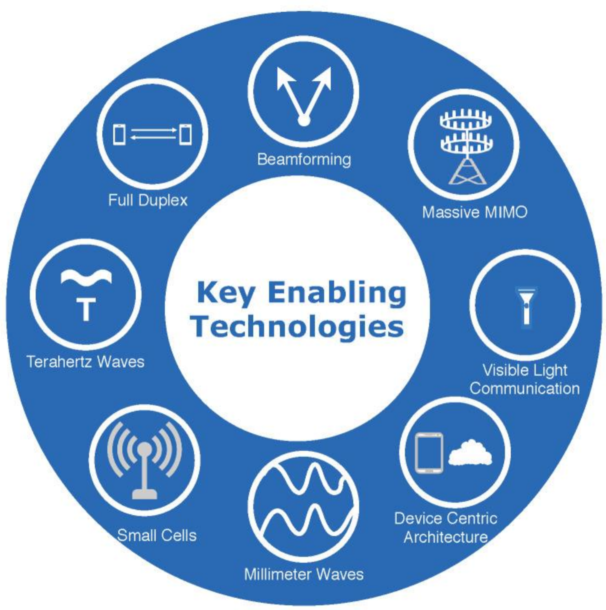

Figure 2. 3 5G and beyond wireless communication system enabling technologies (Chataut & Akl, 2020)

In addition to 5G, other technologies such as millimeter-wave (mmWave) and Future wireless communication systems are anticipated to make extensive use of massive multiple-input multiple-output (MIMO) technology. While massive MIMO technology makes use of numerous antennas to expand network capacity and boost signal quality, millimeter-wave technology uses higher frequency bands to enable faster data transmission rates (Osseiran et al., 2014). Future wireless communication system development is anticipated to result in significant energy efficiency improvements. In the future, electronics won't require constant charging or battery replacement because of new technologies like energy harvesting and wireless power transfer.

Another key aspect of future wireless communication systems is network architecture. Traditional cellular networks are based on a hierarchical architecture, with a limited number of cell towers serving a sizable user base. However, in the future, networks are expected to be more distributed, with smaller cells and more localized data processing (Farhang-Boroujeny & Moradi, 2016). This will enable faster data transfer rates and lower latency, as well as improved reliability and security.

The emergence of new wireless communication technologies is expected to bring significant improvements in terms of security and privacy. New technologies such as block-chain and secure multi-party computation will enable secure and private data transmission, protecting users from cyber threats and ensuring that their data remains confidential. In general, the development of future wireless communication systems is crucial to meet the growing demand for high-speed data transmission and the proliferation of connected devices. 5G, mmWave, and massive MIMO technologies, as well as energy harvesting and wireless power transfer, will drive the development of future wireless communication systems. Network architecture and security and privacy technologies will also play a critical role in ensuring that Systems for wireless communication in the future are quick, dependable, and secure.

2.4. Modulation in Wireless Communication System

In wireless communication systems, modulation is a method for converting digital data to radio signal waves which is capable of being sent over a wireless channel. In modulation, the digital data is superimposed onto a carrier wave; it can be sent over a wireless channel as well as is a high-frequency signal (Lu et al., 2014). The resulting signal, is referred to as the modulated signal, can then be sent over the wireless channel and received by a receiver, where it is demodulated to recover the original digital data.

Amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), and their variants are just a few of the modulation techniques utilized in wireless communication systems. Each of these modulation methods has benefits and drawbacks, and the best option will be determined by a number of variables, including the system's needs, the wireless channel's characteristics, and the hardware that is available.

AM is a type of modulation where the carrier wave's amplitude varies in proportion to the digital data. In FM, the carrier wave's frequency varies in direct proportion to the digital data, whereas in PM, the carrier wave's phase varies in direct proportion to the digital data. These modulation techniques are typically used in low-speed applications such as voice communication and low-speed data transmission, as they have a relatively low data rate and are susceptible to interference and noise (Osseiran et al., 2014).

In contrast, higher-speed applications like digital television transmission and high-speed internet access use more sophisticated modulation methods like quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM). While OFDM is a multicarrier modulation technique that separates the digital data into several sub-channels, each of which is sent using a different carrier wave, QAM changes the amplitude and phase of the carrier wave. The choice of modulation technique also depends on the available hardware. For example, some hardware may be more suited to certain modulation techniques than others, or may be more suitable for certain frequency bands or wireless channels (Chataut & Akl, 2020).

In general, Modulation is a vital component of wireless communication systems that convert radio waves into digital data for transmission via wireless channels. The choice of modulation technique is influenced by a number of variables, including the system requirements, the wireless channel characteristics, and the hardware that is available. Each modulation approach has its own pros and disadvantages.

2.4.1. Single Carrier and Multi-Carrier Modulation Techniques

Single carrier modulation (SCM) and multicarrier modulation (MCM) are two different techniques used in wireless communication systems to transmit digital data over a wireless channel. While both techniques have their advantages and disadvantages, they are used in different applications depending on the specific requirements of the system.

Single carrier modulation techniques transmit data using a single carrier wave, which is modulated to carry the digital data. Amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM) are the three most widely utilized SCM techniques (Mishra et al., 2016). In SCM, the entire bandwidth of the carrier wave is used to transmit the signal(Yang et al., 2018), which makes it vulnerable to interference and noise. However, SCM is relatively simple and can be implemented using low-cost hardware, making it suitable for applications with low data rates and low complexity.

In contrast, multicarrier modulation techniques divide the digital data into multiple sub-channels, each of which is transmitted using a separate carrier wave. As a result, MCM is able to transmit data more effectively and consistently than SCM since each sub-channel can be tailored to the unique properties of the wireless channel. Orthogonal frequency-division multiplexing (OFDM) and its variants, such as discrete multi-tone modulation (DMT) and filtered multi-tone modulation (FMT), are the MCM techniques that are most frequently utilized. MCM is used in applications with high data rates and high complexity, such as digital television broadcasting and high-speed internet access (Chataut & Akl, 2020).

One of the main advantages of MCM is its ability to overcome the problem of multipath fading, which occurs when the signal is reflected off obstacles and arrives at the receiver at different times. In SCM, this can cause interference and reduce the signal quality, but in MCM, each sub-channel can be optimized to deal with the specific characteristics of the wireless channel, reducing the effects of multipath fading.

However, MCM also has some disadvantages. Because it requires more complex hardware and signal processing algorithms than SCM, it can be more expensive and require more power. In addition, MCM can be more vulnerable to interference from other wireless signals, as each sub-channel is transmitted at a lower power than the entire bandwidth in SCM.

In general, SCM and MCM are two different modulation techniques used in wireless communication systems. SCM is relatively simple and low-cost, making it suitable for applications with low data rates and low complexity. MCM, on the other hand, is more complex and expensive, but provides higher data rates and better reliability, making it suitable for applications with high data rates and high complexity (Jiang et al., 2016). The choice between SCM and MCM depends on the specific requirements of the system, including data rate, complexity, cost, and reliability.

2.5. Pedestrian and Vehicular Channel Models

Wireless channel models for vehicles and pedestrians are two main categories utilized in wireless communication systems. These models are used to forecast how the wireless channel will behave, including aspects like signal strength, fading, and interference. Wireless channels are modeled for pedestrian environments using pedestrian channel models and for automobile environments using vehicular channel models (Chataut & Akl, 2020).

Pedestrian channel models are used to model wireless channels in environments such as urban areas, parks, and indoor spaces, where pedestrians are likely to be present. These models take into account the movement of pedestrians, which can cause rapid fluctuations in signal strength and interference. Pedestrian channel models typically use statistical methods to model the wireless channel, based on measurements of the channel in similar environments (Belbase et al., 2018). They might also consider elements that may have an impact on how the wireless channel behaves, such as the presence of structures, trees, and other obstructions.

Vehicular channel models are used to model wireless channels in environments such as highways, streets, and parking lots, where vehicles are likely to be present. These models take into account the movement of vehicles, which can cause rapid fluctuations in signal strength and interference. Vehicular channel models typically use statistical methods to model the wireless channel, based on measurements of the channel in similar environments (ITU-R, 2015). They may also take into account factors such as the speed of the vehicles, the density of the vehicles, and the presence of buildings, trees, and other obstacles.

Figure 2. 4 Sub-urban wireless communication barriers (ITU-R, 2015)

One of the main challenges in modeling pedestrian and vehicular channels is the rapid fluctuations in signal strength and interference caused by the movement of pedestrians or vehicles. To address this challenge, channel models typically use statistical methods to model the wireless channel over short time intervals, such as a few milliseconds. This allows the model to capture the rapid fluctuations in signal strength and interference, and to predict the wireless channel's behavior over time (ITU-R, 2015).

In general, there are two basic kinds of wireless channel models utilized in wireless communication systems: pedestrian channel models and vehicular channel models. These models are used to forecast how the wireless channel will behave in pedestrian and vehicular contexts, respectively, taking into consideration variables like the movement of pedestrians and/or vehicles, the existence of obstacles, and the quick changes in interference and signal strength. These models can aid in optimizing the design and functionality of wireless communication systems by foretelling the behavior of the wireless channel in various settings (Chataut & Akl, 2020).

2.6. Frequency Band

Frequency band refers to a range of frequencies with a common characteristic. In various fields such as telecommunications, signal processing, and audio engineering, frequency bands are an essential concept. Understanding frequency bands is crucial for anyone working in these fields. Frequency bands are typically defined by two parameters: the lower and upper frequencies of the band. The range of frequencies between these two parameters is the frequency band. The distinction between an audio spectrum's upper and lower frequencies is known as the band width. Hertz (Hz) or kilohertz (kHz) are typically the units used to express frequency bands (Chataut & Akl, 2020).

In telecommunications, frequency bands are used to allocate different frequency ranges for different applications. For example, the frequency band between 700 MHz and 2700 MHz is used for mobile communication services such as 4G and 5G. The frequency band between 2.4 GHz and 2.4835 GHz is used for Wi-Fi communication. The allocation of frequency bands allows different services to operate without interfering with each other (X. Zhang et al., 2015).

In signal processing, frequency bands are used to analyze and filter signals. Signals can be decomposed into their frequency components using techniques such as Fourier analysis. The frequency components can then be manipulated or filtered to achieve specific objectives. For example, in audio engineering, a high-pass filter can be used to remove low-frequency components (Chataut & Akl, 2020) from a signal, while a low-pass filter can used to eliminate high-frequency components.

In music, frequency bands are used to describe the different ranges of frequencies produced by musical instruments and the human voice. For example, the bass range is typically between 20 Hz and 250 Hz, while the treble range is between 4 kHz and 20 kHz. Understanding frequency bands in music is essential for audio engineers and producers, who use equalizers to adjust the balance between different frequency bands in a mix.

In radio astronomy, frequency bands are used to observe and study celestial objects. Different frequency bands are used to observe different types of objects and phenomena. For example, the frequency band between 1.4 GHz and 1.7 GHz is used to observe hydrogen gas in the Milky Way galaxy. The frequency band between 30 MHz and 230 MHz is used to observe radio emissions from the Sun (Albreem et al., 2021; Santhi et al., 2003).

In conclusion, frequency bands are an essential concept in various fields such as telecommunications, signal processing, audio engineering, music, and radio astronomy. Understanding frequency bands allows professionals in these fields to allocate frequencies, analyze and filter signals, adjust the balance between different frequency bands, and observe celestial objects (Zeng et al., 2020). In 5G technology, frequency bands are classified in to two. The sub 6 GHz frequency band and the millimeter wave (mm Wave).

2.6.1. Sub 6 GHz Frequency Band

Although it won't be able to offer faster downlink speeds, sub-6 band 5G technology will be able to deliver 5G coverage over a broader geographic area. Sub-6 GHz bands are frequency ranges where cell phone towers transmit at a frequency lower than 6GHz. China is continuing at the frequency bands of 2.5-2.6 GHz, 3.4-3.6 GHz, and 4.8-4.9 GHz. (Ikki et al., 2013), Korean designs call for 3.4–3.7 GHz. 3.1-3.55 GHz and 3.7-4.2 GHz are the frequency ranges that the US intends to use. In general, the primary sub-6 GHz frequency band for V2X communications ranges in frequency from 2.5 GHz to 5.9 GHz.(Zeng et al., 2020).

The Sub-6 GHz frequency band refers to a range of wireless frequencies below 6 GHz, which is used multiple wireless communication systems, including cellular networks, Wi-Fi, Bluetooth, and other wireless technologies. The Sub-6 GHz frequency band is a critical part of wireless communication infrastructure, as it provides the foundation for most wireless communication systems.

One of the most significant advantages of the Sub-6 GHz frequency band is its ability to transmit over long distances and penetrate through obstacles such as walls and buildings. This makes it well-suited for providing coverage in urban and suburban areas, where buildings and other obstacles can obstruct wireless signals. Additionally, Sub-6 GHz frequencies have lower path loss than higher frequency bands, meaning that they can provide more reliable coverage over longer distances.

Another advantage of the Sub-6 GHz frequency band is its ability for the purpose of supporting a variety of wireless communication applications, from low-bandwidth applications such as voice communication to high-bandwidth applications such as video streaming. This makes it a versatile frequency band that can be used for a range of wireless communication requirements. In addition, the Sub-6 GHz frequency band is less regulated than higher frequency bands such as millimeter-wave (mmWave), which can make it easier and less expensive to deploy wireless communication infrastructure. This has led to widespread adoption of Sub-6 GHz frequency bands in cellular networks, Wi-Fi, and other wireless communication systems.

However, the Sub-6 GHz frequency band also has some disadvantages. One of the main limitations of the Sub-6 GHz frequency band is its limited bandwidth. It can restrict the maximum data transmission rates that can be reached. Additionally, as the frequency band is shared by multiple wireless communication systems, it can be subject to interference from other wireless signals, which can impact the quality and reliability of the wireless communication.

In general, the Sub-6 GHz frequency band is a critical part of wireless communication infrastructure, providing the foundation for most wireless communication systems. Its ability to transmit over long distances and penetrate through obstacles, support a wide range of wireless communication applications, and be less regulated than higher frequency bands have made it a popular choice for cellular networks, Wi-Fi, and other wireless communication systems. While it has some limitations, the Sub-6 GHz frequency band is likely to remain an important part of wireless communication infrastructure for the foreseeable future.

2.6.2. Millimeter Wave

Class-leading downlink speeds will be possible with mm Wave 5G technology, but at the expense of a smaller geographic coverage area. High-frequency mm Wave (millimeter wave, above 24GHz) bands are necessary for the faster speeds that actually set 5G apart from any of the 4G LTE flavors. These high frequencies have wide bandwidths, making them perfect for maintaining connectivity in crowded spaces like stadiums (Zeng et al., 2020).

The deployment of hotspots with extremely high throughput will be possible thanks to the extremely high 5G frequency bands at mm Wave, such as the 24.25–27.5 GHz schemed in Europe, the 24.2–27.5 GHz and 37–43.5 GHz schemed in China, and the 27.5–28.35 GHz and 37–40 GHz schemed in the United States (Choi et al., 2016).

The millimeter wave (mm Wave) frequency band refers to a range of wireless frequencies between 30 GHz and 300 GHz. This frequency band has gained a lot of attention in recent years as a potential solution for high-speed wireless communication, such as 5G cellular networks and point-to-point wireless links.

One of the major benefits of the mm Wave frequency band its capacity to provide support very high data transfer rates, much higher than those supported by the Sub-6 GHz frequency band. This is because the mm Wave frequencies have a wider bandwidth, which allows more data to be transmitted simultaneously. In addition, the mm Wave frequencies have shorter wavelengths, which allows for more antennas to be packed into a smaller area, increasing the potential data transfer rates. Another advantage of the mm Wave frequency band is its high frequency, which makes it less prone to interference from other wireless signals.

However, there are also some significant challenges associated with the mm Wave frequency band. One of the main challenges is the limited range of the mm Wave frequencies, which have much shorter wavelengths than the Sub-6 GHz frequencies. This means that they are more easily absorbed by obstacles such as buildings and trees, and can have difficulty penetrating through walls and other obstacles. This limits the coverage area of mm Wave wireless communication systems, and requires more infrastructure and antennas to provide coverage.

Another challenge associated with the mm Wave frequency band is the increased complexity of the wireless communication systems. Because of the shorter wavelengths, mm Wave frequencies require more antennas and sophisticated beam forming algorithms to direct the wireless signal towards the receiver. This can increase the cost and complexity of the wireless communication system.

In general, mm Wave frequency range is a potential remedy for high-speed wireless communication, with the ability to support very high data transfer rates and reduced interference from other wireless signals. However, it also presents significant challenges, including limited range and increased complexity regarding the wireless communication system. As a result, the mm Wave frequency band is likely to be used in combination with other frequency bands, such as the Sub-6 GHz frequency band, to provide a comprehensive solution for wireless communication.

2.7. Related Works

The Hermite filter was the major topic of the study. By replacing a Hermite filter in place of the PHYDYAS filter, the bit error rate performance and power spectral density of the FBMC have been altered. Additionally, using a Hermite filter, the effectiveness of each multicarrier approach was evaluated in terms of power spectral density and bit error rate. For the channel models for vehicular A and B as well as pedestrian A and B, the bit error rate is decreased (Dumari et al., 2023). However higher order QAM and channel models, such as Extended Vehicular A and Extended Pedestrian A are not analyzed.

The major challenge still lies in choosing a multi-carrier modulation for the fifth generation air interface. For the physical layer's design, a potential multi-carrier modulation or prospective waveforms are needed. The advantages and disadvantages of the latest candidate waveforms for fifth-generation wireless communication systems are highlighted in this research. Power spectral density and bit error rate on F-OFDM, UFMC, FBMC, and GFDM have been some of the metrics compared (Nilofer et al., 2021). Extended Vehicular A and Extended Pedestrian A are channel models that are not, however, studied.

High improved data rates and the required mobility of new wireless applications have become difficult issues for researchers and mobile communication technology designers to solve. In order to handle various services, changes, and waveforms, more effective waveforms are also required as the number of users grows daily. In reality, this is one of the elements at the physical level that affects the output, dependability, and complexity of the system. Because of this, careful consideration is paid to their design to satisfy various 5G service needs. As a result, the performance of three multicarrier modulation techniques is compared in this paper: UFMC, FBMC, and FODDM (Hasan Mahmud et al., 2020). Never the less, analysis is not done for higher order QAM and channel models, such as Extended Vehicular A, Extended Vehicular B, Pedestrian A, Pedestrian B and AWGN.

Analysis of Bit Error Rate and Peak to Average Power Ratio for Multi-carrier Modulation Techniques is studied. OFDM, SC-OFDM, and FBMC were the multi-carrier waveforms that were compared in this paper. As a result, the wideband signals are divided into narrowband signals, which lowers the system's PAPR overall. Performance metrics are used to examine FBMC, SCFDMA, and OFDM using variables like Signal to Noise Ratio (SNR), BER, and PAPR (Marian Joseph Jeffery et al., 2020). However, analysis is not done for higher order QAM and channel models, such as Extended Vehicular A, Extended Vehicular B, Pedestrian A, Pedestrian B and AWGN.

The Filter Bank Multi Carrier (FBMC), Universal Filtered Multi-carrier (UFMC), and Generalized Frequency Division Multiplexing (GFDM) systems are examples of Multi-Carrier Modulation (MCM) systems that are used to address the drawbacks of OFDM. The hardware specifications for the 5G waveform generations are reviewed in this article. Advantages and disadvantages of the candidate waveforms have been compared (Kumar & Prasad, 2020). However, the candidate waveforms have not been analyzed in vehicular and pedestrian channel models.

The performance of a new waveform known as Weighted Overlap and Add based OFDM (WOLA-OFDM), which recently made its introduction, is examined in this work under a relaxed synchronization scenario. Its performance will be examined and contrasted with the traditional CP-OFDM and the well-known UFMC, which has unique advantages for 5G use cases. According to the results, WOLA-OFDM outperforms CP-OFDM and UFMC in every asynchronous circumstance, making it a potentially interesting candidate waveform (Zayani et al., 2016). But still these candidate waveforms had not be analyzed in channel models like pedestrian A, B and Vehicular A, B.

Due to the addition of the cyclic prefix and the employment of the IFFT, the OFDM prototype filter exhibits poor stop band behavior, which causes spectral leakage across the sub channels and results in low efficiency. Due to the drawbacks of OFDM, a Multi Carrier system based on Filter Banks and using Offset Quadrature Amplitude Modulation has been suggested. Utilizing the frequency sampling approach of filter design, the prototype filter for the FBMC-OQAM system is created from which the entire filter bank is created using exponential modulation. High PAPR is the primary problem for every multicarrier system. Along with having strong BER performance, FBMC-OQAM scheme outperforms existing approaches in PAPR reduction (Varghese et al., 2014). But still FBMC_OAQM waveforms had not be analyzed in channel models like pedestrian A, B and Vehicular A, B.

The capacity of the networks could be significantly increased by another modulation called OFDM/OQAM. This modulation gives a great deal of flexibility in the construction of the prototype filter that shapes its symbols because it merely imposes an orthogonally condition in the actual field. This contribution illustrates the throughputs attained by OFDM/OQAM in a domestic PLC context while employing various prototype filters and adhering to the HPAV specification mask. Additionally, these throughputs are contrasted with those offered by windowed OFDM modulation (Achaichia et al., 2011). However the modulation technique OFDM/OQAM has not been analyzed using channel models like Extended Vehicular A, Extended Vehicular B, Pedestrian A, Pedestrian B.

Implementation of the FBMC-New Multicarrier Modulation Technique and the 5G Filtered OFDM Waveform Candidate are provided in (Khudhair & Singh, 2020; Nissel et al., 2017) . The fundamental multicarrier modulation method used in wireless and cellular communications is known as OFDM. It faces a variety of challenges, including as low spectrum efficiency and significant out-of-band emissions. One modulation technique being investigated at the present to solve these issues is Filter Bank Multi Carrier (FBMC) however; its performance is not analyzed under different channel models. The peak average power ratio of UFMC with OFDM and FBMC is thoroughly investigated utilizing a range of subcarriers and modulation methods. Attempts to address the benefits and drawbacks of OFDM are made by the candidate waveforms FBMC and UFMC. It briefly describes how UFMC and FBMC are advantageous. The use of channel models such Extended Vehicular A, Extended Vehicular B, Pedestrian A, Pedestrian B, and AWGN are advised as the best option when analyzing performance.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Chapter Overview

This chapter mainly focuses on materials and methods used to accomplish the research work, Multicarrier techniques system model, Existing multicarrier modulation techniques, channel models and their mathematical representation and performance metrics which used to analyses the systems

3.2. Materials

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

3.3. Methods

First different literatures are reviewed and the research gap is identified. Then the data that are directly related to the research problem is collected. The collected data are studied and analyzed. Then by understanding the concept the MATLAB code is written on MATLAB R2021a. From simulation result the best solution for particular and specified case according to scientific research method is recommended.

