

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE  
MINISTERE DE L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE SCIENTIFIQUE



**UNIVERSITY OF MOHAMED BOUDIAF - M'SILA  
TECHNOLOGY FACULTY  
ELECTRONICS DEPARTMENT**



**End of study memory  
Presented for the graduation of MASTER  
Domain: Electronics  
Field: Telecommunications  
Specialty: Telecommunications systems  
By: Cheriat Mohamed Achraf  
Ziam Saad Eddine**

**THEME**

**Filter Bank Multicarrier Modulation Techniques for 5G  
Communication Systems**

**Publicly supported on: 18/06/2025 before the jury composed of:**

<b>Dr. Benmeddour Fadila</b>	<b>University of M'sila</b>	<b>President</b>
<b>Dr. ZERDOUMI Zohra</b>	<b>University of M'sila</b>	<b>Supervisor</b>
<b>Dr. LALAOUI Lahouaoui</b>	<b>University of M'sila</b>	<b>Examiner</b>

**Promotion: 2024 /2025**

# ***Acknowledgments***

*At the end of this modest work, we would like to thank Almighty **Allah** for granting us the strength, health, and willpower to complete this project, which would not have been possible without the help and encouragement of several people, whom we thank.*

*We would like to express my deep gratitude to our supervisor, **Dr. Zerdoumi Zohra**, for her availability, advice, generosity, encouragement, and invaluable assistance.*

*We also thank **the jury members** who honored us with judging our work.*

*Sincere thanks to:*

*All **teachers** in the Electronic Department.*

*All **staff** at University of Mohamed Boudiaf.*

*Finally, a sincere thank you to all those who contributed directly or indirectly to the development of this modest work.*

# *Dedication*

*I dedicate this thesis to my dear parents, who can be proud of me and find here the result of long years of sacrifice and deprivation for their help in helping me move forward in my life.*

*No dedication, no words could express their true values, the gratitude and love they have for us. Every line of this thesis, every word and every letter, expresses gratitude, respect, and esteem to them.*

*Thanks to Allah, that they are my parents.*

- *To my sisters and brothers.*
- *To those who have always been by in my side.*
- *To my extended family, especially my loved ones, my friends, and all those who encourage me to carry out this modest work, from near or far.*
- *To all the students of our class, may each find our sincere friendship through these lines.*

*Cheriat Mohamed Achraf*

# *Dedication*

*I dedicate this thesis to my dear parents, who can be proud of me and find here the result of long years of sacrifice and deprivation for their help in helping me move forward in my life.*

*No dedication, no words could express their true values, the gratitude and love they have for us. Every line of this thesis, every word and every letter, expresses gratitude, respect, and esteem to them.*

*Thanks to Allah, that they are my parents.*

- *To my sisters and brothers.*
- *To those who have always been by in my side.*
- *To my extended family, especially my loved ones, my friends, and all those who encourage me to carry out this modest work, from near or far.*
- *To all the students of our class, may each find our sincere friendship through these lines.*

*Ziam Saad Eddine*

## Abstract

This thesis investigates multicarrier modulation techniques for 5G telecommunications, comparing Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier (FBMC). It addresses 4G limitations, such as spectral efficiency and interference, and evaluates FBMC's potential for 5G. Using MATLAB simulations, the study compares power spectral density (PSD), peak-to-average power ratio (PAPR), and bit error rate (BER). Results show FBMC's superior spectral efficiency and lower PAPR, positioning it as a strong 5G candidate, though OFDM's simplicity is advantageous in some cases. Future research on FBMC is recommended to optimize 5G performance.

