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Performance Analysis of Modulation Techniques for 5G Networks

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By

GETACHEW HAGOS

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Examiners Approval Sheet

We, the undersigned, members of the Board of Examiners of the final open defense by **Getachew Hagos Geleta** have read and evaluated his thesis in titled **“Performance Analysis of Modulation Techniques for 5G Networks”** and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirement of the degree of Master of Science in Communication Engineering and Networking.

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This is to certify that the work entitled “Performance Analysis of Modulation Techniques for 5G Networks” submitted by Getachew Hagos Geleta Department of Electrical Engineering, Hawassa University Institute of Technology, Hawassa, Ethiopia is a record of a bona fide research carried out by him under my supervision and guidance. The thesis work in my opinion, has reached the requisite fulfilling the requirement of Master of Science Degree. The results contained in the thesis have not been submitted in part or full to any other University or Institute for the award of any degree.

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DECLARATION

I, the undersigned, declare that this thesis work is my original work, that has not been presented for accomplishment of any project or thesis in this or any other University, and all sources of materials used for the thesis research have been fully acknowledged.

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ABSTRACT

The new 5G cellular network systems will feature several innovative strategies as compared to existing LTE systems, such as extensive adoption of small cells, use of mm-wave communications for short-range links, large scale antenna arrays installed on macro base stations, cloud-based radio access network, cognitive radio etc. All these strategies will be impacted by the modulation format used at the physical layer. At the same time, 5G cellular networks will have more stringent requirements than LTE in terms of latency, energy efficiency and data rates, which again are impacted by the adopted modulation scheme.

Hence, proper selection and utilizing efficient modulation scheme is critical. The current modulation technique such as orthogonal frequency division multiplexing (OFDM) suffers from high peak to average power ratio which results in low efficiency of power amplifier and increases the battery consumption. Moreover, the OFDM spectrum has high out of band side lobes or side lobe leakage causing problem of low spectral efficiency. Therefore, OFDM can fulfill the requirements of 5G wireless networks in a limited way.

In order to overcome some of these drawbacks of OFDM, new modulation techniques for 5G communication systems are considered. Among them, Filter bank multicarrier (FBMC), and Universal filtered multicarrier (UFMC) are expected be in race to be considered for the selection. In this paper, we perform the performance analysis of OFDM, UFMC, and FBMC in terms of its spectral efficiency (SE), power spectral density (PSD), peak to average power ratio (PAPR), and bit error rate (BER) using the MATLAB software tools. We analyze the results by varying the parameters of the modulation techniques which affects the performance of OFDM, UFMC, and FBMC. The plot shows that, FBMC has better SE for large burst durations but for small burst duration the SE of UFMC is better. In terms of PSD and BER FBMC is better. In terms of PAPR UFMC is better. The result of this research will play a significant role in selecting efficient modulation scheme for the upcoming 5G cellular networks.

Key words: 5G, OFDM, FBMC, UFMC

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ABBREVIATIONS

1G ……………………………………..First generation wireless networks

2G …………………………………..... Second generation wireless networks

3GPP …………………………………..Third Generation Partnership Project

4G ……………………………………...Fourth generation

5G ……………………………………...Fifth generation

BER……………………………………Bit Error Rate

CP………………………………………Cyclic prefix

FBMC …………………………………Filter bank multicarrier

FFT …………………………….……….…Fast Fourier transform

f-OFDM…………………………….. …Filtered Orthogonal frequency division multiplexing

GFDM…………………………………..Generalized frequency division multiplexing

GI DFT-S OFDM ………………………Guard interval discrete Fourier transform spread OFDM

IFFT ………………………………….……...Inverse Fast Fourier transform

ISI ………………………………………Inter symbol interference

NOMA …………………………………....Non Orthogonal multiple access

MIMO…………………………………...Multiple input Multiple output

OFDM …………………………………Orthogonal frequency division multiplexing

OOB………………………………….....Out-of-band

OQAM…………………………………Offset Quadrature amplitude modulation

OMA …………………………………......Orthogonal multiple access

OTFS …………………………………...Orthogonal time frequency and space

PAPR …………………………………...Peak to average power ratio

PSD ……………………………………..Power Spectral Density

QAM……………………………….........Quadrature amplitude modulation

RB-f-OFDM …………………………….Resource block filtered

OFDMSE………………………………..Spectral efficiency

SNR ……………………………………..Signal to noise ratio

SP-OFDM………………………………Spectrally-pre coded OFDM

UFMC……………………………………Universal filtered multicarrier

WOFDM………………………………...Windowed OFDM

1 INTRODUCTION

1.1. Background

Wireless communications have become an essential tool for our life. Starting from the first-generation wireless networks (1G), there has been an exponential growth in number of users and their applications. Owing to a broad range of applications spanning from wireless regional area networks to machine type communications, future wireless networks have challenging objectives such as very high spectral and energy efficiency, very low latency and very high data rate, which require more effective physical layer solutions. In this context, the vision and overall objectives of future wireless networks for 2020 and beyond have been defined by the International Telecommunication Union and standardization activities for 5G wireless networks have been started through discussions about scenarios and requirements by Third Generation Partnership Project (3GPP) [1].

5G planning aims at higher capacity than current 4G, allowing a higher density of mobile broadband users, and supporting device-to-device, more reliable, and massive machine communications. 5G research and development also aims at lower latency than 4G equipment and lower battery consumption, for better implementation of the Internet of things. In addition to providing simply faster speeds, they predict that 5G networks also will need to meet new use cases, such as the Internet of Things (internet connected devices), as well as broad cast-like services and lifeline communication in times of natural disaster [2].

OFDM is the core of the physical layer of fourth generation (4G) wireless networks and fulfills the requirements and challenges of 4G scenarios. Despite of its proven advantages, OFDM has some shortcomings that make it difficult to address the scenarios foreseen for future 5G wireless networks. In OFDM, every symbol requires a cyclic prefix (CP). The insertion of CP reduces the spectral efficiency and prevents obtaining a low latency by shortening the symbols. Furthermore, OFDM is very sensitive to time and frequency synchronization errors and has high out-of-band (OOB) emission due to rectangular pulse shaping [3]. Thus, OFDM can fulfill the requirements of 5G wireless networks in a limited way.

In recent years, several waveforms have been proposed to overcome the aforementioned limitations of OFDM. The proposed methods can be categorized into two main classes: cyclically-prefixed OFDM (CP-OFDM) based and non-CP-OFDM based. The first category, such as filtered OFDM (f-OFDM) and windowed OFDM (WOFDM) [4], make attempts to resolve the aforementioned problems by keeping the orthogonality. The second category of waveforms initially dismiss orthogonality to obtain better temporal and spectral characteristics, thus, causes a major paradigm shift in the context of waveform design, which may yield some backward compatibility issues [5].

1.2. Statement of the problem

Many researchers have done the comparative analysis of the novel modulation schemes of 5G networks, such as UFMC, OFDM, FBMC, GFDM, and F-OFDM based on different comparative parameters such as PAPR, computational complexity, BER, spectral efficiency and power spectral density. Though many researchers have done such comparative analysis to find the best modulation techniques that meets the requirements and challenges of 5G networks, the comparative analyses are not sufficient to aid the choice of the best modulation technique for the future cellular networks. The existing comparative studies on this subject are not comprehensive. Because, in the existing comparative studies, it is not clearly shown how the performance of the individual modulation techniques can be improved rather than comparison of each modulation techniques. Moreover, most of the existing comparative analyses are not helpful for selecting proper type of modulation technique for different types of applications. In this work, we will provide a comprehensive performance analysis and comparison between candidate waveforms for 5G networks.

1.3. Objective

1.3.1. General Objective

The main aim of this thesis work is to identify the best modulation technique, for 5G networks, in terms of spectral efficiency, power spectral density, BER, and PAPR for the candidate waveforms such as OFDM, UFMC, and FBMC.

1.3.2. Specific Objective

The specific objective of this research work includes the following tasks:

- ✓ Evaluate the BER and PAPR using different mapping schemes for OFDM, FBMC, and UFMC.
- ✓ Select the best mapping schemes and SNR value to compensate BER and PAPR.
- ✓ Analyze the performance of OFDM, FBMC, and UFMC modulation techniques in terms of SE, PSD, BER, and PAPR.
- ✓ Compare the performance of OFDM, FBMC, and UFMC modulation techniques using SE, PSD, BER, and PAPR.
- ✓ To suggest ways to enhance the performance of each modulation techniques.

1.4. Literature review

Y. Cai and Z. Qin et al. [3] compared the performance of FBMC, OFDM, F-OFDM, GI DFT-s-OFDM, and OTFS waveforms as contenders for 5G wireless communication systems. The comparative analysis has been performed based on spectral efficiency and BER. Performance analysis of the modulation techniques using PSD and PAPR has not been considered in this work.

N. Rani and S. Rani [6] reported UFMC as candidate modulation technique for 5G networks. This work describes the aspects of UFMC system and highlights the merits of new modulation method for emerging 5G Wireless Communication Systems. This paper also discusses peak to average power ratio (PAPR) and Bit Error Rate (BER) of UFMC system for various mapping schemes and compared the power spectral density (PSD) of UFMC versus OFDM waveforms as contenders for 5G wireless communication systems. However, the performance of the UFMC has not been compared comprehensively with other candidate waveforms of 5G networks.

Kansal P. and Shankhwar A.K. [7] compared the performance of FBMC versus OFDM waveforms as contenders for 5G wireless communication systems. The comparative analysis of FBMC and OFDM has been performed based on power spectral densities, sub-channels, computational complexity and prototype filter comparison. The comparative analysis reported in this work did not consider other important performance parameters BER and PAPR.

In Banelli et al. [8] works, a review of modulation formats suited for 5G (i.e. OFDM and FBMC) were provided by comparing their performance in a cellular environment, and by including on their interactions with specific 5G ingredients. The interaction with a massive multiple input multiple output system was also considered by employing real channel measurements. But, other performance parameters of modulation techniques such as SE, PED, BER, and PAPR parameters were not considered.

Y. Liu et al. [9] work, a review of modulation formats suited for 5G (such as OFDM, UFMC, FBMC, and F-OFDM) was given. The comparative analysis of these modulation techniques has been performed based on PSD and BLER. The performance analysis shown in this work doesn't include parameters such as SE, BER, and PAPR.

Gerzaguetet et al.[10] work, a review of modulation formats suited for 5G (such as OFDM, UFMC, FBMC, and GFDM). The comparative analysis of these modulation techniques has been performed based on SE, PSD and PAPR comparison. But, this work has not considered the performance analysis in terms of BER.

R. Reyhani et al. [11] compared the performance of GFDM and C-FBMC waveforms as contenders for 5G wireless communication systems. They evaluate the BER performance of different receivers for GFDM and C-FBMC through numerical simulations. But, the performance of these modulation techniques in terms SE, PSD, and PAPR were not shown.

A.B. Üçüncü [12] compared the performance of generalized frequency division multiplexing (GFDM) and windowed cyclic prefix circular offset quadrature amplitude modulation (WCP-COQAM), which are candidate physical layer modulation schemes for the 5G systems, are compared to orthogonal frequency division multiplexing (OFDM) in terms of out-of-band (OOB) radiation levels and carrier frequency offset immunity Like the previous works, only OOB radiation levels and carrier frequency offset immunity are considered as performance parameters.

V. Eeckhaute et al. [13] reported the comparison among the most promising waveform contenders for the 5G air interface. The considered waveform contenders, namely filter-bank multi-carrier (FBMC), universal-filtered multi-carrier(UFMC), generalized frequency-division multiplexing (GFDM) and resource-block filtered orthogonal frequency-division multiplexing (RB-F-OFDM) are compared to OFDM used in 4G in terms of SE, numerical complexity, robustness towards multi-user interference (MUI) and resilience to power amplifier non-linearity. But, other important performance evaluation parameters are not taken into consideration.

K. Kishore et al. [14] reported comprehensive analysis of UFMC, OFDM, and FBMC in terms of PAPR for various techniques. The comparative analysis has been performed based on PAPR by varying both subcarriers and number of FFT at the same time. So, this is somewhat difficult to know the effect of the parameters. Performance analysis of the modulation techniques using SE, PSD and BER has not been considered in this work.

Generally, from the literature review, all of the research works focused on comparative analysis of two or more modulation techniques of 5G cellular networks by considering one or more different types of comparative parameters such as BER, power spectral density, spectral efficiency and computational complexity. But, in all cases they don't discuss or show the effect of the parameters of modulation techniques. Moreover, in some of the works which have been done on the comparative analysis of more than two modulation techniques, they don't use or select better SNR value and mapping scheme to compensate the PAPR and BER value for the comparison purpose. And also they don't show the mechanism of how the SE and PSD of the modulation techniques can be improved. In addition to this, the reported works didn't propose solution for better usage of the modulation techniques.

A comprehensive analysis and comparison of modulation technique, OFDM, UFMC and FBMC, using performance evaluation parameters, namely SE, PSD, BER and PAPR is presented in this work. We also vary the parameters of the modulation techniques which affects the performance of OFDM, FBMC, and UFMC in order to propose solutions for better utilization of the modulation techniques.

1.5. Scope and Limitation of the Research

Comparison of the 5G modulation techniques in terms of several parameters is possible but, the scope of this work is limited to the comparative study of OFDM, FBMC, and UFMC modulation techniques of 5G networks in terms of its SE, PSD, BER, and PAPR.

1.6. Methodology

Generally, the methodology mainly consists of the following tasks:

- ✓ First, reviews of different research papers which are closely related to this thesis work **will be** performed.
- ✓ After reviewing relevant literatures, we provide theoretical explanation about the 5G modulation techniques.
- ✓ Then, model the modulation techniques, such as OFDM, FBMC, and UFMC using the respective detailed block diagrams and description of each block.
- ✓ The performance evaluation **will be** done by simulating these modulation techniques in terms of SE, PSD, BER and PAPR using MATLAB software.
- ✓ Finally, the comparative analysis of the simulation results of the SE, PSD, BER, and PAPR for all modulation techniques **will be** discussed in detail.

1.7. Organization of the Thesis

This thesis contains five chapters. A brief introduction is given in chapter one and the overall modulation techniques of 5G networks and their requirements is discussed in chapter two. OFDM, UFMC and FBMC system model details is discussed in chapter three. Chapter four and chapter five deal with simulation results and discussion; and conclusion with recommendations, respectively.

2 5G MODULATION TECHNIQUES

2.1. Introduction

5G wireless networks have involved broad research interest in the recent years. According to the 3GPP enhanced mobile broad band, massive machine type communications, and ultra-reliable and low-latency communications are three major families of applications that are expected to be supported by 5G networks. In addition to this, enhanced vehicle-to-everything communications are also considered as a significant service that should be supported by 5G networks. These scenarios need massive connectivity with high system throughput and improved spectral efficiency, and impose significant challenges to the design of general 5G networks. Therefore, in order to meet these new requirements, new modulation and multiple access schemes are being explored [3].

OFDM has been implemented in 4G networks with an appropriate cyclic prefix and then it is able to combat the delay spread of wireless channels with simple detection methods, which makes it a popular solution for current broadband transmission. But, traditional OFDM is not capable to meet many new demands required for 5G networks. For instance, in the massive machine type communications scenario sensor nodes usually transmit different types of data asynchronously in narrow bands whereas OFDM requires different users to be highly synchronized, otherwise there will be large interference among adjacent sub bands [3].

Various types of modulations have been proposed to address the new challenges that 5G networks are expected to solve such as pulse shaping, filtering, and pre coding to reduce the OOB leakage of OFDM signals. Filtering is the most straightforward approach to reduce the OOB leakage and with a properly designed filter, the leakage over the stop-band can be greatly suppressed. Pulse shaping can be regarded as a type of subcarrier-based filtering that reduces overlaps between subcarriers even inside the band of a single user. Introducing pre coding to transmit data before OFDM modulation is also an effective approach to reduce leakage. In addition to the abovementioned approaches to reduce the leakage of OFDM signals, some new types of modulations have also been proposed specifically for 5G networks. For instance, to deal with high Doppler spread in enhanced vehicle-to-everything communications scenarios, transmit data can be modulated in the delay-Doppler domain [15].

The above modulations can be used with OMA in 5G networks. OMA is core to all previous and current wireless networks; time-division multiple access and frequency-division multiple access are used in the 2G systems, code-division multiple access in the 3G systems, and OFDMA in the 4G systems. For these systems, resource blocks are orthogonally divided in time, frequency, or code domains, therefore there is minimal interference among adjacent blocks and makes signal detection relatively simple. However, OMA can only support limited numbers of users due to limitations in the numbers of orthogonal resources blocks, which limits the SE and the capacity of current networks [15]. To address the various challenges of 5G networks, either develop new modulation techniques to reduce multiple user interference for OMA or directly use NOMA. So, in this section the new modulation candidates for OMA in 5G networks are discussed.

2.2. Modulations with OMA

The new modulation techniques for 5G networks will discuss in this section starting from the traditional OFDM. Because, OFDM is broadly used in recent wireless systems and standards, thus almost all the new modulation schemes for 5G networks are delivered from OFDM for backward compatibility reasons.

A. Traditional OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a basic technique for succeeding high data rates as well as SE requirements for today's wireless communication systems. Its transmissions are emerging as significant modulation technique for the reason that its capacity of confirming high level of robustness in contradiction of any interference [17].

In OFDM the frequency band is discrete into a number of sub channels. Thus, OFDM is a multi-carrier transmission technology. Usual multiplexing techniques involve a number of filters to avoid interference among the sub-carriers and the non – overlapping must be preserved with a minimum frequency separation. In the other way, OFDM uses signal processing techniques which thus eliminates this issue. Moreover; the subcarriers are orthogonal in nature eliminating the need of many filters [28].

Basically, OFDM is a modulation method of digital multiple carriers that is characterized by its ability to sustain adverse channel condition in wireless networks. It is also known to offer maximized spectral efficiency with implementation of fast Fourier Transforms (FFT). Different from convention frequency-division multiplexing (FDM) schemes, it doesn't require tuned receivers for sub channels. Examples of the waveform supported by OFDM based multi-carriers are CP-OFDM (this is adopted in LTE specification), Universal Filtered Multi-Carrier (UFMC), Filter Bank Multicarrier (FBMC), and Generalized Frequency Division Multiplexing (GFDM) [28].

OFDM is highly sensitive to issues of frequency synchronization as well as Doppler shift. It is also known for its maximized PAPR (Peak-to-Average Power Ratio) followed by minimized efficiency due to guard interval (or cyclic prefix). OFDM can effectively deal with the delay spread of broadband wireless channels and FFT can be used to significantly simplify its complexity. Therefore, it has been widely used in the current wireless communication systems and standards. However, the OFDM signal is time-limited. Therefore, its OOB leakage is pretty high, especially when users are Asynchronies as typical of 5G networks. To address this issue, a guard band is usually inserted between the signals of two adjacent users in the frequency domain in addition to a CP or a guard interval in the time domain, which reduces the SE of OFDM. This is even more severe for the users using a narrow frequency band [3].

5G networks have to support not only a massive number of users but also dramatically different types of users that have different demands. Traditional OFDM can no longer satisfy these requirements, and therefore novel modulation techniques with much lower OOB leakage are required. The new modulation techniques for 5G networks currently need to consider backward compatibility with traditional OFDM systems but should also have the following key features to address the new challenges [3]:

- ✓ High spectral efficiency: New modulation techniques should be able to mitigate OOB leakage among adjacent users so that the system spectral efficiency can be improved significantly by reducing the guard band.
- ✓ Loose synchronization requirements: Massive numbers of users are expected to be supported, especially for the Internet of things, which makes synchronization difficult. Therefore, new modulation techniques are expected to accept asynchronous scenarios.

- ✓ Flexibility: The modulation parameters (e.g., subcarrier width and symbol period) for each user should be configured independently and flexibly to support users with different data rate requirements.

The modulation techniques for OMA mainly include pulse shaping, sub band filtering, pre coding design, guard interval shortening, and modulation in the delay-Doppler domain. In this section, introduce those promising modulation techniques subsequently.

B. Modulations based on Pulse Shaping

Pulse shaping can be considered as subcarrier-based filtering. It effectively reduces OOB leakage. Filter Bank Multicarrier (FBMC) and Generalized Frequency Division Multiplexing (GFDM) are two typical modulations based on pulse shaping.

1) **FBMC**: FBMC is one of the novels of modulation formats in which subcarriers are passed through filters that suppress signal side lobes, making them eventually strictly band limited. This modulation format transmitter and receiver structure still implemented through FFT/IFFT blocks or poly phase filter structures and band limitedness may deliver larger spectral efficiency than OFDM. The use of this modulation format for 5G cellular networks is mainly allowed for its ability (due to signal band limitedness) to cope with network a synchronicity that naturally arises in the uplink and/or in the downlink with coordinated transmission for its greater robustness to frequency misalignments among users when compared to OFDM and for its more flexible exploitation of frequency white spaces in cognitive radio networks. FBMC is usually either coupled with QAM or with Offset QAM (OQAM) modulation formats [3].

The prototype filter in FBMC performs the pulse shaping. The length of the pulse in the time domain is determined by the required performance and is usually several times the length of the symbol period. The bandwidth of the pulse, which is different from the pulse in the traditional OFDM that has a long tail, is limited within a few sub bands. To achieve the best spectral efficiency, OQAM is usually applied to make FBMC real-domain orthogonal in time and frequency domains [3].

2) GFDM: is also one of novel modulation format in which OFDM and single-carrier frequency division multiplexing (SC-FDM) can be regarded as two special cases of GFDM. The unique feature of GFDM is to use circular shifted filters, rather than linear filters that are used in FBMC, to perform pulse shaping. By carefully choosing the circular filter, the out-of-block leakage can be reduced even if the orthogonality is completely given up.

Besides FBMC and GFDM, other modulations based on pulse shaping, such as pulse-shaped OFDM and QAM-FBMC have also been proposed for 5G networks. Generally, modulations based on pulse shaping try to restrict transmitted signals within a narrow bandwidth and thus mitigate the OOB leakage so that they can work in asynchronous scenarios with a narrow guard band. FBMC also uses OQAM to achieve real-domain orthogonality, which saves the cost of the GI and interference cancellation [3].

C. Modulations based on Sub band Filtering

Sub band filtering is another technique to reduce the OOB leakage. UFMC and filtered f-OFDM are two typical modulations based on sub band filtering.

1) **UFMC**: is a novel modulation format in which groups of subcarriers (sub bands) are filtered. The sub bands are with equal size, and each filter is a shifted version of the same prototype filter. OFDM is applied within a sub band for this modulation. Since the bandwidth of the filter in UFMC is much wider than that of the modulations based on the pulse shaping, the length in time domain is much shorter. Therefore, interference caused by the train of the filter can be easily eliminated by adopting a zero-padding (ZP) prefix with a reasonable length.

2) **f-OFDM**: is also a novel modulation format based on Sub band filtering in which it has a similar transmitter structure as UFMC. The main difference is that f-OFDM employs a CP and usually allows residual ISI. Therefore, at the receiver, the matching filter is applied instead of the zero padding. Besides, down sampling can be applied before the discrete Fourier transform operation, which can reduce complexity significantly since the CP can mitigate most of interference caused by the tail of the filter; the residual interference is with much lower power and can be treated as noise. Thus, the filter in f-OFDM can be longer than that in UFMC and has better attenuation outside the band. With the aid of effective channel coding, the performance degradation caused by residual interference in f-OFDM can be negligible. Another difference from UFMC is that the subcarrier spacing and the CP length do not have to be the same for different users in f-OFDM.

Besides UFMC and f-OFDM, other modulations based on sub band filtering have also been proposed. For example, resource block f-OFDM (RB-f-OFDM) utilizes filters based on resource block instead of the whole band of users in f-OFDM. In general, modulations based on sub band filtering can effectively reduce OOB leakage and achieve better performance in comparison with the traditional OFDM [3].

D. Other Modulation Techniques

In addition to pulse shaping and sub band filtering, there are also some other techniques to suppress the OOB leakage and meet the requirements of 5G networks. In the following, three other modulations, including guard interval discrete Fourier transform spread spectrally-pre coded OFDM (SP-OFDM), OFDM (GI DFT-S OFDM), and orthogonal time frequency and space (OTFS) are introduced.

1) GI DFT-S-OFDM: In GI DFT-S -OFDM, the known sequence is used as the GI instead of a CP. numerous kinds of the known sequences, such as the zero sequence and a well-designed unique word can be used. By a fixed known sequence with constant amplitude in GI DFT-S -OFDM, the PAPR of the modulated signal can be reduced. Moreover, the known sequence can also be utilized to estimate the parameters, such as the carrier frequency offset in the synchronization process. By utilizing a proper sequence as the GI, the discontinuity between the adjacent time blocks in the traditional OFDM/DFT-S-OFDM can be avoided. As a result, the OOB leakage is reduced.

For GI DFT-S-OFDM, the overall length of the guard interval and useful signal for different users is same. Thus, the Discrete Fourier Transform windows for different users at the receiver can still be aligned even if the lengths of the guards are different. Therefore, the mutual interference due to asynchronization of users can be mitigated [3].