3.4. Multicarrier Modulation Techniques System Model

Multicarrier modulation (MCM) is a technique used in telecommunications to transmit data over multiple carrier frequencies. MCM works by dividing the available bandwidth into a number of subcarriers, each of which carries a percentage of the total amount of data. As a result, the available bandwidth can be utilized more effectively because distinct subcarriers can be assigned to various users or data streams.

3.5. Existing Modulation Techniques

3.5.1. OFDM System

Orthogonal frequency-division multiplexing (OFDM) is a multicarrier modulation technique used in modern telecommunications systems such as Wi-Fi, 4G and 5G cellular networks, digital television broadcasting, and more. OFDM is a highly efficient technique for transmitting data over a wide bandwidth, and it is widely used due to its ability to mitigate the effects of channel impairments such as multipath fading and interference. The basic idea behind OFDM is to divide the available bandwidth into a large number of orthogonal subcarriers, each of which carries a separate data stream. These subcarriers are closely spaced in frequency and are modulated using a technique such as quadrature amplitude modulation (QAM). The resulting signal is a time-domain waveform that is generated by combining the modulated subcarriers using an inverse fast Fourier transform (IFFT) (Dumari et al., 2023).

One of OFDM's main benefits is its capacity to reduce frequency selective fading, an issue that frequently arises in wireless communications. When a signal's frequency components undergo varying degrees of attenuation and delay as it passes through the channel, it fades at a frequency that is chosen at random. This can result in inter-symbol interference (ISI), where the symbols from adjacent time slots interfere with each other. OFDM overcomes this problem by dividing the data stream into small, narrowband subcarriers that are less susceptible to frequency selective fading. The subcarriers are orthogonal to one another, so at the receiver they can be easily distinguished from one another and do not interfere with one another.

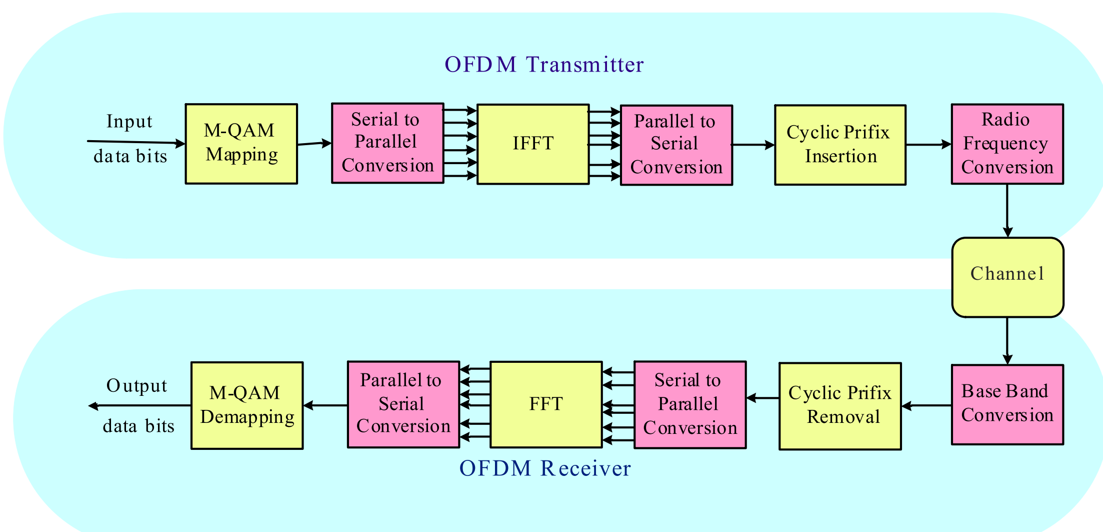

Figure 3.1 OFDM System (Bendimerad et al., 2021)

Another advantage of OFDM is its ability to mitigate the effects of interference from other signals operating in the same frequency band. Interference can cause errors in the received signal, which can be especially problematic in crowded frequency bands. OFDM can overcome this problem by allocating different subcarriers to different users or applications, and by using advanced interference cancellation techniques.

An OFDM-based MCM system has three components: a transmitter, a channel, and a receiver. The input data is split into several parallel data streams at the transmitter before being modulated using a method like QAM onto a different subcarrier for each stream. The time-domain OFDM signal is created by combining the subcarriers using an inverse fast Fourier transform (IFFT).

The OFDM signal is then transmitted over the channel, which may introduce noise, interference, and other impairments that can degrade the signal quality. At the receiver, the OFDM signal is first converted back to the frequency domain using a fast Fourier transform (FFT). The subcarriers are then demodulated to recover the original data streams, which are combined to reconstruct the original input data. To ensure reliable transmission over the channel, OFDM-based MCM systems typically use various techniques to mitigate the effects of channel impairments. These include forward error correction (FEC) coding to detect and correct errors in the received data, channel equalization to compensate for frequency-selective fading, and adaptive modulation and power control to optimize the transmission parameters based on the channel conditions (Dumari et al., 2023).

OFDM has several key advantages over other modulation techniques, including its high spectral efficiency, robustness to frequency selective fading and interference, and ability to support high data rates. However, it also has some drawbacks; including its sensitivity to carrier frequency offset and phase noise, and its high peak-to-average power ratio (PAPR). These challenges can be addressed using various techniques, such as phase-locked loop (PLL) frequency synchronization and peak clipping or clipping and filtering to reduce the PAPR.

OFDM is a multicarrier transmission method that divides the frequency band into 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 (Tazeb & Kassaw, 2019)

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

Where, 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 an OFDM symbols which is $T_s = NT_d$ and T_d is the serial symbol duration. The orthogonality of the sub-carriers is ensured, if the distance between neighboring sub carrier frequencies equals and subcarriers are located at (Tazeb & Kassaw, 2019) The output of the channel, after RF conversion, is the received signal $r(t)$ obtained from

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

convolution of $s(t)$ with the channel impulse response $h(t)$ and addition of a noise signal $n(t)$, i.e

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

The output of the FFT is the multicarrier demodulated sequence consisting N complex valued symbols.

$$\hat{d}_n = \sum_{m=0}^{N-1} r_m e^{-(\frac{j2\pi nm}{N})} \qquad \text{n=0,1,2,...,N-1} \tag{3.4}$$

Generally the time domain expression of OFDM is given as

$$x_{OFDM}(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \{x_k \times \Pi(t) \times e^{-j2\pi f_k t}\} \tag{3.5}$$

Where, x_k denoted the complex symbols that emanate from a given constellation, $\Pi(t)$ denote the rectangular wave form filter and N the number of sub-carriers (Bendimerad et al., 2021).

3.5.2. Filtered OFDM System

Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is a variation of the traditional OFDM modulation technique that is widely used in modern wireless communication systems. F-OFDM offers several advantages over traditional OFDM, including improved spectral efficiency, better robustness against interference, and lower out-of-band radiation. In traditional OFDM, the modulated signal is transmitted on multiple sub-carriers that are orthogonal to each other. The orthogonally between the sub-carriers allows for efficient use of the frequency spectrum, but it also leads to a high peak-to-average power ratio (PAPR) in the transmitted signal. This high PAPR can cause distortion and non-linear effects in the transmitter, which can degrade the quality of the transmitted signal.

F-OFDM addresses this issue by introducing a filter bank at the transmitter that applies a set of filters to the modulated signal before it is transmitted on the sub-carriers. These filters are designed to shape the frequency response of the signal, reducing the PAPR and improving the spectral efficiency of the system. One of the key benefits of F-OFDM is its improved spectral efficiency. By shaping the frequency response of the signal, F-OFDM can reduce the amount of out-of-band radiation, which allows for more efficient use of the available frequency spectrum. This makes F-OFDM particularly well-suited for use in dense urban environments, where the available frequency spectrum is limited.

Another advantage of F-OFDM is its improved robustness against interference and fading. The filter bank used in F-OFDM can be designed to provide better frequency selectivity, which allows the system to better reject interference from neighboring channels and to mitigate the effects of multipath fading. This makes F-OFDM a good choice for use in environments where signal interference and fading are likely to occur, such as in mobile communication systems.

F-OFDM can also be used to improve the energy efficiency of wireless communication systems. By reducing the PAPR of the transmitted signal, F-OFDM can help to minimize the power requirements of the transmitter, which can lead to longer battery life for mobile devices and lower energy consumption for base stations.

Despite its advantages, F-OFDM is not without its challenges. One of the main challenges is the increased complexity of the system due to the filter bank. The design and implementation of the filter bank can require significant computational resources, which can increase the cost and complexity of the system. Additionally, the filter bank can introduce some delay in the transmission of the signal, which can be a concern in real-time communication systems.

Another challenge with F-OFDM is the potential for inter-symbol interference (ISI) due to the filtering process. The filtering can cause some delay and distortion in the transmitted signal, which can lead to ISI if the receiver is not able to compensate for these effects. However, this can be mitigated through careful design of the filters and the use of advanced equalization techniques at the receiver.

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

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

where, $f(n) = p(n).w(n),\ for\ \ n = 0,1,2,...,N-1$

$p(n)$: is the ideal band pass filter $w(n)$: is the Hanning Window

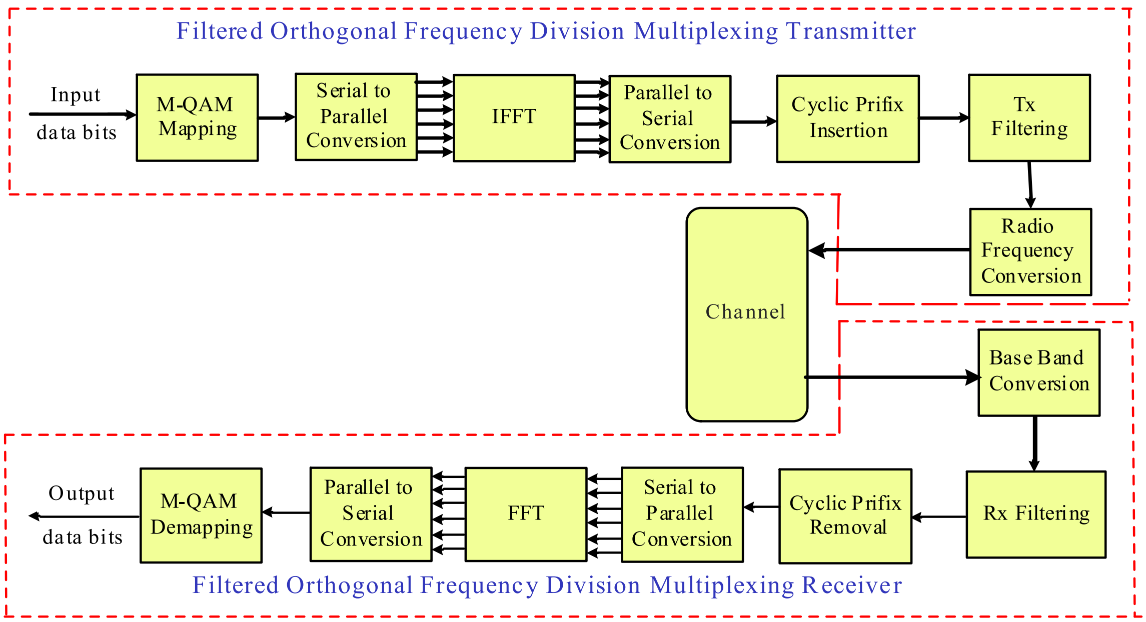

Figure 3. 2 Filtered OFDM system (Bendimerad et al., 2021)

In conclusion, F-OFDM is a promising variation of traditional OFDM that offers several advantages over the traditional technique. Its improved spectral efficiency, robustness against interference and fading, and energy efficiency make it a good choice for use in modern wireless communication systems. However, it also presents some challenges, such as increased complexity and potential for inter-symbol interference. With careful design and implementation, F-OFDM can be a valuable tool for improving the performance and efficiency of wireless communication systems.

3.5.3. UFMC System

Universal Filtered Multi-Carrier (UFMC) is a modulation technique that is similar to Filtered OFDM (F-OFDM), but with some key differences. Like F-OFDM, UFMC uses a filter bank to shape the frequency response of the transmitted signal, but it also introduces additional filtering at the receiver to further improve the performance of the system. One of the main advantages of UFMC is its ability to provide better spectral containment compared to traditional OFDM (Krishna & Kumar, 2019). In traditional OFDM, the sub-carriers are designed to be orthogonal, which can lead to high out-of-band radiation and spectral leakage. UFMC avoids this issue by using a filter bank at the transmitter to shape the frequency response of the signal before it is transmitted on the sub-carriers. This results in a more compact spectral shape and reduced out-of-band radiation (Dumari et al., 2023).

Another advantage of UFMC is its improved flexibility compared to other multi-carrier modulation techniques. UFMC uses a filter bank with variable filter lengths, which allows for more precise shaping of the frequency response of the transmitted signal. This flexibility enables UFMC to be used in a wide range of communication scenarios, including those with non-contiguous frequency bands and high Doppler shifts. UFMC also offers improved robustness against interference and fading compared to traditional OFDM. The filtering at the transmitter and receiver can be designed to provide better frequency selectivity, which allows the system to better reject interference from neighboring channels and to mitigate the effects of multipath fading. In addition, UFMC can be used to provide better support for multiple access scenarios, such as in multi-user and multi-cell environments (Nilofer et al., 2021). The variable filter lengths used in UFMC can be designed to provide different levels of spectral containment for different users or cells, which can help to improve the overall spectral efficiency of the system.

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

$$x_{UFMC}(n) = \sum_{k=0}^{K-1} S_k(n) * f_k(n) \tag{3.7}$$

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):

$$S_k(n) = \sum_{k=0}^{K-1} s_{k,m}(n - m(N + N_g)) \tag{3.8}$$

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

$$s_{k,m} = \sum_{l=(k-1)L}^{KL-1} A_{l,k,m} \times e^{\left(j\frac{2\pi l n}{N}\right)} \tag{3.9}$$

Where, $A_{l,k,m}$ represents the data transmitted over l^{th} sub-carrier, the m^{th} temporal symbol block and the k^{th} sub-band.

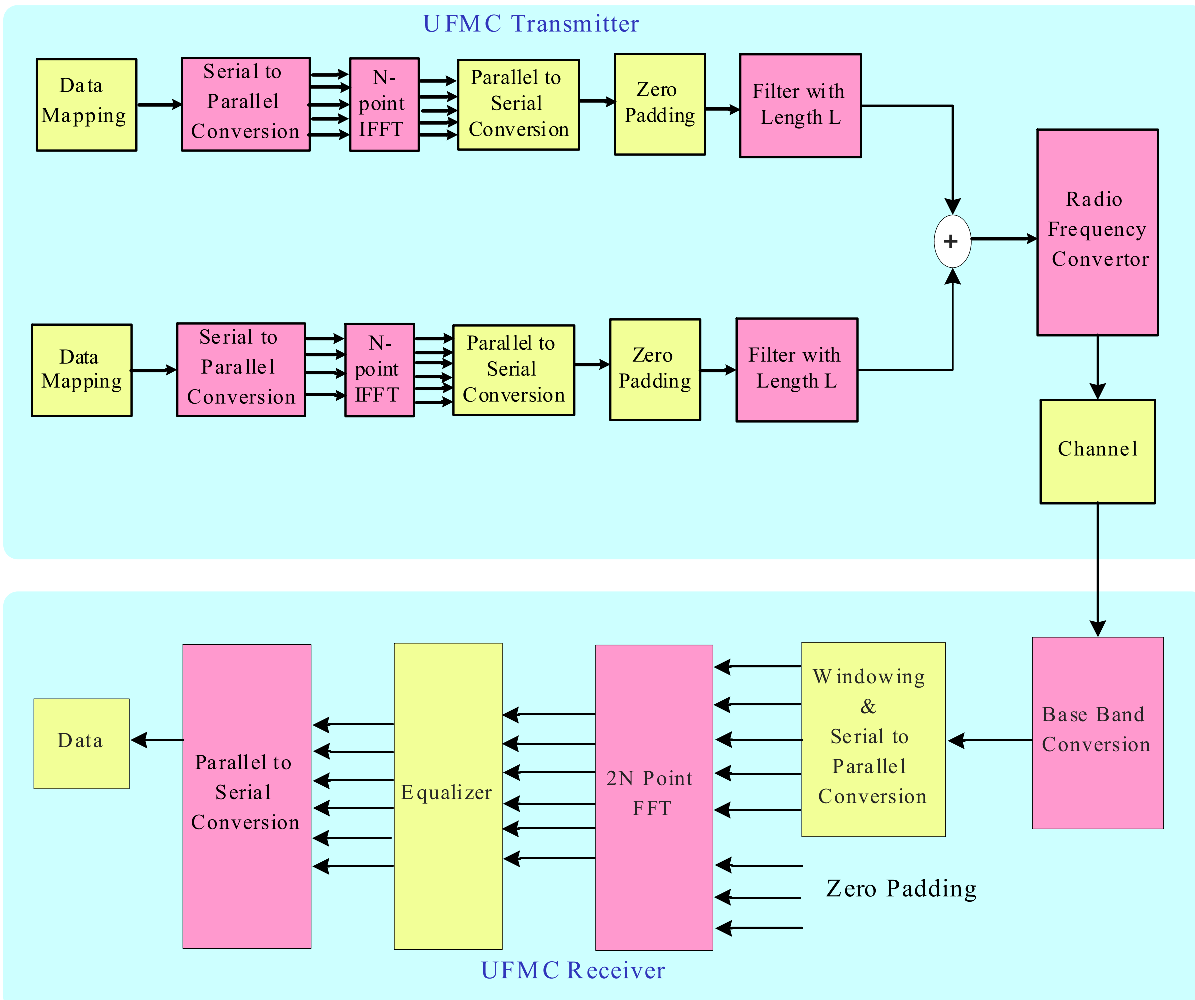

Figure 3. 3 UFMC System (Bendimerad et al., 2021)

One of the key differences between UFMC and F-OFDM is the additional filtering that is applied at the receiver in UFMC. This filtering, which is known as a matched filter, is designed to further improve the performance of the system by reducing inter-symbol interference (ISI) and improving the signal-to-noise ratio (SNR) at the receiver. The matched filter is designed to be the inverse of the filter applied at the transmitter, which allows for maximum signal recovery at the receiver.

UFMC also has some disadvantages and challenges that need to be considered. One of the main challenges is the increased complexity of the system due to the filter bank and matched filtering. The design and implementation of the filter bank and matched filter can require significant computational resources, which can increase the cost and complexity of the system.

Another challenge with UFMC is the potential for inter-carrier interference (ICI) due to the use of overlapping sub-carriers. The overlapping sub-carriers can lead to ICI if the receiver is not able to accurately estimate the channel response and compensate for the effects of the sub-carrier overlap. However, this challenge can be mitigated through the use of advanced equalization techniques at the receiver, such as iterative frequency-domain equalization or channel estimation methods.

In summary, UFMC is a promising modulation technique that offers several advantages over traditional OFDM and F-OFDM. Its improved spectral containment, flexibility, and robustness make it a good choice for use in a wide range of communication scenarios, including those with non-contiguous frequency bands and high Doppler shifts. However, it also presents some challenges, such as increased complexity and potential for inter-carrier interference. With careful design and implementation, UFMC can be a valuable tool for improving the performance and efficiency of wireless communication systems.

3.5.4. FBMC System

Filter Bank Multi-Carrier (FBMC) is a modulation technique that is similar to OFDM and UFMC, but with some key differences. FBMC uses a filter bank to divide the signal into multiple sub-bands, with each sub-band being modulated using a separate carrier. Unlike OFDM and UFMC, FBMC uses overlapping sub-bands, which allows for a more efficient use of the available frequency spectrum. One of the main advantages of FBMC is its improved spectral efficiency compared to traditional OFDM. In traditional OFDM, the sub-carriers are designed to be orthogonal, which can lead to high out-of-band radiation and spectral leakage. FBMC avoids this issue by using a filter bank with overlapping sub-bands, which allows for a more compact spectral shape and reduced out-of-band radiation. The overlapping sub-bands also allow for a more efficient use of the available frequency spectrum, which can be particularly useful in environments where the frequency spectrum is limited.

Another advantage of FBMC is its improved flexibility compared to other multi-carrier modulation techniques. FBMC can be used in a wide range of communication scenarios, including those with non-contiguous frequency bands and high Doppler shifts. The filter bank used in FBMC can be designed to provide different levels of spectral containment for different users or cells, which can help to improve the overall spectral efficiency of the system.

FBMC also offers improved robustness against interference and fading compared to traditional OFDM. The filtering at the transmitter and receiver can be designed to provide better frequency selectivity, which allows the system to better reject interference from neighboring channels and to mitigate the effects of multipath fading. In addition, FBMC can be used to provide better support for multiple access scenarios, such as in multi-user and multi-cell environments. The variable filter lengths used in FBMC can be designed to provide different levels of spectral containment for different users or cells, which can help to improve the overall spectral efficiency of the system.