**Key words:** 5G, multicarrier modulation, OFDM, FBMC and Spectral Efficiency.

## الملخص

تتناول هذه الأطروحة تقنيات التعديل متعدد الحاملات لاتصالات الجيل الخامس (5G)، مقارنة بين تعديل تقسيم التردد المتعامد (OFDM) وتعديل بنك الفلاتر متعدد الحاملات (FBMC) تعالج قيود الجيل الرابع، مثل كفاءة الطيف والتداخل، وتقيم إمكانات FBMC للجيل الخامس. باستخدام محاكاة MATLAB، تقارن الدراسة كثافة الطيف الطاقوي (PSD)، نسبة الذروة إلى المتوسط للطاقة (PAPR)، ومعدل خطأ البت (BER) تظهر النتائج تفوق FBMC في كفاءة الطيف وانخفاض PAPR، مما يجعلها مرشحة قوية للجيل الخامس، رغم أن بساطة OFDM مفيدة في بعض الحالات. يوصى بإجراء بحوث مستقبلية حول FBMC لتحسين أداء الجيل الخامس.

**الكلمات المفتاحية:** تعديل متعدد الحاملات، كفاءة الطيف، مرشحات متعددة الموجات الحاملة، الجيل الخامس، إرسال متعدد بتقسيم التردد المتعامد.

## Résumé

Cette thèse examine les techniques de modulation multi porteuse pour les télécommunications 5G, comparant le multiplexage par répartition orthogonale de la fréquence (OFDM) et la modulation multi porteuse à banc de filtres (FBMC). Elle aborde les limites de la 4G, telles que l'efficacité spectrale et les interférences, et évalue le potentiel du FBMC pour la 5G. À l'aide de simulations MATLAB, l'étude compare la densité spectrale de puissance (PSD), le rapport crête-à-moyenne (PAPR) et le taux d'erreur binaire (BER). Les résultats montrent une meilleure efficacité spectrale et un PAPR plus faible pour le FBMC, le positionnant comme un candidat solide pour la 5G, bien que la simplicité de l'OFDM soit avantageuse dans certains cas. Des recherches futures sur le FBMC sont recommandées pour optimiser les performances de la 5G.

**Les mots clés :** 5G, Modulation Multi porteuse, OFDM, FBMC, et Efficacité Spectrale.

---



---

**Table of content**

<b>ACKNOWLEDGMENTS.....</b>	<b>I</b>
<b>DEDICATION.....</b>	<b>II</b>
<b>ABSTRACT .....</b>	<b>IV</b>
<b>LIST OF FIGURES.....</b>	<b>VIII</b>
<b>LIST OF TABLES.....</b>	<b>X</b>
<b>LIST OF ABBREVIATIONS.....</b>	<b>XI</b>
<b>GENERAL INTRODUCTION .....</b>	<b>1</b>
<b>Chapter 1: Generalities on 5G Telecommunications</b>	
<b>1.1 INTRODUCTION.....</b>	<b>2</b>
<b>1.2 MULTIPATH PROPAGATION AND INTERFERENCE .....</b>	<b>2</b>
<b>1.2.1 CAUSES AND EFFECTS OF MULTIPATH PROPAGATION.....</b>	<b>4</b>
<b>1.2.1.1 CAUSES .....</b>	<b>4</b>
<b>1.2.1.2 EFFECTS.....</b>	<b>5</b>
<b>1.2.2 DOPPLER SHIFT AND MOBILITY IMPACT ON TRANSMITTED SIGNALS .....</b>	<b>5</b>
<b>1.2.2.1 DOPPLER SHIFT.....</b>	<b>5</b>
<b>1.2.2.2 IMPACT OF MOBILITY.....</b>	<b>5</b>
<b>1.2.3 INTERFERENCE TYPES IN DIGITAL COMMUNICATION .....</b>	<b>6</b>
<b>1.3 EVOLUTION OF TELECOMMUNICATION GENERATIONS (1G TO 5G AND BEYOND).....</b>	<b>8</b>
<b>1.4 NECESSITY OF MULTICARRIER MODULATION .....</b>	<b>12</b>
<b>1.4.1 SINGLE-CARRIER MODULATION .....</b>	<b>13</b>
<b>1.4.2 PRINCIPLE OF MULTI CARRIER MODULATION.....</b>	<b>13</b>
<b>1.4.3 USE CASES OF MULTICARRIER MODULATION IN 5G AND BEYOND.....</b>	<b>14</b>
<b>1.4.3.1 Enhanced Mobile Broadband (eMBB) .....</b>	<b>14</b>
<b>1.4.3.2 Ultra-Reliable and Low-Latency Communications (URLLC).....</b>	<b>14</b>
<b>1.4.3.3 Massive Machine-Type Communications (mMTC) .....</b>	<b>14</b>
<b>1.4.3.4 Massive MIMO and Beamforming .....</b>	<b>15</b>
<b>1.5 PERFORMANCES METRICS IN WIRELESS COMMUNICATIONS .....</b>	<b>15</b>
<b>1.5.1 CONSTELLATIONS DIAGRAM .....</b>	<b>15</b>
<b>1.5.2 SPECTRAL EFFICIENCY .....</b>	<b>15</b>