2)SP-OFDM: Generally, the data symbols mapped on subcarriers are pre-coded by a rank-deficient matrix in order to project the signal into a properly selected lower dimensional subspace so that the pre-coded signal can be high-order continuous, and results in much lower leakage compared with the traditional OFDM. Even if pre-coded by a rank-deficient matrix can reduce the capacity of the channel, the OOB leakage of the OFDM signals can be significantly suppressed at the cost of only few reduced dimensions [3].

3) OTFS: The structure of OTFS is similar to SP-OFDM the main difference is that the spectral pre-coder and the iterative detector are substituted by the two-dimensional symplectic Fourier transforms and the corresponding inverse transform modules. OTFS maps the symbols in the delay-Doppler domain [15]. Through two-dimensional symplectic Fourier transforms, the corresponding data in the time-frequency domain can be calculated. Then, the calculated data can be transmitted via a time-frequency-domain modulation method as in OFDM. Since the two-dimensional symplectic Fourier transform is relatively independent of the time-frequency-domain modulation method, pulse shaping and sub band filtering can also be applied together to further reduce the leakage in OTFS. When a mobile is with a high speed, the channel experiences fast fading. Channel parameters need to be estimated and tracked very often therefore, which significantly increases resource costs. In addition, a number of modulations based on other techniques have been also proposed, such as windowed OFDM (W-OFDM) which utilizes windowing to deal with the discontinuity between adjacent OFDM symbols [3].

2.3. Interactions with 5G Architecture and Requirements

In this section we discuss the interactions between the reviewed modulation formats and some key requirements and features of 5G networks.

Huge data rates: by a combination of technologies for instance the use of larger bandwidths, the use of multiple antennas, and the use of adaptive modulation schemes 5G networks will have to support very large data rates. Therefore, this leads to promote the use of a multicarrier modulation for two reasons:

I. with multicarrier schemes adaptive modulation is easily implemented, in which according to the channel status on each subcarrier smart bit loading algorithms may permit to tune the modulation cardinality and the coding rate; and
II. Multipath distortion is increased due to the use of larger bandwidths, so that with respect to a single carrier modulation the task of equalization simplifies by using a multicarrier scheme [17].

Small cells with mm-wave communications: one of the key techniques planed at increasing the overall capacity of wireless networks is the use of small cells. To supporting short-range cellular communications, mm-wave communications has been a growing interest at this time for future wireless networks [18, 19]. While there is still slight knowledge about mm-wave propagation in urban areas, studies are ongoing [20]. It is expected that mm-wave will be used on short distances, thus implying that line-of sight links might be available. Then, we will have large bandwidths, rather stable propagation environments, and low Doppler offsets. The design of a modulation scheme suited for these conditions is still an open problem, although again multicarrier schemes appear to be much more suited than single-carrier schemes.

Uncoordinated access (internet of things): In the coming years there will be a remarkable increase in the number of connected devices [22, 23]. Actually, the current trend is to include a wireless transmitter and receiver in almost all every electronic-equipment. And thus, researchers have been studying for some years the so-called internet of things which is also called Machine-to-Machine (M2M) communications. To transmit short messages a large number of connected devices will require accessing the network. The challenge posed by the internet of things lies, rather than in a capacity shortage, in the overwhelming burden that it produces on the signaling functions of the network. For this reason, the use of FBMC modulations is better with respect to classical OFDM since it allows uncoordinated (i.e. asynchronous) access to the subcarriers. This is one of the main messages conveyed by the ongoing 5GNOW European research project [17].

Small latency: 5G wireless cellular systems is planned to ensure low latency communications with a target round trip delay of 1ms. This is seen as a main change of 5G network with respect to existing LTE networks, since it will enable the so-called tactile Internet [24], which will permit the growth of brand new real-time applications for monitoring and control. To reduce latency at the physical layer, a single-carrier modulation seems to be desirable, since it prevents block-processing of the data which introduces additional delays. A tunable OFDM system, with an adaptive choice of the length of the data block would also be an option.

More energy efficiency: 5G cellular networks will be estimated far more energy-efficient than previous cellular systems [25]. Energy saving is primarily a matter that concerns higher-layer of the network protocol stack, since it includes use of renewable energy sources, design of energy-harvesting protocols, adaptive base station switch on/off algorithms, base station sharing among network operators during off-peak hours, etc. However, at the physical layer, adaptively switching off unused carriers is a key strategy that may be used to save energy from the RF transceiver chain of base stations. This once again promotes the use of multicarrier systems with respect to single-carrier modulation.

Software radio with Cloud techniques: Another attractive feature of future wireless networks is the chance of having a cloud-based radio access network [26, 27]. In practice, base stations will be replaced by light devices, carrying out baseband-to-RF conversion and signal transmission, and linked via wired optical links to a data center, wherein data coding/decoding and higher-layer functionalities such as resource allocation will take place. The benefits of this structure are represented by the fact that centralized/cooperative strategies (such as the well-known coordinated multipoint) can be readily executed, as well as by the fact that data modulation can be implemented by software running in a data center. This adds a lot of flexibility to the choice of the modulation format, in the sense that paves the way to adaptive modulation schemes wherein not only the cardinality and the coding rate may be tuned, but even the waveform itself, including the cyclic prefix; the recent 5G overview [17] thus proposes the use of ‘‘tunable OFDM,” a sort of adaptive scheme with parameters chosen based on the instantaneous operating conditions. Thus, according to the channel conditions, to the requested throughput, and to the available resources in terms, e.g., of number of antennas, adaptive schemes may be designed wherein the modulation format itself is a parameter to be enhanced.

3 SYSTEM MODEL

3.1. Orthogonal Frequency Division Multiplexing

To transmit digital data a large number of sub channels or sub-carriers are used in an OFDM scheme. Each sub-channel or sub-carriers divide the accessible bandwidth and each subcarrier is orthogonal to every other. They are closely spaced and narrow band. The separation of the sub-channels is as minimal as possible to obtain high spectral efficiency [17].

The transmitter and receiver of OFDM system block diagram is shown in Figure 3.1 and Figure 3.2 respectively [29]. By Appling different modulation techniques the signal is mapped into a suitable constellation. Then, this serial data is then converted into parallel data stream, to which OFDM is performed. It consists of N sub carriers which carries the symbols. An OFDM transmitter involves an IFFT block. To reduce ISI a Cyclic prefix is added to the output. Then it processed to a serial output which is passed through the corresponding channel. And then at the receiver the data is converted into parallel input and the cyclic prefix is removed. So, this is then subjected to FFT.

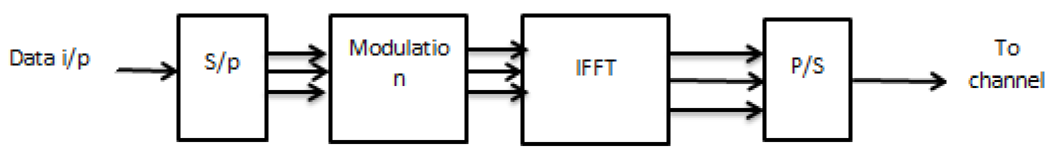

Figure 3.1 OFDM transmitter block diagram

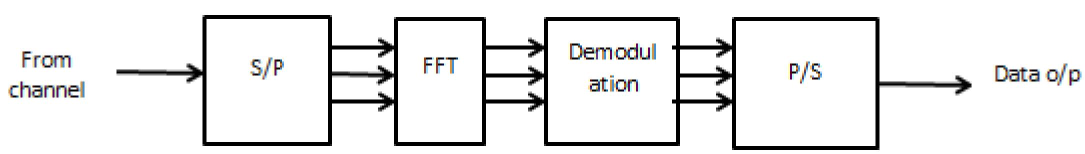

Figure 3.2 OFDM receiver block diagram

For the transmitted complex symbols d_k, for k = 0, 1…, N -1 the baseband OFDM signal can be expressed as [3]:

$$S(t) = \sum_{k=0}^{N-1} d_k \, e^{j2\Pi f_k t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

For $0 \leq t \leq T_S$, where $f_k = k\Delta f$, Δf is the subcarrier bandwidth and Ts is the symbol duration. To ensure that transmit symbols can be recovered without distortion, $\Delta f \cdot Ts = 1$, which is also called the orthogonal condition. It can be easily shown that

$$d_k = \int_0^{Ts} S(t)\, e^{-j2\Pi f_k t}\, dt \qquad (2)$$

if the orthogonal condition holds,

Denote $s(n\Delta t)$ to be the sampled version of $s(t)$, where $\Delta t = Ts / N$. It can be easily seen that

$\{s(0), s(\Delta t), \cdot\cdot\cdot, s((N-1)\Delta t)\}$ is the inverse discrete Fourier transform (IDFT) of $\{d_0, d_1, \cdot\cdot\cdot, d_{N-1}\}$, which can be implemented by fast Fourier transform (FFT) and significantly simplifies OFDM modulation and demodulation.

To address the delay spread of wireless channels, a CP is usually used in OFDM. If the length of the CP is larger than the delay span (the duration between the first and the last taps/paths of a channel), then the demodulated OFDM signal can be expressed as

$$\hat{d}_k = H_k d_k + n_k \qquad (3)$$

Where H_k is the frequency response of the wireless channel at $f_k = k\Delta f$ and n_k is the impact of additive channel noise. Therefore, the channel distortion becomes a multiplication of channel frequency response in OFDM systems while it is convolution in single-carrier systems, which makes the detection of OFDM signal much easier.

3.2. Filter Bank Multi-Carrier Modulation

FBMC filters each subcarrier modulated signal in a multicarrier system. The prototype filter is the one used for the zero frequency carriers and is the basis for the other subcarrier filters. The filters are characterized by the overlapping factor, K which is the number of multicarrier symbols that overlap in the time domain. The current FBMC implementation uses frequency spreading. It uses an $N*K$ length IFFT with symbols overlapped with a delay of $N/2$, where N is the number of subcarriers. This design choice makes it easy to analyze FBMC and compare with other modulation methods [7].

The FBMC technique overcomes the limitations of OFDM by adding generalized pulse shaping filters which delivers a well localized sub channel in both time and frequency domain. Consequently, FBMC systems have more spectral containment signals and offer more effective use of the radio resources where no CP is required. In Fig.3.3 and Fig.3.4 it can be seen that the filter banks on the transmitter side and the receiver side consist of an array of N filters that processes N input signals to give N outputs. If the inputs of these N filters are associated together, the system in analogous manner can be measured as an analyzer to the input signal based on each filter characteristics.

In the filter bank used at the transmitter side is called synthesis filter bank and the filter bank used in receiver side is called analysis filter bank. As shown in Fig.3.3 the input signal is first converted from serial to parallel form and then passed through synthesis filter bank and then it is converted back to serial form after coming out of synthesis bank. After this it can be seen in Fig.3.4 that is in the receiver side after the signal passes through the channel it is converted to parallel form by serial to parallel converter and passed through analysis filter bank. Finally when the output signal is obtained it is again converted to serial form by parallel to serial converter. Hence the synthesis analysis configuration depicted in is called trans-multiplexer [7].

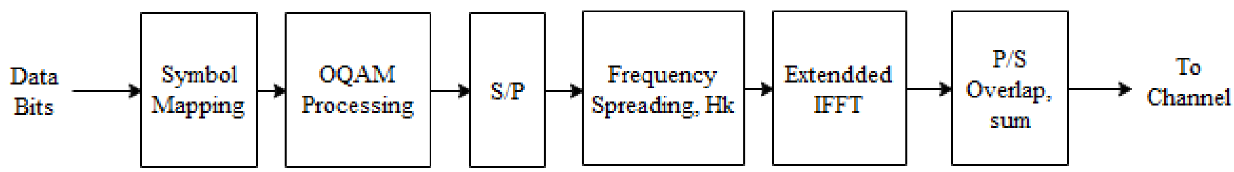

Figure 3.3 FBMC transmitter block diagram

To achieve full capacity, OQAM processing is employed. The real and imaginary parts of a complex data symbol are not transmitted simultaneously, thus the imaginary part is delayed by half the symbol duration. The processing includes matched filtering followed by OQAM separation to form the received data symbols. These are de mapped to bits and the resultant bit error rate is determined. In the presence of a channel, linear multi-tap equalizers may be used to mitigate the effects of frequency-selective fading.

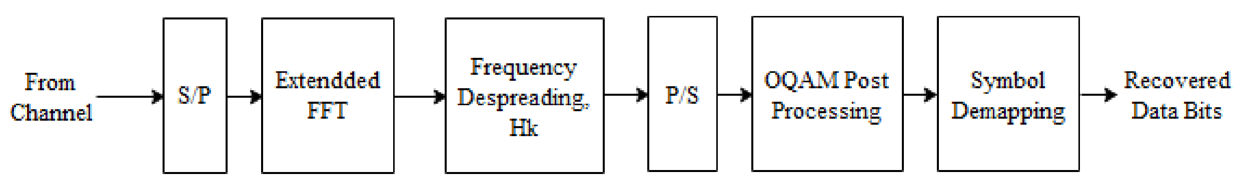

Figure 3.4FBMC receiver block diagram

To achieve the best SE, OQAM is usually applied to make FBMC real-domain orthogonal in time and frequency domains. Therefore, the transmit signal over $\frac{M}{2}$ consecutive block periods one can be expressed as in [9].

$$S(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} d_{k,m} \theta_{k,m} g(n - mk/2) e^{\frac{j2\pi kn}{K}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where K and M are the numbers of subcarriers and symbols, respectively, $d_{k,m}$ is the transmit symbol at subcarrier k and symbol m, and g(n) is the prototype filter coefficient at the n^{th} time-domain sample. Thus the interval between two adjacent blocks is only half of the block period due to the offset in OQAM. The parameter, $\theta_{k,m}$ in Eq.4, is defined as:

$$\theta_{k,m} = \begin{cases} \pm 1, \text{if } m + k \text{ is even} \\ \pm j, \text{if } m + k \text{ is odd} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

And it is used to form the OQAM structure.

With a properly designed prototype filter such as OQAM structure, the interference from the nearby overlapped symbols caused by a matched filter receiver becomes pure imaginary, which can be easily cancelled.

The output signals are only nearly delayed versions of the input signals, i.e., assured amount of filter bank structure based alterations can be tolerated as long as they are lesser related to those caused by a transmission channel. So the main filter bank design parameters are:

a. The number of sub channels M is essentially a random even number, but characteristically it is a power of two acceptable to deliver effectual application.
b. The greatest motivating prototype filter lengths are selected to be L p = KM-1, L p = KM, and L p = KM+1. Where K is a positive integer called as overlapping factor and it is chosen to be 3 or higher.
c. The prototype filter is intended in such a manner that only instantly adjacent sub channel filters are pointedly overlapping with each other in the frequency domain.

3.3. Universal Filtered Multi-Carrier Modulation

UFMC is seen as a generalization of Filtered OFDM and FBMC modulations. The entire band is filtered in filtered OFDM and individual subcarriers are filtered in FBMC, while groups of subcarriers (sub bands) are filtered in UFMC. This subcarrier grouping allows one to reduce the filter length (when compared with FBMC). Also, UFMC can still use QAM as it retains the complex orthogonality (when compared with FBMC), which works with existing MIMO schemes [6].

The UFMC transmitter and receiver block diagram is shown below in Fig.3.5 and Fig.3.6 respectively [6]. UFMC employs the full band of subcarriers (N) is divided into sub bands. Each sub band has a fixed number of subcarriers and not all sub bands need to be employed for a given transmission. The modulation technique processes these sub bands individually and each sub band consists of fixed number of subcarriers.

The narrow band and closely spaced individual sub bands undergoes N-point IFFT to get time domain (xi) of each sub band from Frequency Domain (Xi) of each sub band. An N-point IFFT for each sub band is computed, inserting zeros for the unallocated carriers. After performing N point IFFT on each sub band the output can be expressed as:

$$y_i = \text{IFFT}\{x_i\} \quad \ldots\ldots (6)$$

Each sub band output resulting from IFFT is filtered by filter length L. The resulting output signal is expressed as

$$y = H.\ \sim Q.\ y_i \quad \ldots\ldots (7)$$

H is Toeplitz matrix with dimensions (N+L-1)*N and ~Q represents inverse Fourier matrix. IFFT operation ensures that the sub band carriers do not interfere. UFMC uses Band filter to perform A Chebyshev filtering operation. Band Filter filters each sub band and each sub band responses summed. The filtering approach in UFMC reduces out of band spectral emission for proper design of filter. Filter with parameterized side lobe attenuation is employed to filter the IFFT output per sub band.

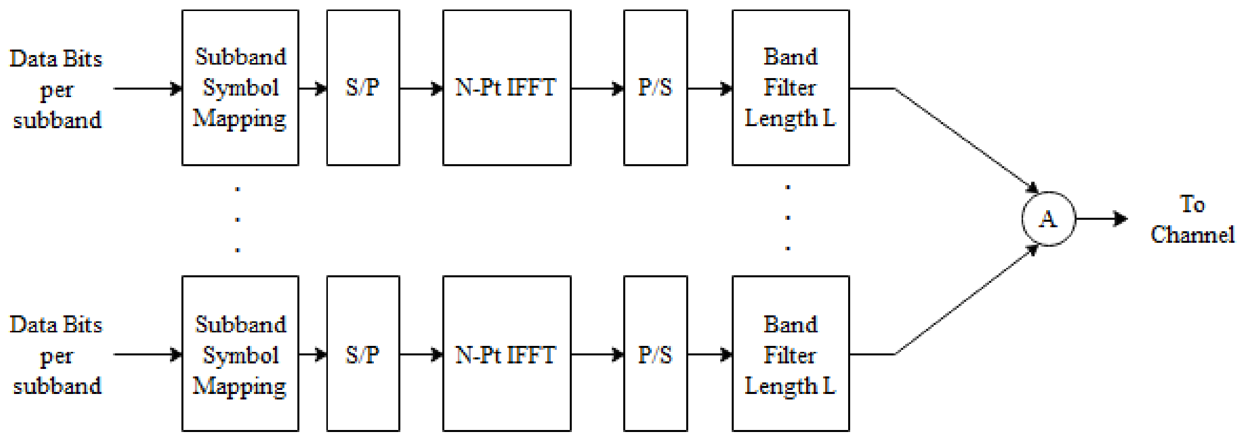

Figure 3.5 UFMC transmitter block diagram

The UFMC receiver performs 2N point FFT on data obtained from channel. A guard interval of Zeros is added between successive IFFT symbols [6]. This prevents ISI due transmitter filter delay.

$$\sim Y = FFT\ \{[y^T, 0, 0, \ldots\ldots\ldots, 0]\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where ~ Y is 2N point FFT and y^T is successive IFFT symbols

Discard even subcarrier points to get N length frequency domain receive signal Y. FFT block is used to process the received signal and coverts data received in time domain into frequency domain. Equalization detects the transmitted data. The Symbol de-mapping is performed after to the frequency domain equalization to get the original data bits.

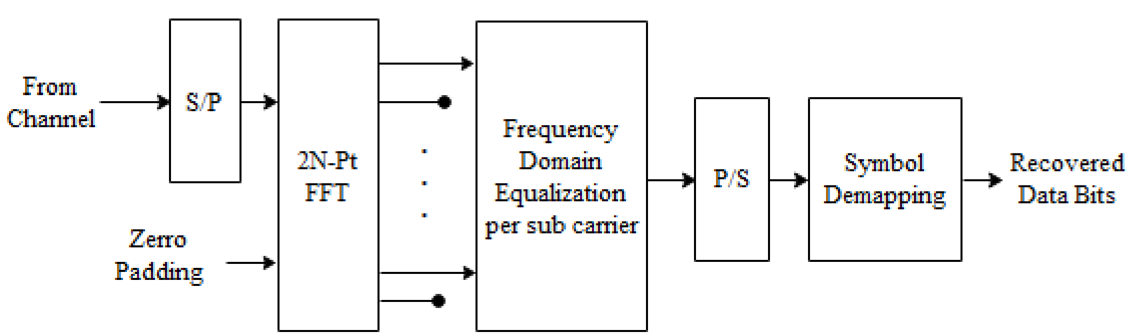

Figure 3.6 UFMC receiver block diagram

The aim of Serial to Parallel converters is for converting the input serial bit stream into several parallel bit streams to divided whole bandwidth among the individual carriers. The data allocated to each symbol on individual carriers depends on the modulation scheme used and the number of subcarriers. Thus, the parallel to serial conversion stage is the process of summing all sub-carriers and combining them into one signal.

Since the bandwidth of the filter in UFMC is much wider than that of the modulations based on the pulse shaping, the length in time domain is much shorter. Therefore, interference caused by the tail of the filter can be easily eliminated by adopting a zero-padding prefix with a reasonable length [3]. Assuming that N subcarriers are divided into K sub bands, each with $L = \frac{N}{K}$ consecutive subcarriers, the transmit signal in UFMC can be expressed as:

$$S(n) = \sum_{k=0}^{K-1} s_k(n) * f_k(n), \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Where, $f_k(n)$is the filter coefficient of subband k, and$s_k(n)$is the OFDM modulated signal oversubband k that can be expressed as:

$$s_k(n) = \sum_{m=0}^{M-1} s_{k,m}(n - m(N + N_g))\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

With Ng denoting the length of the zero padding, M denoting the number of symbol blocks and $s_{k,m}(n)$ denoting the signal at subcarrier k and symbol m. In Eq.9, $s_{k,m}(n)$ can be expressed as:

$$s_{k,m}(n) = \sum_{l=(k-1)L}^{KL-1} d_{l,m} e^{j\frac{2\pi ln}{N}}, 0 \leq n \leq N-1, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

Where $d_{l,m}$denotes the l^{th} transmit symbol at the m^{th} symbol block.

At the receiver, the signal at each symbol interval is with the length of N + Ng and is zero-padded to have a length of 2N so that a 2N-point FFT can be performed. Please note that only the even subcarriers are considered for signal detection after the 2N-point FFT [7].

3.4. Comparative Parameters

The parameters which are used for the comparative analysis of each modulation techniques in this research are discussed below:

Spectral Efficiency

Since frequency spectrum is limited, it has to be utilized efficiently. A given bandwidth is said to be used effectively if maximum information can be transmitted over it. The term SE is used to describe the rate of information being transmitted over a given bandwidth in specific communication systems. SE may also be called bandwidth efficiency. It is measured in bits per second per hertz (b/s/Hz). The spectral efficiency of UFMC and FBMC modulation schemes is given by [30]:

$$\eta_{OFDM}=\frac{m\,x N_{FFT}}{N_{FFT}+N_{CP}} \quad \text{.....}(11)$$

$$\eta_{FBMC}=\frac{m\,x S}{S+K-\frac{1}{2}} \quad \text{.....}(12)$$

$$\eta_{UFMC}=\frac{m\,x N_{FFT}}{N_{FFT}+L-1} \quad \text{.....}(13)$$

Where: N_{FFT} = number of FFT S = duration of burst

m = bits per subcarrier K = Overlapping factor

L = filter length N_{CP} = number of Cyclic prefix

Power Spectral Density

PSD is the measure of signal's power content versus frequency. A PSD is typically used to characterize broadband random signals. The amplitude of the PSD is normalized by the spectral resolution employed to digitize the signal.

PSD is the frequency response of a random or periodic signal. It tells us where the average power is distributed as a function of frequency. The PSD is deterministic, and for certain types of random signals is independent of time. This is useful because the Fourier transform of a random time signal is itself random, and therefore of little use calculating transfer relationships (i.e., finding the output of a filter when the input is random). The PSD of a random time signal x(t) can be expressed in one of two ways that are equivalent to each other

- ✓ The PSD is the average of the Fourier transform magnitude squared, over a large time interval

$$S_x(f)=\lim_{T\to\infty} E\left\{\frac{1}{2T}\left|\int_{-T}^{T} x(t)e^{-j2\pi ft}dt\right|^2\right\} \quad \text{.....}(14)$$

- ✓ The PSD is the Fourier transform of the auto-correlation function.

$$S_x(f) = \int_{-T}^{T} R_x(\tau) e^{-j2\pi ft} dt \quad \text{.................................... (15)}$$

Where $R_x(\tau) = E\{x(t)x^*(t+\tau)\}$ .... (16)

The power can be calculated from a random signal over a given band of frequencies as follows:

- ✓ Total Power in x(t): $P = \int_{-\infty}^{\infty} S_x(f)df = R_x(0)$ .... (17)
- ✓ Power in x(t) in range f1 - f2: $P_{12} = \int_{f_1}^{f_2} S_x(f)df = R_x(0)$ .... (18)

Peak to Average Power Ratio

One of the significant drawbacks of multi-carrier modulation is the high peak-to-average power ratio (PAPR). In fact, the PAPR problem is one of the most detrimental aspects in the OFDM systems as it can cause power degradation and spectral spreading. But there are methods like DFT pre-coding used in conjunction with CP- OFDM to build up single-carrier FDMA for bringing down PAPR. A low PAPR is of great importance for battery powered mobile terminals. The lower PAPR allows decreasing the power amplifier back-off, which in turn extends the operation time of a mobile terminal, at a certain transmission rate, compared to modulation schemes with a higher PAPR. Moreover, it enables to increase the coverage at cell edge. A high PAPR makes the PA work with large IBOs, resulting in inefficient use of the amplifier. It also increases the complexity of the ADC and DAC.