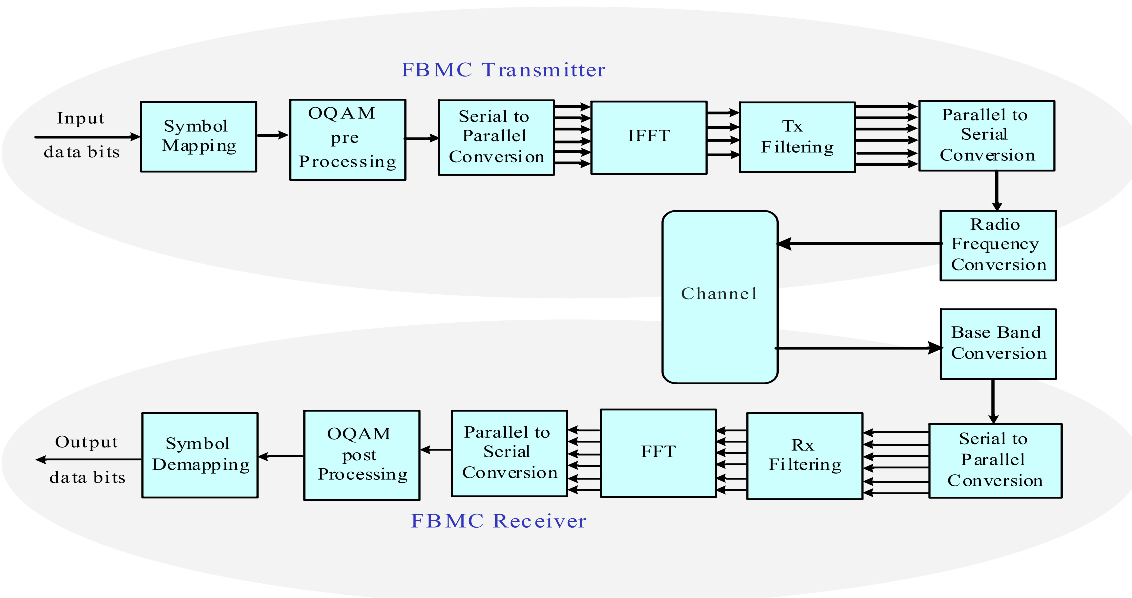

Figure 3. 4 FBMC System (Jeon et al., 2016)

FBMC has some distinct advantages over other multi-carrier modulation techniques. One of the key advantages is its ability to provide better time-frequency localization of the signal compared to OFDM. In OFDM, each subcarrier can be seen as a pulse in the frequency domain, while in FBMC, the overlapping sub-bands can be seen as narrow-band pulses in both the time and frequency domains. This time-frequency localization can be particularly useful in scenarios where the channel response varies rapidly over time, such as in high-mobility environments. Another advantage of FBMC is its ability to provide better support for low-latency communication. The time-frequency localization of the signal allows for more precise timing information to be extracted from the received signal, which can be useful in applications such as real-time communication and low-latency control.

FBMC also has some disadvantages and challenges that need to be considered. One of the main challenges is the increased complexity of the system due to the filter bank. The design and implementation of the filter bank can require significant computational resources, which can increase the cost and complexity of the system. Additionally, the overlapping sub-bands can lead to inter-symbol interference (ISI) if the receiver is not able to accurately estimate the channel response and compensate for the effects of the sub-band overlap. This challenge can be mitigated through the use of advanced equalization techniques at the receiver, such as iterative frequency-domain equalization or channel estimation methods. Another challenge with FBMC is the potential for interference between adjacent sub-bands. The overlapping sub-bands can lead to interference between adjacent sub-bands, which can degrade the performance of the system. However, this challenge can be mitigated through careful design of the filter bank and the use of advanced interference cancellation techniques at the receiver.

The transmitted signal of a discrete time FBMC system is expressed in (Jeon et al., 2016) as.

$$s[n] = \sum_{k=-\infty}^{\infty} \sum_{m=0}^{M-1} d_{m,k} \theta_{m,k} f[n - k\frac{M}{2}] e^{j\frac{2\pi}{M}m(n-D)} \tag{3.10}$$

Where n is the time index, m is the subcarrier index, k is the symbol index, $d_{m,k}$ is real valued symbol, M is the number of subcarriers, and f[n] is a synthesis filter impulse response that maps $d_{m,k}$ in to the signal space. $\theta_{m,k} = j^{k+m}$ is an addition phase term. The filter delay D appears to produce a causal discrete time prototype filter f[n], and it is fixed D= (L-1)/2 with a filter length equal to L.

In summary, FBMC is a promising modulation technique that offers several advantages over traditional OFDM and other multi-carrier modulation techniques. Its improved spectral efficiency, flexibility, and robustness make it a good choice for use in a wide range of communication scenarios, including those with non-contiguous frequency bands and high Doppler shifts. Additionally, its ability to provide better time-frequency localization and support for low-latency communication make it a valuable tool for applications such as real-time communication and low-latency control. However, it also presents some challenges, such as increased complexity and potential for interference between adjacent sub-bands. With careful design and implementation, FBMC can be a valuable tool for improving the performance and efficiency of wireless communication systems.

3.6. Channel Models with their Mathematical Expression

3.6.1. Pedestrian A Channel Model

The Pedestrian A (PA) channel model is a radio propagation model used for wireless communication systems in pedestrian environments, such as shopping malls, airports, and sports arenas. The PA model is a statistical model that captures the effects of the multipath propagation and shadowing caused by obstacles in the environment, as well as the time-varying nature of the channel due to the motion of the transmitter and receiver.

The PA channel model assumes that the received signal is a superposition of a large number of multipath components, each with a different delay and amplitude. The amplitudes and delays of the multipath components are assumed to be random variables, following a log-normal distribution for the amplitude and a Gaussian distribution for the delay. The model also includes a parameter for the root-mean-square (RMS) delay spread, which reflects the spread in the delay of the multipath components due to the varying path lengths.

The PA channel model also includes a parameter for the shadow fading, which reflects the attenuation of the signal due to obstacles in the environment. This parameter is modeled as a log-normal distribution with a zero-mean and a standard deviation that depends on the distance between the transmitter and receiver and the density of obstacles in the environment.

Mathematical expression of Pedestrian A is given as (Zhou et al., 2022)

$$h(t) = \sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} e^{-j2\pi\Delta f(t)\tau_n(t)} g(t-\tau_n) \tag{3.11}$$

where: $h(t)$ is the impulse response of the channel at time *t*, *N* is the number of multipath components, $\alpha_n(t)$ is the complex amplitude of the n^{th} multipath component at time t, f is the carrier frequency τ_n is the delay of the n^{th} multipath component at time *t*, $\Delta f(t)$ is the Doppler shift due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

Generally, the PA channel model is a useful tool for simulating wireless communication systems in pedestrian environments, where the propagation characteristics can be complex and highly variable. The model can be used to evaluate the performance of different communication protocols and antenna configurations, and to optimize the design of wireless networks in these environments.

3.6.2. Pedestrian B

The Pedestrian B (PB) channel model is a radio propagation model used for wireless communication systems in pedestrian environments, such as urban streets, pedestrian zones, and outdoor public spaces. The PB model is a statistical model that captures the effects of the multipath propagation and shadowing caused by obstacles in the environment, as well as the time-varying nature of the channel due to the motion of the transmitter and receiver.

The PB channel model assumes that the received signal is a superposition of a large number of multipath components, each with a different delay and amplitude. The amplitudes and delays of the multipath components are assumed to be random variables, following a Rician distribution for the amplitude and a Gaussian distribution for the delay. The Rician distribution models the presence of a strong line-of-sight (LOS) component, which is typically present in outdoor environments with relatively unobstructed paths between the transmitter and receiver.

The PB channel model also includes a parameter for the RMS delay spread, which reflects the spread in the delay of the multipath components due to the varying path lengths. In addition, the model includes a parameter for the Doppler spread, which reflects the variation in the frequency of the received signal due to the motion of the transmitter and receiver. The Doppler spread is typically larger in outdoor environments than in indoor environments, due to the higher speeds and longer distances involved.

The PB channel model also includes a parameter for the shadow fading, which reflects the attenuation of the signal due to obstacles in the environment. This parameter is modeled as a log-normal distribution with a zero-mean and a standard deviation that depends on the distance between the transmitter and receiver and the density of obstacles in the environment.

The pedestrian B channel model is another widely used radio propagation model for wireless communication systems in urban and suburban areas. The mathematical expression for the pedestrian B channel model is given by (Zhou et al., 2022):

$$h(t) = \sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} e^{-j2\pi \Delta f(t) \tau_n(t)} g(t - \tau_n) \tag{3.12}$$

where: $h(t)$ is the impulse response of the channel at time *t*, *N* is the number of multipath components, $\alpha_n(t)$ is the complex amplitude of the n^{th} multipath component at time t, f is the carrier frequency τ_n is the delay of the n^{th} multipath component at time *t*, $\Delta f\ (t)$ is the Doppler shift due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

The mathematical equation of Pedestrian B channel model is similar to the Pedestrian A channel model, but with different parameter values. It is typically used for scenarios where pedestrians are moving at higher speeds or with more irregular motion patterns than in the pedestrian A channel model. Generally, the PB channel model is a useful tool for simulating wireless communication systems in pedestrian environments, where the propagation characteristics can be complex and highly variable. The model can be used to evaluate the performance of different communication protocols and antenna configurations, and to optimize the design of wireless networks in these environments.

3.6.3. Vehicular A

The Vehicular A (VA) channel model is a radio propagation model used for wireless communication systems in vehicular environments, such as highways, urban streets, and parking lots. The VA model is a statistical model that captures the effects of the multipath propagation and shadowing caused by vehicles and obstacles in the environment, as well as the time-varying nature of the channel due to the motion of the transmitter and receiver.

The VA channel model assumes that the received signal is a superposition of a large number of multipath components, each with a different delay and amplitude. The amplitudes and delays of the multipath components are assumed to be random variables, following a Ricean distribution for the amplitude and a Gaussian distribution for the delay. The Ricean distribution models the presence of a strong line-of-sight (LOS) component, which is typically present in vehicular environments with relatively unobstructed paths between the transmitter and receiver.

The VA channel model also includes a parameter for the RMS delay spread, which reflects the spread in the delay of the multipath components due to the varying path lengths. In addition, the model includes a parameter for the Doppler spread, which reflects the variation in the frequency of the received signal due to the motion of the transmitter and receiver and the scatters in the environment. The Doppler spread is typically larger in vehicular environments than in pedestrian or indoor environments, due to the higher speeds and longer distances involved.

The VA channel model also includes a parameter for the shadow fading, which reflects the attenuation of the signal due to vehicles and obstacles in the environment. This parameter is modeled as a log-normal distribution with a zero-mean and a standard deviation that depends on the distance between the transmitter and receiver and the density of obstacles in the environment.

The vehicular B channel model is another radio propagation model used for wireless communication systems in vehicular environments. The mathematical expression for the vehicular B channel model is given by (Ou et al., 2022):

$$h(t) = \sum_{n=1}^{N} \alpha_n (t) e^{-j2\pi f_c \tau_n(t)} e^{-j2\pi \Delta f(t) \tau_n(t)} g\left(t - \tau_n(t)\right) \tag{3.13}$$

where: $h(t)$ is the impulse response of the channel at time t N is the number of multipath components $\alpha_n(t)$ is the complex amplitude of the n^{th} multipath component at time t f is the carrier frequency $\tau_n(t)$ is the delay of the n^{th} multipath component at time t $\Delta f(t)$ is the Doppler spread due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

The vehicular A channel model is similar to the pedestrian A channel model, but with different parameter values that reflect the different propagation characteristics of vehicular environments. In particular, the vehicular A channel model takes into account the effects of large-scale fading due to the distance between the transmitter and receiver, as well as the shadowing caused by obstacles such as buildings and vehicles. It also models the Doppler spread due to the high speed of the vehicles, which can cause time-varying frequency shifts in the received signal. Generally, the VA channel model is a useful tool for simulating wireless communication systems in vehicular environments, where the propagation characteristics can be complex and highly variable. The model can be used to evaluate the performance of different communication protocols and antenna configurations, and to optimize the design of wireless networks in these environments.

3.6.4. Vehicular B

The Vehicular B (VB) channel model is a radio propagation model used for wireless communication systems in vehicular environments, such as highways, urban streets, and parking lots. The VB model is a statistical model that captures the effects of the multipath propagation and shadowing caused by vehicles and obstacles in the environment, as well as the time-varying nature of the channel due to the motion of the transmitter and receiver.

The VB channel model is an extension of the Vehicular A (VA) channel model, with additional parameters to model the spatial characteristics of the multipath components. The VB model assumes that the multipath components are organized into clusters, with each cluster representing a group of rays that arrive from the same direction. Rays within each cluster have slightly different delays and angles of arrival, reflecting the scattering and reflection of the signal by vehicles and other obstacles in the environment.

The VB channel model includes parameters for the number of clusters, the number of rays per cluster, and the angular spread of the clusters. The model also includes a parameter for the RMS delay spread, which reflects the spread in the delay of the multipath components due to the varying path lengths. In addition, the model includes a parameter for the Doppler spread, which reflects the variation in the frequency of the received signal due to the motion of the transmitter and receiver and the scatters in the environment. The Doppler spread is typically larger in vehicular environments than in pedestrian or indoor environments, due to the higher speeds and longer distances involved.

The VB channel model also includes a parameter for the shadow fading, which reflects the attenuation of the signal due to vehicles and obstacles in the environment. This parameter is modeled as a log-normal distribution with a zero-mean and a standard deviation that depends on the distance between the transmitter and receiver and the density of obstacles in the environment.

The mathematical expression for the pedestrian B channel model is given by (Ou et al., 2022):

$$h(t) = \sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} e^{-j2\pi \Delta f(t) \tau_n(t)} g\left(t - \tau_n(t)\right) \tag{3.14}$$

where: $h(t)$ is the impulse response of the channel at time t, N is the number of multipath components, $\alpha_n(t)$ is the complex amplitude of the n^{th} multipath component at time t, f is the carrier frequency τ_n is the delay of the n^{th} multipath component at time t, $\Delta f(t)$ is the Doppler shift due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

Generally, the VB channel model is a useful tool for simulating wireless communication systems in vehicular environments, where the propagation characteristics can be complex and highly variable. The model can be used to evaluate the performance of different communication protocols and antenna configurations, and to optimize the design of wireless networks in these environments.

3.6.5. Proposed Channel Models

The summarized proposed channel models block diagram is given in Figure 3.5. The performance of wireless systems in vehicle and Pedestrian situations is expressed using the Extended Pedestrian A (EVA) and Extended Vehicular A (EVA) wireless communication channel models. As we are talking about wireless communication, between the transmitter and Receiver we assumed a channel which is vehicular and pedestrian based.

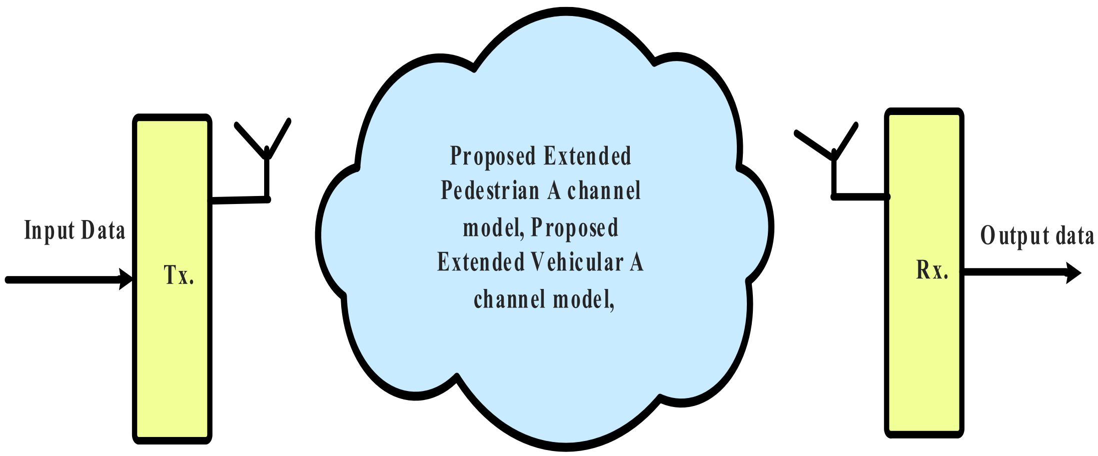

Figure 3. 5 Proposed Channel model Block Diagram

3.6.6. Proposed Extended Pedestrian A

Extended Pedestrian A (EPA) is a wireless communication channel model that are designed to simulate scenarios in urban and suburban environments where mobile users are walking. This model is an extension of the Pedestrian A, and is more accurate in certain scenarios. EPA is designed for environments where the mobile user is surrounded by buildings with low to medium height, and there may be some trees or other obstacles as well. The model takes into account the diffraction of waves around the corners of buildings and also includes a reflected wave component. These factors can cause signal attenuation and delay, which can affect the performance of wireless systems. The Extended Pedestrian A (EPA) channel model is a radio propagation model used for wireless communication systems in pedestrian environments.

The mathematical expression for the EPA channel model is given by (Zhou et al., 2022):

$$h(t,\tau)=\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{nm}e^{-j2\pi f_c\tau_{nm}}\,e^{-j2\pi\Delta f(t)\tau_{nm}}\,g\left(t-\tau_{nm}\right) \tag{3.15}$$

$h(t,\tau)$ is the impulse response of the channel at time t and delay τ , N is the number of clusters M is the number of rays per cluster α_{nm} is the complex amplitude of the m^{th} ray in the n^{th} cluster f_C is the carrier frequency τ_{nm} is the delay of the m^{th} ray in the n^{th} cluster $\Delta f(t)$ is the Doppler spread due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

The EPA channel model is an extension of the pedestrian A channel model that takes into account the spatial structure of the multipath components. Clusters represent groups of rays that arrive from the same direction, while rays within each cluster have slightly different delays and angles of arrival. The EPA model also includes a parameter for the angular spread of each cluster, which affects the power and delay spread of the received signal. The EPA channel model is often used for simulating wireless communication systems in crowded urban environments, such as shopping malls, train stations, and sports stadiums.

Generally, EPA is useful for predicting the performance of wireless systems in pedestrian environments. Its mathematical equations can be used to determine factors such as signal strength and error rate, which are important for designing and optimizing wireless networks in urban areas.

3.6.7. Proposed Extended Vehicular A

Extended Vehicular A (EVA) is a wireless communication channel model used to simulate the performance of wireless systems in vehicular environments. EVA is designed for rural highways and suburban roads where vehicles travel at lower speeds. The model includes line-of-sight and non-line-of-sight propagation as well as Doppler shift caused by the motion of the vehicles. The model assumes that there are no tall buildings or other obstacles near the roadway, so there is little attenuation or shadowing due to large objects.

Mathematical equation of EVA given as (Zhou et al., 2022)

$$h(t,\tau)=\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{nm}e^{-j2\pi f_C\tau_{nm}}\,e^{-j2\pi\Delta f(t)\tau_{nm}}\,g\left(t-\tau_{nm}\right) \tag{3.16}$$

where: $h(t,\tau)$ is the impulse response of the channel at time t and delay τ N is the number of clusters M is the number of rays per cluster α_{nm} is the complex amplitude of the m^{th} ray in the n^{th} cluster f_C is the carrier frequency τ_{nm} is the delay of the m^{th} ray in the nth cluster $\Delta f(t)$ is the Doppler spread due to the motion of the transmitter, receiver, and scatters $g(t)$ is the pulse shaping filter.

The EVA channel model is an extension of the vehicular A channel model that takes into account the spatial structure of the multipath components. Clusters represent groups of rays that arrive from the same direction, while rays within each cluster have slightly different delays and angles of arrival. The EVA model also includes a parameter for the angular spread of each cluster, which affects the power and delay spread of the received signal.

Generally, EVA is to predict important signal parameters such as path loss, shadowing effects, and delay spread for the design and optimization of wireless communication networks in vehicular environments. It takes into account parameters such as the speed of the vehicles, the types of obstacles present, and the frequency of the signal being transmitted.

3.7. Performance Metrics

3.7.1. Signal to Noise Ratio

Signal-to-noise ratio (SNR) is an indicator of strength of the desired signal in a wireless communication system relative to the background noise. It is defined as the ratio of the power of the signal to the power of the noise. In wireless communication systems, the transmitted signal may be distorted by various factors such as interference, fading, and attenuation. These factors can cause the signal to become weaker and more difficult to distinguish from the background noise.

A high SNR indicates that the signal is strong relative to the noise, which means that the receiver can more accurately and reliably decode the information. In contrast, a low SNR indicates that the signal is weak relative to the noise, which can result in errors in the received data. To improve the SNR in a wireless communication system, various techniques are used, such as increasing the power of the transmitted signal, using directional antennas, reducing interference, and using coding and modulation techniques that are robust to noise.

3.7.2. Bit Error Rate

Bit Error Rate (BER) is another important parameter that is used to measure the quality of a digital wireless communication system. It is a measure of the number of bit errors that occur in a given time period, typically expressed as a ratio or percentage of the total number of bits transmitted. In a digital communication system, the transmitted signal is composed of a sequence of bits that are encoded and modulated to represent the information being transmitted. The received signal may be distorted by various factors such as noise, interference, and fading, which can cause errors in the received data.

A lower BER indicates that the communication system is more reliable in transmitting data, while a higher BER indicates that errors are more likely to occur. To improve the BER in a wireless communication system, various techniques are used, such as error-correcting codes, channel coding, and modulation schemes that are more robust to noise and interference. Additionally, techniques such as diversity reception, which involves receiving the same signal through multiple antennas, can be used to improve the reliability of the received signal and reduce the BER.

3.7.3. Signal to Interference Ratio

Signal-to-Interference Ratio (SIR) is a measure of the strength of the desired signal relative to the strength of the interfering signals in a wireless communication system. It is defined as the ratio of the power of the desired signal to the power of the interfering signals. In wireless communication systems, interference can be caused by other signals transmitted on the same frequency or nearby frequencies, as well as environmental factors such as multipath propagation and fading. The presence of interference can reduce the quality of the received signal and make it more difficult to decode the information being transmitted.

A high SIR indicates that the desired signal is strong relative to the interfering signals, which means that the receiver can more accurately and reliably decode the information. In contrast, a low SIR indicates that the interfering signals are strong relative to the desired signal, which can result in errors in the received data. To improve the SIR in a wireless communication system, various techniques are used, such as frequency planning, which involves assigning frequencies to different users or services to minimize interference, and adaptive modulation and coding, which adjusts the modulation and coding scheme based on the strength of the received signal and the level of interference.

CHAPTER FOUR

4. RESULT AND DESCUSSION

4.1. Overview

In this chapter the result of the overall research work discussed briefly. The results are simulated under some parameters. The SNR versus BER, Normalized Time Offset versus Signal to Interference Ratio, Normalized Frequency Offset versus Signal to Interference Ratio analysis are used to check the performances of the systems.