1.5.3 BIT ERROR RATE (BER) AND FRAME ERROR RATE (FER).....	16
1.5.4 PEAK-TO-AVERAGE POWER RATIO (PAPR).....	17
1.6 CONCLUSION.....	17

## Chapter 2: Multicarrier Modulation Techniques for 5G

2.1 INTRODUCTION.....	18
2.2 OVERVIEW OF MULTICARRIER MODULATION .....	18
2.3 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM).....	19
2.3.1 OFDM Principle .....	19
2.3.2 Orthogonality.....	20
2.3.3 OFDM system based on discrete Fourier transform.....	21
2.3.4 Guard intervals.....	22
2.3.5 Cyclic prefix.....	22
2.3.6 OFDM advantages.....	23
2.3.7 OFDM limitations.....	24
2.4 FILTERED AND FILTER BANK MULTICARRIER MODULATION (FBMC) .....	24
2.4.1 Filter Bank Multicarrier (FBMC) .....	24
2.4.2 FBMC Technique .....	24
2.4.3 Architecture of the FBMC.....	25
2.4.4 Filter bank.....	25
2.4.5 Filter Bank Principle.....	25
2.4.6 Filter types.....	26
2.4.7 Benefits of FBMC .....	27
2.4.8 Limitation of FBMC.....	28
2.4.9 Principle of FBMC/OQAM modulation.....	29
2.5 GENERALIZED FREQUENCY DIVISION MULTIPLEXING (GFDM).....	31
2.5.1 Interest of GFDM Technique .....	31
2.5.2 GFDM Transmitter and receiver.....	32
2.5.3 Principle of GFDM.....	33
2.5.4 Advantages of GFDM modulation .....	34
2.6 CONCLUSION.....	35

## Chapter 3: Simulation and Performance Analysis

3.1 Introduction... ..	36
3.2 Prototype filters characteristics .....	36
3.2.1 PHYDYAS Filter characteristics .....	36
3.2.2 Hermite Filter.....	38

---

---

<b>3.2.3 Raised Cosine Root (RRC) Filter .....</b>	<b>40</b>
<b>3.3 FBMC Transmission/Reception system .....</b>	<b>42</b>
<b>3.3.1 Simulation Parameters.....</b>	<b>44</b>
<b>3.3.2 Power Spectral Density performance.....</b>	<b>44</b>
<b>3.3.3 Peak-to-Average Power Ratio (PAPR).....</b>	<b>50</b>
<b>3.3.4 Bit Error Rate (BER) .....</b>	<b>51</b>
<b>3.4 Conclusion.....</b>	<b>55</b>
<b>GENERAL CONCLUSION AND PERSPECTIVES .....</b>	<b>56</b>
<b>REFERENCE .....</b>	<b>57</b>