To sum up, high PAPR signals are usually undesirable for it usually strains the analog circuitry. High PAPR signals would require a large range of dynamic linearity from the analog circuits, which usually results in expensive devices, and higher power consumption/lower efficiency (for example, power amplifier has to operate with larger back-off to maintain linearity), which is critical in case of satellite communications. The PAPR expression is as following:

$$\text{PAPR} = \frac{max|X(n)|^2}{E\{|X(n)|^2\}} \quad \text{........................ (18)}$$

Where $E\{|X(n)|^2\}$ denotes the expectation operation. PAPR increases proportionally with the number of subcarriers. Reducing max x(n) is the principle goal of PAPR reduction techniques. Statistically it is possible to characterize the PAPR using Complementary Cumulative Distribution Function (CCDF). It is the most common way to evaluate the PAPR by estimating the probability of PAPR when it exceeds a certain level.

Bit Error Rate

In digital transmission, the number of bit errors is the number of received bits of a data stream over a communication channel in which that have been altered due to noise, interference, distortion or bit synchronization errors. The BER is the number of bit errors per unit time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. Bit error ratio is a unit less performance measure, often expressed as percentage.

$$\text{BER} = \frac{Number\ of\ bit\ Errors}{Total\ number\ of\ bits\ Sent} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

4 RESULTS AND DISCUSSION

4.1. Spectral Efficiency

This section discusses the Spectral efficiency of OFDM, FBMC, and UFMC modulation techniques for different parameters by varying the values of numbers of FFT (N_{FFT}), cyclic prefix (N_{CP}), burst duration (s), bits per subcarrier (m), Overlapping factor (K), and filter length(L). In all cases of the MATLAB results of the SE, Figures Fig.4.1 to Fig.4.10 bellow, the red graph represents the SE of UFMC, the yellow graph represents the SE of OFDM, and the blue color represents the SE of FBMC.

Fig.4.1 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 100ms with filter length equal to 53, number of FFT 1024, 53 samples of cyclic prefix, bits per subcarrier and overlapping factor equal to four.

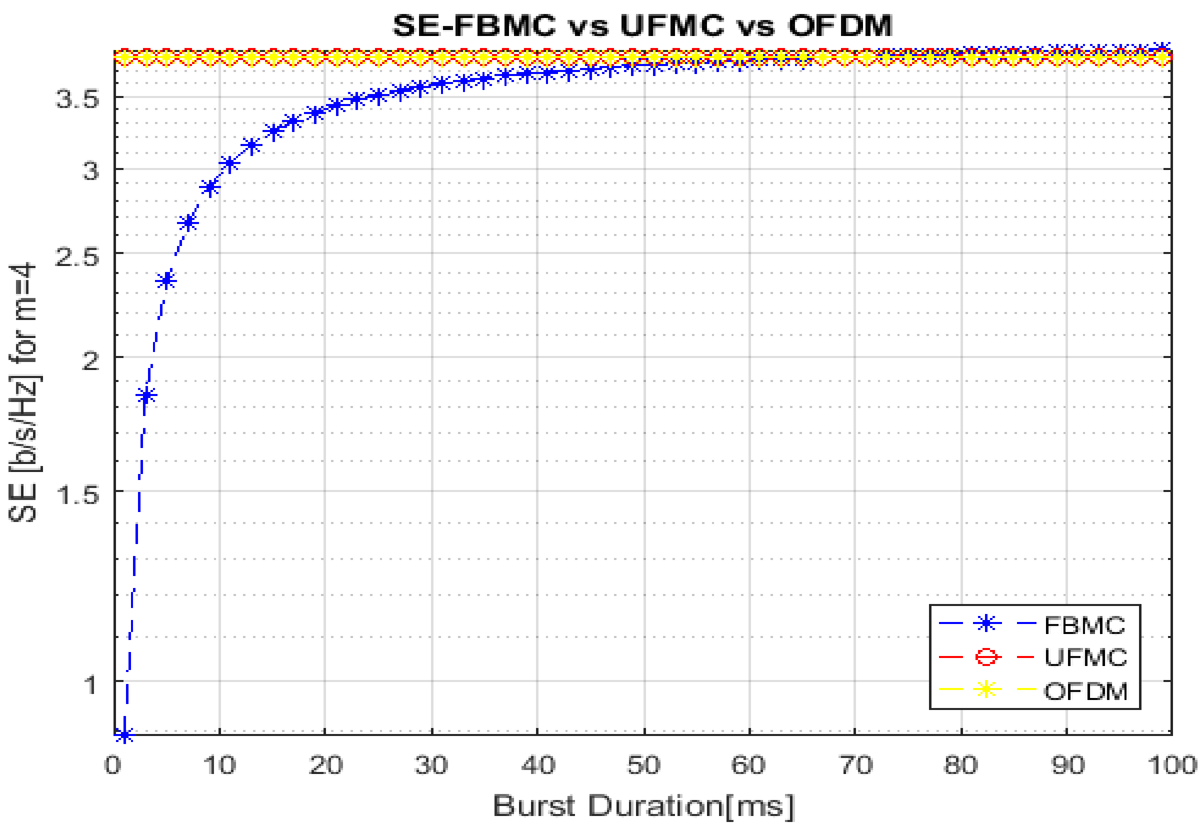

Figure 4.1 SE with burst duration up to 100m/s

As shown in Fig.4.1 above, the SE of FBMC increases rapidly with burst duration till around 50m/s. And then, it smoothly increases with the burst duration till 70ms. However, the SE of OFDM and UFMC is constant throughout the burst duration. In addition to this, the overlap of the yellow and red plot in the graph indicates that the SE of UFMC and OFDM is the same, which is around 3.8b/s/Hz. This is due the value of the filter length of UFMC and the cyclic prefix samples of OFDM are equal. However, unlike OFDM and UFMC, the SE of FBMC increases gradually with the burst duration and it hits this value at around 70ms.

Fig.4.2 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 53, number of FFT 1024, 53 samples of cyclic prefix, bits per subcarrier and overlapping factor equal to four.

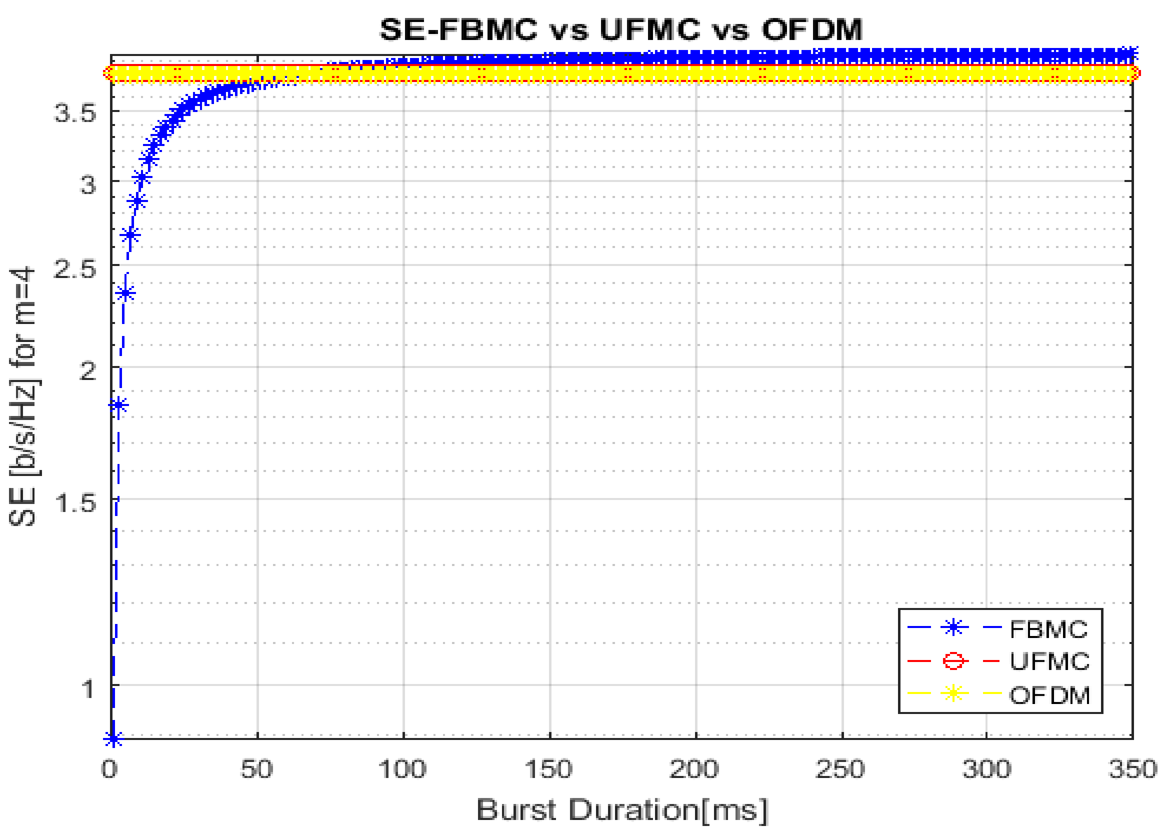

Figure 4.2 SE with burst duration up to 350m/s

As shown in Fig.4.2, the SE of FBMC increases rapidly with burst duration initially and then, it increases smoothly with the burst duration of nearly 70ms but at around 70ms the SE of FBMC, OFDM and UFMC is the same as shown in Fig.4.1 and Fig.4.2, which is around 3.8b/s/Hz. But, after 70ms the SE of FBMC increases gradually with larger SE than OFDM and UFMC; whereas the SE of OFDM and UFMC is constant throughout the burst duration at around 3.85b/s/Hz.

Fig.4.3 below shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with increasing the filter length to 73, number of FFT 1024, 53 samples of cyclic prefix, bits per subcarrier and overlapping factor equal to four.

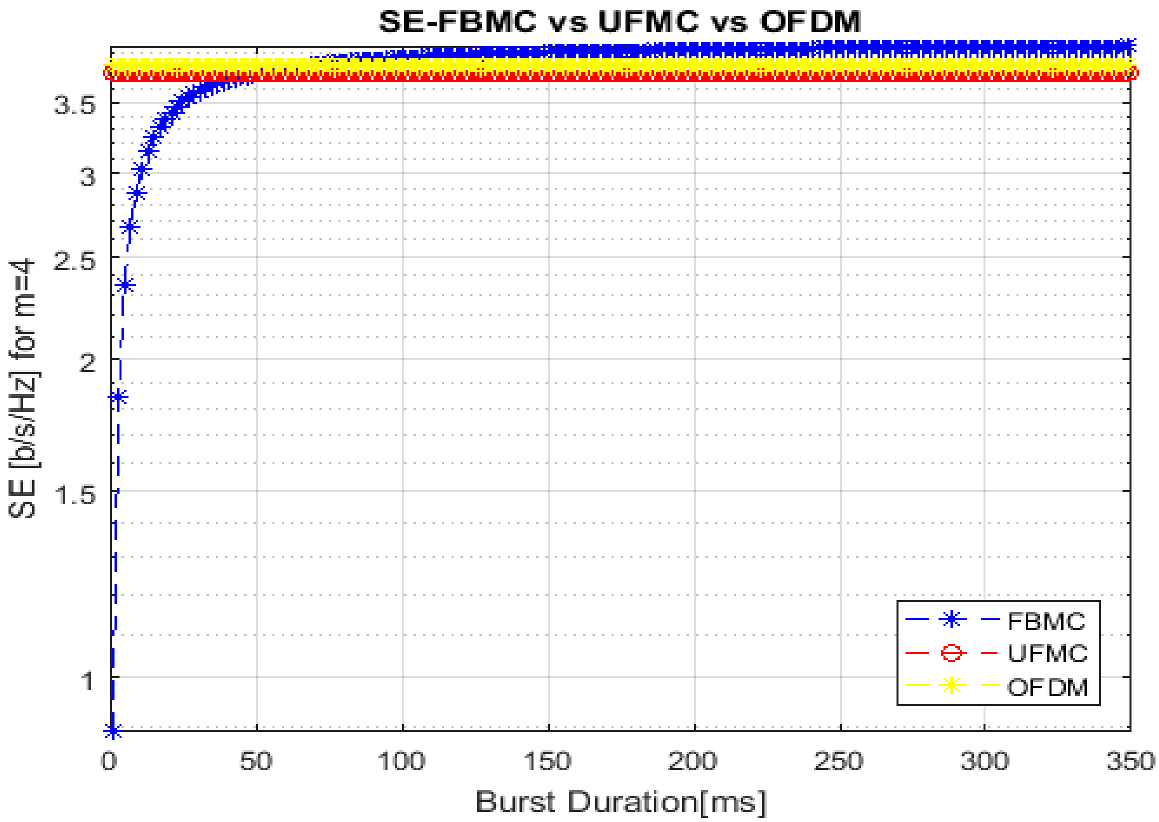

Figure 4.3 SE with filter length equal to 73

As shown in Fig.4.3, the SE of UFMC is reduced with small value with increasing the filter length as compared with the previous simulation results of Fig.4.1 and Fig.4.2, which is around 3.7b/s/Hz. Whereas, as it can be seen from the simulation graphs, the SE of OFDM and FBMC doesn't change with the filter length. In other words, the SE of OFDM and FBMC modulation schemes are not depend on the filter length.

Fig.4.4 below shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with the filter length to 53, number of FFT 1024, with increasing the samples of cyclic prefix to 73, bits per subcarrier and overlapping factor equal to four.

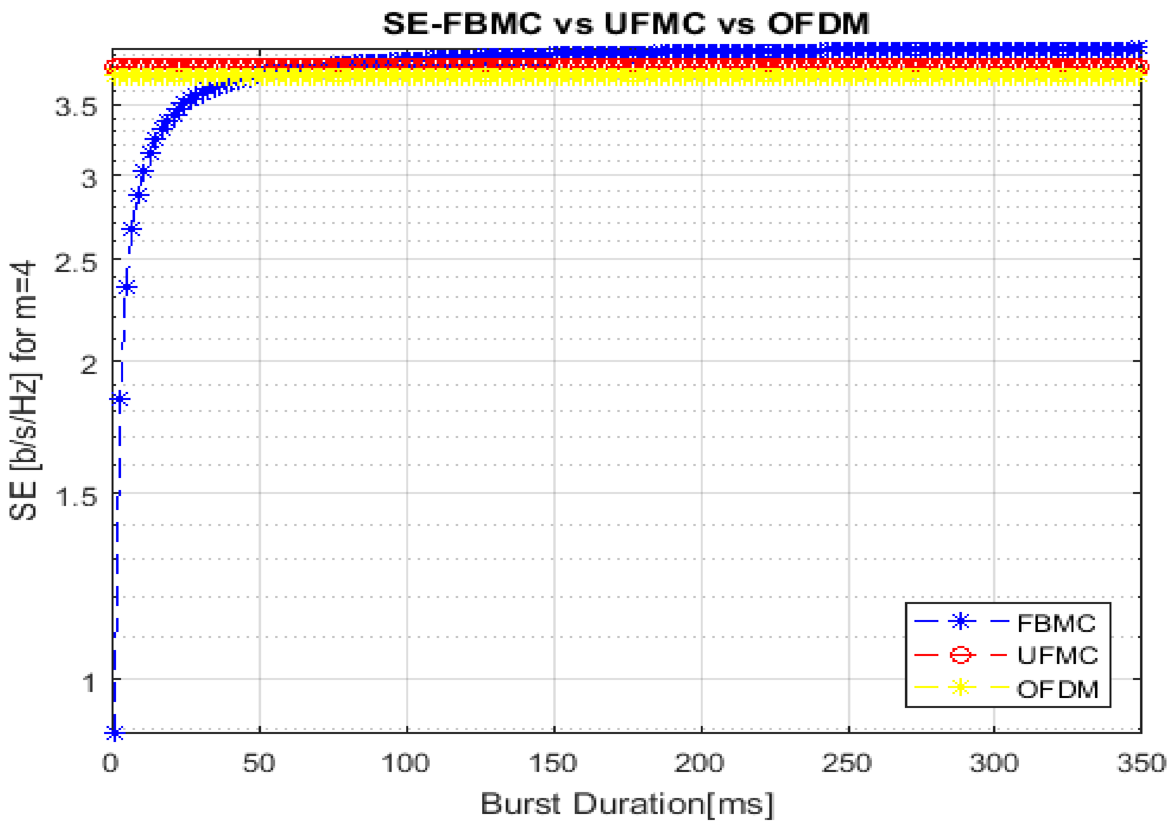

Figure 4.4 SE with samples of cyclic prefix equal to 73

As shown in Fig.4.4 the SE of OFDM is reduced a little bit with increasing the cyclic prefix, which is around 3.7b/s/Hz, as compared with the previous simulation results of Fig.4.2 and Fig.4.3. Whereas, as we have seen from the simulation graphs the SE of UFMC and FBMC is not changing with increasing the cyclic prefix. In other words, the SE of UFMC and FBMC modulation schemes are not depend on the cyclic prefix.

Fig.4.5 bellow shows that the SE of OFDM, FBMC, and UFMC for the burst duration of up to 350ms with filter length equal to 73, number of FFT 1024, 73 samples of cyclic prefix, bits per subcarrier and overlapping factor equal to four.

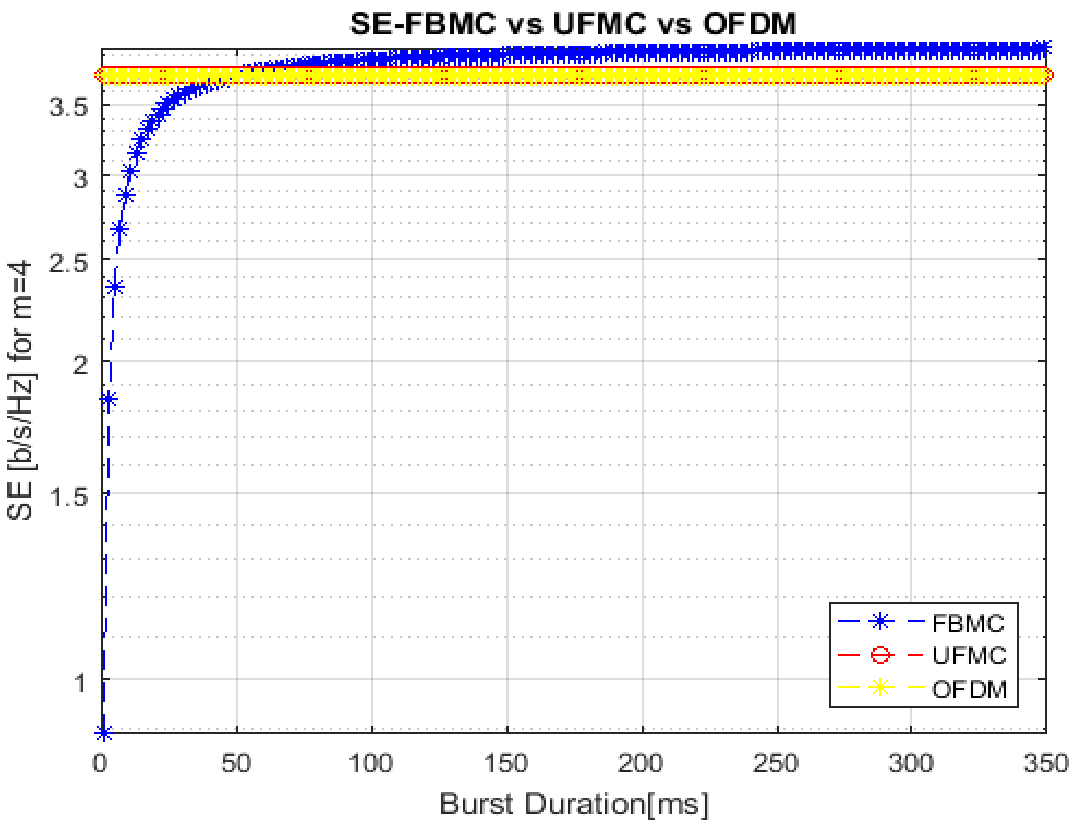

Figure 4.5 SE with filter length and cyclic prefix equal to 73

As shown in Fig.4.5 the SE of FBMC increases rapidly with burst duration till around 50m/s. And then, it smoothly increases with the burst duration till 70ms. However, the SE of OFDM and UFMC is constant throughout the burst duration. In addition to this, the yellow and red graph overlaps one another. This is because the filter length of UFMC and the cyclic prefix samples of OFDM are equal and the SE of OFDM and UFMC is the same which is around 3.8b/s/Hz. FBMC reaches this SE value at around 70ms. However, unlike OFDM and UFMC, the SE of FBMC increases gradually as the burst duration varies beyond 70ms.

Note, as shown in Fig.4.1 and Fig.4.5 the SE of OFDM and UFMC is the same with equal number of cyclic prefix and filter length.

Fig.4.6 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 73, number of FFT 1024, 72 samples of cyclic prefix, bits per subcarrier and overlapping factor equal to four.

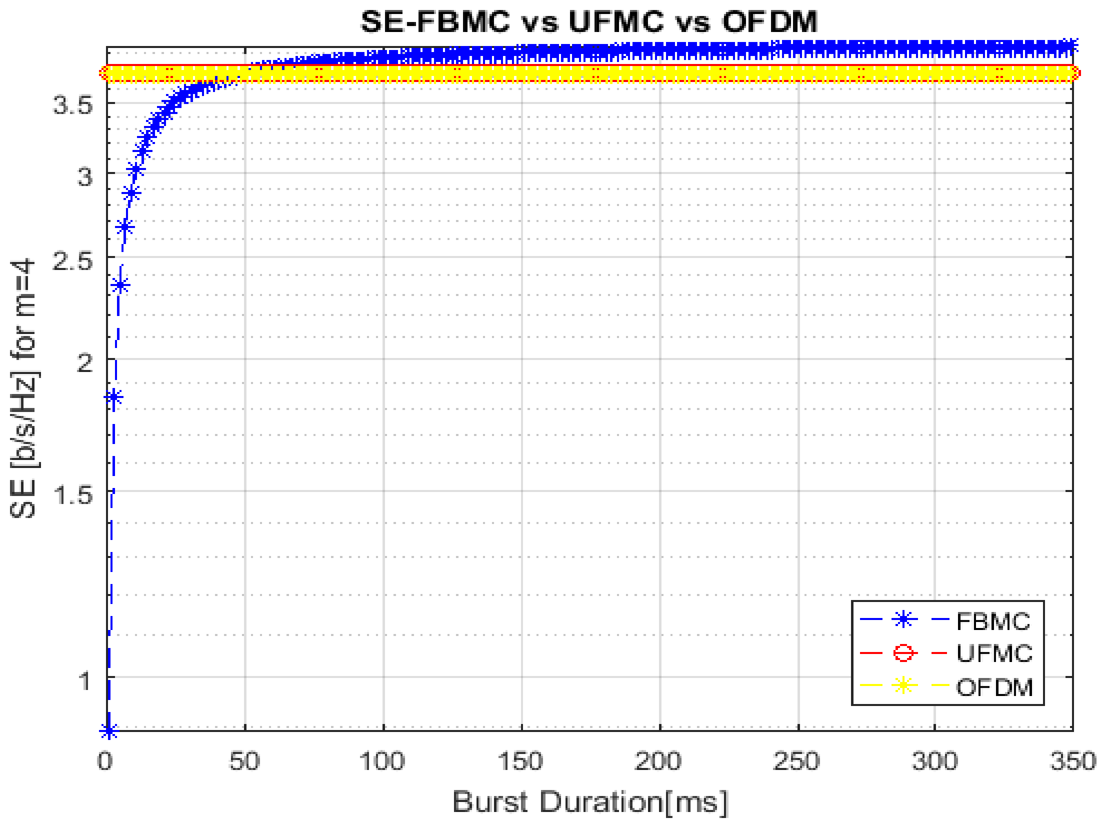

Figure 4.6 SE with cyclic prefix samples equal to 72

As shown in Fig.4.6 the SE of OFDM is reduced in a little bit significant value with increasing the cyclic prefix as we compared with the previous simulation results of Fig.4.2 and Fig.4.3 which is around 3.7b/s/Hz. Whereas, as we have seen from the simulation graphs the SE of UFMC and FBMC is not change with increasing the cyclic prefix from 53 to 73. In other words, the SE of UFMC and FBMC modulation schemes are not dependent on the cyclic prefix.

Note, as shown in Fig.4.5 and Fig.4.6 the SE of OFDM and UFMC is exactly the same when the filter length of UFMC is equal to number of cyclic prefix plus one.

Fig.4.7 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 73, number of FFT 1024, 72 samples of cyclic prefix, overlapping factor equal to four, and bits per subcarrier increased to six.