4.2. Parameters

Table 4. 1 General Parameters for simulation

Parameters	Numerical Value	Remark
QAM Order (M-QAM)	4/16/64/256/1024	Efficient Scheme
Communication Channel Model	Pedestrian A, Pedestrian B, Vehicular A, Vehicular B, Extended Pedestrian A, Extended Vehicular A, AWGN	ITU Standard Channel Models for dynamic environment (ITU-R, 2015).
Number of Sub-carriers	256/1024	Can Vary
Sub-carrier Spacing	15KHz	Can Vary
Channel Velocity in Km/hr	30	Can Vary
Prototype Filter	PHYDYAS	ITU Standard (ITU-R, 2015).
Overlapping Factor	4	For better side lobe of PHYDAS filter (Zeng et al., 2020).
Number of Tx and Rx Antenna	64x64	We call massive MIMO if the number Tx and Rx of antenna greater than 8 (Sharma, 2013)
Normalized Time Offset	0:0.05:0.35	Can Vary
Normalized Frequency Offset	0:0.05:0.35	Can vary
Signal to Noise Ratio		Can vary
Guard Band interval	72	Equal with Cyclic Prefix (Tazeb & Kassaw, 2019)
Length of CP of OFDM	72	As in LTE

4.3. BER Analysis of Waveforms for AWGN Channel Model

A typical model for a communication channel that incorporates noise into a transmitted signal is an Additive White Gaussian Noise (AWGN) channel. In this model, the noise is assumed to be Gaussian distributed with a mean of zero and a constant power spectral density across all frequencies. The AWGN channel is widely used in the analysis and design of digital communication systems because it is a simple and realistic model that captures the effects of noise on the received signal. The noise in the AWGN channel is referred to as "white" because it has a flat power spectral density, meaning that it has equal power at all frequencies. The term "additive" indicates that the noise is added to the transmitted signal at the receiver.

In an AWGN channel, the received signal can be modeled as the sum of the transmitted signal and the noise. The power of the noise is proportional to the noise power spectral density and the bandwidth of the channel. The (SNR) in an AWGN channel is defined as the ratio of the power of the transmitted signal to the power of the noise. The AWGN channel is a useful model for studying the performance of digital communication systems because it allows for the analysis of the effects of noise on the received signal and the design of techniques to mitigate these effects.

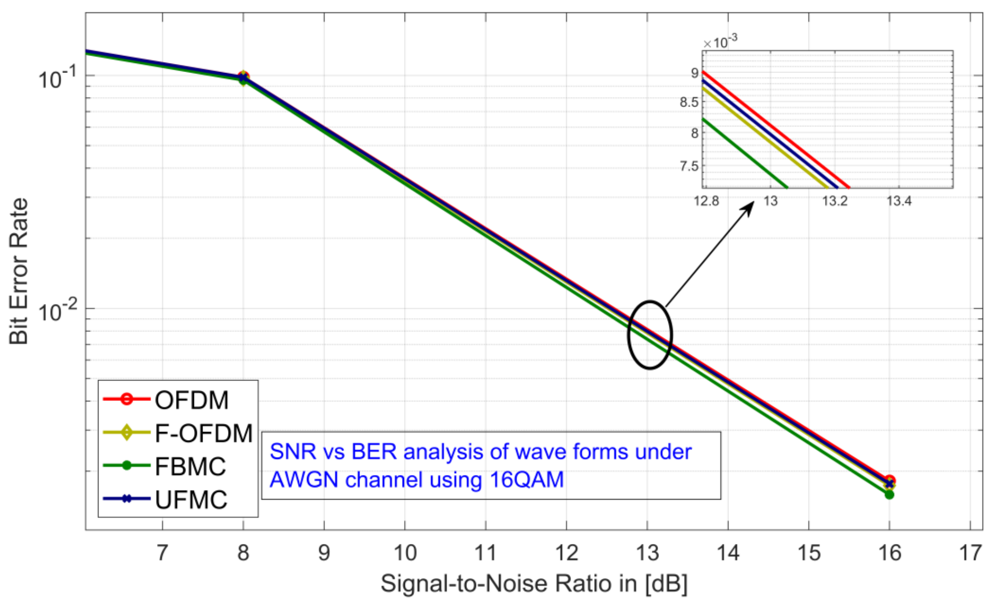

Figure 4. 1 SNR vs BER analysis of OFDM, F-OFDM, UFMC, and FBMC under AWGN channel using 16-QAM

Figure 4.1 shows the signal to noise ratio versus bit error rate analysis of OFDM, F-OFDM, UFMC, and FBMC. It is simulated under additive white Gaussian Channel using 16-QAM modulation order. From figure 4.1 the green graph represents the FBMC SNR versus BER characteristics. As it can be seen from the figure 4.1 the BER values of each waveform may seem as overlapped but, not at all. According to simulation result of figure 4.1 FBMC has the least BER value compared to all other wave forms. The green graph that represents the FBMC waveform is found below all other waveforms graph. Therefore, FBMC outperforms in Additive White Gaussian channel model with 16-QAM modulation schemes than other waveforms like OFDM, F-OFDM, and UFMC.

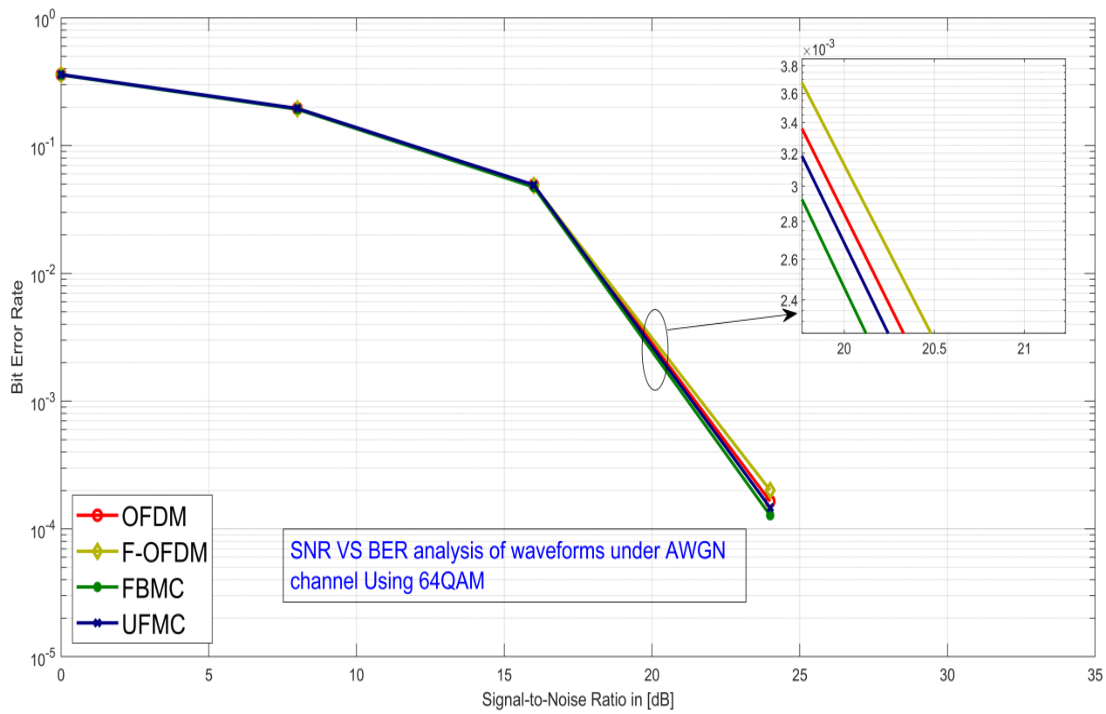

Figure 4. 2 SNR vs BER analysis of OFDM, F-OFDM, UFMC, and FBMC under AWGN channel using 64-QAM

Figure 4.2 shows the signal to noise ratio versus bit error rate analysis of OFDM, F-OFDM, UFMC, and FBMC. It is simulated under additive white Gaussian Channel using 64-QAM modulation order. From figure 4.2 the green graph represents the FBMC signal to noise ratio versus bit error rate characteristics. As it can be seen from the figure 4.2 the BER values of each waveform may seem as overlapped but, not at all. According to simulation result of figure 4.2 FBMC has the least BER value compared to all other wave forms. The green graph that represents the FBMC waveform is found below all other waveforms graph. Therefore, FBMC outperforms in Additive

White Gaussian channel model with 16-QAM modulation schemes than other waveforms like OFDM, F-OFDM, and UFMC.

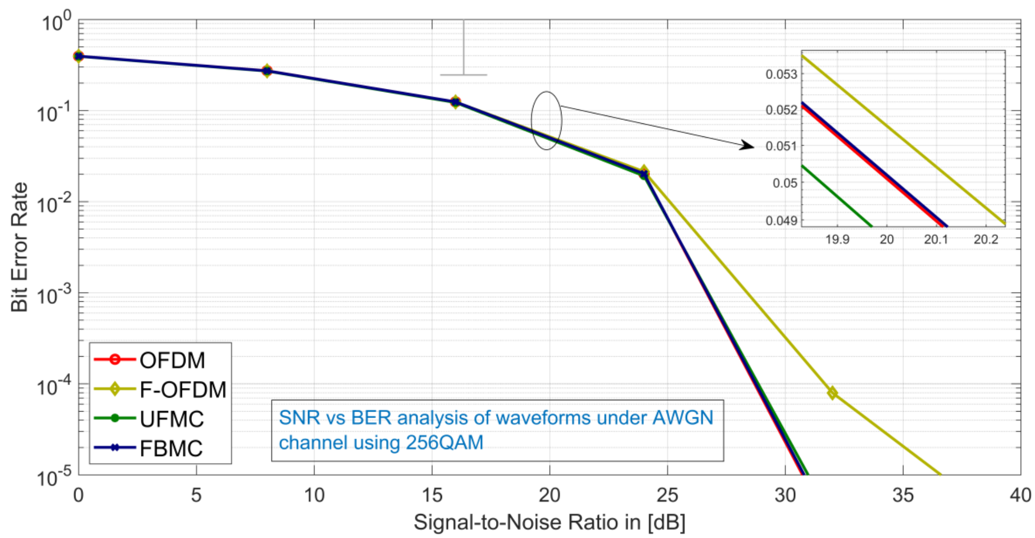

Figure 4. 3 SNR vs BER analysis of OFDM, F-OFDM, UFMC, and FBMC under AWGN channel using 256-QAM

Figure 4.3 shows the signal to noise ratio versus bit error rate analysis of OFDM, F-OFDM, UFMC, and FBMC. It is simulated under additive white Gaussian Channel using 256-QAM modulation order. From figure 4.3 the green graph represents the FBMC signal to noise ratio versus bit error rate characteristics. As it can be seen from the figure 4.3 the BER values of each waveform may seem as overlapped but, not at all. According to simulation result of figure 4.3 FBMC has the least BER value compared to all other wave forms. The green graph that represents the FBMC waveform is found below all other waveforms graph. Therefore, FBMC outperforms in Additive White Gaussian channel model with 256-QAM modulation schemes than other waveforms like OFDM, F-OFDM, and UFMC.

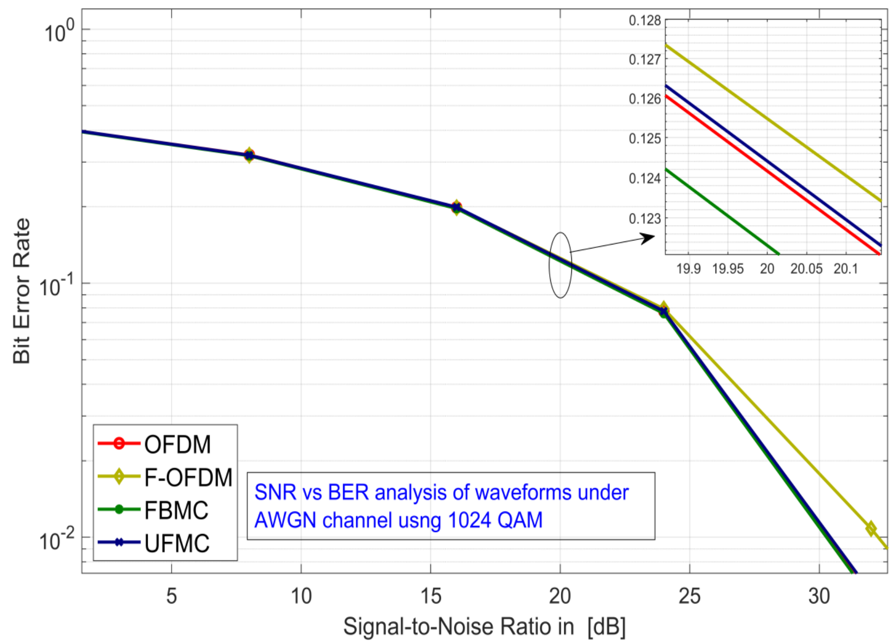

Figure 4. 4 SNR vs BER analysis of OFDM, F-OFDM, UFMC, and FBMC under AWGN channel using 1024-QAM

Figure 4.4 shows the signal to noise ratio versus bit error rate analysis of OFDM, F-OFDM, UFMC, and FBMC. It is simulated under additive white Gaussian Channel using 1024 - QAM modulation order. From figure 4.4 the green graph represents the FBMC signal to noise ratio versus bit error rate characteristics. As it can be seen from the figure 4.4 the BER values of each waveform may seem as overlapped but, not at all. According to simulation result of figure 4.4 FBMC has the least BER value compared to all other wave forms. The green graph that represents the FBMC waveform is found below all other waveforms graph. Therefore, FBMC outperforms in Additive White Gaussian channel model with 1024 - QAM modulation schemes than other waveforms like OFDM, F-OFDM, and UFMC.

Form all Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4 results that shows signal to noise ratio versus bit error rate analysis of OFDM, F-OFDM, UFMC, and FBMC under AWGN channel using 1024-QAM it can be concluded that as the number of QAM Order increase from 16 – QAM to 1024 – QAM the bit error rate is increasing. This is mainly due to extra complexity is added when the QAM order increases from 16 – QAM to 1024 - QAM. However, in order to support multiple services and large number of devices higher order QAM is recommended by most researchers.

4.4. BER Analysis of Waveforms for Pedestrian A Channel Model

Bit Error Rate (BER) analysis is a common method for evaluating the performance of a digital communication system. It involves measuring the number of bit errors that occur in a transmitted signal and comparing it to the total number of bits transmitted. The BER is typically expressed as a ratio or percentage of the total number of bits transmitted.

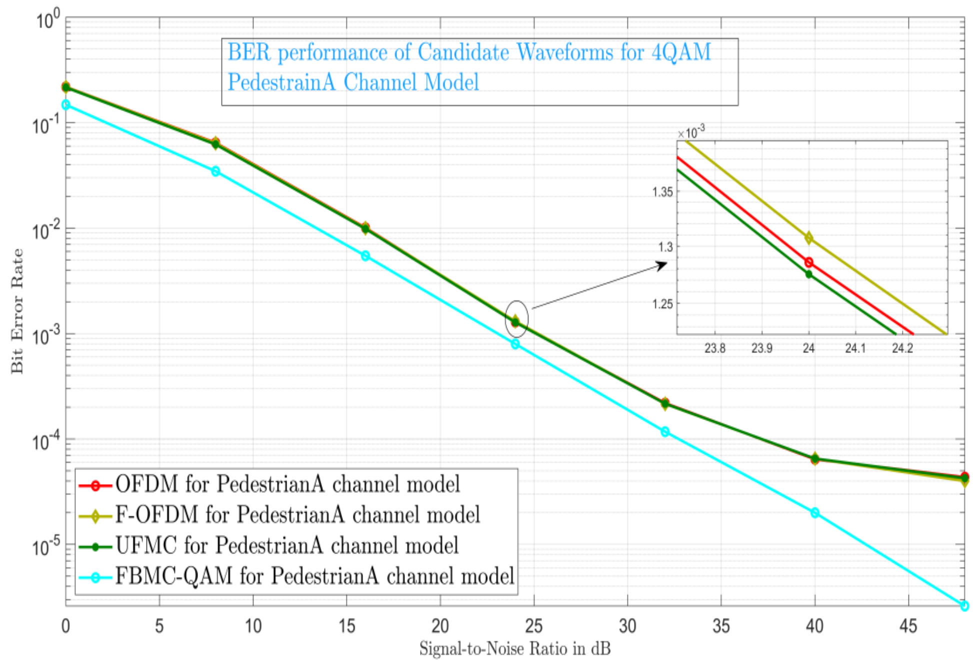

Figure 4. 5 BER performances of OFDM and candidate waveforms for 4-QAM and pedestrian A channel model

Figure 4.5 shows that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Pedestrian A Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally, FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Pedestrian A Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0100712, 0.00995833, 0.00983681, and 0.00983681 respectively. Among those values the bit error rate value of FBMC is 0.00983681. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian A channel model using 4-QAM modulation order is less.

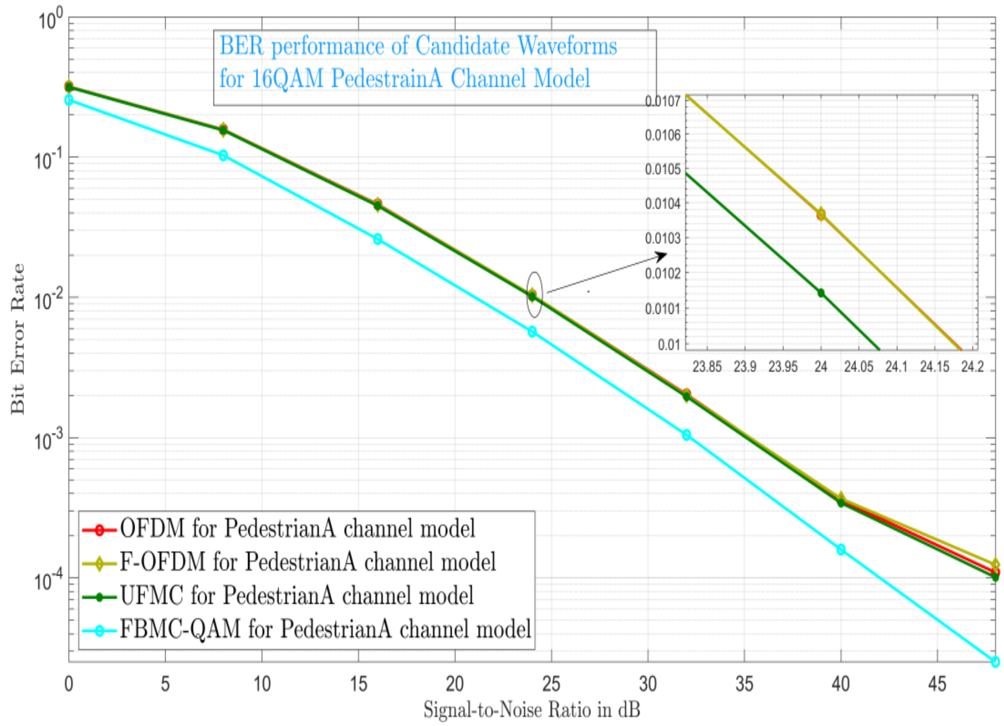

Figure 4. 6 BER performances of OFDM and candidate waveforms for 16-QAM and pedestrian A channel model

Figure 4.6 shows that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.6 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.6 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Pedestrian A Channel Model. From comparison of Figure 4.5 and Figure 4.6 it is concluded that having more QAM order result in increase in BER performance. However, having higher order QAM is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.046046, 0.0456602, 0.0449874, and 0.0260291 respectively. Among those values the bit error rate value of FBMC is 0.0260291. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore the error making probability of FBMC under Pedestrian A channel model using 16-QAM modulation order is less.

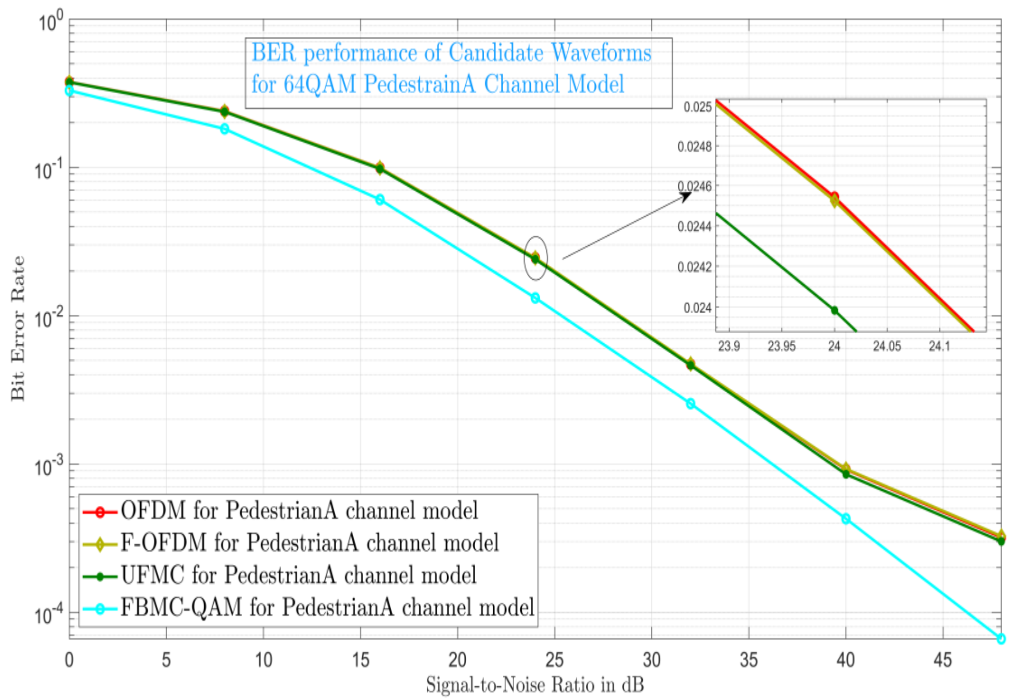

Figure 4. 7 BER performances of OFDM and candidate waveforms for 64-QAM and pedestrian A channel model

Figure 4.7 shows that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.7 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.7 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Pedestrian A Channel Model. From comparison of Figure 4.5, Figure 4.6, and Figure 4.7 it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0992474, 0.0990715, 0.0976565, and 0.0606447 respectively. Among those values the bit error rate value of FBMC is 0.0606447. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore the error making probability of FBMC under Pedestrian A channel model using 16-QAM modulation order is less.