---

## List of Figures

<b>Figure 1:</b> Multipath propagation .....	2
<b>Figure 2:</b> No line of sight (NLOS propagation): Rayleigh channel.....	3
<b>Figure 3:</b> Existence of a line of sight (LOS propagation) Rice channel.....	4
<b>Figure 4:</b> Evolution of mobile networks. ....	8
<b>Figure 5:</b> Examples of 1G devices. ....	9
<b>Figure 6:</b> GSM and GPRS standard .....	10
<b>Figure 7:</b> Standard UMTS.....	11
<b>Figure 8:</b> 4G standard logo.....	11
<b>Figure 9:</b> 5G standard logo.....	12
<b>Figure 10:</b> Spectrum of a Multi-carrier signal with channel response. ....	14
<b>Figure 11:</b> Multi-carrier modulations.....	19
<b>Figure 12:</b> OFDM system principle. ....	20
<b>Figure 13:</b> Spectrum at the output of the OFDM modulator.....	21
<b>Figure 14:</b> Block diagram of an OFDM-FFT system.....	21
<b>Figure 15:</b> Guard intervals in an OFDM symbol .....	22
<b>Figure 16:</b> Insertion of the cyclic prefix.....	23
<b>Figure 17:</b> Architecture of the FBMC.....	25
<b>Figure 18:</b> Architecture of a filter bank.....	25
<b>Figure 19:</b> Synthesis/Analysis Filter Banks. ....	26
<b>Figure 20:</b> General structure of the FBMC/OQAM technique. ....	29
<b>Figure 21:</b> Emission part. ....	30
<b>Figure 22:</b> Reception section.....	31
<b>Figure 23:</b> Overall Diagram of GFDM transceiver. ....	32
<b>Figure 24:</b> GFDM transmitter block diagram. ....	33
<b>Figure 25:</b> detailed GFDM modulator block diagram.....	34
<b>Figure 26:</b> PHYDYAS Filter Impulse and Frequency Responses $k=2$ part (a), $k=3$ part (b) and $k=4$ part (c).....	37
<b>Figure 27:</b> Hermite Filter Impulse and Frequency Responses $k=2$ part (a), $k=3$ part (b) and $k=4$ part (c) .....	39
<b>Figure 28:</b> RRC Filter Impulse and Frequency Responses $k=2$ part (a), $k=3$ part (b) and $k=4$ part (c) .....	41

---

<b>Figure 29:</b> FBMC structure of the transmission chain in transmission.....	42
<b>Figure 30:</b> FBMC structure of the transmission chain in reception .....	43
<b>Figure 31:</b> PSD of FBMC and OFDM; (numFFT=1024, numGuards = 212) .....	45
<b>Figure 32:</b> PSD of FBMC and OFDM; (numFFT=1024, numGuards = 100) .....	46
<b>Figure 33:</b> PSD of FBMC and OFDM (numFFT=1024, numGuards=300) .....	47
<b>Figure 34:</b> PSD of FBMC and OFDM (numFFT=512, numGuards=212) .....	48
<b>Figure 35:</b> PSD of FBMC and OFDM (numFFT=512, numGuards=100) .....	49

---



---

**List of Tables**

<b>Table 1:</b> Comparison of Prototype Filter Characteristics (K=4) .....	44
<b>Table 2:</b> Simulation Parameters for FBMC System Analysis .....	44
<b>Table 3:</b> Peak to Average Power Ratio (PAPR) of OFDM and FBMC versus QAM order, AWGN Channel .....	50
<b>Table 4:</b> Peak to Average Power Ratio (PAPR) of (OFDM; FBMC) versus QAM order, (AWGN+ Rayleigh) Channel.....	50
<b>Table 5:</b> Bit Error Rate (BER) versus SNR, AWGN Channel; 4 QAM (OFDM; FBMC) .....	51
<b>Table 6:</b> Bit Error Rate (BER) versus SNR, AWGN Channel; 16 QAM (OFDM; FBMC) ....	52
<b>Table 7:</b> Bit Error Rate (BER) versus SNR, AWGN Channel; 64 QAM (OFDM; FBMC) ....	52
<b>Table 8:</b> Bit Error Rate (BER) versus SNR, AWGN + Rayleigh channel; 4 QAM (OFDM; FBMC) .....	52
<b>Table 9:</b> Bit Error Rate (BER) versus SNR, AWGN + Rayleigh Channel; 16 QAM (OFDM; FBMC) .....	53
<b>Table 10:</b> Bit Error Rate (BER) versus SNR, AWGN + Rayleigh Channel; 64 QAM (OFDM; FBMC) .....	53