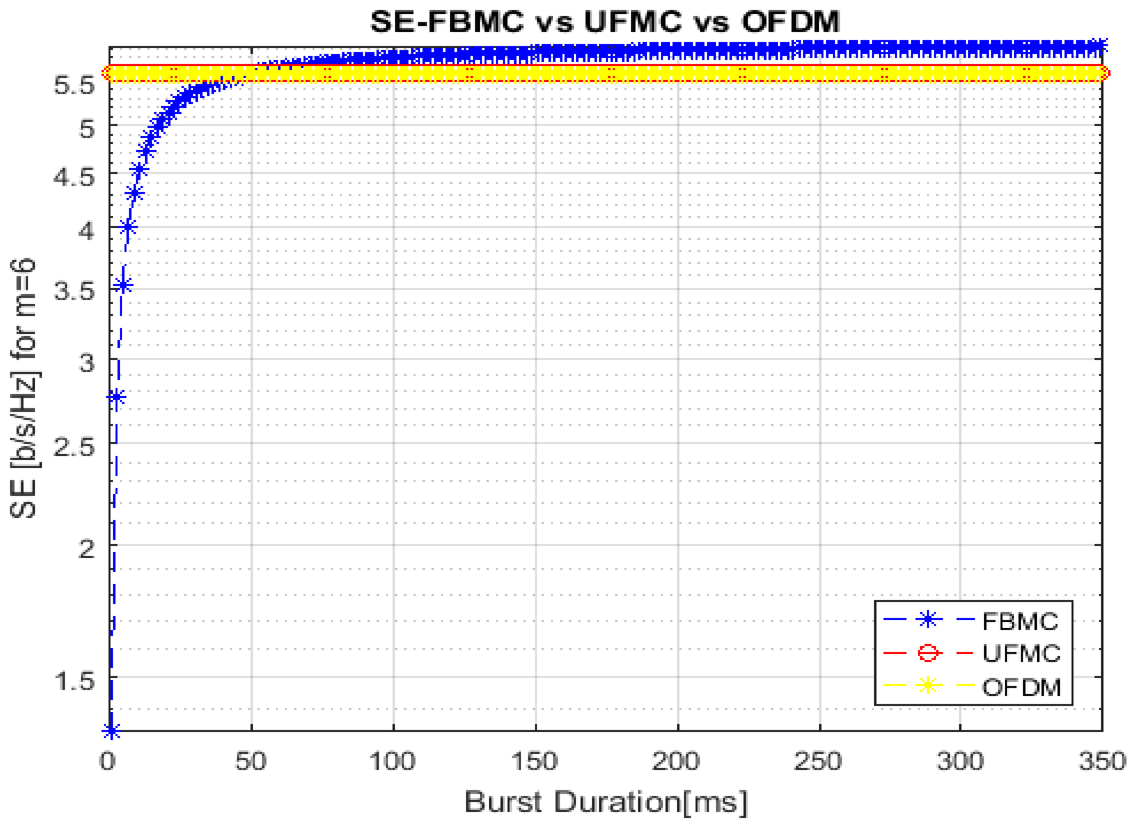

Figure 4.7 SE with bits per subcarrier, m = 6.

As shown in Fig.4.7 the SE of FBMC increases rapidly with burst duration initially and then it increases smoothly with the burst duration till nearly 50ms. After 50ms the SE of FBMC is gradually increases with burst duration and it goes higher than the SE of OFDM and UFMC which is around 5.8b/s/Hz. But, the SE of OFDM and UFMC is constant throughout the burst duration which is around 5.65b/s/Hz.

Note that, the SE of OFDM, FBMC, and UFMC significantly increases with increasing of the bits per subcarrier as shown in Fig.4.1 and Fig.4.7.

Fig.4.8 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 73, with decreasing number of FFT to 512,72 samples of cyclic prefix, overlapping factor equal to four, and bits per subcarrier equal to six.

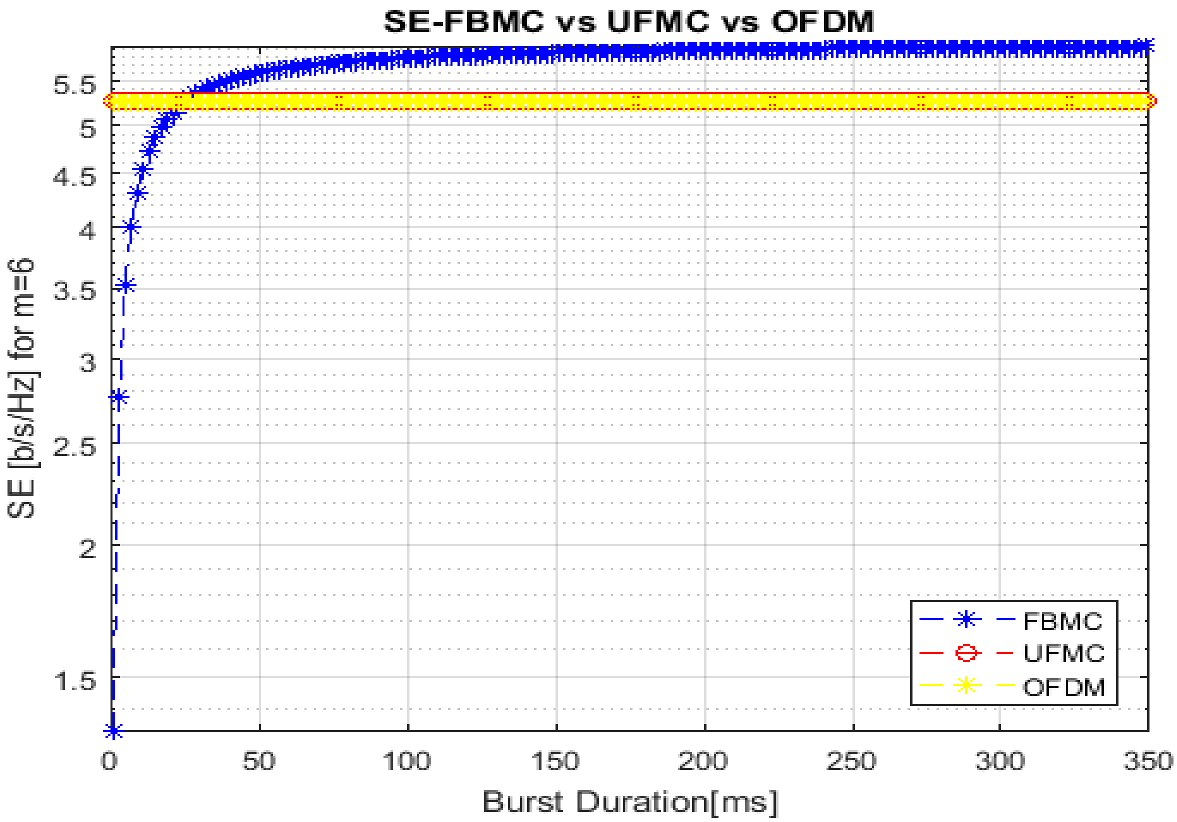

Figure 4.8 SE with number of FFT equal to 512

As shown in Fig.4.8 the SE of FBMC increases rapidly with burst duration and it then increases smoothly with the burst duration till nearly 30ms. After 30ms the SE of FBMC gradually increases with burst duration and it goes higher than the SE of OFDM and UFMC which is around 5.8b/s/Hz. But, the SE of OFDM and UFMC is constant throughout the burst duration which is around 5.35b/s/Hz.

Note that, the SE of the OFDM and UFMC decreases with decreasing of the number of FFT or FFT size as shown in Fig.4.7 and Fig.4.8. But, the SE of FBMC doesn't change with decreasing the number of FFT.

Fig.4.9 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 73, number of FFT to 512, 72 samples of cyclic prefix, with increasing the overlapping factor to six, and bits per subcarrier equal to six.

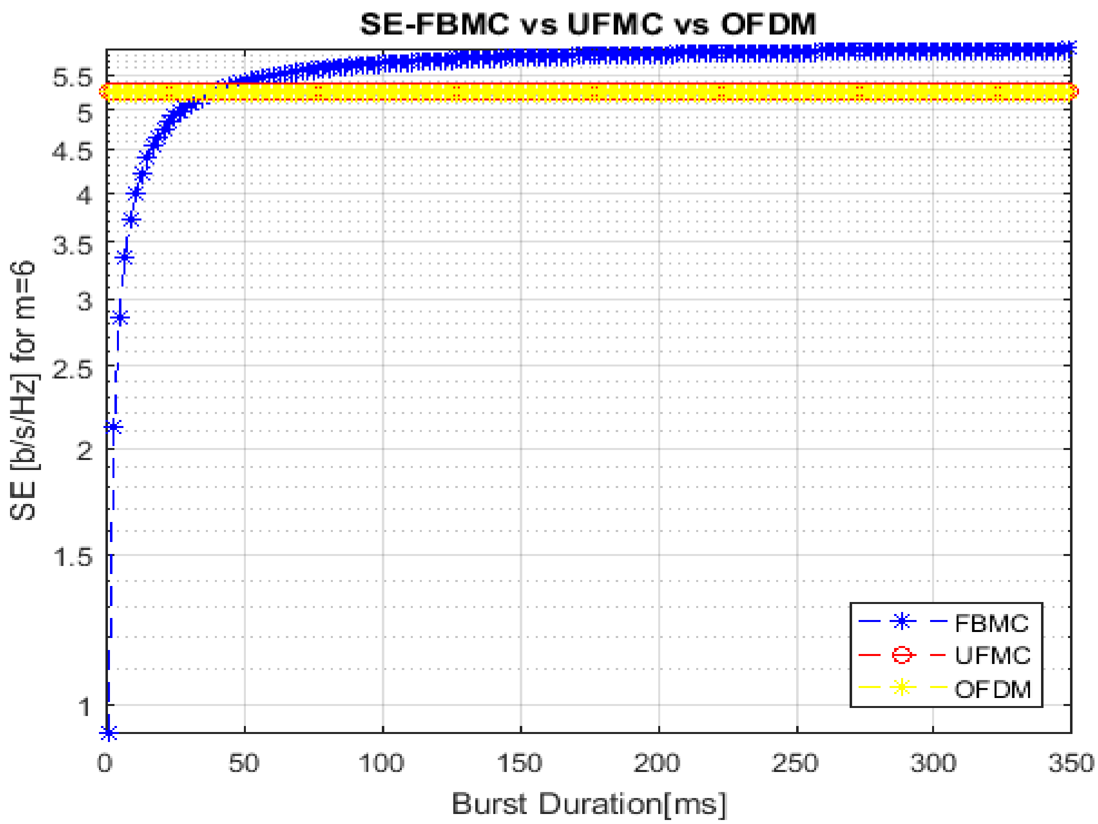

Figure 4.9 SE with overlapping factor, k=6.

As shown in Fig.4.9 the SE of FBMC increases rapidly with burst duration and then, it increases smoothly with the burst duration till nearly 40ms. After 40ms the SE of FBMC is gradually increases with burst duration and it goes higher than the SE of OFDM and UFMC which is around 5.78b/s/Hz. But, the SE of OFDM and UFMC is constant throughout the burst duration which is around 5.35b/s/Hz.

Note that, the SE of the FBMC is decreases with increasing of the number overlapping factor as shown in Fig.4.8 and Fig.4.9. But, the SE of OFDM and UFMC doesn't change with increasing the number overlapping factor.

Fig.4.10 shows that the SE of OFDM, FBMC and UFMC for the burst duration of up to 350ms with filter length equal to 73, number of FFT to 512, 72 samples of cyclic prefix, with decreasing the overlapping factor towards two, and bits per subcarrier equal to six.

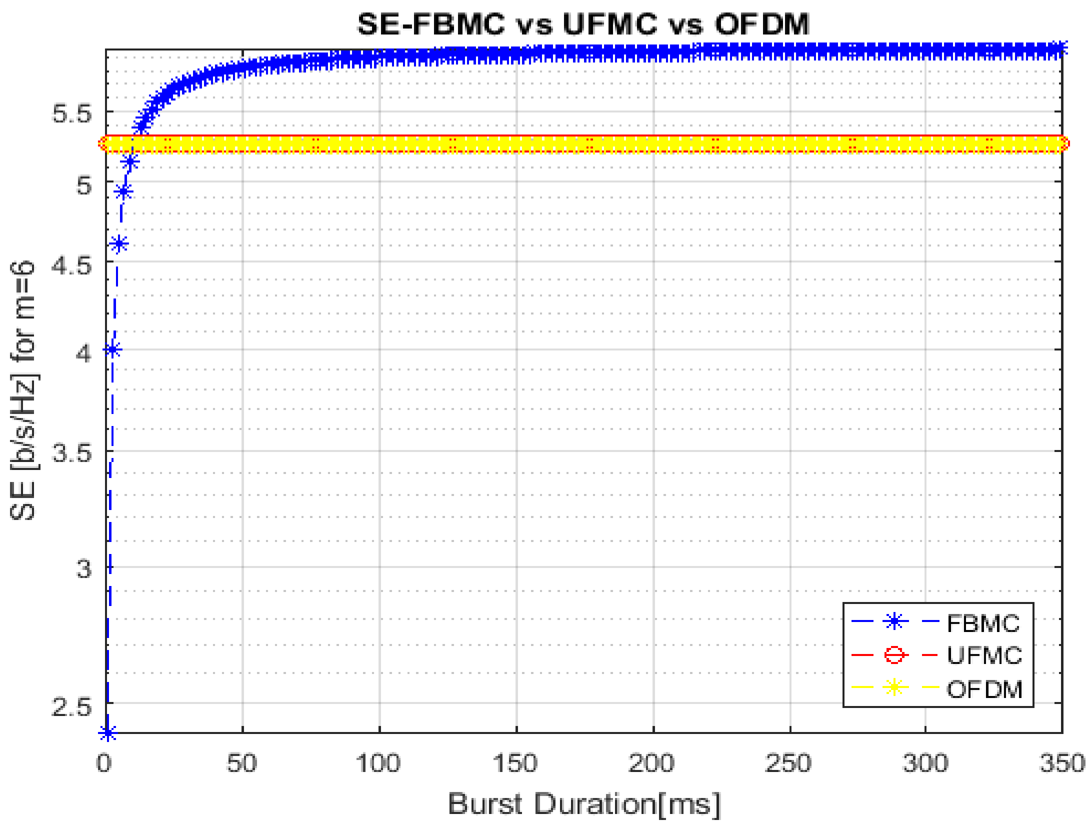

Figure 4.10 SE with overlapping factor equal to two

As shown in Fig.4.10 the SE of FBMC increases rapidly with burst duration initially and then, it increases smoothly with the burst duration till nearly 10ms. After 10ms the SE of FBMC is gradually increases with burst duration and it goes higher than the SE of OFDM and UFMC which is around 5.91b/s/Hz. But, the SE of OFDM and UFMC is constant throughout the burst duration which is around 5.35b/s/Hz.

Note that, the SE of the FBMC increases with decreasing the number of overlapping factor as shown in Fig.4.8, Fig.4.9 and Fig.4.10. But, the SE of OFDM and UFMC is not changing with decreasing the number overlapping factor.

4.1.1. Spectral Efficiency Results Discussion

Generally, all the output graphs shown in Fig.4.1 to Fig.4.10 denote the SE of the OFDM, FBMC and UFMC. It shows that the SE of FBMC increases rapidly for the first few intervals of the burst duration and then, it increases smoothly with the burst duration until it attains the spectral efficiency of UFMC. After that, it looks constant for some range of burst duration like OFDM and UFMC. Then it will increase gradually beyond this constant value. However, the SE of OFDM and UFMC is constant throughout the burst duration.

The SE of OFDM is reduced in a small amount with increasing the cyclic prefix as it can be seen in the simulation results of Fig.4.2 and Fig.4.3. Whereas, the SE of UFMC and FBMC doesn't change with increasing the cyclic prefix.

The SE of UFMC increases with decreasing the filter length. With decreasing the filter length, the value of burst duration for FBMC to attain the SE of OFDM and UFMC (when $N_{CP} = L$) is decreased. However, the SE of OFDM and FBMC is not changed with decreasing the filter length.

The SE of OFDM and UFMC is decreasing with decreasing number of FFT. However, with decreasing number of FFT the range of burst duration for FBMC to attain the SE of OFDM and UFMC (when $N_{CP} = L$) and the range of burst duration intervals to go like as a constant is changed. But, the SE of FBMC is not changed with decreasing number of FFT.

With increasing the overlapping factor, the range of burst duration for FBMC to attain the SE of OFDM and UFMC (when $N_{CP} = L$) and the range of burst duration intervals to go like as a constant is not changed. But, the SE of FBMC is a little bit reduced. However, the SE of OFDM and UFMC is not changed with increasing overlapping factor. The SE of OFDM, FBMC, and UFMC is increasing with increasing bits per subcarriers as shown in Fig.4.7.

In all cases of this study, the simulation result shows that the SE of the OFDM and UFMC is greater than the SE of FBMC for small value of burst durations but for larger burst durations the SE of FBMC is greater than the SE of OFDM and UFMC. To effectively use these modulation techniques, apply UFMC under very tight response time requirements such as for car-to-car communications and for small burst duration communication such as for machine to machine communications, transporting temperature sensors data, and smart phone functionalities which is sporadically transmitting very small packets. Whereas for transmitting long sequences FBMC is very efficient, it suffers when having to transmit short bursts/frames. OFDM is rather inefficient due to wide frequency guards and the cyclic prefix.

The SE of OFDM, FBMC and UFMC can be enhanced by increasing bits per subcarrier. In addition to this, the SE of both OFDM and UFMC can be improved by increasing number of FFT. And also, the SE of OFDM and UFMC can be upgrade by decreasing cyclic prefix samples and number of filter length, respectively. If the filter length is equal to cyclic prefix samples plus one, the SE of OFDM is exactly the same as the SE of UFMC. By decreasing overlapping factor and by increasing burst duration the SE of FBMC can also be improved.

4.2. Power Spectral Density

To simulate the Power spectral density of FBMC, we consider the following system parameters unless otherwise stated:

TABLE 4.1 SIMULATION PARAMETER VALUES OF FBMC FOR PSD

Simulation Parameters	**Value**
Overlapping symbols, K	3
Number of FFT points (N_{FFT})	512
Guard bands on both sides	112
Number of symbols	200
Bits per subcarrier	4 (16QAM)
Signal to noise ratio (SNR)	5dB

Using simulation parameter values as in Table 4.1, the PSD of FBMC modulation technique is shown in Fig.4.11.

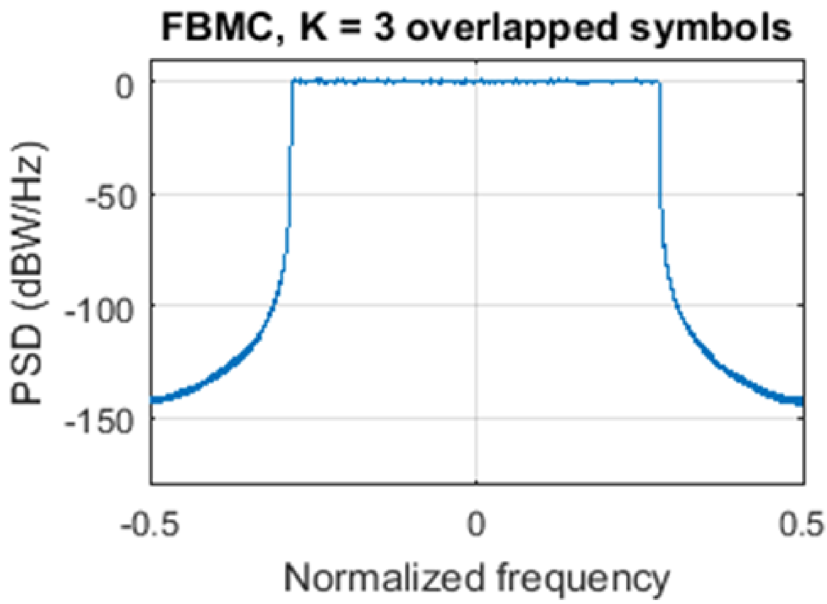

Figure 4.11 PSD of FBMC

But, first and fore most evaluation of the bit error rate (BER) at a given SNR value is vital to select the better mapping scheme for comparison of FBMC with the remaining modulation techniques. Thus, the MATLAB simulation results of the PSD and BER of FBMC at a given SNR value with various QAM techniques is shown in figures Fig.4.12 up to Fig.4.15.

i. The PSD and BER at SNR = 5 dB using 4QAM as mapping technique is

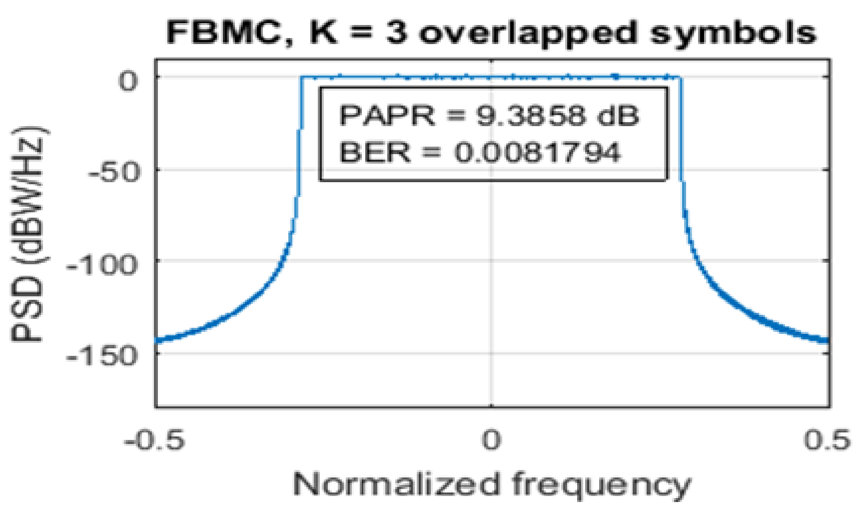

Figure 4.12 PSD of FBMC using 4QAM

ii. The PSD and BER at SNR = 5dB using 16QAM as mapping technique is:

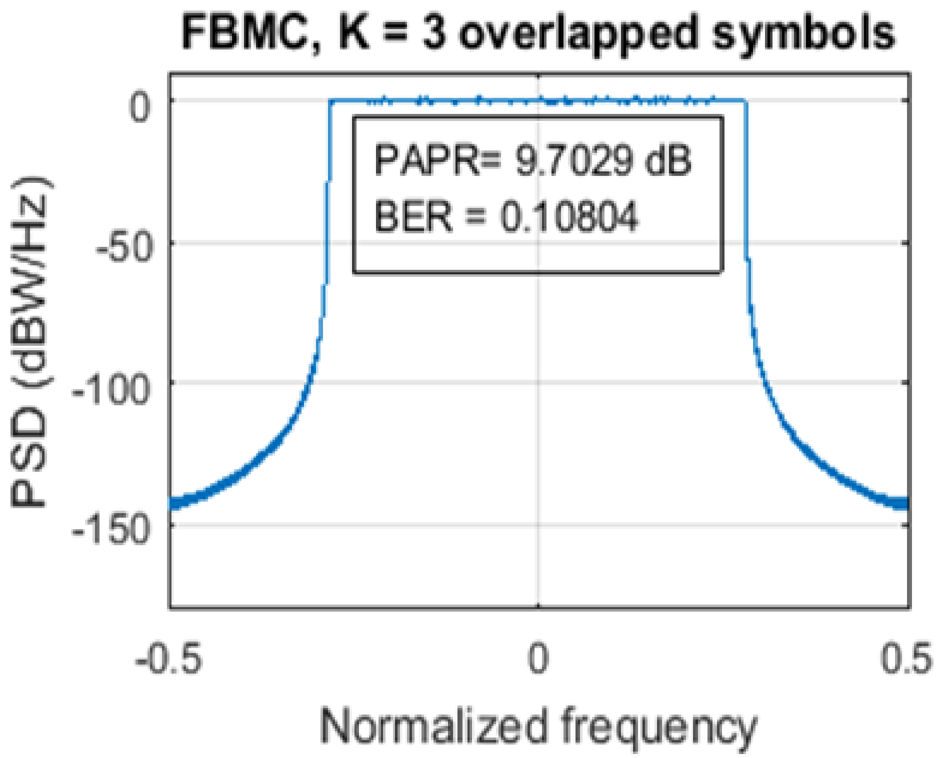

Figure 4.13 PSD of FBMC using 16QAM

iii. The PSD and BER at SNR = 5dB using 64QAM as mapping technique is:

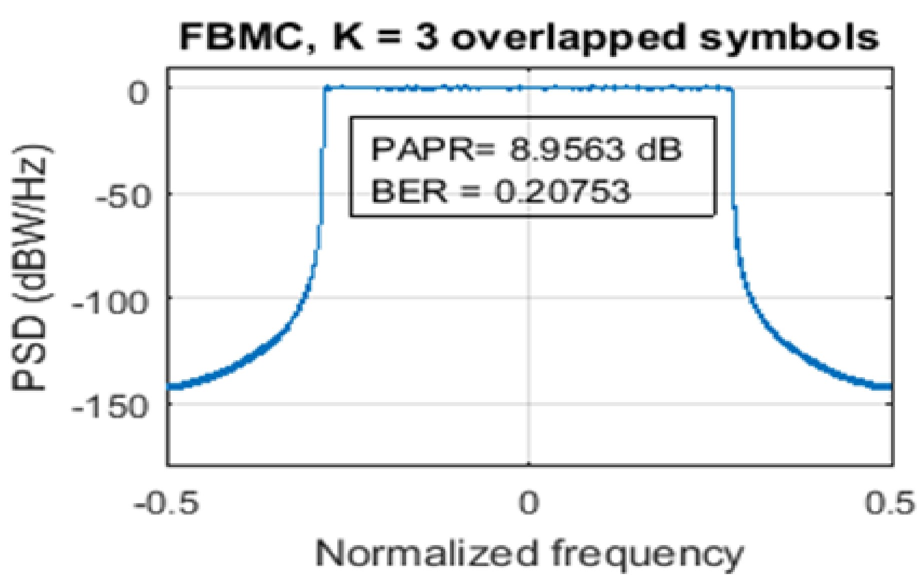

Figure 4.14 PSD of FBMC using 64QAM

iv. The PSD and BER at SNR = 5dB using 256QAM as mapping technique is:

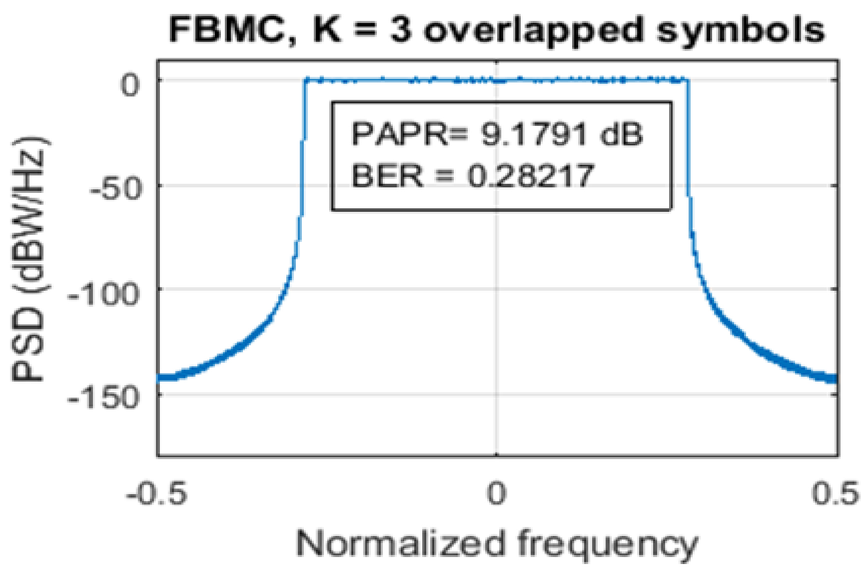

Figure 4.15 PSD of FBMC using 256QAM

As shown in Fig.4.12, Fig.4.13, Fig.4.14 and Fig.4.15, 4QAM has minimum BER value as compared with other mapping schemes. On the other hand, 64QAM has minimum PAPR value as compared to the others. Therefore, to compensate BER value and PAPR value we select 4QAM for comparison analysis of FBMC.