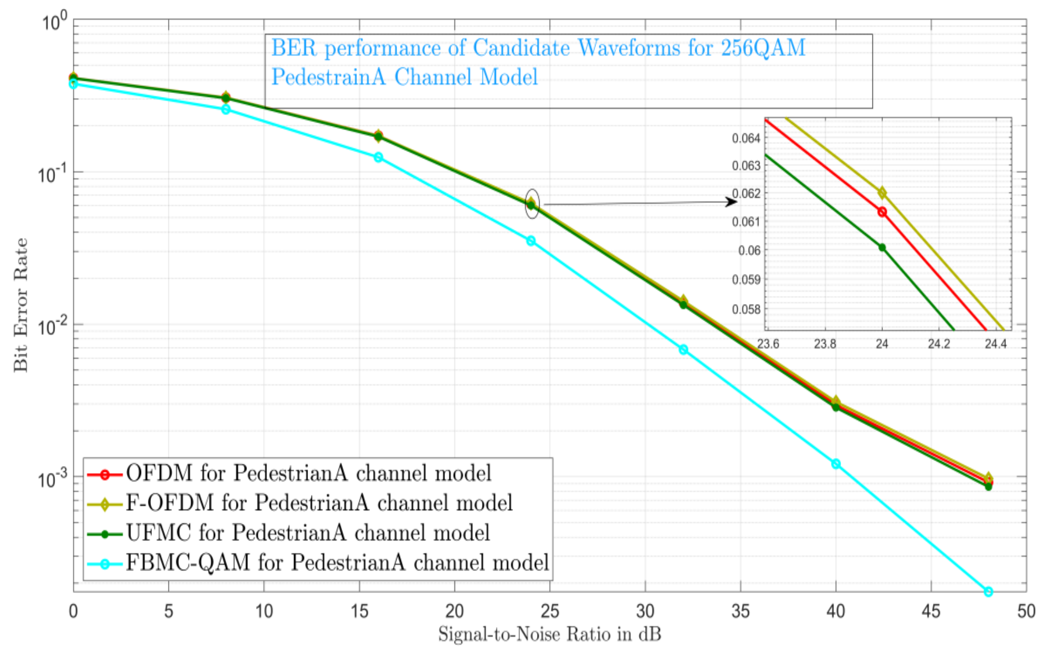

Figure 4. 8 BER performances of OFDM and candidate waveforms for 256-QAM and pedestrian A channel model

Figure 4.8 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 256-QAM under Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.8 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.8 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Pedestrian A Channel Model. From comparison of Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.171899, 0.171442, 0.169711, and 0.124309 respectively. Among those values the bit error rate value of FBMC is 0.124309. In this scenario FBMC has the least BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian A channel model using 16-QAM modulation order is less.

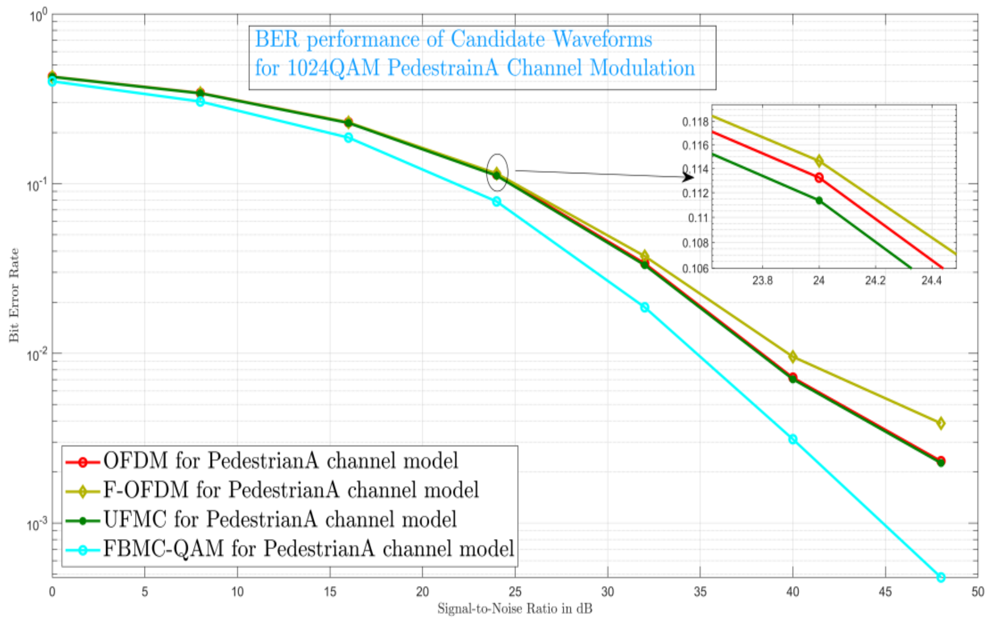

Figure 4. 9 BER performances of OFDM and candidate waveforms for 1024-QAM and Pedestrian A channel model

Figure 4.9 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.9 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. From comparison of Figure 4.5, Figure 4.6, Figure 4.7, Figure 4.8, and Figure 4.9 it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.22961, 0.229405, 0.227599, and 0.186645 respectively. Among those values the bit error rate value of FBMC is 0.186645. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian A channel model using 1024-QAM modulation order is less.

Table 4. 2 Numerical value of BER performances of OFDM and candidate waveforms for 4QAM and Pedestrian A channel model.

BER Performance for Pedestrian A Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24dB, **4QAM**
OFDM	BER	0.0100712	0.00128559
F-OFDM		0.00995833	0.00130729
UFMC		0.00983681	0.00127517
FBMC		0.0054592	0.000796875
		SNR = 16dB, **16QAM**	SNR = 24dB, **16QAM**
OFDM	BER	0.046046	0.0103659
F-OFDM		0.0456602	0.0103672
UFMC		0.0449874	0.0101424
FBMC		0.0260291	0.00570009
		SNR = 16dB, **64QAM**	SNR = 24dB, **64QAM**
OFDM	BER	0.0992474	0.0245422
F-OFDM		0.0990715	0.0245237
UFMC		0.0976565	0.0239838
FBMC		0.0606447	0.0131739
		SNR = 16dB, **256QAM**	SNR = 24dB, **256QAM**
OFDM	BER	0.171899	0.0613242
F-OFDM		0.171442	0.0619974
UFMC		0.169711	0.0600783
FBMC		0.124309	0.0352372
		SNR = 16dB, **1024QAM**	SNR = 24dB, **1024QAM**
OFDM	BER	0.22961	0.113234
F-OFDM		0.229405	0.114619
UFMC		0.227599	0.111366
FBMC		0.186645	0.0784703

Table 4.2 shows the numerical justification of wave forms for specific case of 64QAM and SNR=24dB the BER value of OFDM is 0.0245422, F-OFDM is 0.0245237, UFMC is 0.0239838, FBMC is 0.0131739. FBMC has least BER value compared to all other waveforms BER value. Error making probability of FBMC – QAM is small compared to other waveforms. Therefore, the performance of FBMC – QAM is better in pedestrian A channel model.

4.5. BER Analysis of Waveforms for Pedestrian B Channel Model

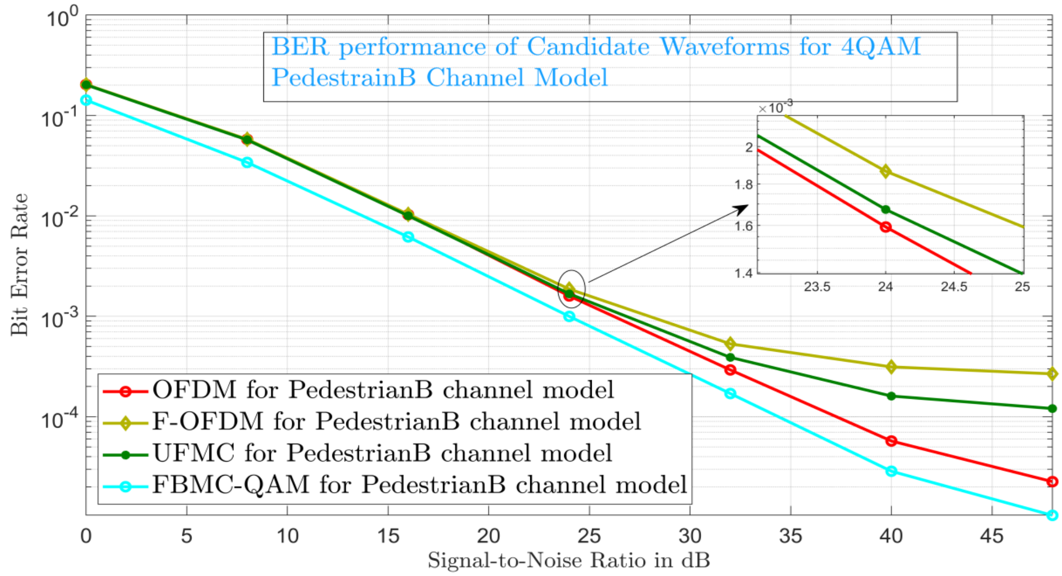

Figure 4. 10 BER performances of OFDM and candidate waveforms for 4-QAM and Pedestrian B channel model

Figure 4.10 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Pedestrian B Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally, FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Pedestrian B Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0577734, 0.0579236, 0.0571398, and 0.00617014 respectively. Among those values the bit error rate value of FBMC is 0.00617014. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian A channel model using 4-QAM modulation order is less.

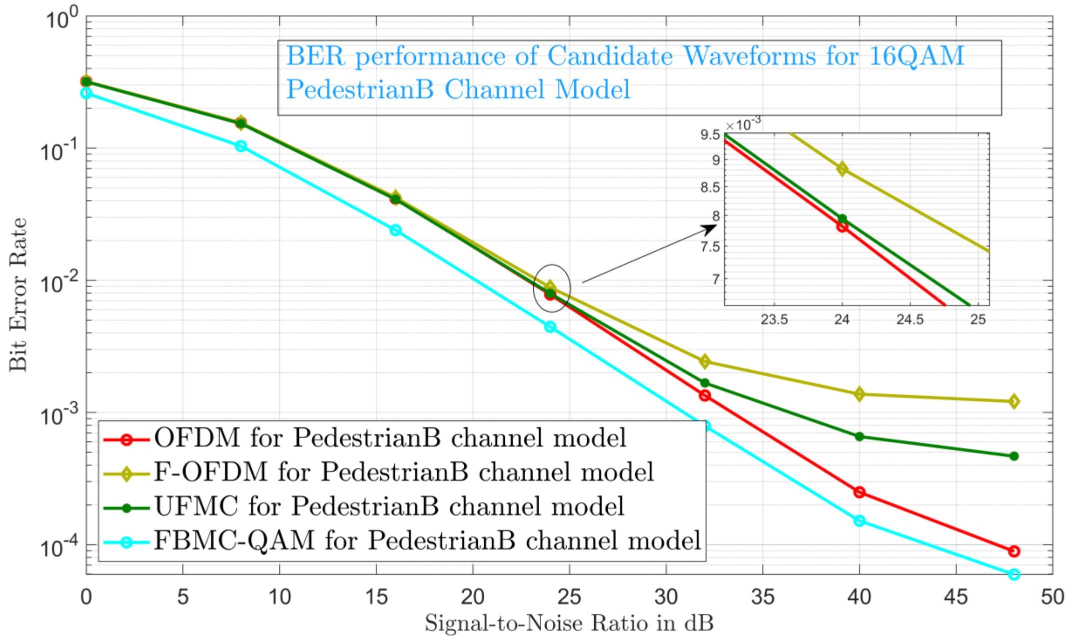

Figure 4. 11 BER performances of OFDM and candidate waveforms for 16-QAM and Pedestrian B channel model

Figure 4.11 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Pedestrian B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.11 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.11 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Pedestrian B Channel Model. From comparison of Figure 4.10 and Figure 4.11, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0414418, 0.0422847, 0.0409709, and 0.0239405 respectively. Among those values the bit error rate value of FBMC is 0.0239405. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian B channel model using 16-QAM modulation order is less.

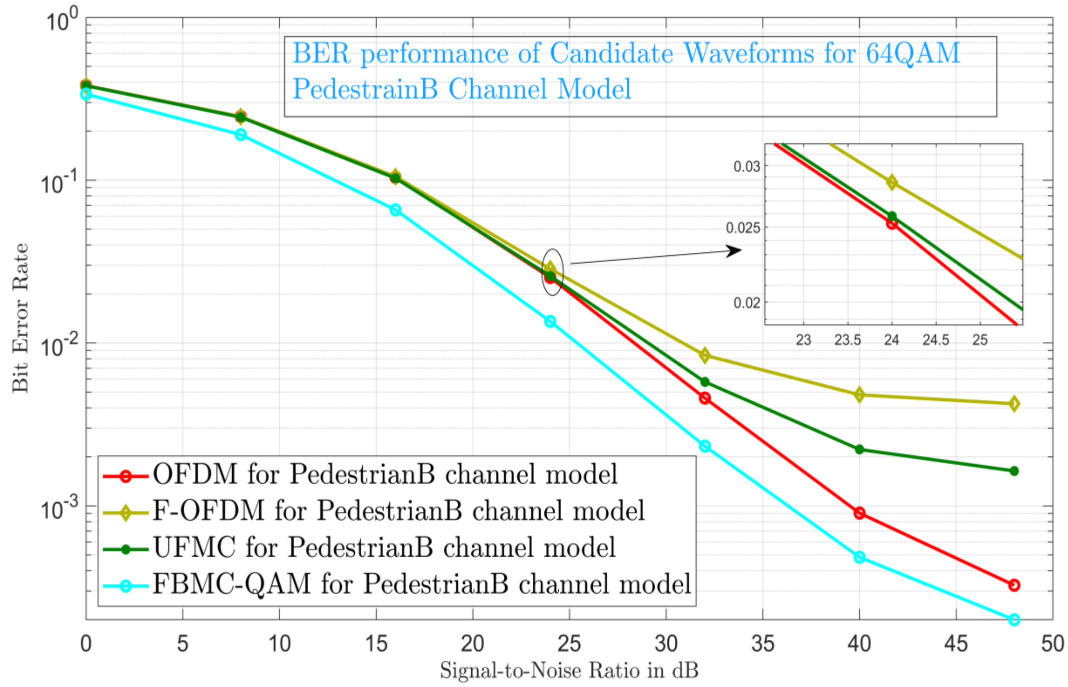

Figure 4. 12 BER performances of OFDM and candidate waveforms for 64-QAM and Pedestrian B channel model

Figure 4.12 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Pedestrian B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.12 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.12 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Pedestrian B Channel Model. From comparison of Figure 4.10, Figure 4.11 and Figure 4.12, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 64-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.104153, 0.105275, 0.102864, and 0.065803 respectively. Among those values the bit error rate value of FBMC is 0.065803. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore the error making probability of FBMC under Pedestrian B channel model using 64-QAM modulation order is less.

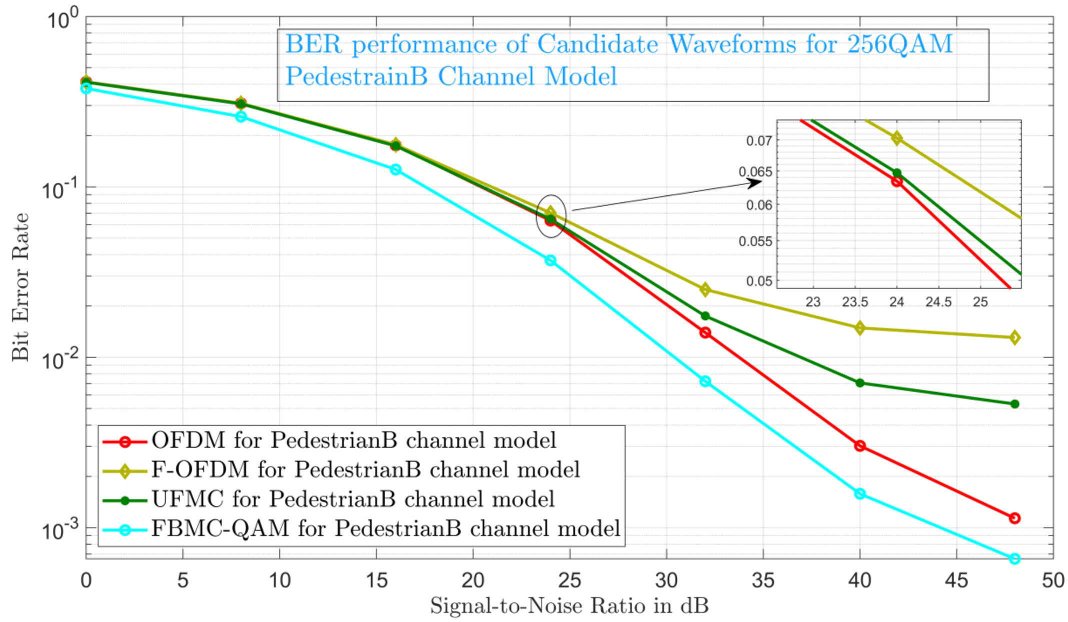

Figure 4. 13 BER performances of OFDM and candidate waveforms for 256-QAM and Pedestrian B channel model

Figure 4.13 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 256-QAM under Pedestrian B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.13 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.13 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Pedestrian B Channel Model. From comparison of Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 256-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.175102, 0.176696, 0.17379, and 0.126352 respectively. Among those values the bit error rate value of FBMC is 0.065803. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian B channel model using 256-QAM modulation order is less.

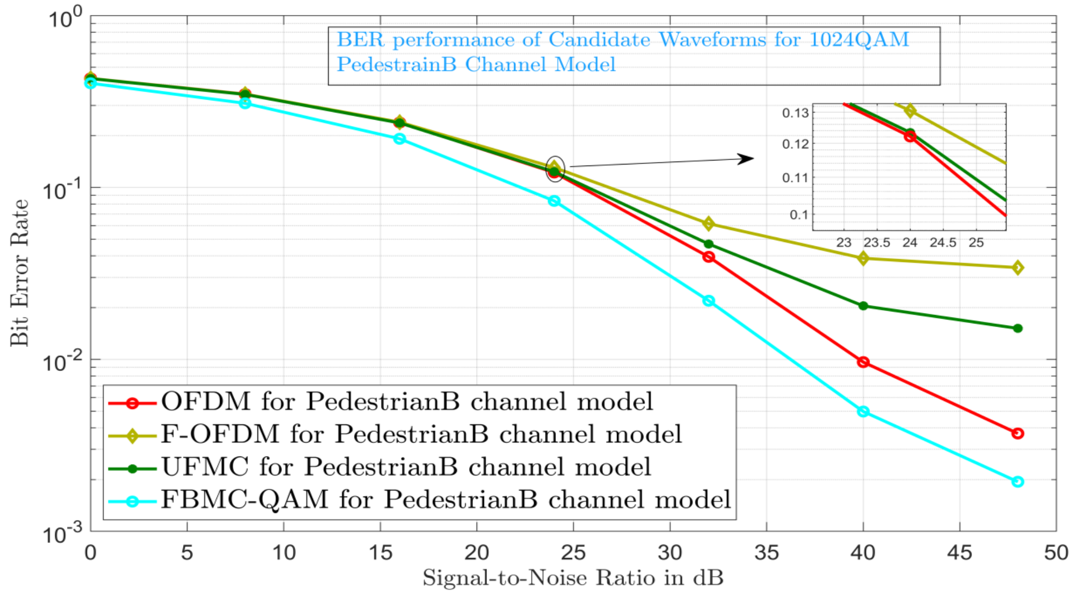

Figure 4. 14 BER performances of OFDM and candidate waveforms for 1024-QAM and pedestrian B channel model

Figure 4.14 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Pedestrian B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.14 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.14 it can be concluded that FBMC outperforms all other waveforms for the case of 1024-QAM over Pedestrian B Channel Model. From comparison of Figure 4.10, Figure 4.11, Figure 4.12, Figure 4.13, and Figure 4.14 it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.23853, 0.239792, 0.237226, and 0.191934 respectively. Among those values the bit error rate value of FBMC is 0.191934. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Pedestrian B channel model using 1024-QAM modulation order is less.

Table 4. 3 Numerical value of BER performances of OFDM and candidate waveforms for over Pedestrian B channel model

BER Performance for Pedestrian B Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24dB, **4QAM**
OFDM	BER	0.0577734	0.00159288
F-OFDM		0.0579236	0.00186545
UFMC		0.0571398	0.00167361
FBMC		0.00617014	0.000997396
		SNR = 16dB, **16QAM**	SNR = 24dB, **16QAM**
OFDM	BER	0.0414418	0.0078151
F-OFDM		0.0422847	0.00882378
UFMC		0.0409709	0.00794184
FBMC		0.0239405	0.00444575
		SNR = 16dB, **64QAM**	SNR = 24dB, **64QAM**
OFDM	BER	0.104153	0.0252743
F-OFDM		0.105275	0.028531
UFMC		0.102864	0.0258021
FBMC		0.065803	0.0135909
		SNR = 16dB, **256QAM**	SNR = 24dB, **256QAM**
OFDM	BER	0.175102	0.0634097
F-OFDM		0.176696	0.070321
UFMC		0.17379	0.0647018
FBMC		0.126352	0.0370256
		SNR = 16dB, **1024QAM**	SNR = 24dB, **1024QAM**
OFDM	BER	0.23853	0.122142
F-OFDM		0.239792	0.130565
UFMC		0.237226	0.123409
FBMC		0.191934	0.0835455

Table 4.3 shows the numerical justification of wave forms. Let consider the case of 64-QAM and SNR=24dB the BER values of OFDM, F-OFDM, UFMC, FBMC are 0.0252743, 0.028531, 0.0258021 and 0.0135909. FBMC has least BER value compared to all other waveforms BER

value. Error making probability of FBMC is small compared to other waveforms. Therefore the performance of FBMC is better in Pedestrian B channel model.