## List of Abbreviations

- 5G: Fifth Generation
- OFDM: Orthogonal Frequency Division Multiplexing
- FBMC: Filter Bank Multicarrier
- GFDM: Generalized Frequency Division Multiplexing
- ISI: Inter-Symbol Interference
- ICI: Inter-Carrier Interference
- CCI: Co-Channel Interference
- ACI: Adjacent Channel Interference
- LOS: Line Of Sight
- NLOS: None Line Of Sight
- FFT: Fast Fourier Transform
- IFFT: Inverse Fast Fourier Transform
- CP: Cyclic Prefix
- eMBB: Enhanced Mobile Broadband
- URLLC: Ultra-Reliable Low-Latency Communication
- mMTC: Massive Machine-Type Communication
- QAM: Quadrature Amplitude Modulation
- OQAM: Offset Quadrature Amplitude Modulation
- BER: Bit Error Rate
- FER: Frame Error Rate
- PAPR: Peak-to-Average Power Ratio
- PSD: Power Spectral Density
- AWGN: Additive White Gaussian Noise
- MIMO: Multiple-Input Multiple-Output
- GSM: Global System for Mobile Communications
- CDMA: Code Division Multiple Access
- GPRS: General Packet Radio Service
- EDGE: Enhanced Data Rates for Global Evolution
- UMTS: Universal Mobile Telecommunications System
- LTE: Long-Term Evolution
- NR: New Radio
- RRC: Root Raised Cosine
- PHYDYAS: Physical Layer for Dynamic Access to Spectrum and Cognitive Radio

# **General Introduction**

## General Introduction

The advent of fifth generation (5G) telecommunications represents a pivotal leap in wireless communication, addressing the escalating demands for high-speed data, ultra-low latency, and massive device connectivity. Designed to support transformative applications such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), 5G relies on innovative technologies to overcome the limitations of prior generations. Multicarrier modulation techniques, notably Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier (FBMC), are central to achieving these goals, offering enhanced spectral efficiency and robust performance in challenging multipath environments.

This thesis conducts a comprehensive study of multicarrier modulation techniques for 5G networks, with a focus on comparing the performance of OFDM and FBMC. Through theoretical analysis and MATLAB-based simulations, it evaluates key performance metrics, including power spectral density (PSD), peak-to-average power ratio (PAPR), and bit error rate (BER), to assess their suitability for 5G requirements. The study also contextualizes these technologies within the evolution of mobile networks from 1G to 5G, highlighting the technological advancements driving modern telecommunications.

The thesis is structured into three chapters. Chapter 1 provides an overview of 5G telecommunications, detailing the challenges of multipath propagation, interference types, and the critical role of multicarrier modulation in addressing these issues. Chapter 2 explores the principles, architectures, and limitations of multicarrier modulation techniques, focusing on OFDM, FBMC, and Generalized Frequency Division Multiplexing (GFDM). Chapter 3 presents simulation-based performance analyses, comparing OFDM and FBMC across various channel conditions and prototype filter configurations to identify their strengths and potential for 5G deployment. The findings aim to contribute to the optimization of 5G systems and guide future research in next-generation wireless communications.