Then, using 4QAM as a mapping scheme the MATLAB simulation result of the BER value at different SNR value becomes as shown in table below.

TABLE 4.2 BER VALUE AT DIFFERENT SNR VALUE

at SNR value of	1dB	2dB	3dB	4dB	5dB	6dB	7dB	8dB	9dB	10dB	11dB
BER	0.066545	0.04487	0.0286601	0.016699	0.0090564	0.0040629	0.0015213	0.00060853	8.949e^{-05}	5.3694e$^{-0.5}$	0

As shown in above table the BER value for FBMC is zero at SNR value of greater than or equal to 11dB with 4QAM mapping scheme. Thus, we choose 11dB SNR value for comparison purpose of FBMC with other modulation techniques.

To simulate the Power Spectral Density of UFMC and OFDM the following system parameters have been considered. And we use these values unless stated otherwise.

TABLE 4.3 SIMULATION PARAMETER VALUES OF UFMC AND OFDM FOR PSD

Simulation Parameters	**Value**
Number of Subcarriers	72
Number of FFT points (N_{FFT})	512
Filter length for UFMC	43
Cyclic prefix length for OFDM	43
Number of symbols	200
Bits per subcarrier, m	2 (4QAM)
Signal to noise ratio (SNR)	10dB

The PSD of UFMC and OFDM modulation technique using the parameters in Table 4.3, is shown in figures Fig.4.16 and Fig.4.17 below, respectively.

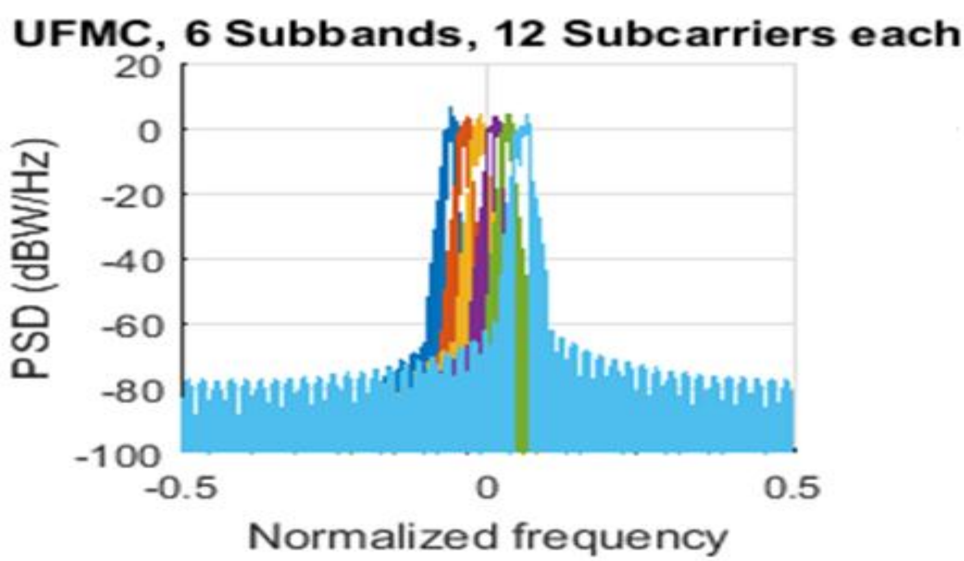

Figure 4.16 PSD of UFMC

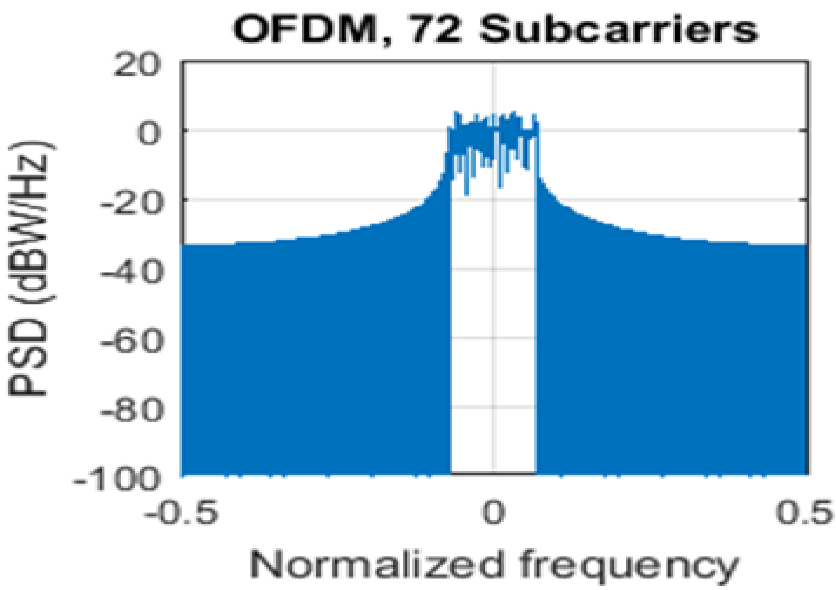

Figure 4.17 PSD of OFDM

Fig.4.16 and Fig.4.17 shows the PSD for 72 subcarriers. The overall band is divided into 6 sub bands, each sub band having 12 subcarriers with less side lobes. To choose the better mapping scheme for UFMC evaluation of the PAPR and BER at a given SNR value with different QAM mapping schemes is required.

Thus, the PAPR and BER result of UFMC at SNR value of 10dB becomes as follows:

i. Using 4QAM as mapping technique

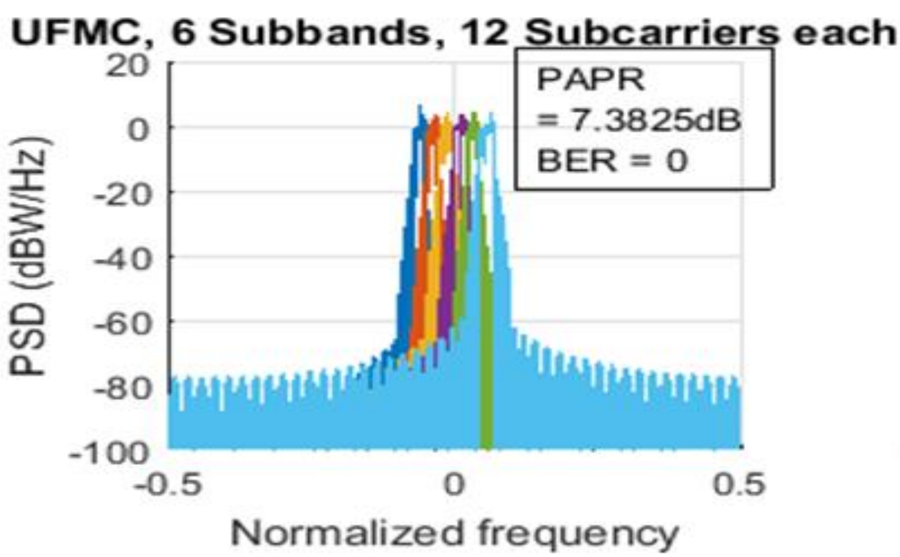

Figure 4.18 PSD UFMC using 4QAM

ii. Using 16QAM as mapping technique

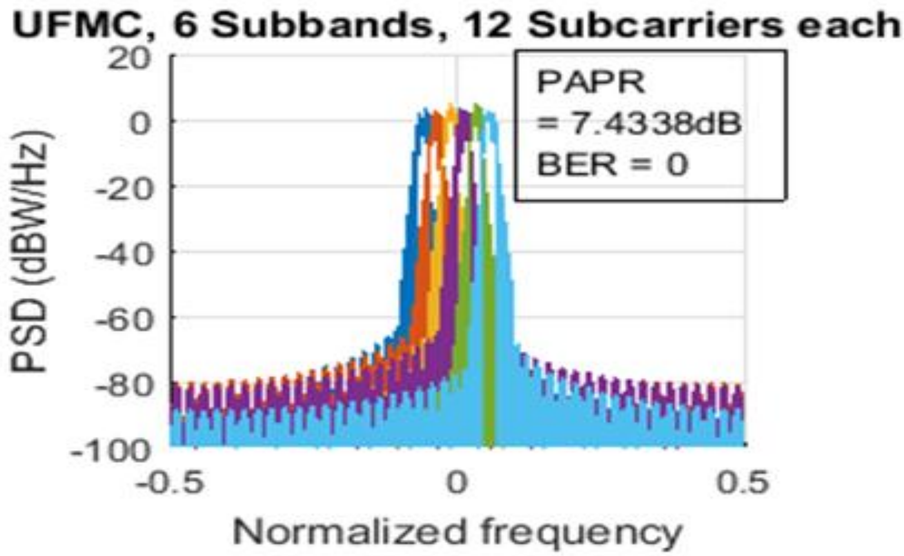

Figure 4.19 PSD UFMC using 16QAM

iii. Using 64QAM as mapping technique

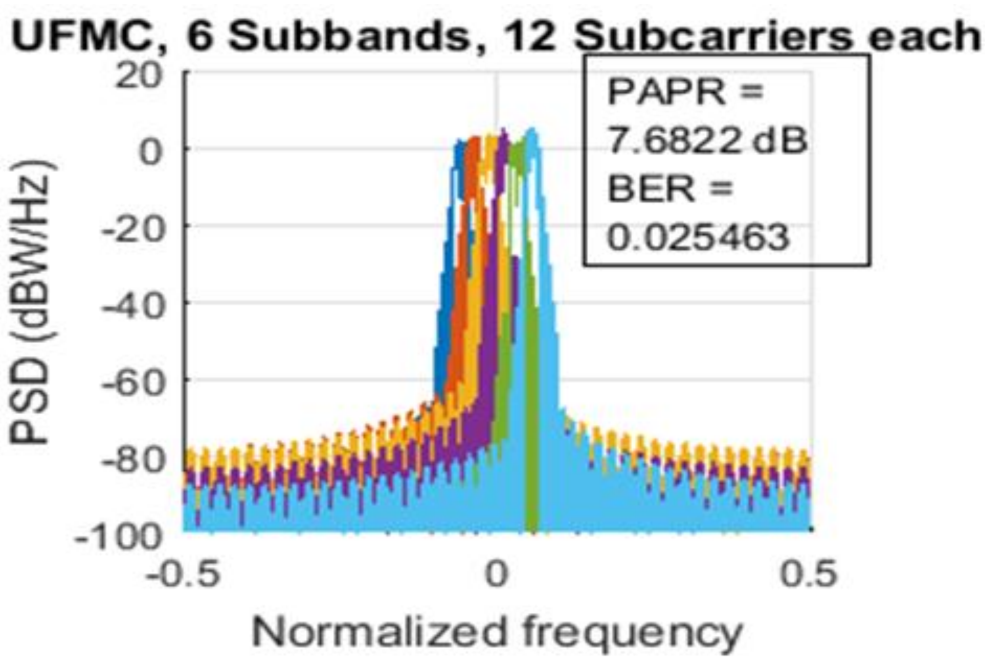

Figure 4.20 PSD UFMC using 64QAM

iv. Using 256QAM as mapping technique

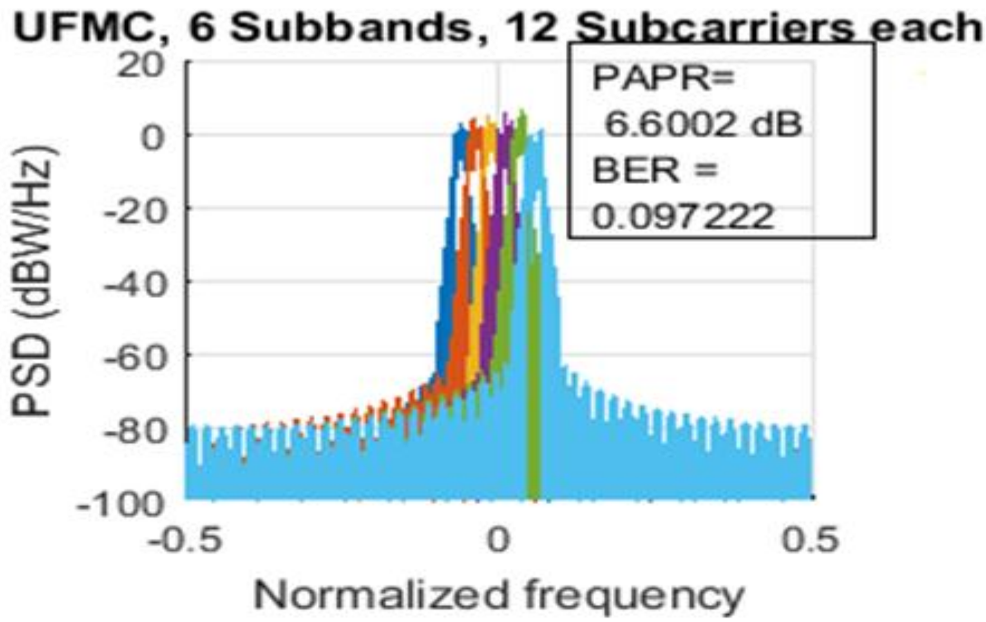

Figure 4.21 PSD UFMC using 256QAM

As shown in Fig.4.33 to Fig.4.36 above, the simulation result shows that both 4QAM and 16QAM have the smallest value of BER than others but they have high PAPR value than 256QAM. However, 256QAM has the smallest value of PAPR than others but it has high BER value than the others. Moreover, from Fig.4.33 and Fig.4.34 the side lobe of the PSD of UFMC with 16QAM is a little bit closer to the normalized frequency than the others. Therefore, by taking into account this as well as to compromise PAPR and BER 16QAM is considered as a mapping scheme for UFMC.

Next step is selecting better SNR value using 16QAM as a mapping scheme. To do this, evaluate the BER value at different SNR value starting from 1dB till BER value becomes zero.

TABLE 4.4 BER VALUE AT DIFFERENT SNR VALUE

at SNR value of	1dB	2dB	3dB	4dB	5dB	6dB	7dB	8dB
BER	0.069444	0.055556	0.034722	0.013889	0.010417	0.0069444	0.0034722	0

Therefore, as shown in table above the UFMC has BER value equal to zero at greater than or equal to 8dB using 16QAM. So, we select 8dB SNR value for comparison of UFMC with the remaining techniques. Since, 4QAM and 16QAM have no effect on the PSD and the PAPR value of 16QAM is less than 4QAM as shown in Fig.4.22 and Fig.4.23 then 16 QAM is also selected for OFDM for comparison purpose.

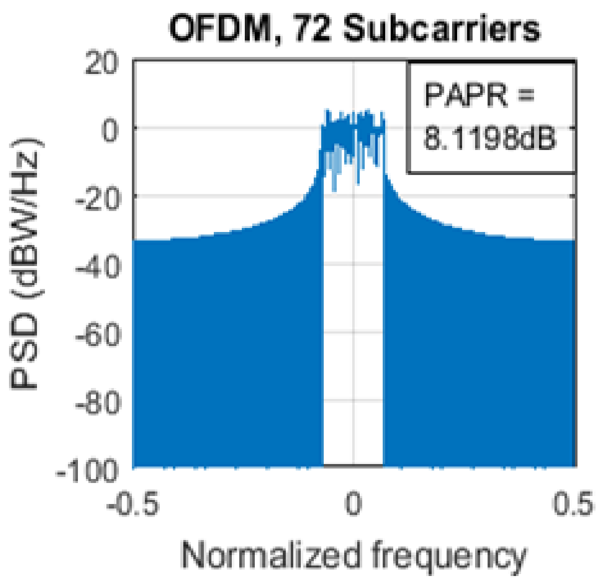

Figure 4.22 PSD of OFDM with 4QAM

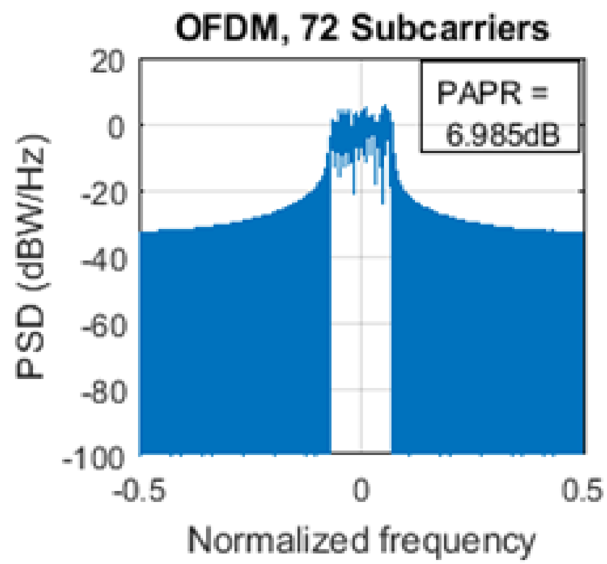

Figure 4.24 PSD of OFDM with 64QAM

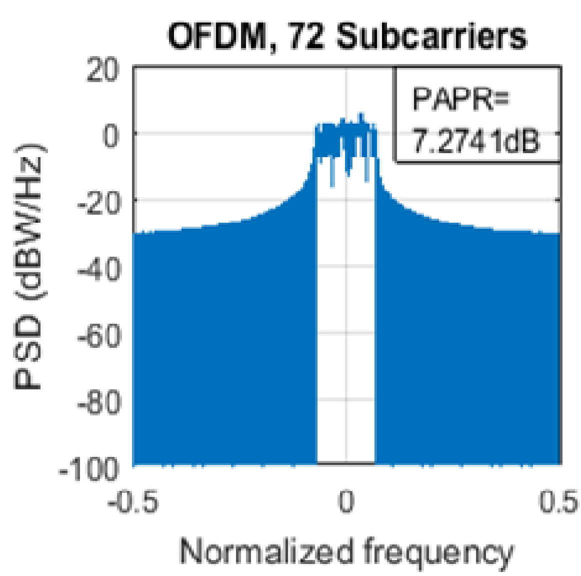

Figure 4.23 PSD of OFDM with 16QAM

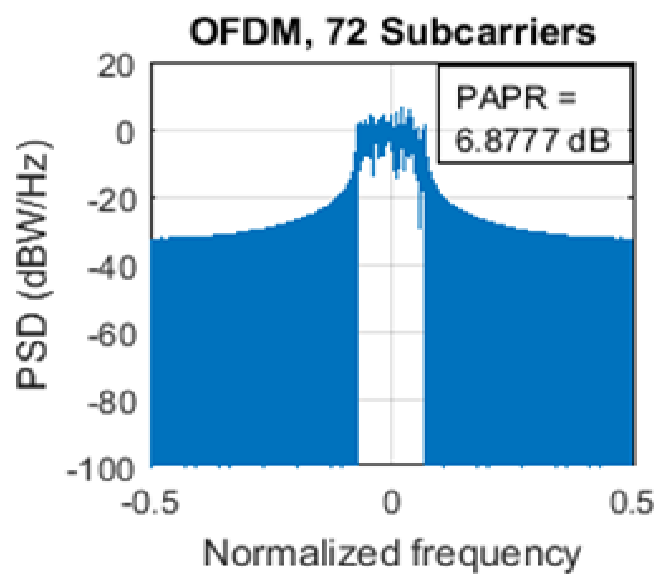

Figure 4.25 PSD of OFDM with 64QAM

Fig.4.26 below shows the PSD of FBMC with number of FFT equal to 512, guard bands on both sides equal to 112, number of symbols equal to 200, and overlapping symbol equal to three with selected SNR value of 11dB and 4QAM mapping scheme.

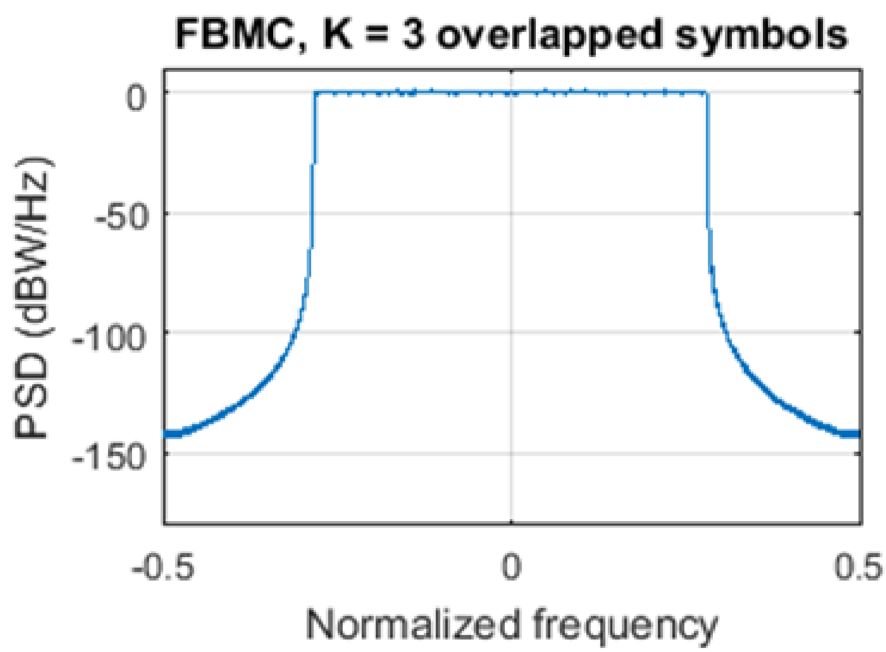

Figure 4.26 PSD of FBMC with Guard bands of 112

As shown in Fig.4.26 above the PSD of FBMC occupies its useful bandwidth within the frequency range of between nearly -0.3 and 0.3 with magnitude of 0dBW/Hz. The magnitude of the PSD of the side lobe is around -140dBW/Hz. Since the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of bound and it leads to inter symbol interference.

Fig.4.27 below shows the PSD of FBMC with increasing the guard bands on both sides equal to 212, number of FFT equal to 512, number of symbols equal to 200, and overlapping symbol equal to three with selected SNR value of 11dB and 4QAM mapping scheme.