4.6. BER Analysis of Waveforms for Vehicular A Channel Model

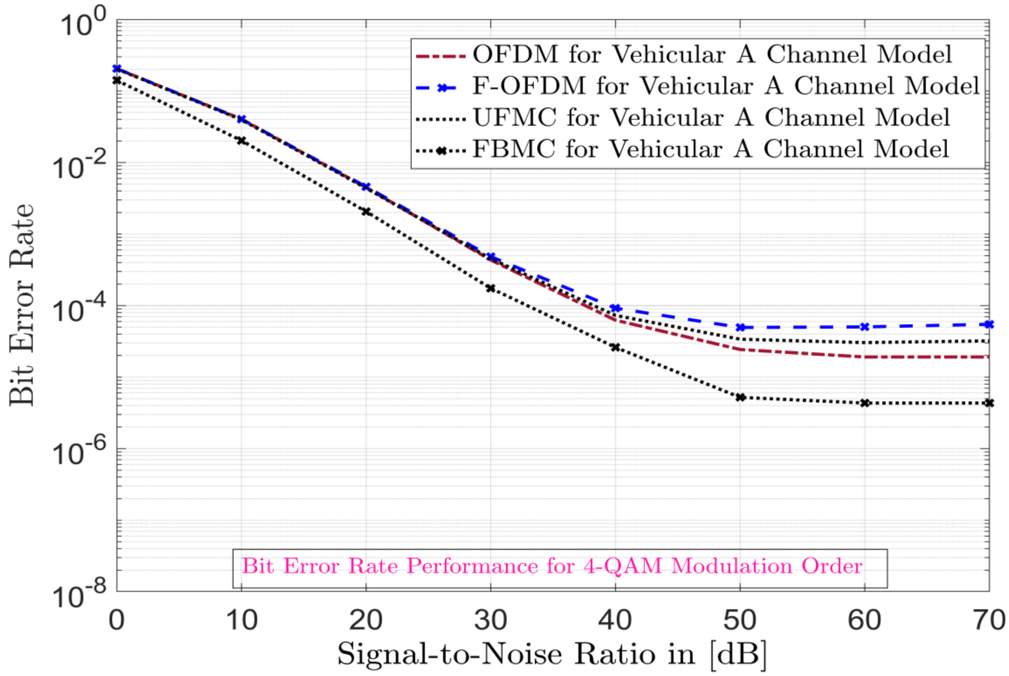

Figure 4. 15 BER performances of OFDM and candidate waveforms for 4-QAM and Vehicular A channel model

Figure 4.15 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Vehicular A Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally, FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Vehicular A Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.040467, 0.0403333, 0.0396944, and 0.0202882 respectively. Among those values the bit error rate value of FBMC is 0.0202882. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular A channel model using 4-QAM modulation order is less.

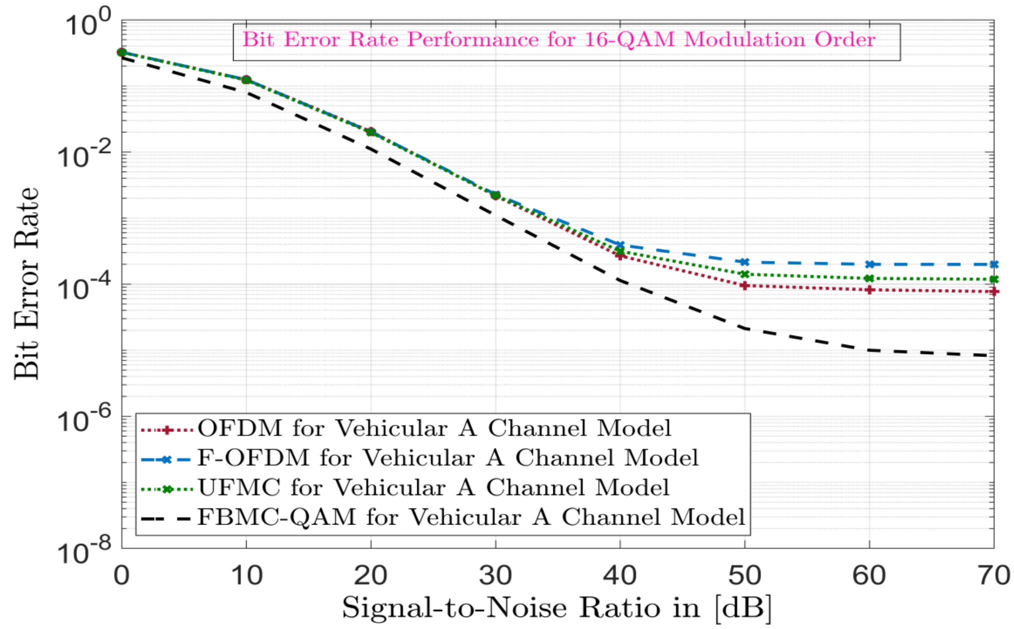

Figure 4. 16 BER performances of OFDM and candidate waveforms for 16-QAM and Vehicular A channel model

Figure 4.16 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.16 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.16 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Vehicular A Channel Model. From comparison of Figure 4.15 and Figure 4.16, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.124382, 0.124186, 0.122151, and 0.0794553 respectively. Among those values the bit error rate value of FBMC is 0.0794553. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular A channel model using 16-QAM modulation order is less.

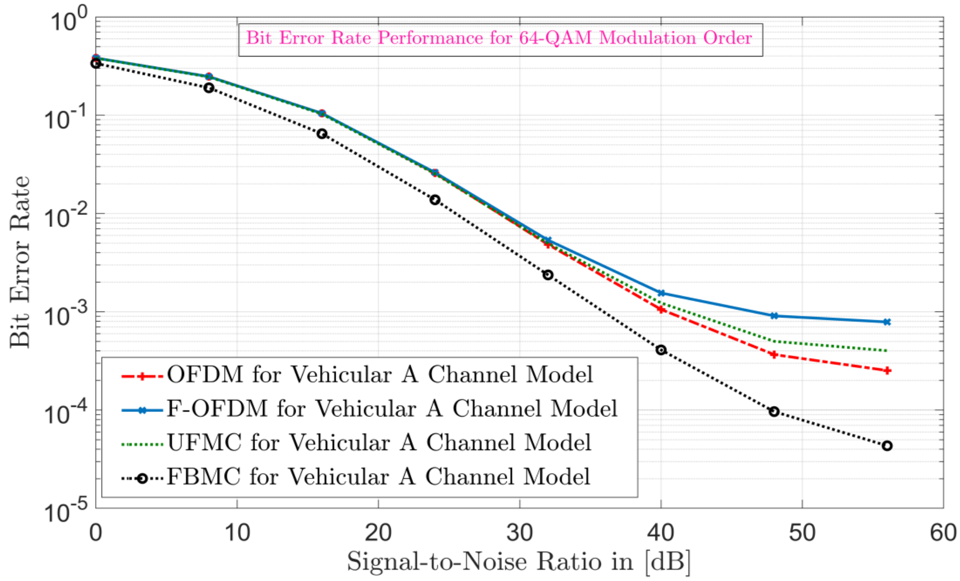

Figure 4. 17 BER performances of OFDM and candidate waveforms for 64-QAM and Vehicular A channel model

Figure 4.17 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.17 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.17 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Vehicular A Channel Model. From comparison of Figure 4.15, Figure 4.16 and Figure 4.17, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 64-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.104647, 0.104481, 0.102851, and 0.064849 respectively. Among those values the bit error rate value of FBMC is 0.064849. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular A channel model using 64-QAM modulation order is less.

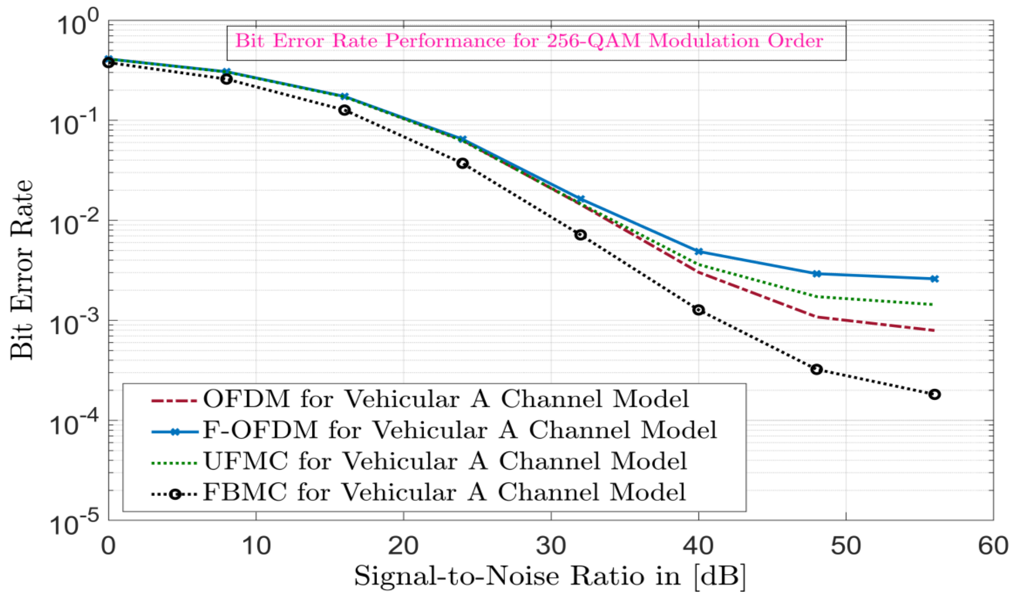

Figure 4. 18 BER performances of OFDM and candidate waveforms for 256-QAM and Vehicular A channel model

Figure 4.18 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 256-QAM under Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.18 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.18 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Vehicular A Channel Model. From comparison of Figure 4.15, Figure 4.16, Figure 4.17 and Figure 4.18, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 256-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.173285, 0.173198, 0.171596, and 0.126533 respectively. Among those values the bit error rate value of FBMC is 0.126533. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular A channel model using 256-QAM modulation order is less.

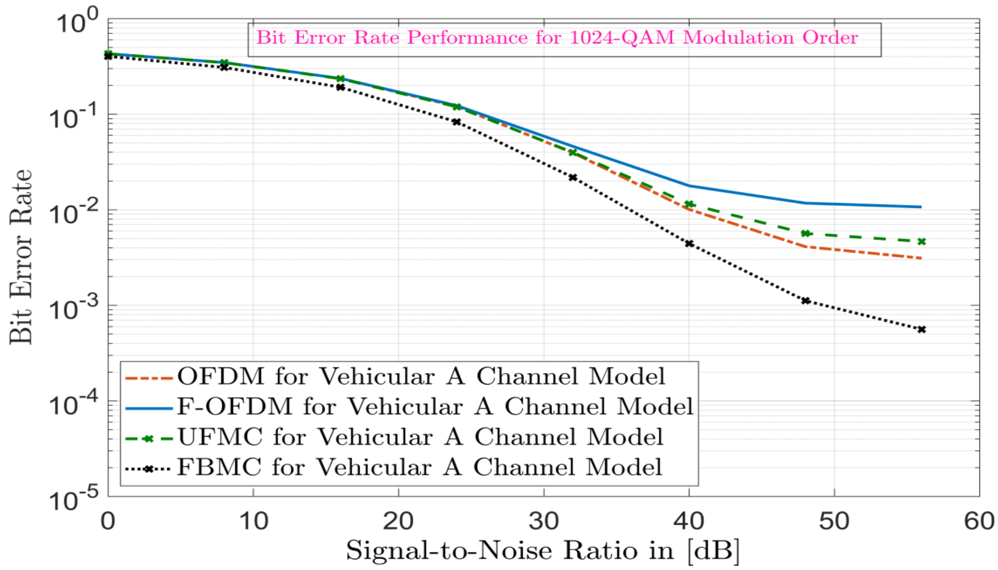

Figure 4. 19 BER performances of OFDM and candidate waveforms for 1024-QAM and Vehicular A channel model

Figure 4.19 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.19 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.19 it can be concluded that FBMC outperforms all other waveforms for the case of 1024-QAM over Vehicular A Channel Model. From comparison of Figure 4.15, Figure 4.16, Figure 4.17, Figure 4.18 and Figure 4.19, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.236613, 0.236645, 0.234962, and 0.191266 respectively. Among those values the bit error rate value of FBMC is 0.191266. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular A channel model using 1024-QAM modulation order is less.

Table 4. 4 Numerical value of BER performances of OFDM and candidate waveforms for Vehicular A channel model

BER Performance for Vehicular A Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24, **4QAM**
OFDM	BER	0.040467	0.00448351
F-OFDM		0.0403333	0.00457812
UFMC		0.0396944	0.00438281
FBMC-QAM		0.0202882	0.0020651
		SNR = 16dB, **16QAM**	SNR = 24, **16QAM**
OFDM	BER	0.124382	0.020398
F-OFDM		0.124186	0.0201202
UFMC		0.122151	0.0196992
FBMC-QAM		0.0794553	0.0110521
		SNR = 16dB, **64QAM**	SNR = 24, **64QAM**
OFDM	BER	0.104647	0.0257989
F-OFDM		0.104481	0.0261305
UFMC		0. 102851	0.0253582
FBMC-QAM		0.064849	0.0137957
		SNR = 16dB, **256QAM**	SNR = 24, **256QAM**
OFDM	BER	0.173285	0.0633806
F-OFDM		0.173198	0.0647318
UFMC		0.171596	0. 625135
FBMC-QAM		0.126533	0. 0371821
		SNR = 16dB, **1024QAM**	SNR = 24, **1024QAM**
OFDM	BER	0.236613	0.120537
F-OFDM		0.236645	0.12299
UFMC		0.234962	0.119294
FBMC-QAM		0.191266	0.0831078

Table 4.4 shows the numerical justification of wave forms. Let consider the case of 64-QAM and SNR=24dB the BER values of OFDM, F-OFDM, UFMC, FBMC are 0.0257989, 0.0261305, 0.0253582 and 0.0137957. FBMC has least BER value compared to all other waveforms BER value. Error making probability of FBMC is small compared to other waveforms.

4.7. BER Analysis of Waveforms for Vehicular B Channel Model

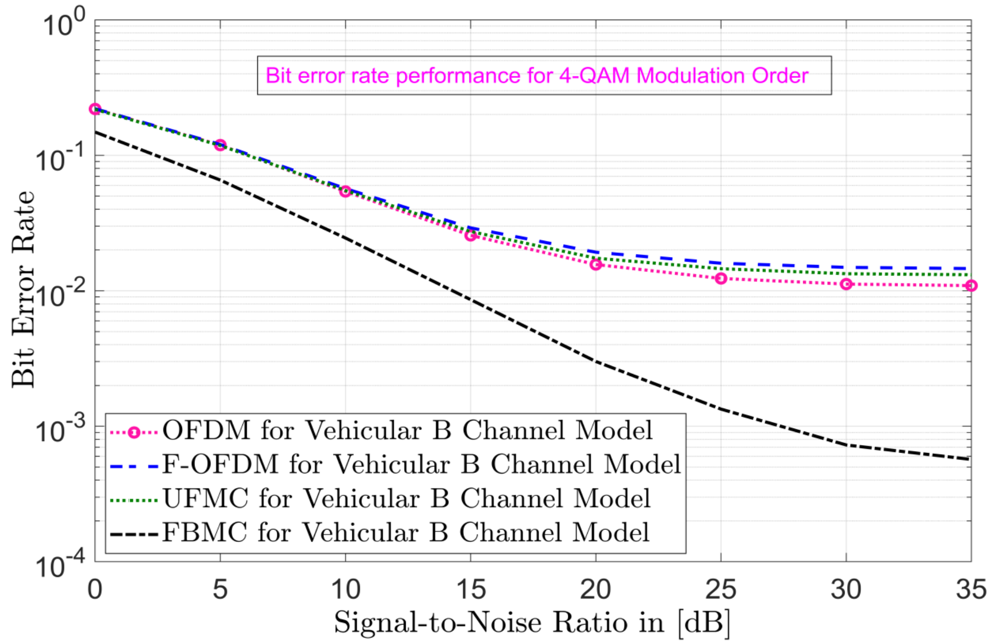

Figure 4. 20 BER performances of OFDM and candidate waveforms for 4-QAM and Vehicular B channel model

Figure 4.20 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Vehicular B Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally, FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Vehicular B Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0256476, 0.0291241, 0.0273802, and 0.00859983 respectively. Among those values the bit error rate value of FBMC is 0.00859983. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular B channel model using 4-QAM modulation order is less.

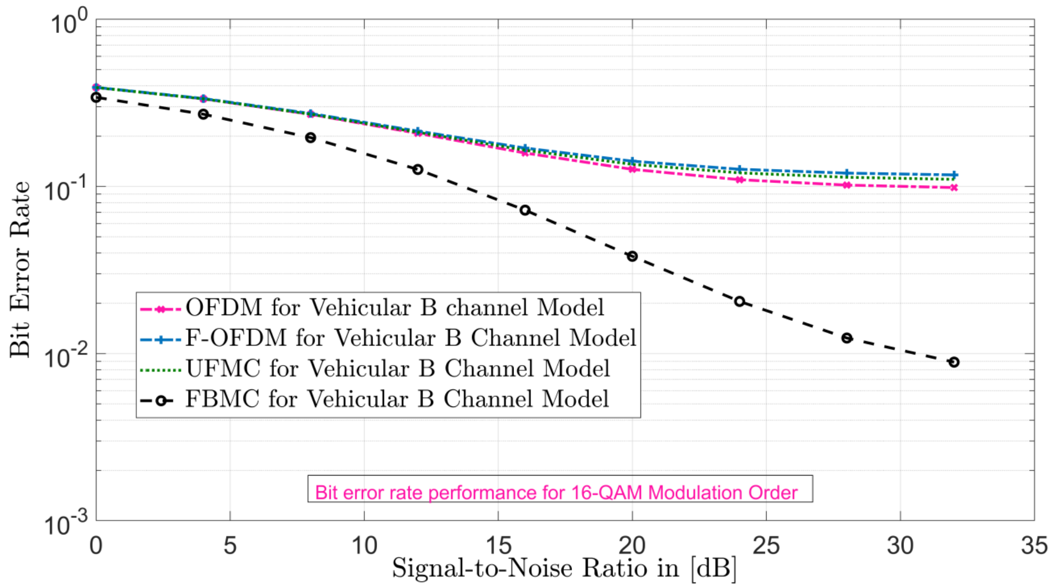

Figure 4. 21 BER performances of OFDM and candidate waveforms for 16-QAM and Vehicular B channel model

Figure 4.21 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Vehicular B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.21 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.21 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Vehicular B Channel Model. From comparison of Figure 4.19, Figure 4.20 and Figure 4.21, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0737161, 0.0813213, 0.0775217, and 0.029355 respectively. Among those values the bit error rate value of FBMC is 0.029355. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular B channel model using 16-QAM modulation order is less.

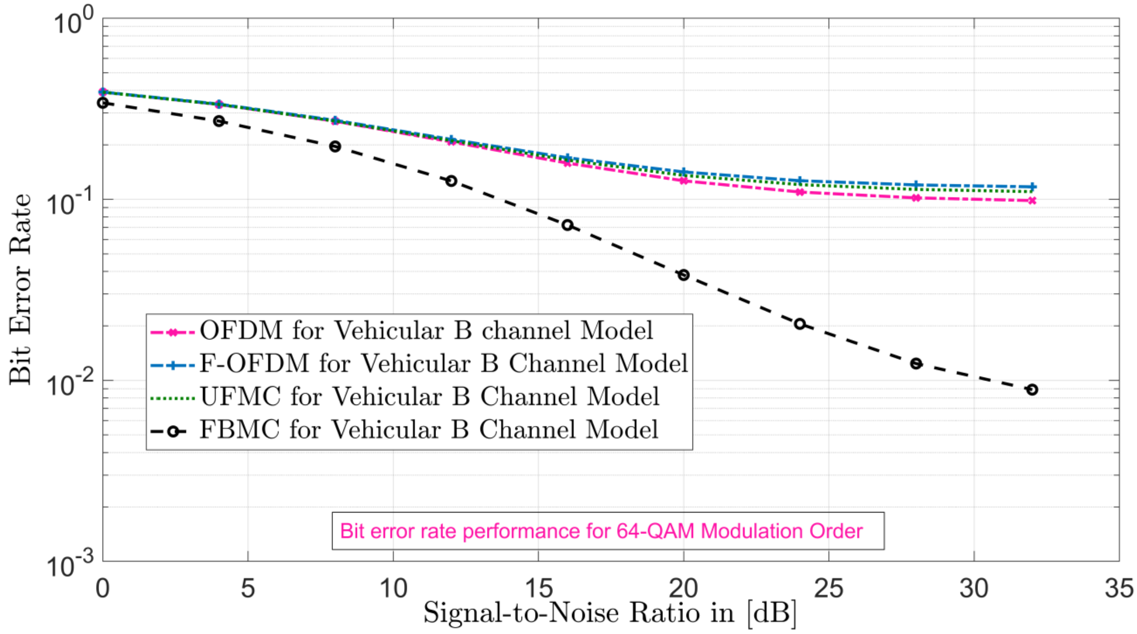

Figure 4. 22 BER performances of OFDM and candidate waveforms for 64-QAM and Vehicular B channel model

Figure 4.22 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Vehicular B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.22 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.22 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Vehicular B Channel Model. From comparison of Figure 4.19, Figure 4.20, Figure 4.21 and Figure 4.22, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 64-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.158433, 0.169636, 0.164692, and 0.0721363 respectively. Among those values the bit error rate value of FBMC is 0.0721363. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular B channel model using 64-QAM modulation order is less.

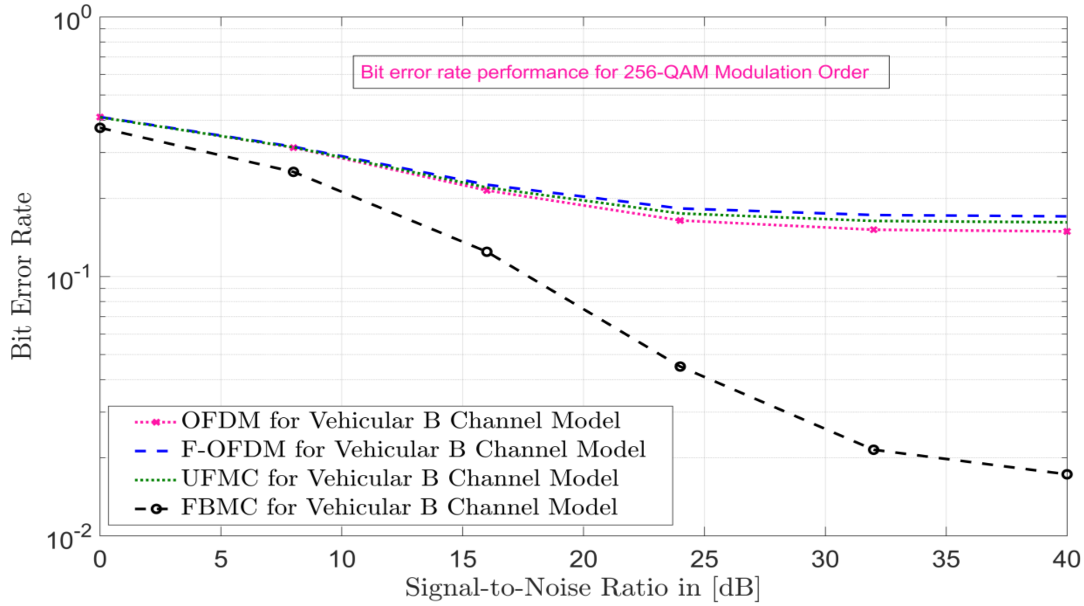

Figure 4. 23 BER performances of OFDM and candidate waveforms for 256-QAM and Vehicular B channel model

Figure 4.23 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Vehicular B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.23 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.23 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Vehicular B Channel Model. From comparison of Figure 4.19, Figure 4.20, Figure 4.21, Figure 4.22, and Figure 4.23, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 256-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.214508, 0.225606, 0.220107, and 0.12445 respectively. Among those values the bit error rate value of FBMC is 0.12445. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular B channel model using 256-QAM modulation order is less.