**CHAPTER 1**

**Generalities on 5G**

**Telecommunications**

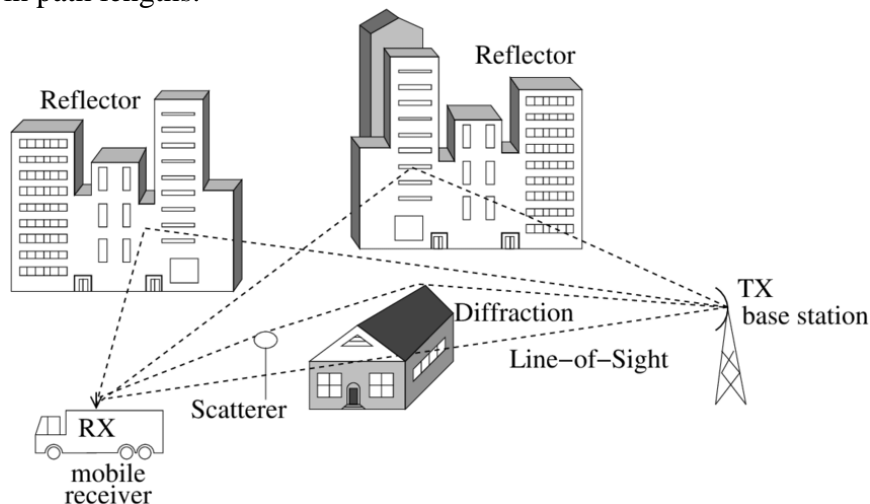
## 1.1 Introduction

The advent of the fifth generation (5G) of telecommunications marks a transformative era in the world of wireless communication. Designed to address the exponential growth of data, the increasing number of connected devices, and the need for faster, more reliable networks, 5G introduces a revolutionary approach to connectivity. This new generation moves beyond the limitations of previous technologies by offering enhanced data rates, ultra-low latency, massive network capacity, and superior energy efficiency. It supports a diverse set of applications ranging from enhanced mobile broadband services to mission-critical communications and the vast Internet of Things (IoT).

This chapter provides a general overview of 5G telecommunications, tracing its development motivations, key performance targets, and enabling technologies. It also highlights the major differences between 5G and earlier generations, setting the stage for a deeper exploration of the technical and practical aspects that define the 5G ecosystem. [1]

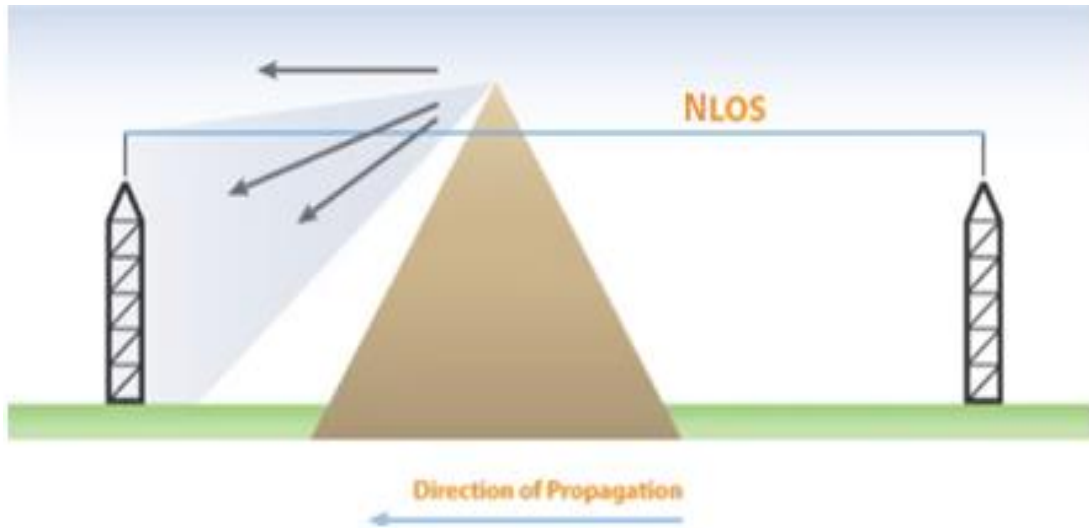
## 1.2 Multipath Propagation and Interference

Free space propagation represents an ideal case. However, the propagation channel involves multiple paths due to obstacles surrounding the transmitter and receiver (Figure 1). In such cases, multiple replicas of the transmitted signal arrive at the receiver through various paths, each experiencing distinct levels of attenuation, phase shift, and delays caused by differences in path lengths.