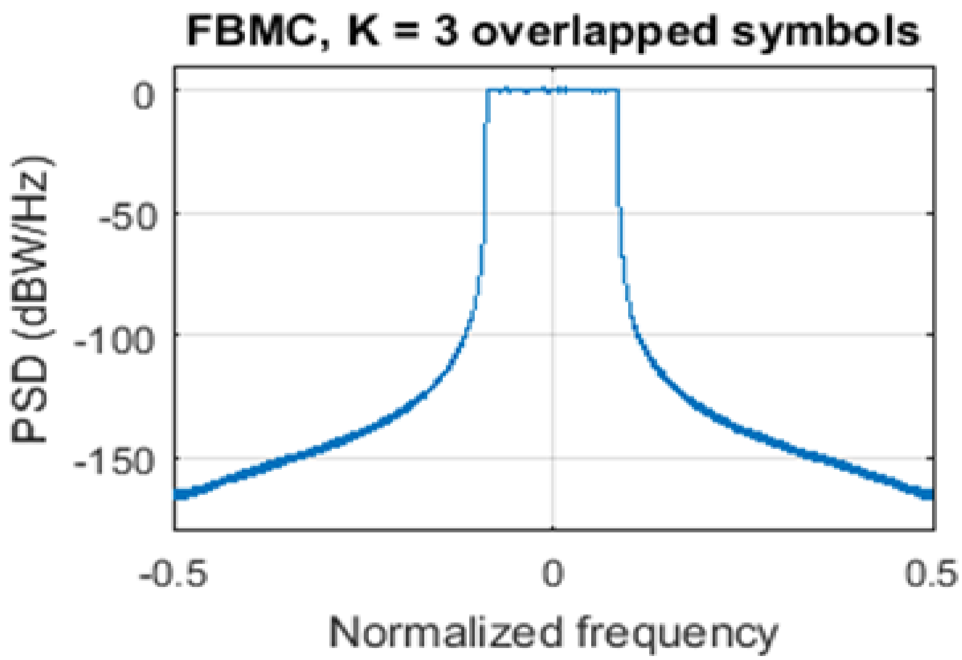

Figure 4.27 PSD of FBMC with Guard bands of 212

As shown in Fig.4.27above, the PSD of FBMC occupies its useful bandwidth within the frequency range of between nearly -0.1 and 0.1 with magnitude of 0dBW/Hz, the bandwidth is small as compared with the previous graph as shown in Fig. 4.26. The magnitude of the PSD of the side lobe is around -160dBW/Hz. Since the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of bound and it leads to inter symbol interference. But, this PSD graph or the side lobe is closer to the normalized frequency than the previous graph which is the PSD with guard band of 112 as shown in Fig.4.26. This shows that with increasing guard bands the FBMC is less affected to the inter symbol interference.

Fig.4.28 below shows, the PSD of FBMC with decreasing overlapping symbol to two, guard bands on both sides equal to 212, number of FFT equal to 512, and number of symbols equal to 200 with selected SNR value of 11dB and 4QAM mapping scheme.

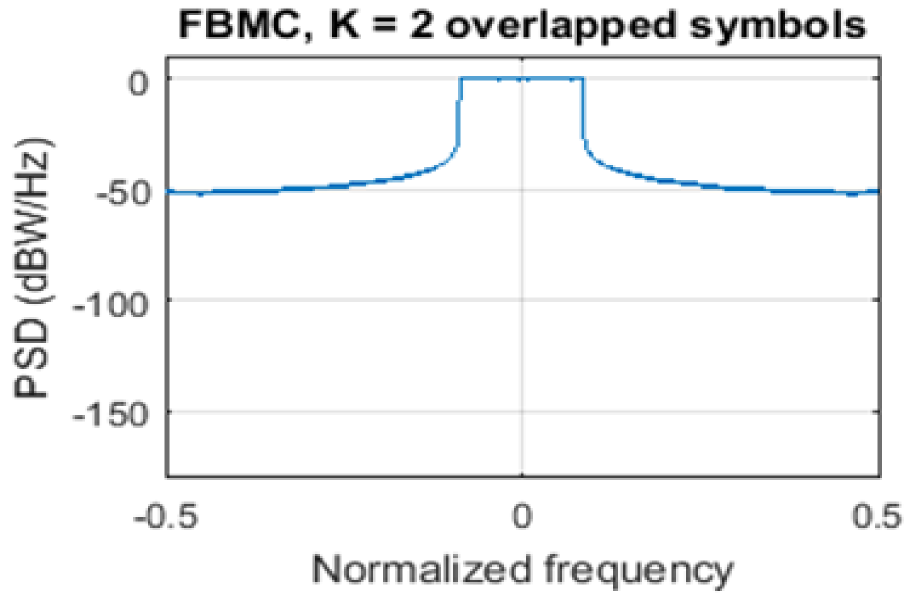

Figure 4.28 PSD of FBMC with overlapping symbol, k= 2

As shown in Fig.4.28 above the PSD of FBMC occupies its useful bandwidth within the frequency range of between nearly -0.1 and 0.1 with magnitude of 0dBW/Hz, the bandwidth is small as compared with figure 4.26. But, the bandwidth is the same with Fig.4.27. The magnitude of the PSD of the side lobe is -50dBW/Hz. Since the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of bound and it leads to inter symbol interference. The PSD graph or the side lobe is far from the normalized frequency than the previous graph which is the PSD with overlapping symbol or factor equal to three as shown in Fig.4.26 and Fig.4.27. This shows that with decreasing overlapping symbol the FBMC is more affected to the inter symbol interference.

Fig.4.29 below shows, the PSD of FBMC with increasing the overlapping symbol to four, guard bands on both sides equal to 212, number of FFT equal to 512, and Number of symbols equal to 200 with selected SNR value of 11dB and 4QAM mapping scheme.

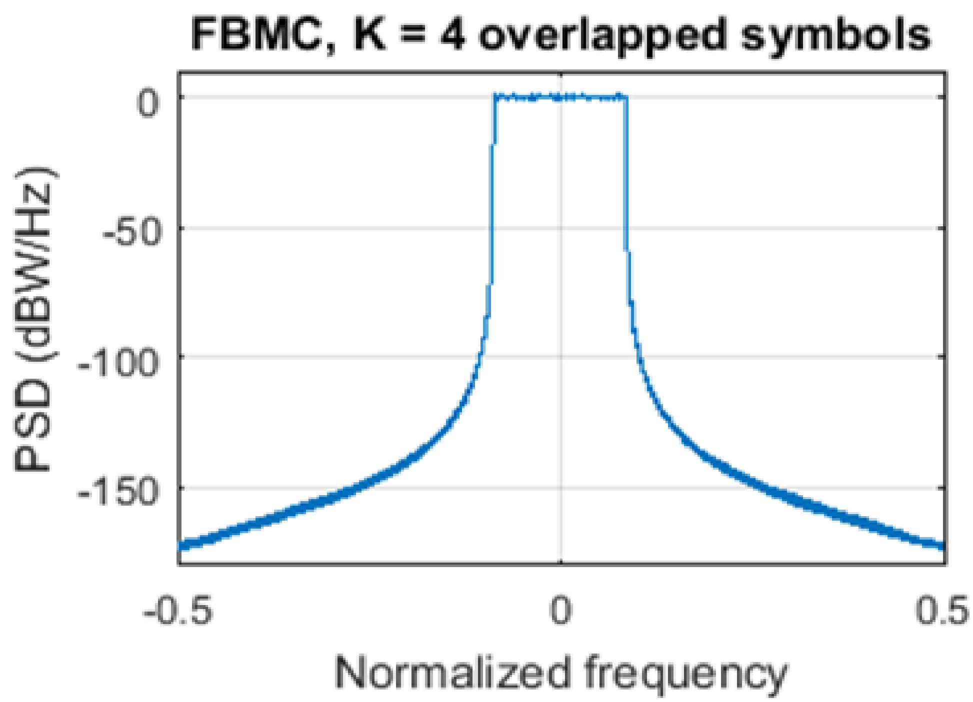

Figure 4.29 PSD of FBMC with overlapping symbol, k= 4

As shown in Fig.4.29 above the PSD of FBMC occupies its bandwidth within the frequency range of between nearly -0.1 and 0.1 with magnitude of 0dBW/Hz, the bandwidth is small as compared with overlapping symbol, k=3 as shown in figure 4.26. But, the bandwidth is the same with overlapping symbol, k=2 as shown in Fig.4.28. The magnitude of the PSD of the side lobe is around -170dBW/Hz. Since the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of bound and it leads to inter symbol interference. The PSD graph or the side lobe is closer to the normalized frequency than the previous graphs which are the PSD with overlapping symbol or factor equal three and two as shown in Fig.4.26 and Fig.4.28, respectively. This shows that with increasing overlapping symbol or factor the FBMC is less affected to the inter symbol interference.

Fig.4.30 below shows the PSD of FBMC with incrementing number of FFT equal to 1024, overlapping symbol equal to four, guard bands on both sides equal to 212, and number of symbols equal to 200 with selected SNR value of 11dB and 4QAM mapping scheme.

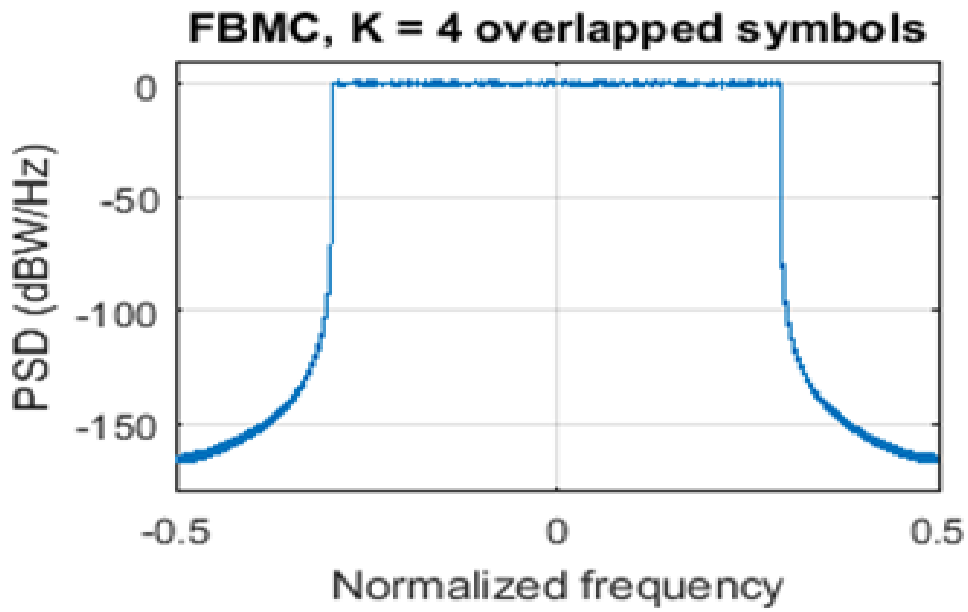

Figure 4.30 PSD of FBMC with number of FFT 1024

As shown in Fig.4.30 above the PSD of FBMC occupies its bandwidth within the frequency range of between nearly -0.3 and 0.3 with magnitude of 0dBW/Hz, the bandwidth is large as compared with number of FFT equal to 512 as shown in Fig.4.29. The magnitude of the PSD of the side lobe is around -165dBW/Hz which is a little bit far from the normalized frequency as compared with number of FFT equal to 512. Thus, the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of bound and it leads to inter symbol interference. This shows that with increasing number of FFT the FBMC is more affected to the inter symbol interference.

Fig.4.31 below shows the PSD of FBMC with decreasing Number of symbols to 100, number of FFT equal to 1024, overlapping symbol equal to four, and Guard bands on both sides equal to 212, with selected SNR value of 11dB and 4QAM mapping scheme.

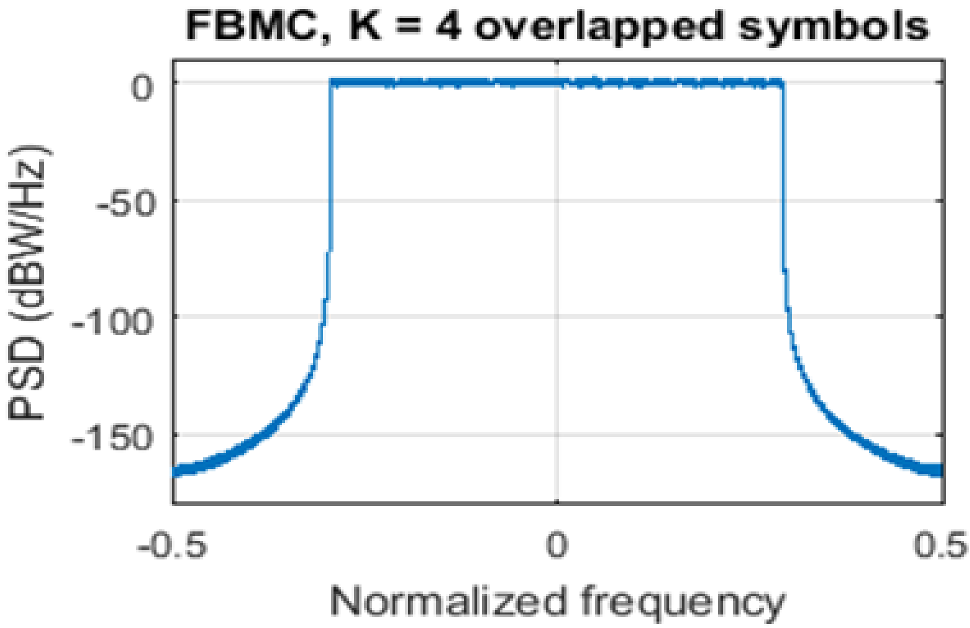

Figure 4.31 PSD of FBMC with number of symbols 100

As shown in Fig.4.31 above the PSD of FBMC occupies its bandwidth within the frequency range of between nearly -0.3 and 0.3 with magnitude of 0dBW/Hz, the bandwidth is large as compared with number of symbols equal to 200 and number of FFT equal to 512 as shown in Fig.4.29. But, this result is exactly the same with number of symbols equal to 200 and number of FFT equal to 1024 as shown in Fig.4.30. The magnitude of the PSD of the side lobe is around -165dBW/Hz which is a little bit far from the normalized frequency as compared with number of FFT equal to 512. Thus, the frequency range of the side lobe is outside of the useful bandwidth then, the PSD of this range is not necessary because it is considered as out of band and it leads to inter symbol interference. As shown in Fig.4.30 and Fig.4.31 the PSD of FBMC with number of symbols 100 and 200 is exactly the same. This shows that with increasing and/or decreasing number symbols the PSD of FBMC is not changed.

Fig.4.32 below shows that the PSD of UFMC with filter length equal to 43, number of FFT equal to 512 for 6 sub bands, each sub band having 12 subcarriers with the selected SNR value of 8dB and 16QAM.

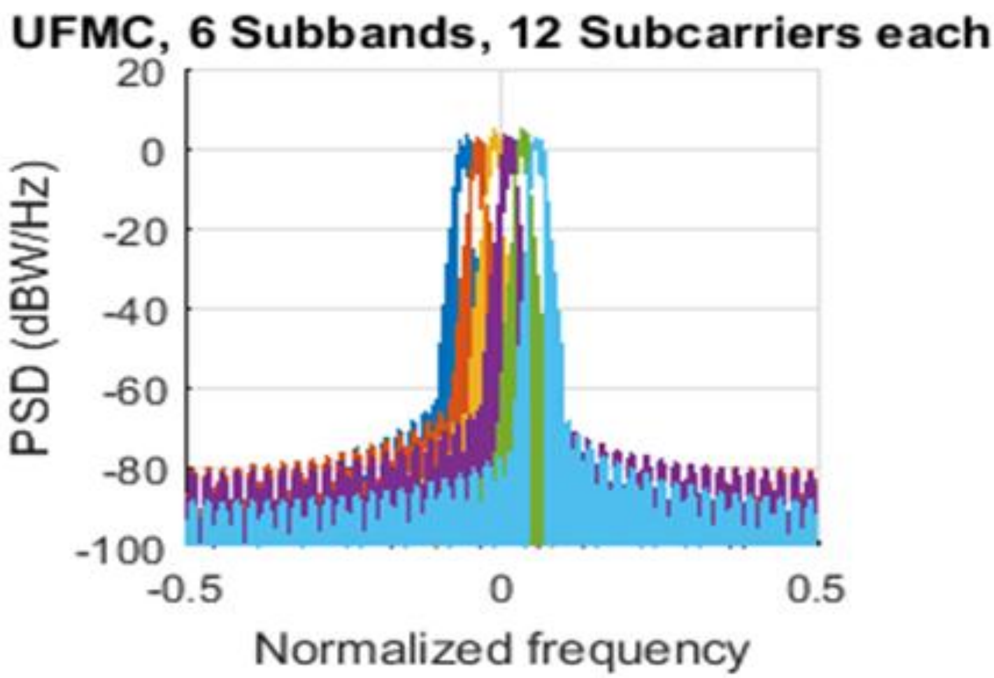

Figure 4.32 PSD of UFMC with 72 subcarriers

As shown in Fig.4.32, the PSD for 72 subcarriers with filter length equal to 43, the useful bandwidth occupies within the frequency range of between nearly -0.1 and 0.1 with magnitude of 0dBW/Hz. Thus, the overall band is divided into 6 sub bands, each sub band having 12 subcarriers with -80dBW/Hz side lobes. The required bandwidth range is covered between the normalized frequency of -0.1 and 0.1. Then, outside of this range of frequency is unwanted because it leads to inter symbol interference.

Fig. 4.33 below shows that the PSD of UFMC with increasing the filter length to 114, number of FFT equal to 512 for 6 sub bands, each sub band having 12 subcarriers with the selected SNR value of 8dB and 16QAM.

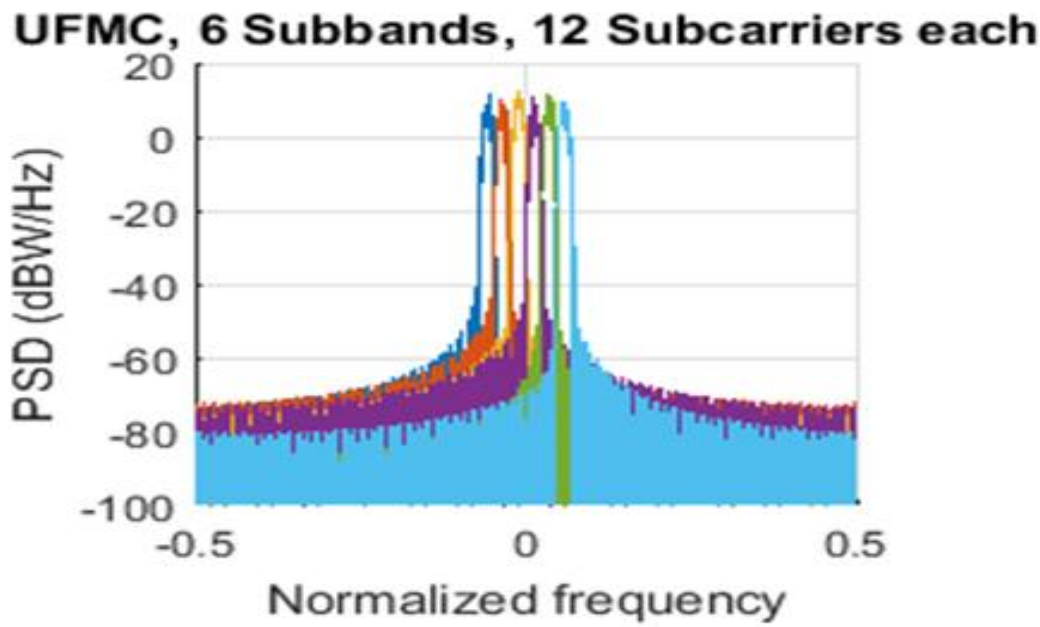

Figure 4.33 PSD of UFMC with filter length 114

As shown in Figure 4.33 the PSD for 72 subcarriers with filter length equal to 114, the useful bandwidth occupies within the frequency range of between nearly -0.1 and 0.1 with magnitude of 0dBW/Hz. Thus, the overall band is divided into 6 sub bands, each sub band having 12 subcarriers with around -72dBW/Hz side lobes. The required bandwidth range is covered between the normalized frequency of -0.1 and 0.1. Then, outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.32 and Fig.4.33 the PSD of UFMC with filter length equal to 114 is far from the normalized frequency than the PSD of UFMC with filter length equal to 43. This shows that, with increasing the filter length UFMC modulation technique is more affected to inter symbol interference.

Fig.4.34 below shows that the PSD of UFMC with filter length equal to 43, number of FFT increase to 1024 for 6 sub bands, each sub band having 12 subcarriers with the selected SNR value of 8dB and 16QAM.

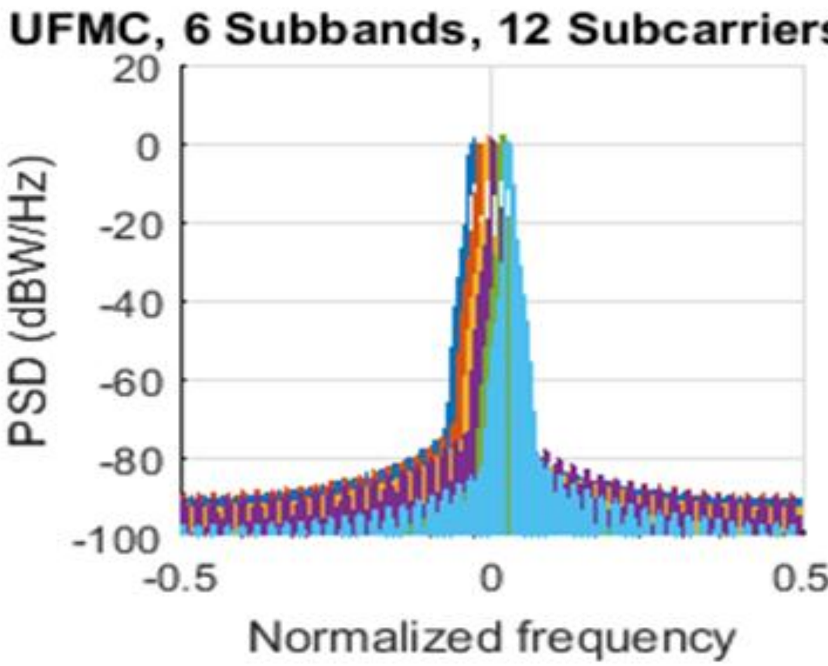

Figure 4.34 PSD of UFMC with number of FFT 1024

As shown in Fig.4.34 the PSD for 72 subcarriers with filter length equal to 43 and number of FFT increased to 1024, the useful bandwidth occupies within the frequency range of between nearly -0.08 and 0.08 with magnitude of 0dBW/Hz. Thus, the overall band is divided into 6 sub bands, each sub band having 12 subcarriers with around -92dBW/Hz side lobes. The required bandwidth range is covered between the normalized frequency of -0.08 and 0.08. Then, outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.32 and Fig.4.34, the PSD of UFMC with number of FFT equal to 1024 is closer to the normalized frequency than the PSD of UFMC with number of FFT equal to 512. This shows that with increasing the number of FFT, UFMC modulation technique is less affected to inter symbol interference.

Fig.4.35 below shows the PSD of UFMC with 9 sub bands and 18 sub-carries, filter length equal to 43 and number of FFT 1024.

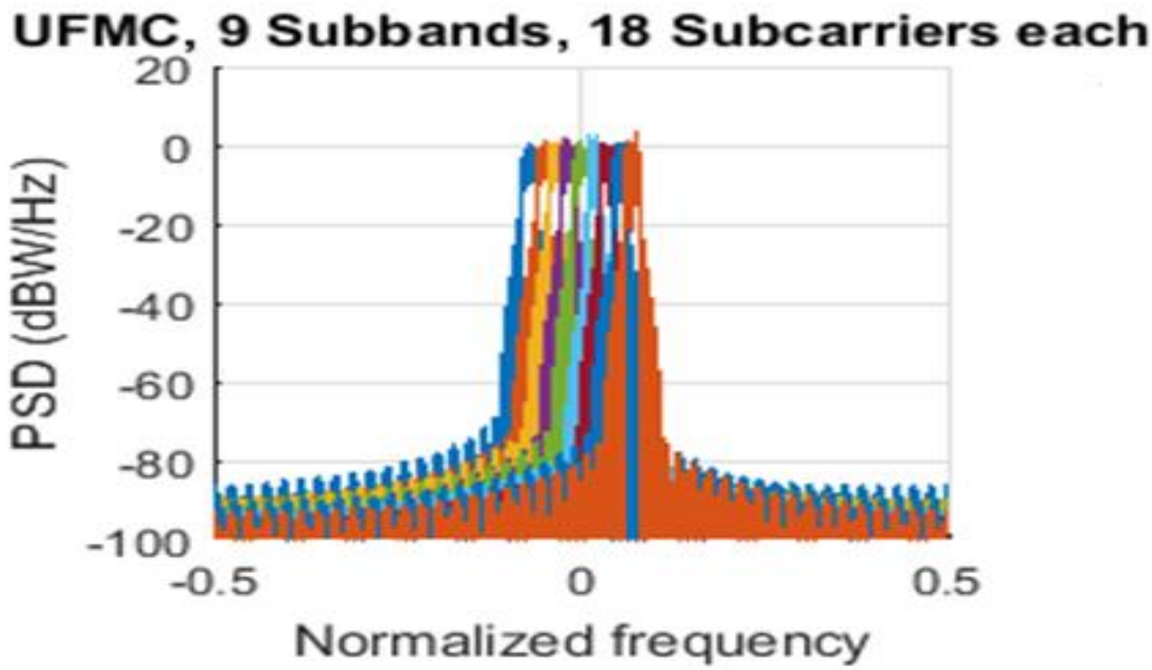

Figure 4.35 PSD of UFMC with 162 subcarriers

As shown in Fig.4.35 the PSD of UFMC for 162 subcarriers with filter length equal to 43 and number of FFT 1024. Thus, the overall band is divided into 9 sub bands, each sub band having 18 subcarriers with around -90dBW/Hz side lobes. The required bandwidth range is approximately covered between the normalized frequency of -0.1 and 0.1. Then, outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.34 and Fig.4.35 with increasing number of subcarriers the UFMC modulation technique is more affected to inter symbol interference.