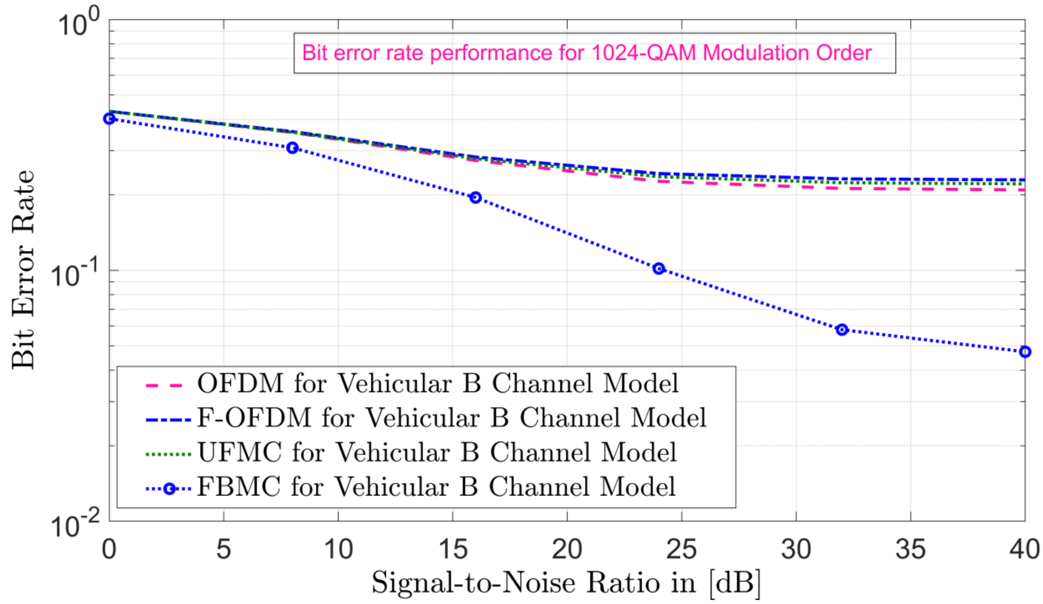

Figure 4. 24 BER performances of OFDM and candidate waveforms for 1024-QAM and Vehicular B channel model

Figure 4.24 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Vehicular B Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.24 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.24 it can be concluded that FBMC outperforms all other waveforms for the case of 1024-QAM over Vehicular B Channel Model. From comparison of Figure 4.19, Figure 4.20, Figure 4.21, Figure 4.22, Figure 4.23, and 4.24, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.274151, 0.282954, 0.278763, and 0.195138 respectively. Among those values the bit error rate value of FBMC is 0.195138. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Vehicular B channel model using 1024-QAM modulation order is less.

Table 4. 5 Numerical value of BER performances of OFDM and candidate waveforms for Vehicular B channel model

BER Performance for Vehicular B Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24, **4QAM**
OFDM	BER	0.0256476	0.0156302
F-OFDM		0.0291241	0.0192509
UFMC		0.0273802	0.0173984
FBMC-QAM		0.00859983	0.00300694
		SNR = 16dB, **16QAM**	SNR = 24, **16QAM**
OFDM	BER	0.0737161	0.0477873
F-OFDM		0.0813213	0.0569427
UFMC		0.0775217	0.0530378
FBMC-QAM		0.029355	0.0109952
		SNR = 16dB, **64QAM**	SNR = 24, **64QAM**
OFDM	BER	0.158433	0.126544
F-OFDM		0.169636	0.141617
UFMC		0. 164692	0.135549
FBMC-QAM		0.0721363	0.0382127
		SNR = 16dB, **256QAM**	SNR = 24, **256QAM**
OFDM	BER	0.214508	0.164312
F-OFDM		0.225606	0.182768
UFMC		0.220107	0. 174821
FBMC-QAM		0.12445	0.044949
		SNR = 16dB, **1024QAM**	SNR = 24, **1024QAM**
OFDM	BER	0.274151	0.22646
F-OFDM		0.282954	0.243124
UFMC		0.278763	0.236226
FBMC-QAM		0.195138	0.101684

Table 4.5 shows the numerical justification of wave forms. Let consider the case of 64-QAM and SNR=24dB the BER values of OFDM, F-OFDM, UFMC, FBMC are 0.126544, 0.141617, 0.135549 and 0.0382127. FBMC has least BER value compared to all other waveforms BER value. Error making probability of FBMC is small compared to other waveforms.

4.8. BER Analysis of Waveforms for Proposed Extended Pedestrian A Channel Model

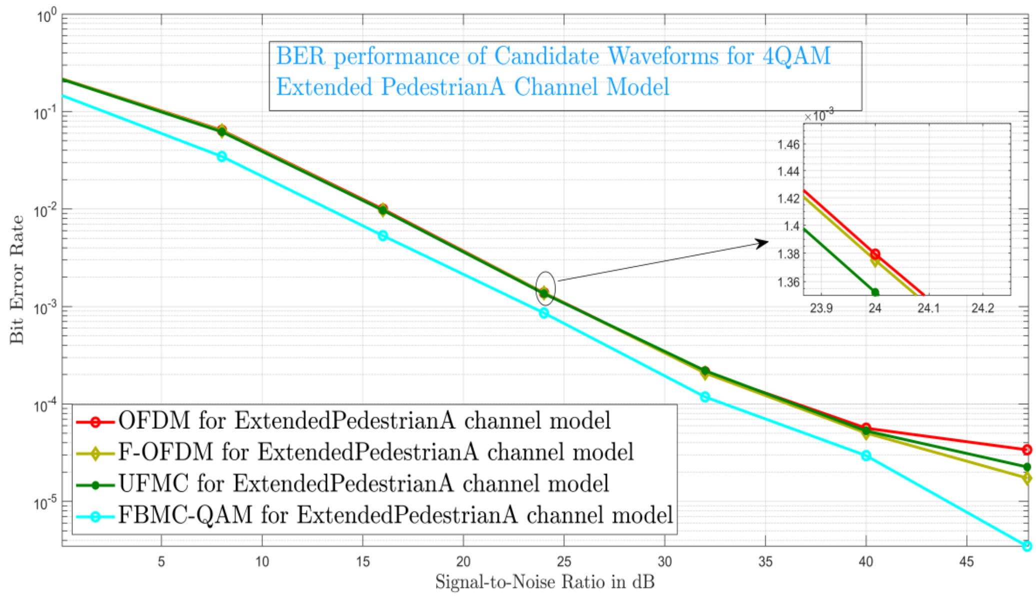

Figure 4. 25 BER performances of OFDM and candidate waveforms for 4-QAM and Extended Pedestrian A channel model

Figure 4.25 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Extended Pedestrian A Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Extended Pedestrian A Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0098942, 0.00974915, 0.00968178, and 0.00523085 respectively. Among those values the bit error rate value of FBMC is 0.00523085. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore the error making probability of FBMC under Extended Pedestrian A channel model using 4-QAM modulation order is less.

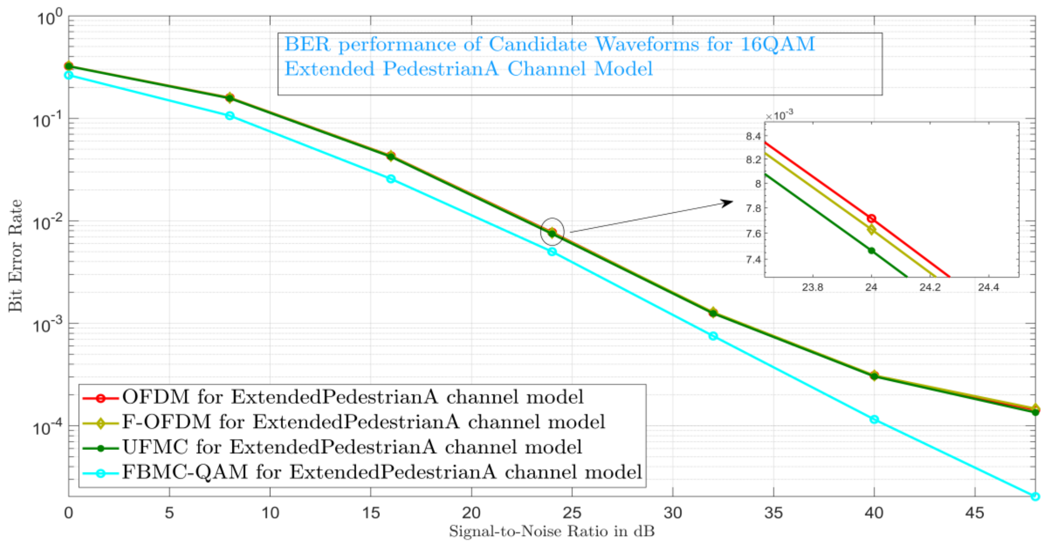

Figure 4. 26 BER performances of OFDM and candidate waveforms for 16-QAM and Extended Pedestrian A channel model

Figure 4.26 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Extended Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.26 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.26 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Extended Pedestrian A Channel Model. From comparison of Figure 4.25 and Figure 4.26, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0430213, 0.0428346, 0.0421454, and 0.0256376 respectively. Among those values the bit error rate value of FBMC is 0.0256376. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore the error making probability of FBMC under Extended Pedestrian A channel model using 16-QAM modulation order is less.

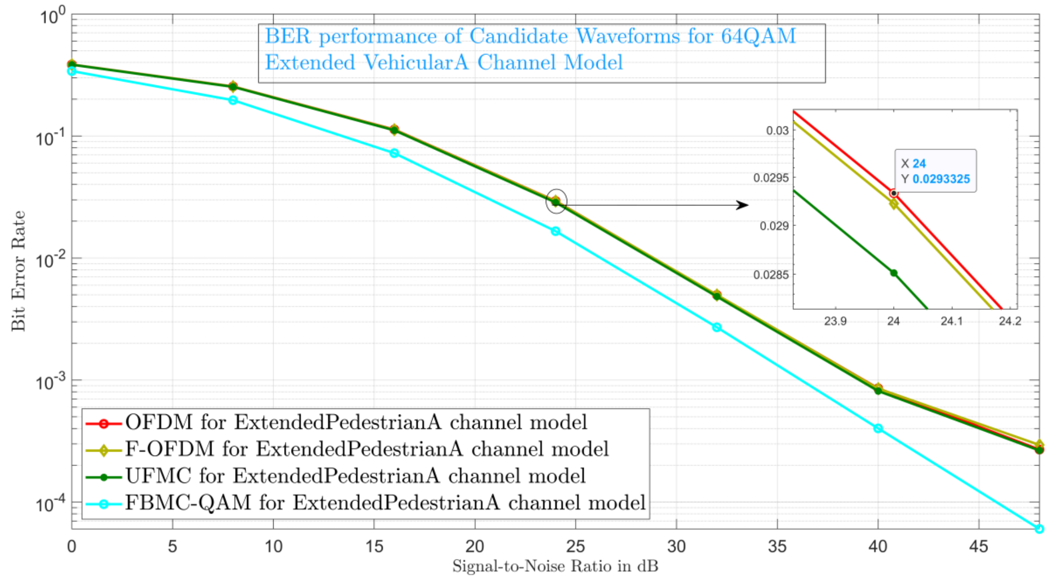

Figure 4. 27 BER performances of OFDM and candidate waveforms for 64-QAM and Extended Pedestrian A channel model

Figure 4.27 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Extended Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.27 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.27 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Extended Pedestrian A Channel Model. From comparison of Figure 4.25, Figure 4.26, and Figure 4.27, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 64-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.112939, 0.112452, 0.111226, and 0.0722865 respectively. Among those values the bit error rate value of FBMC is 0.0722865. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Pedestrian A channel model using 64-QAM modulation order is less.

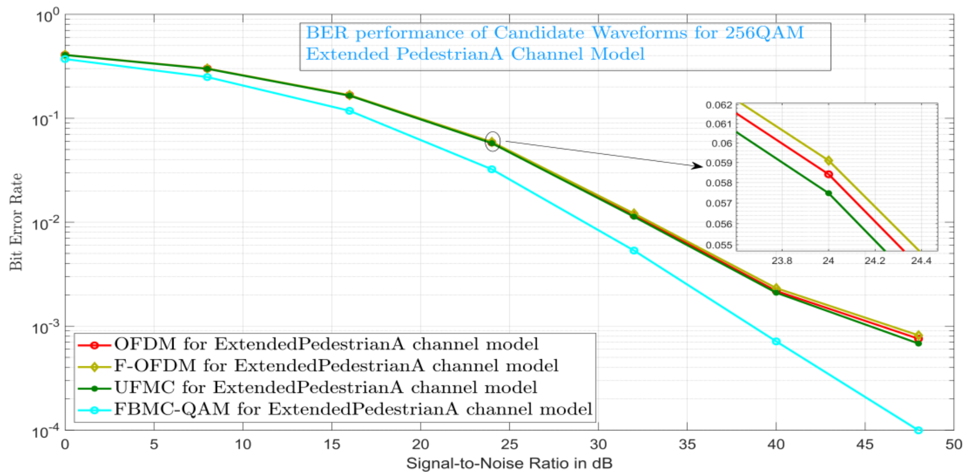

Figure 4. 28 BER performances of OFDM and candidate waveforms for 256-QAM and Extended Pedestrian A channel model

Figure 4.28 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 256-QAM under Extended Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.28 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.28 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Extended Pedestrian A Channel Model. From comparison of Figure 4.25, Figure 4.26, Figure 4.27 and Figure 4.28, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 256-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.166831, 0.166925, 0.164827, and 0.117872 respectively. Among those values the bit error rate value of FBMC is 0.117872. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Pedestrian A channel model using 256-QAM modulation order is less.

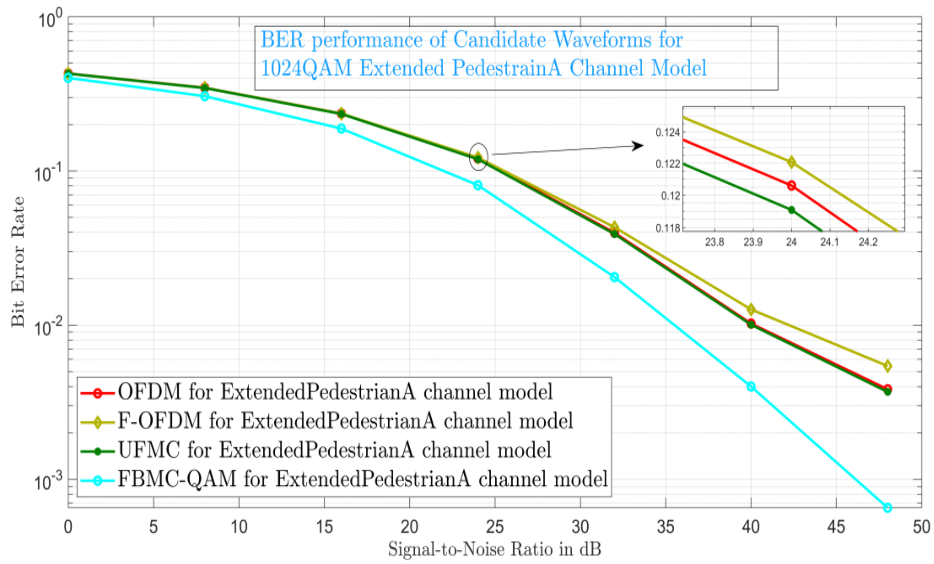

Figure 4. 29 BER performances of OFDM and candidate waveforms for 1024-QAM and Extended Pedestrian A channel model

Figure 4.29 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Extended Pedestrian A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.29 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.29 it can be concluded that FBMC outperforms all other waveforms for the case of 1024-QAM over Extended Pedestrian A Channel Model. From comparison of Figure 4.25, Figure 4.26, Figure 4.27, Figure 4.28, and Figure 4.29, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.235896, 0.235606, 0.234173, and 0.188282 respectively. Among those values the bit error rate value of FBMC is 0.188282. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Pedestrian A channel model using 1024-QAM modulation order is less.

Table 4. 6 Numerical value of BER performances of OFDM and candidate waveforms for Extended Pedestrian A channel model.

BER Performance for Extended Pedestrian A Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24, **4QAM**
OFDM	BER	0.0098942	0.00137934
F-OFDM		0.00974915	0.001375
UFMC		0.00968178	0.00135243
FBMC-QAM		0.00523085	0.000857639
		SNR = 16dB, **16QAM**	SNR = 24, **16QAM**
OFDM	BER	0.0430213	0.00771484
F-OFDM		0.0428346	0.00762891
UFMC		0.0421454	0.00746441
FBMC-QAM		0.0256376	0.00499957
		SNR = 16dB, **64QAM**	SNR = 24, **64QAM**
OFDM	BER	0.112939	0.0293325
F-OFDM		0.112452	0.0292248
UFMC		0.111226	0.0285122
FBMC-QAM		0.0722865	0.0165891
		SNR = 16dB, **256QAM**	SNR = 24, **256QAM**
OFDM	BER	0.166831	0.0584143
F-OFDM		0.166925	0.0591066
UFMC		0.164827	0.0574768
FBMC-QAM		0.117872	0.0322832
		SNR = 16dB, **1024QAM**	SNR = 24, **1024QAM**
OFDM	BER	0.235896	0.120597
F-OFDM		0.235606	0.122066
UFMC		0.234173	0.119082
FBMC-QAM		0.188282	0.0808658

Table 4.6 shows the numerical justification of wave forms. For specific case of 64QAM and SNR=24dB the BER value of OFDM is 0.0293325, F-OFDM is 0.0292248, UFMC is 0.0285122,

FBMC is 0.0165891. FBMC has least BER value compared to all other waveforms BER value. Error making probability of FBMC is small compared to other waveforms.

4.9. BER Analysis of Waveforms for Proposed Extended Vehicular A Channel Model

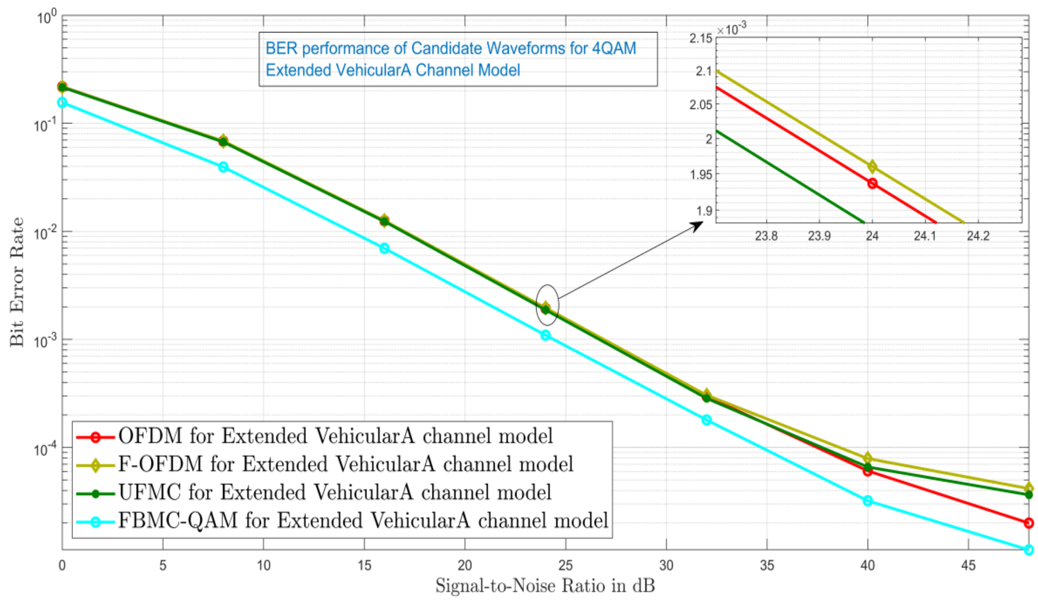

Figure 4. 30 BER performances of OFDM and candidate waveforms for 4-QAM and Extended Vehicular A channel model

Figure 4.30 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely F-OFDM, UFMC and FBMC for 4-QAM under Extended Vehicular A Channel Model. In this scenario FBMC has smallest BER value and this implies FBMC has better BER performance than all other waveforms. Generally, FBMC outperforms than all other wave forms for the case of 4-QAM modulation order under Extended Vehicular A Channel Model.

To clarify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 4-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.012408, 0.012579, 0.012355, and 0.00697135 respectively. Among those values the bit error rate value of FBMC is 0.00697135. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Vehicular A channel model using 4-QAM modulation order is less.