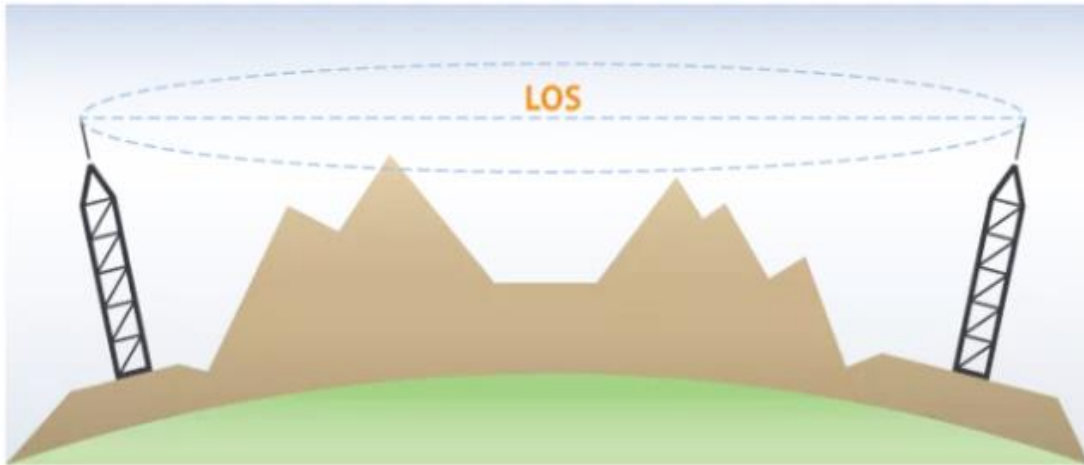
**Figure 1:** Multipath propagation

In multipath propagation, two propagation situations are generally distinguished. The first is referred to as NLOS (None Line Of Sight) where there is no direct visibility between the transmitter and the receiver. In this case, the probability density of the fading amplitude of the total received signal follows Rayleigh's law (Figure 2)



**Figure 2:** No line of sight (NLOS propagation): Rayleigh channel.

The second situation will occur when there is a predominant direct path called LOS (Line Of Sight) and therefore the fading amplitude is characterized by the Rice distribution (Figure 3)



**Figure 3:**Existence of a line of sight (LOS propagation) Rice channel

Depending on the nature of the objects encountered during the multipath path, various electromagnetic phenomena are generated, such as reflection, diffraction, and scattering on obstacles.

The multipath transmission channel produces inter symbol interference (ISI). In this situation, the transmitted signal can take two or more paths to reach the receiver: a direct path and a reflected path. Since the propagation times are different on these two paths, the receiver observes the superposition of two shifted versions of the transmitted signal.

The presence of inter symbol interference prevents the receiver from making a symbol-by-symbol decision that is also an optimal one. Several approaches are then considered: the first consists of ensuring that the ISI term is always zero; this results in the Nyquist criterion. However, this approach has weaknesses in that it does not allow for effective use of the available bandwidth. The second and third approaches are linear equalization (suboptimal equalizer) and Viterbi algorithm (optimal equalizer) respectively.[2]

## 1.2.1 Causes and effects of multipath propagation

### 1.2.1.1 Causes

Multipath propagation occurs when a transmitted signal reaches the receiving antenna via two or more different paths. These paths result from reflection, refraction, diffraction, and scattering objects such as buildings, mountains, vehicles, and even atmospheric layers. Common causes include:

- Reflection from surfaces (e.g., walls, water, metal objects)
- Refraction through atmospheric layers

- Scattering by small objects or rough surfaces
- Diffraction around obstacles

### **1.2.1.2 Effects**

- **Interference:** The multiple signal copies can arrive at the receiver with different phases. When these combine, they cause constructive or destructive interference, leading to signal fading or enhancement.
- **Fading:** Rapid fluctuations in signal strength, known as small-scale fading, occur due to the vector sum of the multipath components. This can cause deep fades (signal drops) or occasional signal amplification.
- **Inter Symbol Interference (ISI):** Delayed signal copies can overlap with subsequent symbols, causing smearing of the information and making it difficult for the receiver to correctly interpret the data. This is particularly problematic at high data rates and in environments with significant delay spreads.
- **Shadowing:** Obstacles may block the direct path, causing additional attenuation and signal variability.
- **Data Corruption:** Multipath can lead to bit errors and data corruption, often requiring retransmissions and reducing communication reliability and throughput.