Fig.4.36 below shows the PSD of UFMC with 15 sub bands and 30 sub-carries, filter length equal to 43 and number of FFT 1024.

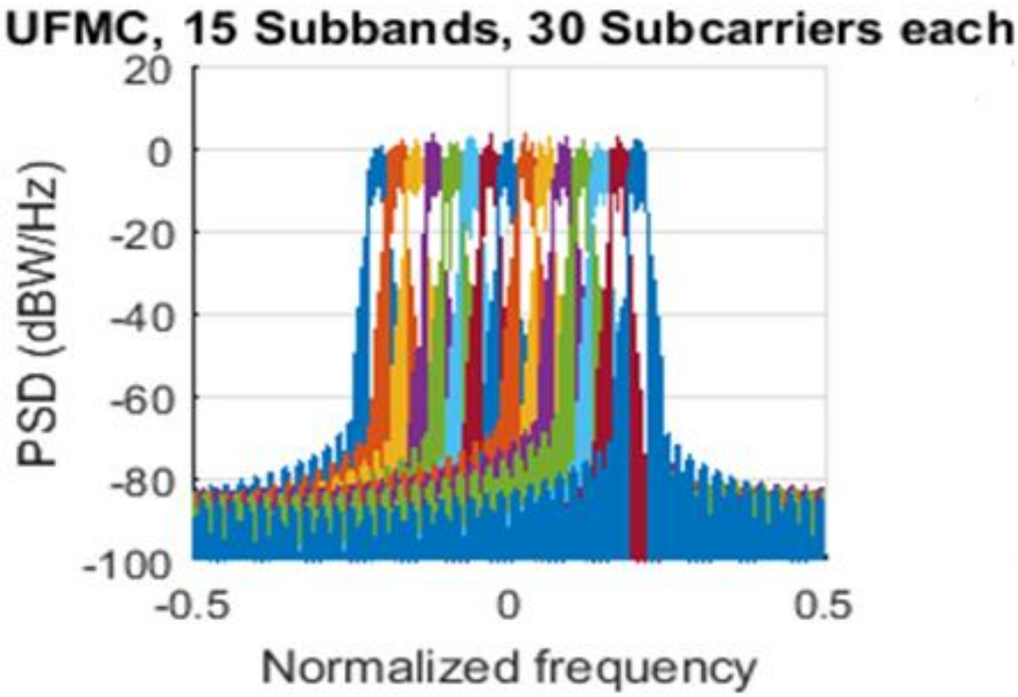

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Figure 4.36 PSD of UFMC with 450 subcarriers

Fig.4.36 shows the PSD for 450 subcarriers. The overall band is divided into 15 sub bands, each sub band having 30 subcarriers with 81dBW/Hz side lobes. The required bandwidth range is approximately covered between the normalized frequency of -0.35 and 0.35. Outside of this range of frequency is unwanted because it leads to inter symbol interference. This result shows that the bandwidth and the power occupied at this bandwidth is higher than that of 72 and 162 subcarriers. And also, the gap between the PSD and the normalized frequency increases when we compare with the 72 and 162 sub carries. So, it is more affected to inter symbol interference than 72 and 162 subcarriers. Therefore, its power spectral density is less efficient compared to the 72 and 162 subcarriers.

Fig.4.37 below shows that the PSD of OFDM with filter length equal to 43, number of FFT equal to 512, and cyclic prefix equal to 43 for 72 subcarriers with the selected SNR value of 8dB and 16QAM.

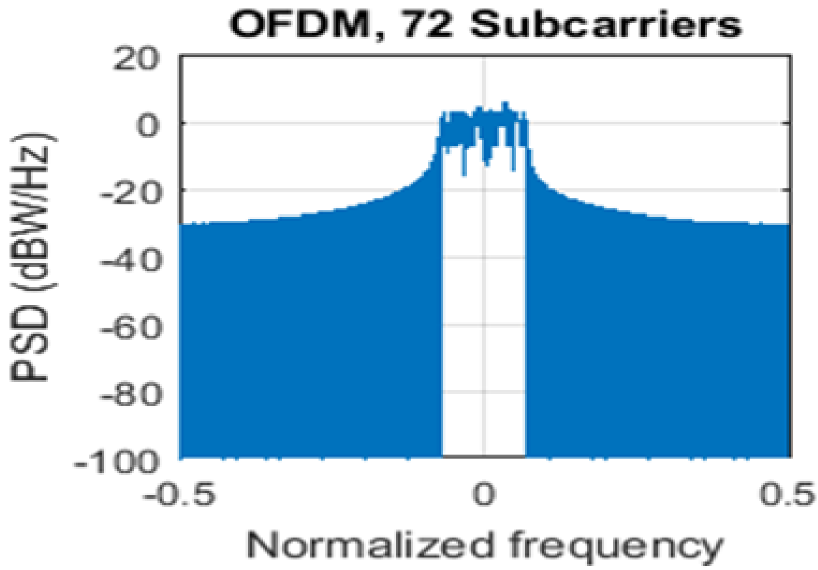

Figure 4.37 PSD of OFDM with 72 subcarriers

Fig.4.37 shows the PSD for 72 subcarriers. The required bandwidth range is approximately covered between the normalized frequency of -0.05 and 0.05. Outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in this figure the PSD of OFDM is 0dBW/Hz which consists of around -30dBW/Hz side lobes.

Fig.4.38 below shows the PSD of OFDM with increasing the cyclic prefix to 114, number of FFT equal to 512, for 72 subcarriers with the selected SNR value of 8dB and 16QAM.

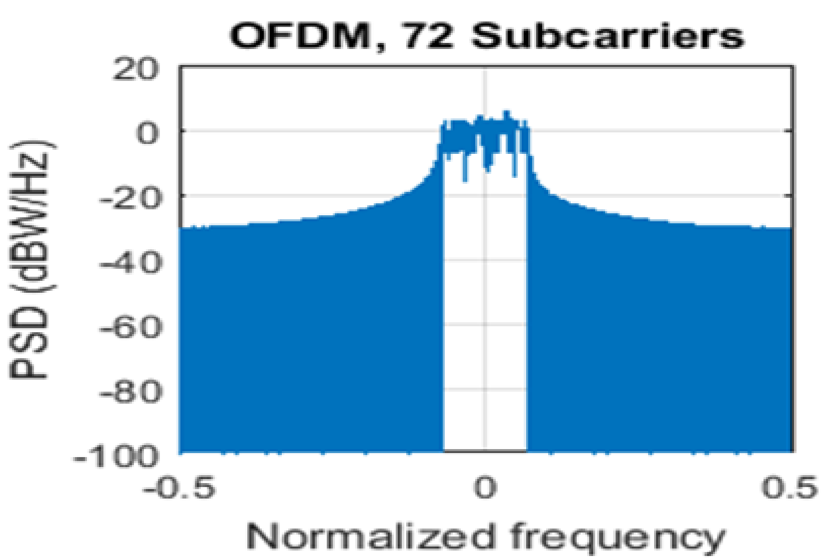

Figure 4.38 PSD of OFDM with cyclic prefix 114

As shown in Fig.4.38, the required bandwidth range is approximately covered between the normalized frequency of -0.05 and 0.05 which is the same as with cyclic prefix equal to 43 as shown in Fig.4.37. Outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.65, the PSD of OFDM is 0dBW/Hz which consists of around -30dBW/Hz side lobes. This shows that the PSD of OFDM is not changed with increasing or decreasing the cyclic prefix length.

Fig.4.39 below shows the PSD of OFDM with cyclic prefix equal to 43, number of FFT increased to 1024 for 6 sub bands, each sub band having 12 subcarriers with the selected SNR value of 8dB and 16QAM.

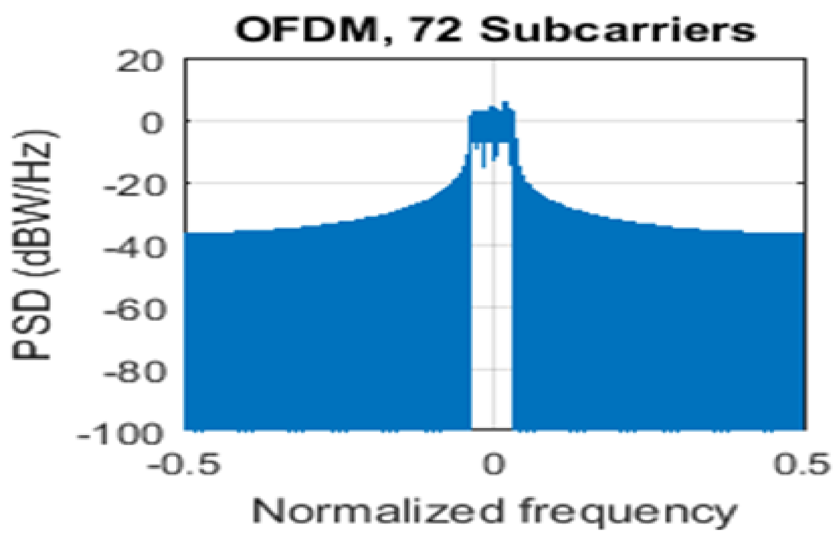

Figure 4.39 PSD of OFDM with number of FFT 1024

As shown in Fig.4.39 the PSD for 72 subcarriers, the required bandwidth range is approximately covered between the normalized frequency of -0.03 and 0.03 which is smaller than with number of FFT 512 as shown in Fig.4.64. Outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.38 the PSD of OFDM is 0dBW/Hz which consists of around -35dBW/Hz side lobes. This shows that the PSD of OFDM with number of FFT 1024 side lobes is lower than number of FFT 512 as shown in Fig.4.37 and Fig.4.39. This shows that, the PSD of OFDM is more efficient with increasing number of FFT.

Fig.4.40 below shows the PSD of OFDM with 450 subcarriers, filter length equal to 43 and number of FFT 1024.

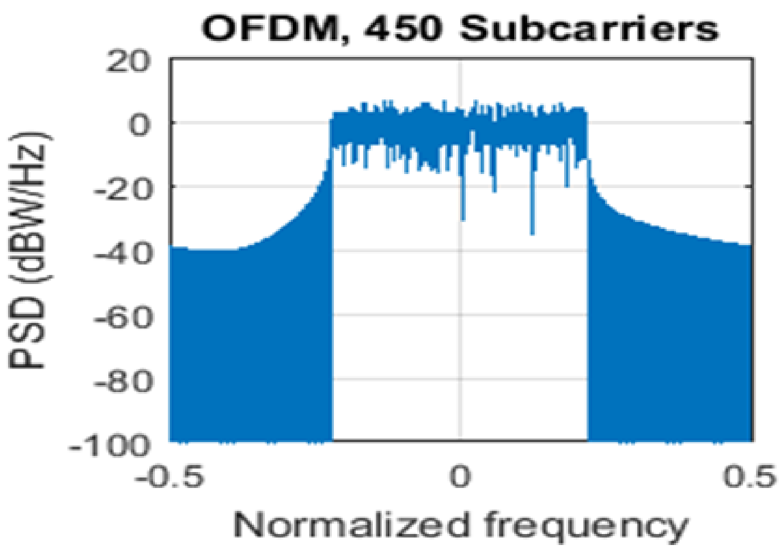

Figure 4.40 PSD of OFDM with 450 subcarriers

As shown in Fig.4.40 the PSD of OFDM for 450 subcarriers, the required bandwidth range is approximately covered between the normalized frequency of around -0.3 and 0.3 which is larger than with number of subcarriers equal to 72 as shown in Fig.4.39. Outside of this range of frequency is unwanted because it leads to inter symbol interference. As shown in Fig.4.38 the PSD of OFDM is 0dBW/Hz which consists of around -40dBW/Hz side lobes. This shows that the PSD of OFDM with number of subcarriers equal to 450 the side lobes is lower than number of subcarriers equal to 72 as shown in Fig.4.39 and Fig.4.40. This shows that, the PSD of OFDM is more efficient with increasing number of subcarriers.

4.1.2. Power Spectral Density Results Discussion

Fig.4.26 to Figure 4.31 of FBMC shows that, with decreasing number of FFT the strength of the PSD of FBMC or the side lobe of FBMC is closer to the normalized frequency and it decreases the occupied bandwidth. With decreasing the guard bands, the gap between the strength of the PSD of FBMC and normalized frequency increases. Therefore, FBMC is more affected to inter symbol interference with decreasing the guard bands. And with decreasing the overlapping factor the gap between the PSD and normalized frequency increases. Please note that for the overlapping factor equal to two the gap between the PSD and normalized frequency is extremely increased. Therefore, the FBMC with this overlapping factor is extremely affected to inter symbol interference.

Fig.4.32 to Fig.4.36 of UFMC shows that, the PSD of UFMC with increasing number of sub bands and subcarriers or with increasing total number of subcarriers the gap between the PSD of UFMC and the normalized frequency is increased. And also, the range of frequency occupied by the transmitted signal or in other words its bandwidth is increased. This shows that, the amount of power within the bandwidth increases with increasing the number of sub bands and subcarriers. Therefore, UFMC is more affected to inter symbol interference with increasing number of subcarriers. But, with decreasing the filter length and with increasing the number of FFT the gap between the PSD of UFMC and the normalized frequency is decreased. Thus, UFMC is less affected to inter symbol interference with decreasing the filter length and with increasing the number of FFT.

Fig.4.37 to Fig.4.40 of OFDM shows that, the PSD of OFDM with increasing number of FFT the gap between the PSD of OFDM and the normalized frequency is decreased. Therefore, OFDM is less affected to inter symbol interference with increasing number of FFT. It also shows that with increasing number of subcarriers the gap between the PSD of OFDM and the normalized frequency is decreased. So, OFDM is less affected to inter symbol interference with increasing number of subcarriers.

If the strength of the PSD is closer to the normalized frequency the modulation's spectral density is efficient because it is less affected to the inter symbol interference. In all cases of this study, FBMC is more close to the normalized frequency than OFDM and UFMC. Therefore, the spectral density of FBMC is greater than that of the OFDM and UFMC. Thus, FBMC is more preferable in order to minimize the inter symbol interference than OFDM and UFMC. But, the PSD of UFMC is greater than the PSD of OFDM.

The analysis also shows that the PSD of FBMC can be improved by increasing guard bands, increasing overlapping symbols, and decreasing number of FFT. In the case of UFMC, its PSD can be enhanced by decreasing filter length, increasing number of FFT, and decreasing number of subcarriers. The PSD of OFDM can also be improved by increasing number of FFT and by increasing number of subcarriers.

4.3. Peak to Average Power Ratio

The peak to average power ratio is the peak amplitude squared divided by the RMS value squared power. It plays a vital role in signal processing applications. The system is more efficient if the PAPR is less. However, the modulation techniques with multiple inputs have higher PAPR, whereas those with single input have lower PAPR. The following comparative analysis of FBMC, UFMC, and OFDM has been done for 200 subcarriers for different or various types of mapping schemes, such as 4QAM, 16QAM, 64QAM, and 256QAM. Therefore, the MATLAB simulation results for 200 subcarriers of FBMC with 11dB SNR value and also for UFMC and OFDM with 8dB SNR value is listed out in the following tables.

TABLE 4.5 PAPR VALUES FOR NUMBER OF FFT 512

Mapping scheme	**FBMC**	**UFMC**	**OFDM**
4QAM	9.6503 dB	9.04 dB	8.4377 dB
16QAM	8.7711 dB	8.2379 dB	8.8843 dB
64QAM	8.1743 dB	8.6229 dB	9.9269 dB
256QAM	9.3654 dB	8.0416 dB	7.2553 dB

As shown in Table 4.5 FBMC has minimum PAPR value at 64QAM which is 8.1743dB for number of bits per subcarriers equal to six. Whereas, UFMC and OFDM have minimum PAPR values at 256QAM which is 8.0416dB and 7.2553dB respectively. In this case, OFDM has minimum PAPR value when compared with FBMC and UFMC. So, OFDM is efficient for number of FFT equal to 512 than FBMC and UFMC with 256QAM mapping scheme for number of bits per subcarriers equal to eight and number of FFT equal to 512.

TABLE 4.6 PAPR VALUES FOR NUMBER OF FFT 1024

Mapping scheme	**FBMC**	**UFMC**	**OFDM**
4QAM	9.3883 dB	7.7732 dB	8.4377 dB
16QAM	8.8375 dB	8.2967 dB	8.8843 dB
64QAM	8.9976 dB	9.6202 dB	9.9269 dB
256QAM	8.9561 dB	7.5373 dB	7.4133 dB

As shown in Table 4.6, FBMC has minimum PAPR value at 16QAM which is 8.8375dB for number of bits per subcarriers equal to four. Whereas, UFMC and OFDM have minimum PAPR value at 256QAM which is 7.5373dB and 7.4133dB respectively. In this case, OFDM has minimum PAPR value when compared with FBMC and UFMC. So, OFDM is efficient for number of FFT equal to 1024 than FBMC and UFMC with 256QAM mapping scheme for number of bits per subcarriers equal to eight and number of FFT equal to 1024.

TABLE 4.7 PAPR VALUES FOR NUMBER OF FFT 2048

Mapping scheme	FBMC	UFMC	OFDM
4QAM	9.501 dB	8.1008 dB	8.5165 dB
16QAM	10.3033 dB	8.0195 dB	8.8843 dB
64QAM	9.754 dB	9.2209 dB	9.9269 dB
256QAM	10.3408 dB	7.3563 dB	7.4833 dB

As shown in Table 4.7 FBMC has minimum PAPR value at 4QAM which is 9.501dB for number of bits per subcarriers equal to two. Whereas, UFMC and OFDM have minimum PAPR values at 256QAM which is 7.3563dB and 7.4833dB respectively. In this case, UFMC has minimum PAPR value when compared with FBMC and OFDM. So, UFMC is efficient for number of FFT equal to 2048 other than FBMC and OFDM with 256QAM mapping scheme for number of bits per subcarriers equal to eight and number of FFT equal to 1024.

4.1.3. Peak to Average Power Ratio Results Discussion

As shown in Table 4.5 of PAPR values with number of FFT equal to 512; for FBMC the PAPR value is decreasing with increasing number of bits per subcarrier except for the number of subcarriers equal to eight at which point it increases again although it is smaller than the PAPR value with two bits per subcarrier. In FBMC 64QAM has minimum PAPR value with number of FFT equal to 512 as compared with UFMC and OFDM of 64QAM mapping scheme. In the case of UFMC, the PAPR values haven't shown continuity behavior with increasing number of bits per subcarriers. In other words, it decreases the PAPR value with 16QAM as compared with 4QAM and it increases in 64QAM as compared with 16QAM. 256QAM has minimum PAPR value for UFMC with number of FFT equal to 512. In OFDM, the PAPR value is increasing with increasing number of subcarriers except for 256QAM (with eight bits per subcarriers). And it has minimum PAPR value with this mapping scheme (256QAM) as compared with all modulation techniques. UFMC is efficient as compared with FBMC except for 64QAM. With 64QAM, FBMC is efficient as compared with both UFMC and OFDM.

As shown in Table 4.6 of PAPR values with number of FFT equal to 1024; for FBMC the PAPR values haven't shown continuity behavior with increasing number of bits per subcarriers. In other words, it decreases the PAPR value with 16QAM as compared with 4QAM and it increases in 64QAM as compared with 16QAM. Thus, 16QAM has minimum PAPR value. FBMC is efficient in 64QAM with number of FFT equal to 1024. In UFMC and OFDM, the PAPR value is increasing with increasing number of subcarriers except for 256QAM (with eight bits per subcarriers). And they have minimum PAPR value with this mapping scheme (256QAM). Meaning they are efficient with 256QAM even as compared with FBMC.

As shown in Table 4.7 of PAPR values with number of FFT equal to 2048; for FBMC the PAPR values haven't shown continuity behavior with increasing number of bits per subcarriers. In other words, it increases the PAPR value with 16QAM as compared with 4QAM and it decreases in 64QAM as compared with 16QAM and it increases in 256QAM. In this case, 4QAM has minimum PAPR value. Thus, FBMC is efficient with 4QAM. In UFMC, it decreases the PAPR value with 16QAM as compared with 4QAM and it increases in 64QAM as compared with 16QAM after that it decreases in 256QAM. Thus, at 256QAM UFMC is efficient with number of FFT equal to 2048 even as compared with FBMC. Because, it has minimum PAPR value with this mapping scheme. In OFDM, the PAPR value is increasing with increasing number of bits per subcarrier except for the number of subcarriers equal to eight. Thus, at 256QAM it has minimum PAPR value.

Generally, the system can be efficient by using either 64QAM for number of FFT equal to 512, or by using 16QAM for number of FFT equal to 1024, or by using 4QAM for number of FFT equal to 2048 for FBMC. Moreover, for UFMC and OFDM use 256QAM with number of FFT 512, number of FFT 1024, and number of FFT 2048.

4.4. Bit Error Rate

The BER of each modulation techniques were simulated by using parameters that yield the best performance of SE, PSD, and PAPR as depicted in Section 4.1, 4.2 and 4.3 of this Chapter. Thus, to simulate the BER of FBMC the following system parameters have been considered.

TABLE 4.8 SIMULATION PARAMETER VALUES OF FBMC FOR BER

Simulation Parameters	**Value**
Overlapping symbols, K	4
Number of FFT points (N_{FFT})	512
Guard bands on both sides	212
Number of symbols	100
Bits per subcarrier, m	2 (4QAM)
Signal to noise ratio (SNR)	12dB

To simulate the BER of UFMC and OFDM for the initial condition the following system parameters have been considered.

TABLE 4.9 SIMULATION PARAMETER VALUES OF UFMC AND OFDM FOR BER

Simulation Parameters	**Value**
Number of Subcarriers	288
Number of FFT points (N_{FFT}) for OFDM	1024
Number of FFT points (N_{FFT}) for UFMC	512
Filter length for UFMC	43
Cyclic prefix length for OFDM	43
Number of symbols	200
Bits per subcarrier, m	4 (16QAM)
Signal to noise ratio (SNR)	15dB

The BER versus SNR of the modulation techniques with the above parameters becomes as follows.

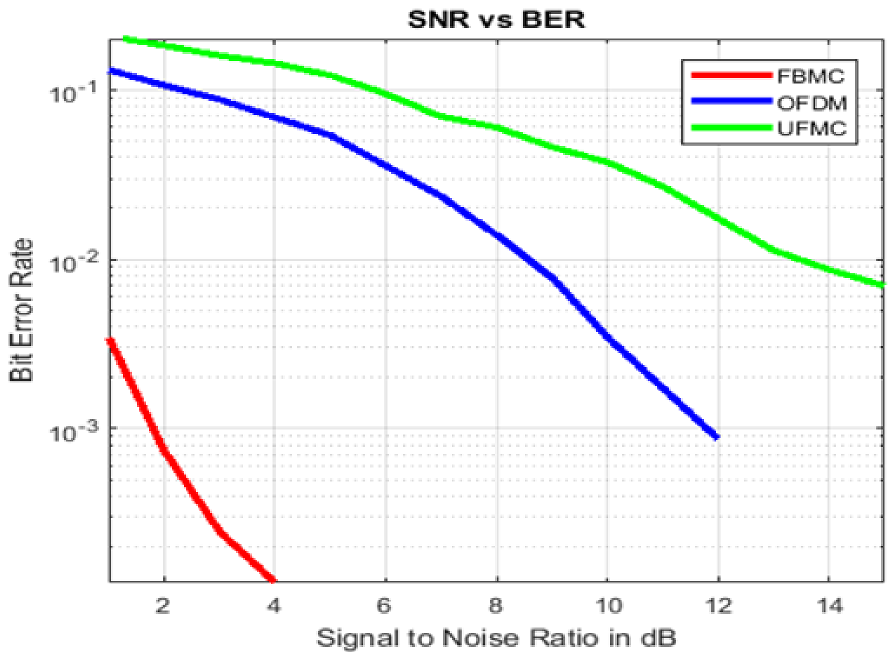

Figure 4.41 BER versus SNR of FBMC, OFDM, and UFMC

As shown in Fig.4.41 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero for SNR value of 4dB and it is small as compared with OFDM and UFMC which are closer to 10^{-1}. Whereas, the BER value of OFDM is small as compared with UFMC. In this case, FBMC shows best performance than OFDM and UFMC. OFDM also shows better performance than UFMC.