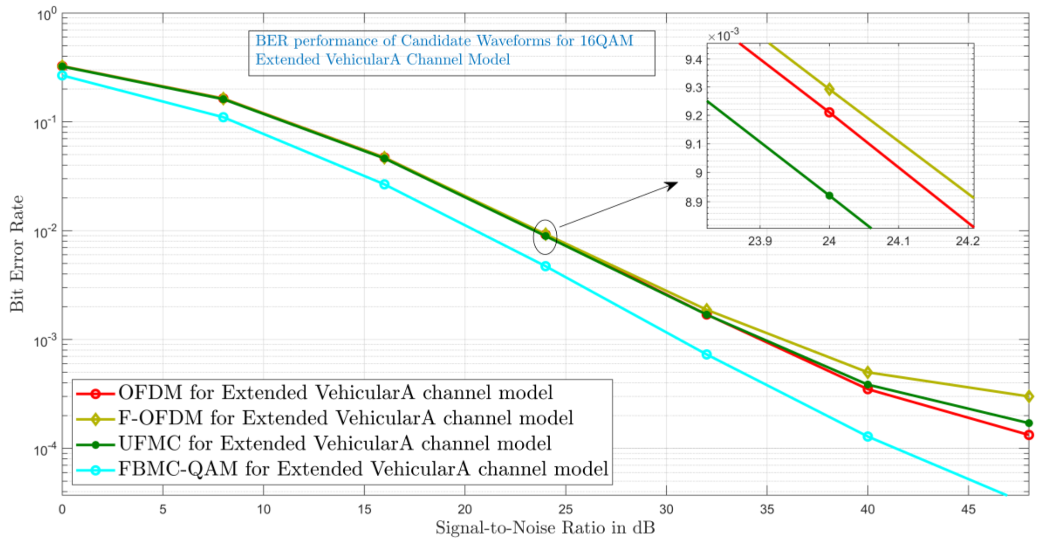

Figure 4. 31 BER performances of OFDM and candidate waveforms for 16-QAM and Extended Vehicular A channel model

Figure 4.31 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 16-QAM under Extended Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.31 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.31 it can be concluded that FBMC outperforms all other waveforms for the case of 16-QAM over Extended Vehicular A Channel Model. From comparison of Figure 4.30 and Figure 4.31, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 16-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.0470699, 0.0468898, 0.0461089, and 0.026638 respectively. Among those values the bit error rate value of FBMC is 0.026638. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Vehicular A channel model using 16-QAM modulation order is less.

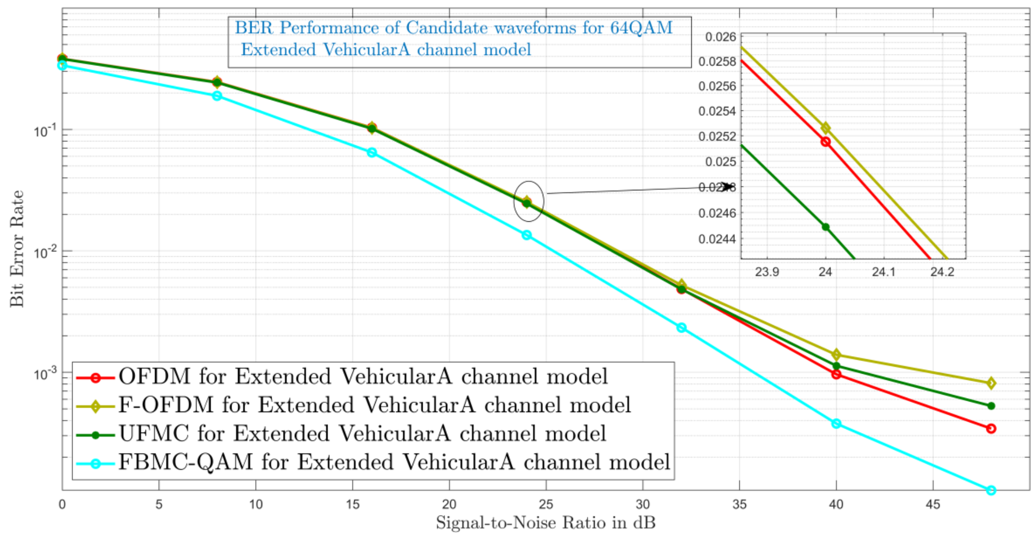

Figure 4. 32 BER performances of OFDM and candidate waveforms for 64-QAM and Extended Vehicular A channel model

Figure 4.32 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 64-QAM under Extended Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.32 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.32 it can be concluded that FBMC outperforms all other waveforms for the case of 64-QAM over Extended Vehicular A Channel Model. From comparison of Figure 4.30, Figure 4.31, and Figure 4.32, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 64-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.103394, 0.103021, 0.101525, and 0.0646039 respectively. Among those values the bit error rate value of FBMC is 0.0646039. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Vehicular A channel model using 64-QAM modulation order is less.

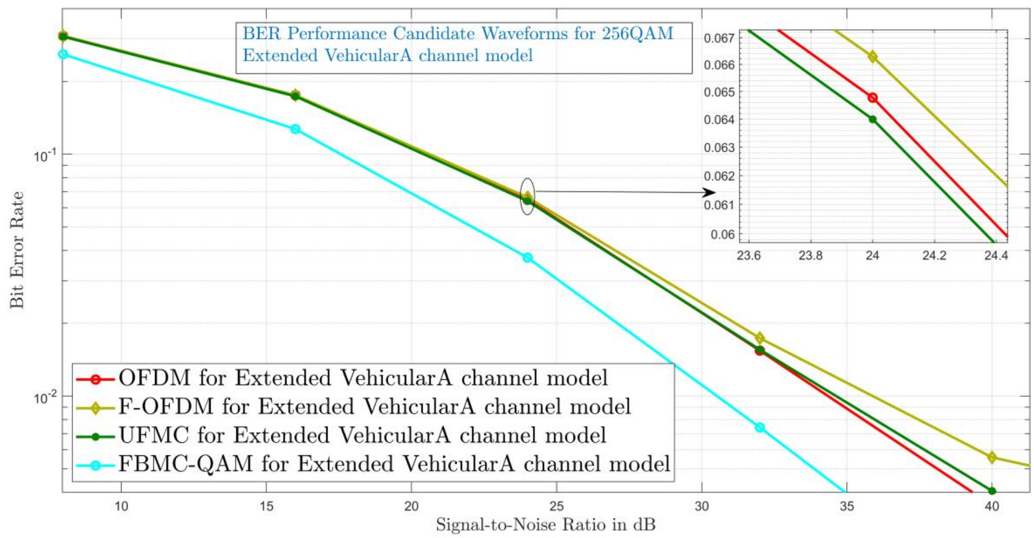

Figure 4. 33 BER performances of OFDM and candidate waveforms for 256-QAM and Extended Vehicular A channel model

Figure 4.33 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 256-QAM under Extended Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.33 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.33 it can be concluded that FBMC outperforms all other waveforms for the case of 256-QAM over Extended Vehicular A Channel Model. From comparison of Figure 4.30, Figure 4.31, Figure 4.32, and Figure 4.33, it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 256-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.175354, 0.175386, 0.173606, and 0.127068 respectively. Among those values the bit error rate value of FBMC is 0.127068. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Vehicular A channel model using 256-QAM modulation order is less.

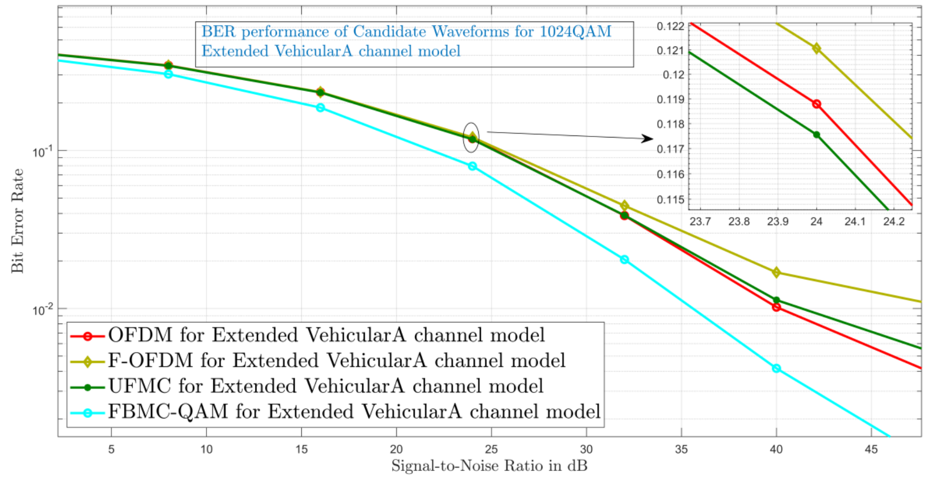

Figure 4. 34 BER performances of OFDM and candidate waveforms for 1024-QAM and Extended Vehicular A channel model

Figure 4.34 indicates that the BER performance of OFDM and Candidate wave forms that expected to replace OFDM namely: F-OFDM, UFMC and FBMC for 1024-QAM under Extended Vehicular A Channel Model. In this scenario FBMC has smallest BER value because according to figure 4.34 the graph of FBMC is found below the graph of F-OFDM, UFMC and OFDM. Then this justifies FBMC has better BER performance than all other waveforms. Generally, form simulation result of figure 4.34 it can be concluded that FBMC outperforms all other waveforms for the case of 1024-QAM over Extended Vehicular A Channel Model. From comparison of Figure 4.30, Figure 4.31, Figure 4.32, Figure 4.33, and Figure 4.34 it is concluded that having more QAM order result in the increase the BER value. However, higher QAM order is a solution to support large number of user and SNR.

To justify with numerical bit error rate value let consider the performance of waveforms for signal to noise ratio of 16dB and the modulation order of 1024-QAM. The bit error rate values of OFDM, F-OFDM, UFMC, and FBMC are 0.233956, 0.233962, 0.232656, and 0.186543 respectively. Among those values the bit error rate value of FBMC is 0.186543. In this scenario FBMC has the leas BER values compared to all other wave forms. Therefore, the error making probability of FBMC under Extended Vehicular A channel model using 1024-QAM modulation order is less.

Table 4. 7 Numerical value of BER performances of OFDM and candidate waveforms for Extended Vehicular A channel model.

BER Performance for Extended Vehicular A Channel Model			
		SNR = 16dB, **4QAM**	SNR = 24, **4QAM**
OFDM	BER	0.012408	0.00193663
F-OFDM		0.012579	0.00196007
UFMC		0.012355	0.00187587
FBMC-QAM		0.00697135	0.00109462
		SNR = 16dB, **16QAM**	SNR = 24, **16QAM**
OFDM	BER	0.0470699	0.00921007
F-OFDM		0.0468898	0.0092921
UFMC		0.0461089	0.00892101
FBMC-QAM		0.026638	0.00471701
		SNR = 16dB, **64QAM**	SNR = 24, **64QAM**
OFDM	BER	0.103394	0.0251531
F-OFDM		0.103021	0.0256616
UFMC		0.101525	0.0244887
FBMC-QAM		0.0646039	0.0135006
		SNR = 16dB, **256QAM**	SNR = 24, **256QAM**
OFDM	BER	0.175354	0.0647763
F-OFDM		0.175386	0.066288
UFMC		0.173606	0.0639939
FBMC-QAM		0.127068	0.0373739
		SNR = 16dB, **1024QAM**	SNR = 24, **1024QAM**
OFDM	BER	0.233956	0.118791
F-OFDM		0.233962	0.121064
UFMC		0.232656	0.117553
FBMC-QAM		0.186543	0.0795967

Table 4.7 shows the numerical justification of wave forms. For specific case of 64QAM and SNR=24dB the BER value of OFDM is 0.0251531, F-OFDM is 0.0256616, UFMC is 0.0244887, FBMC is 0.0135006. FBMC has least BER value compared to all other waveforms BER value. Error making probability of FBMC is small compared to other waveforms.

4.10. Signal to Interference Ratio Analysis of Waveforms

The normalized frequency offset is a parameter that is used to describe the frequency offset between the carrier frequency of the transmitted signal and the carrier frequency of the local oscillator at the receiver in a wireless communication system. In a wireless communication system, the receiver must synchronize its local oscillator with the carrier frequency of the transmitted signal in order to correctly demodulate the signal and recover the transmitted information. However, due to various factors such as Doppler shift, clock drift, and frequency drift, there may be a difference between the carrier frequency of the transmitted signal and the local oscillator frequency at the receiver.

The normalized frequency offset is defined as the ratio of the frequency offset to the symbol rate of the transmitted signal. It is expressed as a fraction or a percentage and represents the relative deviation of the local oscillator frequency from the carrier frequency of the transmitted signal. The normalized frequency offset is an important parameter in the design and analysis of digital communication systems because it can affect the performance of the system. A large frequency offset can cause the demodulated signal to be distorted or even lost, leading to errors in the received data. Techniques such as frequency synchronization, carrier recovery, and equalization can be used to compensate for the frequency offset and improve the performance of the system.

The normalized frequency offset versus signal-to-interference ratio (NFOSIR) graph is a plot that shows how the performance of a digital communication system varies with the amount of frequency offset and interference in the received signal.

In the graph, the x-axis represents the normalized frequency offset, which is the relative deviation of the local oscillator frequency from the carrier frequency of the transmitted signal. The y-axis represents the signal-to-interference ratio (SIR), which is the ratio of the power of the desired signal to the power of the interfering signals. The NFOSIR graph is used to analyze the performance of digital communication systems in the presence of frequency offset and interference. As the frequency offset increases, the performance of the system degrades due to the distortion and loss of the demodulated signal. As the interference level increases, the performance of the system also degrades due to the increased noise and distortion in the received signal. The NFOSIR graph can be used to determine the range of frequency offset and interference levels that the communication system can tolerate while maintaining an acceptable level of performance. By analyzing the graph, it is possible to determine the optimal design parameters for the communication system, such as the modulation scheme, error-correcting code, and equalization technique, to minimize the effects of frequency offset and interference and improve the performance of the system.

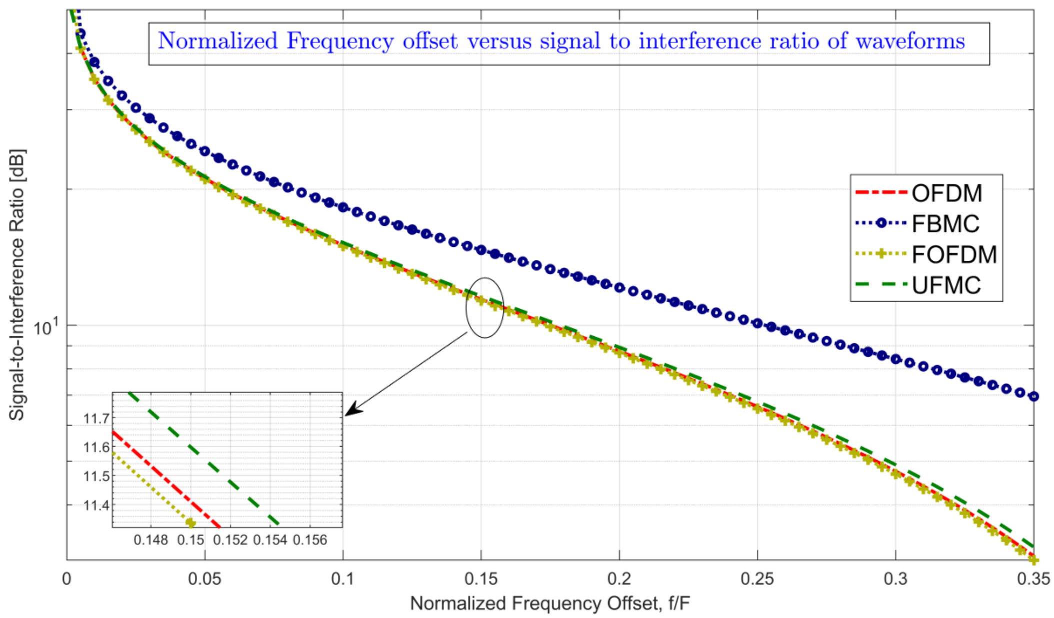

Figure 4. 35 Normalized Frequency Offset versus Signal to Interference Ratio analysis of waveforms

Figure 4.35 shows that the Normalized frequency offset versus signal to interference ratio analysis of OFDM, F-OFDM, UFMC and FBMC. Signal-to-Interference Ratio (SIR) is a measure of the strength of the desired signal relative to the strength of the interfering signals in a communication system. It is defined as the ratio of the power of the desired signal to the power of the interfering signals. According to figure 4.35 FBMC have highest signal to interference ratio. But as the normalized frequency offset increases the signal to interference ratio value of the waveforms degrade.

Normalized time offset is a parameter that is used to describe the timing offset between the transmitted signal and the received signal in a digital communication system. In a digital communication system, the receiver must synchronize the timing of its receiver clock with the timing of the transmitter clock in order to correctly demodulate the signal and recover the transmitted information. However, due to various factors such as clock drift and propagation delay, there may be a timing offset between the transmitted signal and the received signal.

The normalized time offset is defined as the ratio of the timing offset to the symbol duration of the transmitted signal. It is expressed as a fraction or a percentage and represents the relative deviation of the receiver clock from the transmitter clock. The normalized time offset is an important parameter in the design and analysis of digital communication systems because it can affect the performance of the system. A large timing offset can cause the demodulated signal to be distorted or even lost, leading to errors in the received data. Techniques such as timing synchronization, symbol timing recovery, and equalization can be used to compensate for the timing offset and improve the performance of the system.

In a digital communication system, the receiver must synchronize the timing of its receiver clock with the timing of the transmitter clock in order to correctly demodulate the signal and recover the transmitted information. However, due to various factors such as clock drift and propagation delay, there may be a timing offset between the transmitted signal and the received signal. The normalized time offset is defined as the ratio of the timing offset to the symbol duration of the transmitted signal. It is expressed as a fraction or a percentage and represents the relative deviation of the receiver clock from the transmitter clock.

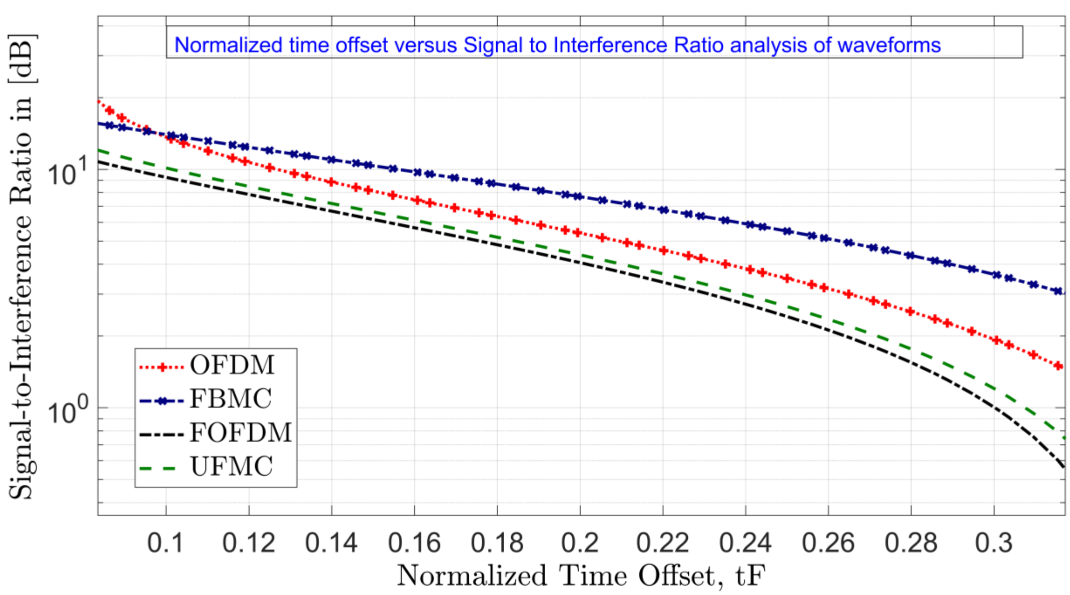

Figure 4. 36 Normalized Time Offset versus Signal to Interference Ratio analysis of waveforms

The Normalized Time Offset versus Signal-to-Interference Ratio graph is a plot that shows how the performance of a digital communication system varies with the amount of timing offset and interference in the received signal. In Figure 4.36, the x-axis represents the normalized time offset, which is the relative deviation of the receiver clock from the transmitter clock. The y-axis represents the signal-to-interference ratio (SIR), which is the ratio of the power of the desired signal to the power of the interfering signals.

The Normalized Time Offset versus SIR graph is used to analyze the performance of digital communication systems in the presence of timing offset and interference. As the timing offset increases, the performance of the system degrades due to the distortion and loss of the demodulated signal. As the interference level increases, the performance of the system also degrades due to the increased noise and distortion in the received signal.

The Normalized Time Offset versus Signal-to-Interference Ratio graph can be used to determine the range of timing offset and interference levels that the communication system can tolerate while maintaining an acceptable level of performance. By analyzing the graph, it is possible to determine the optimal design parameters for the communication system, such as the timing synchronization technique, symbol timing recovery method, and equalization approach, to minimize the effects of timing offset and interference and improve the performance of the system.

CONCLUSION AND RECOMENDATION

Conclusion

In this thesis work performance of existing OFDM and Proposed 5G and beyond candidate waveforms with higher order QAM for massive MIMO under Vehicular and Pedestrian channel models are addressed. The waveforms that are focused in this research work are OFDM, F-OFDM, UFMC and FBMC. These waveforms are analyzed under various channel models like: Pedestrian A, Pedestrian B, Vehicular A, Vehicular B, Extended Pedestrian A, and Extended Vehicular A. The thesis results under different higher order QAM modulation schemes like 4 QAM, 16 QAM, 64 QAM, 256 QAM and 1024 QAM. The performance of waveforms examined by using performance metrics like SNR versus BER, SIR versus Normalized Time Offset and SIR versus Normalized frequency offset. The simulation result shows that among 5G and beyond technology waveforms, FBMC out performs in the proposed Extended Pedestrian A channel model, proposed Extended Vehicular A channel model, SIR versus Normalized Time Offset and SIR versus Normalized frequency offset. In general, Less FBMC errors are likely to occur when employing the QAM modulation order for the channel models. More QAM orders are found to be the source of the increase in BER value. Higher QAM order is the solution to supporting a large user base and SNR, though. The results of the simulation demonstrate that when the signal to noise ratio rises above 35dB, the BER performance of the FBMC drops below 10-4.

Recommendation

This thesis work contributed detailed analysis of wave form under various channels like, Pedestrian A, Pedestrian B, Vehicular A, Vehicular B, Extended Pedestrian A, and Extended Vehicular A. The multicarrier modulation techniques used in this research are OFDM, F-OFDM, UFMC, and FBMC.

Some points recommended for the future works are:

1. Analysis of multicarrier modulation techniques over Extended Vehicular B and Extended Pedestrian B channel models and other practical channels.
2. It is better if the interference further reduced while using candidate wave form in practical scenario

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