Fig.4.42 below shows the BER versus SNR of FBMC, OFDM, and UFMC with increasing the number of FFT of FBMC to 1024.

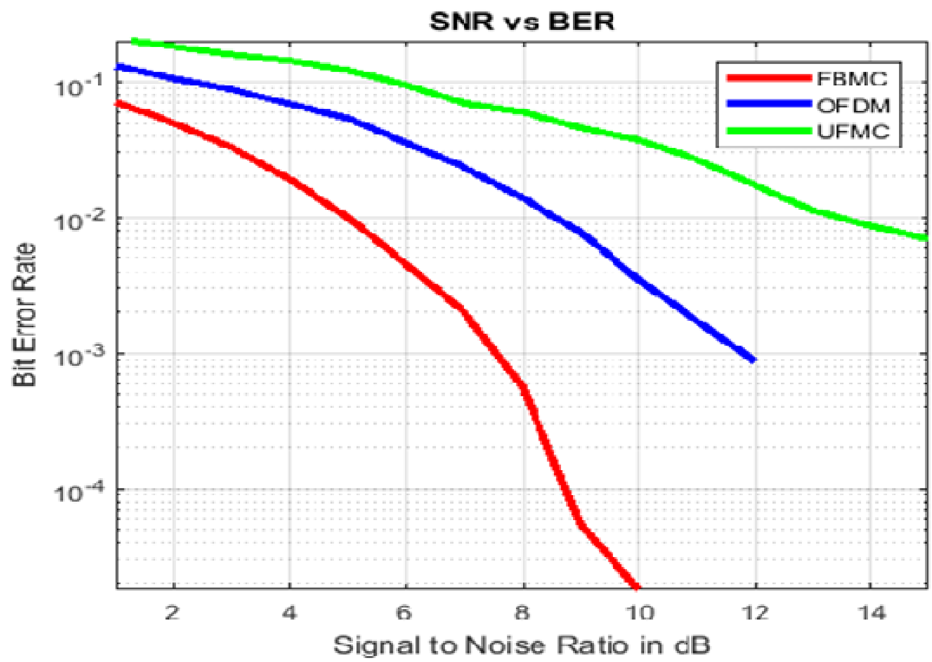

Figure 4.42 BER with increasing number of FFT of FBMC to 1024

Fig.4.42 shows the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero at around 10dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of OFDM is small as compared with UFMC. In this case also, FBMC shows as best performance than OFDM and UFMC. However, as compared with Fig.4.41 the BER value of FBMC increases with increasing number of FFT. In other words, FBMC has less performance with increasing number of FFT. OFDM also shows better performance than UFMC.

Fig.4.43 below shows the BER versus SNR of FBMC, OFDM, and UFMC with decreasing number of guard bands to 102.

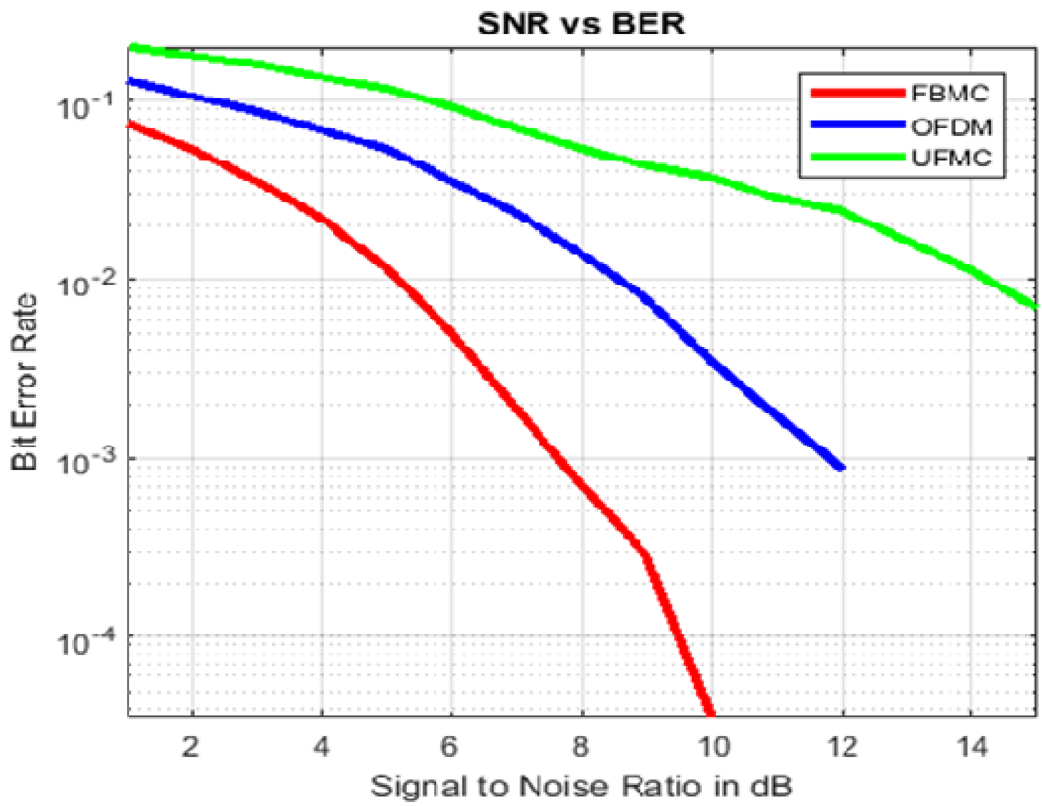

Figure 4.43 BER with decreasing number of guard bands of FBMC to 102

As shown in Figure 4.43 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero around 10dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of OFDM is small as compared with UFMC. In this case also, FBMC shows best performance than OFDM and UFMC. However, as compared with Fig.4.41, the BER value of FBMC increases with increasing number of FFT. In other words, FBMC has less performance with decreasing number of guard bands. OFDM also shows better performance than UFMC.

Fig.4.44 below shows the BER versus SNR of FBMC, OFDM, and UFMC with increasing number of FFT of OFDM to 2048.

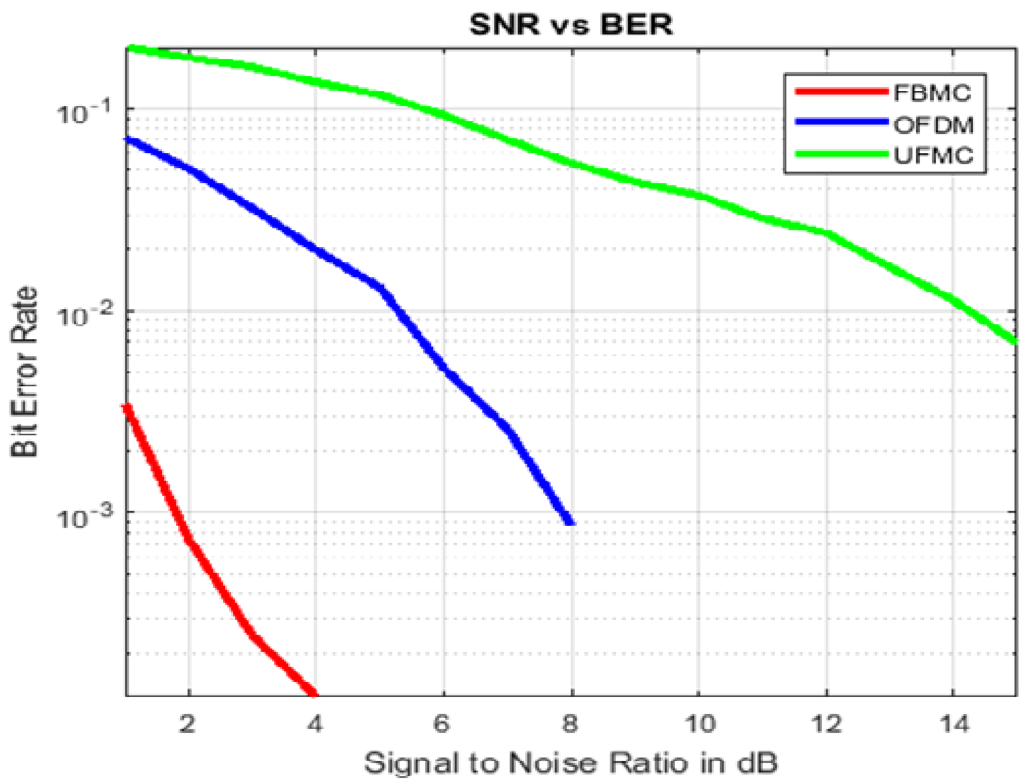

Figure 4.44 BER with number of FFT of OFDM to 2048

As shown in Fig.4.44 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero around 4dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of OFDM is small as compared with UFMC. In this case also, FBMC shows as best performance than OFDM and UFMC. However, OFDM also shows better performance than UFMC. Moreover, as compared with Figure 4.41 the BER value of OFDM is decreasing with increasing number of FFT. In other words, OFDM has better performance with increasing number of FFT.

Fig.4.45 below shows the BER versus SNR of FBMC, OFDM, and UFMC with increasing number of subcarriers to 512 with sub band size of 16 and each sub band contains 36 subcarriers.

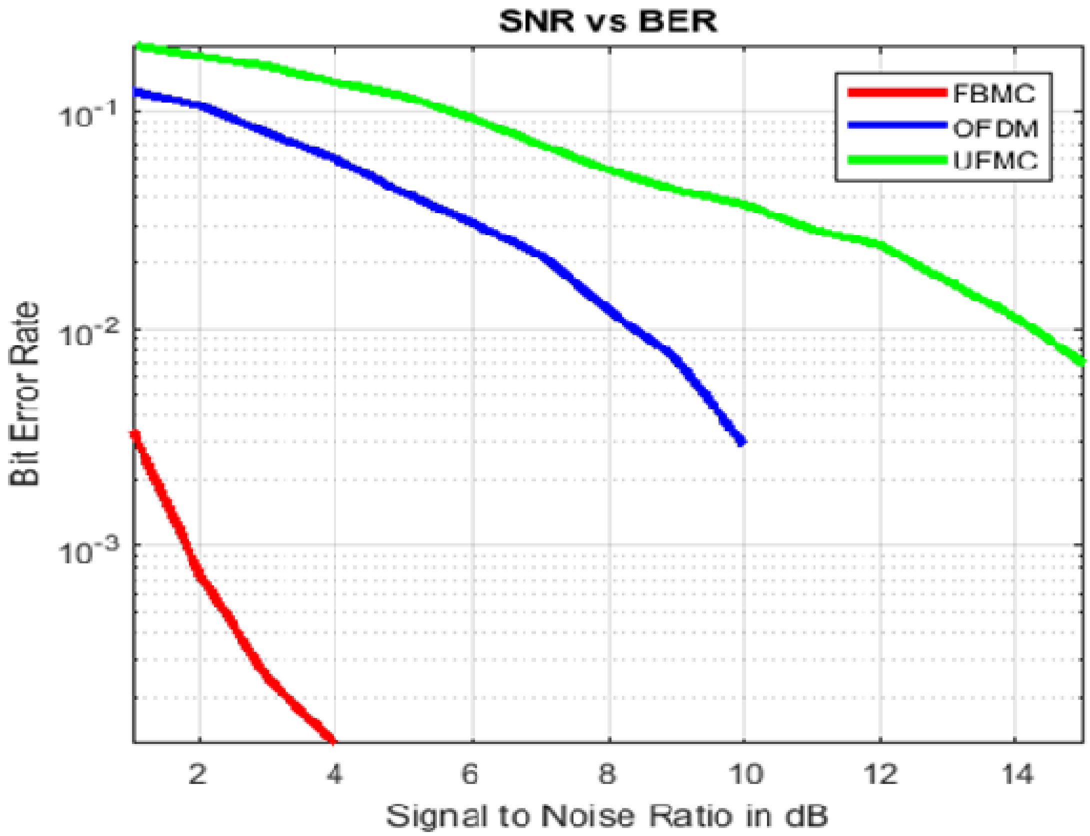

Figure 4.45BER with number of subcarriers to 512

As shown in Fig.4.45 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero around 4dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of OFDM is small as compared with UFMC. In this case also, FBMC shows best performance than OFDM and UFMC. However, OFDM also shows better performance than UFMC. Moreover, as compared with Fig.4.41 and Fig.4.45 the BER value of OFDM increases with increasing number of subcarriers. In other words, OFDM has less performance with increasing number of subcarriers.

Fig.4.46 below shows the BER of FBMC, OFDM, and UFMC with decreasing number of subcarriers of UFMC to 128 with sub band size of 8 and each sub band contains 16 subcarriers.

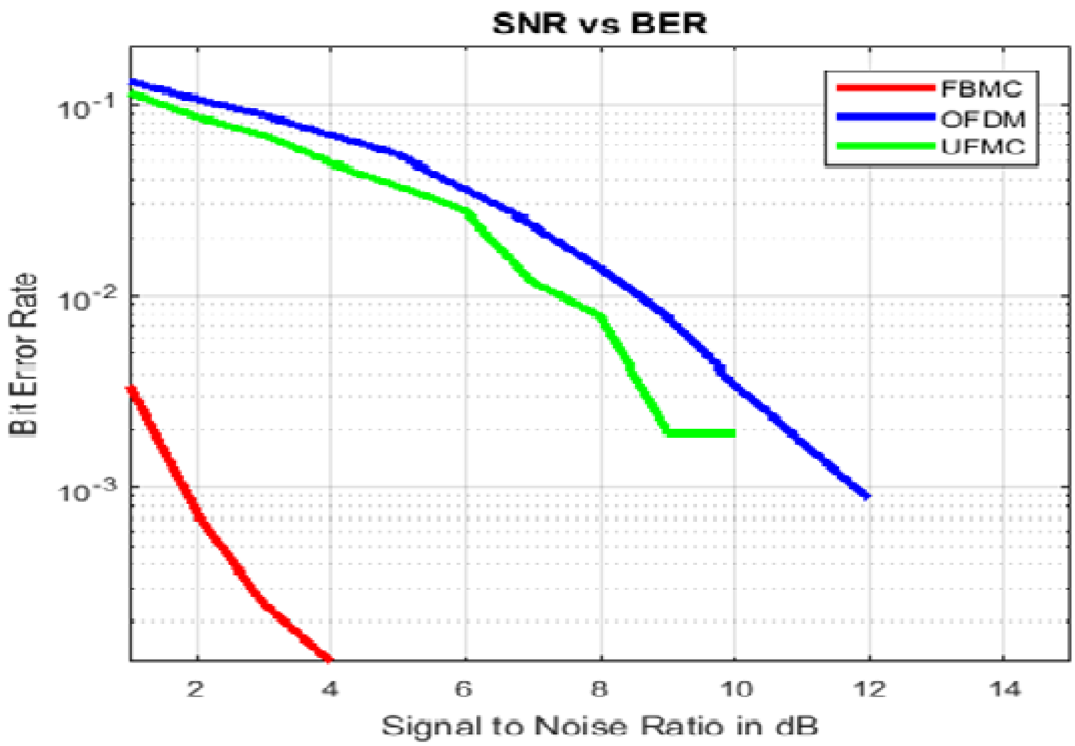

Figure 4.46 BER with decreasing number of subcarriers of UFMC to 128

As shown in Fig.4.73 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero from 4dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of UFMC is small as compared with OFDM. Thus, FBMC shows best performance than OFDM and UFMC. However, UFMC shows that better performance than OFDM. Moreover, as compared with Fig.4.41 the BER value of UFMC is reduced with decreasing number of subcarriers. In other words, UFMC has better performance with decreasing number of subcarriers.

Fig.4.47 below shows the BER of FBMC, OFDM, and UFMC with increasing number of FFT of UFMC to 1024.

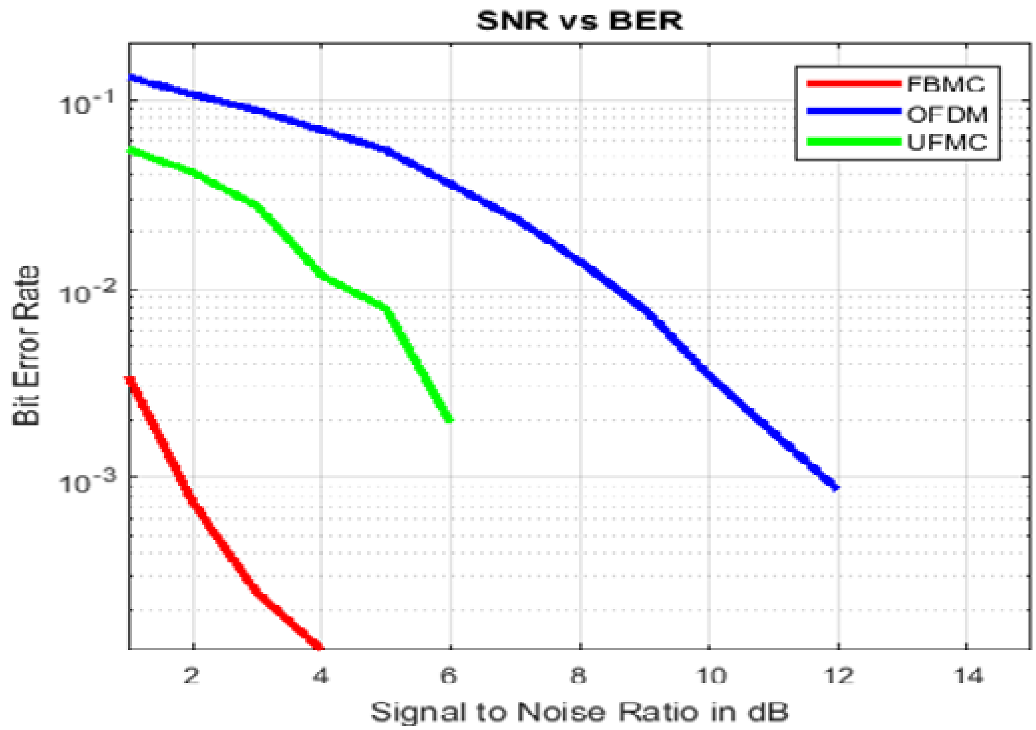

Figure 4.47 BER with increasing number of FFT of UFMC to1024

As shown in Fig.4.47 of the BER versus SNR graphs of FBMC, OFDM, and UFMC; the BER value of each modulation technique is decreasing with increasing SNR value. The BER value of FBMC is closer to zero around 4dB and it is small as compared with OFDM and UFMC. Whereas, the BER value of UFMC is small as compared with OFDM. Thus, FBMC shows best performance than OFDM and UFMC. However, UFMC shows that better performance than OFDM. Moreover, as compared with Fig.4.41 the BER value of UFMC is reduced with increasing number of FFT. In other words, UFMC has better performance with increasing number of FFT.

4.1.4. Bit Error Rate Results Discussion

In all simulation result graphs of BER versus SNR, Fig.4.41 to Fig.4.47 the red color represents for the BER of FBMC, the blue color represents for the BER of OFDM, and the green color represents for the BER of UFMC. In all cases of the graph, the BER value is decreasing with increasing SNR value. In addition to this, the BER graph of FBMC is closer to zero before

OFDM and UFMC; and it has the smallest BER value than OFDM and UFMC. Thus, FBMC has the best performance as compared to OFDM and UFMC.

As shown in Fig.4.42 and Fig.4.43 the BER value of FBMC can be improved by decreasing number of FFT and by increasing guard bands. And the BER value of OFDM can be enhanced by increasing number of FFT and by decreasing number of subcarriers. Moreover, the BER value of UFMC can also improve by decreasing number of subcarriers and by increasing the number of FFT.

5 CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The goal of this research is to obtain the comparative analysis of 5G modulation schemes, that is Filter Bank Multi-Carrier (FBMC), Universal Filter Multi-Carrier (UFMC), and Orthogonal Frequency Division multiplexing (OFDM) which are candidate waveforms in 5G communications, in terms of parameters of Spectral Efficiency, power Spectral Density, Peak to Average Power Ratio, and Bit Error Rate. To perform this comparative analysis, we chose to use a system model for UFMC from [6], FBMC from [7], and OFDM from [28].

The SE comparative analysis is done first by developing a MATLAB code. After that, evaluation of the SE characteristics at different filter length, bits per subcarrier, number of FFT, overlapping factor is implemented.

The comparative analysis of PSD is done first with finding the best mapping scheme by comparing BER and PAPR values at 5dB SNR value for FBMC whereas 10dB SNR values for both UFMC and OFDM using MATLAB simulation result. This results 4QAM for FBMC, 16QAM for UFMC and OFDM. By taking into account these mapping schemes for each modulation techniques, the BER is evaluated at different SNR values starting from 1dB till the SNR value gives zero BER. The result shows that, FBMC BER value becomes zero starting from SNR value of 11dB; whereas UFMC and OFDM starts from SNR value of 8dB. To compensate the BER value and PAPR value of the modulation techniques 11dB SNR value is selected for FBMC whereas 8dB SNR value for both UFMC and OFDM for comparison purpose. After that, the effect of those modulation techniques at different values of number of FFT, guard bands, overlapping factor, and number of symbols for FBMC; at different number of subcarriers, number of FFT, and filter length for UFMC; at different number of subcarriers, number of FFT, and cyclic prefix for OFDM is analyzed.

The comparative analysis of PAPR has been done for 200 subcarriers with different number of FFT and by applying various types of QAM mapping schemes with the appropriate selection of

SNR for each modulation techniques. That is 11dB SNR value for FBMC and 8dB SNR value for both UFMC and OFDM.

The BER comparative analysis of the modulation techniques is implemented by varying number of FFT, number of subcarriers, and guard bands for the appropriate selection of the remaining parameters.

In all cases of this study, the simulation result of the SE shows that the SE of the OFDM and UFMC is greater than the SE of FBMC for small value of burst durations but for larger burst durations the SE of FBMC is greater than the SE of OFDM and UFMC. If the filter length is equal to the cyclic prefix samples plus one, the SE of OFDM is exactly the same as with the SE of UFMC. However, if the filter length is greater than the cyclic prefix by more than one, the SE of OFDM is greater than the SE of UFMC. Whereas, if the number of cyclic prefix samples is greater than or equal to the filter length, the SE of UFMC is greater than the SE of OFDM.

To effectively use these modulation techniques, apply UFMC under very tight response time requirements such as for car-to-car communications and for small burst duration communication such as for machine to machine communications, transporting temperature sensor data, and smart phone functionalities which is sporadically transmitting very small packets. Whereas for transmitting long sequences FBMC is very efficient, it suffers when having to transmit short bursts/frames. OFDM is rather inefficient due to wide frequency guards and the cyclic prefix.

The SE of FBMC can be improved by increasing the number of bits per subcarrier, by increasing burst duration, and by decreasing overlapping factor. The SE of UFMC can also be improved by decreasing the filter length, by increasing bits per subcarrier, and by increasing the number of FFT. The SE of OFDM can also be enhanced by increasing bits per subcarrier, by increasing number of FFT, and by decreasing cyclic prefix samples.

The PSD strength of FBMC is closer to the normalized frequency than UFMC and OFDM, which results the spectral density of FBMC is greater than that of the UFMC and OFDM. The results also show that, the PSD strength of OFDM is more far from the normalized frequency than FBMC and UFMC. Thus, OFDM is highly affected to inter symbol interference. From these finding we conclude that FBMC is more preferable to minimize the opportunity of inter symbol interference.

The PSD of FBMC can be improved by increasing guard bands, increasing overlapping symbol, and decreasing number of FFT. By decreasing the number of subcarriers, increasing number of FFT, and decreasing filter length the PSD of UFMC can be improved. The PSD of OFDM can also be enhanced by increasing the number of FFT and by increasing number of subcarriers.

The PAPR values with different number of FFT and various types of mapping scheme UFMC and OFDM have minimum PAPR value than FBMC. The system can be efficiently use by using 64QAM for number of FFT equal to 512, by using 16QAM for number of FFT equal to 1024, and by using 4QAM for number of FFT equal to 2048 in the case of FBMC. For UFMC and OFDM use 256QAM with number of FFT 512, number of FFT 1024, and number of FFT 2048.

The BER value of FBMC is closer to zero before OFDM and UFMC and it has the smallest BER value than OFDM and UFMC. Thus, FBMC has the best performance as compared to OFDM and UFMC. The BER value of FBMC can be improved by decreasing number of FFT and by increasing the guard bands. And the BER value of OFDM can be enhanced by increasing number of FFT and by decreasing number of subcarriers. Moreover, the BER value of UFMC can also be improved by decreasing number of subcarriers and by increasing the number of FFT.

5.2. Recommendations

To choose or select the best modulation schemes for 5G networks the following recommendations are suggested:

i. Study the comparative analysis of UFMC, OFDM, and FBMC in terms of other parameters which are not covered with this study such as computational complexity, and delay.
ii. Study the comparative analysis of the remaining types of modulations such as f-OFDM, GFDM, etc. in terms of different parameters such as spectral efficiency, power spectral density, computational complexity, and delay.

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