## **1.2.2 Doppler shift and mobility impact on transmitted signals**

### **1.2.2.1 Doppler Shift**

When the transmitter, receiver, or surrounding objects are in motion, the frequency of the received signal is shifted due to the Doppler effect. The amount of shift depends on the relative speed and the direction of movement with respect to the signal path.

Each multipath component can experience a different Doppler shift, broadening the received signal's spectrum (Doppler spread).

### **1.2.2.2 Impact of Mobility**

- **Rapid Signal Fluctuations:** As a mobile receiver moves through the environment, it encounters different interference patterns, causing the signal amplitude and phase to vary rapidly. These variations can occur at rates proportional to the speed of movement and the carrier frequency.

- **Frequency Modulation:** The superposition of multipath components with different Doppler shifts leads to random frequency modulation of the received signal, further complicating demodulation and decoding.
- **Channel Coherence Time:** Mobility reduces the coherence time of the channel (the time over which the channel impulse response is essentially invariant). High mobility leads to fast fading, where the channel characteristics change rapidly, making reliable communication more challenging.
- **Data Errors:** Increased Doppler spread, and reduced coherence time can result in higher bit error rates, especially for systems not designed to handle fast time variations.

### **1.2.3 Interference types in digital communication**

Digital communication systems are susceptible to various types of interference that can degrade signal quality and reliability. The primary interference types include Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI), Co-Channel Interference (CCI), and Adjacent Channel Interference (ACI).

#### **1.2.3.1 Inter-Symbol Interference (ISI)**

- ISI occurs when one symbol interferes with subsequent symbols, causing distortion in the received signal. This typically happens due to the spreading of a pulse beyond its allotted time interval, causing it to overlap with neighboring pulses.
- Main causes include multipath propagation (where signals take different paths and arrive at different times) and the non-ideal frequency response of the communication channel.
- ISI increases the error rate in digital communication and is particularly problematic in high-speed data transmission.
- Mitigation techniques include adaptive equalization, pulse shaping, and error-correcting codes.

#### **1.2.3.2 Inter-Carrier interference (ICI)**

- ICI is primarily associated with multicarrier systems like Orthogonal Frequency Division Multiplexing (OFDM).
- It occurs when subcarriers, which are supposed to be orthogonal, lose this property often due to Doppler shifts, frequency offsets, or insufficient cyclic prefix length in OFDM systems.

- The loss of orthogonality causes energy from one subcarrier to spill into others, resulting in interference and degraded performance.
- ICI can be mitigated by careful synchronization, frequency offset correction, and appropriate design of the cyclic prefix.

### 1.2.3.3 Co-channel and adjacent channel interference (CCI) and (ACI)

#### *Co-Channel Interference (CCI)*

- CCI arises when multiple transmitters use the same frequency channel, typically in cellular networks where frequency reuse is practiced maximizing spectrum efficiency.
- Signals from distant transmitters operating on the same frequency can interfere with the desired signal, leading to crosstalk and reduced signal quality.
- This is a major concern in densely packed wireless networks and is managed through careful frequency planning, power control, and cell sectorization.

#### *Adjacent Channel Interference (ACI)*

- ACI is caused by signals from transmitters operating on adjacent frequency channels.
- It typically results from inadequate filtering, transmitter non-linearity, or improper frequency allocation, causing power to leak into neighboring channels.
- ACI leads to increased noise, signal distortion, and reduced signal-to-noise ratio.
- Mitigation involves proper filtering, guard bands between channels, and precise frequency planning.

### 1.3 Evolution of telecommunication generations (1G to 5G and beyond)

As already mentioned in the introduction, mobile networks have undergone a very significant evolution since the deployment of the first mobile network in the United States in the 1970s (Figure 4). In the following we present a brief history of this evolution



**Figure 4:** Evolution of mobile networks.

#### a) Emergence of 1G

The first generation of networks: 1G was the beginning of a major revolution in the world of telephony. It operated analogically and consisted of numerous bulky devices.

Appearing in 1976 in the United States, AMPS (Advanced Mobile Phone System) was the first cellular network standard used primarily across the Atlantic, in Russia, and in Asia. It was easy to hack this system because it had weak security mechanisms, making it more likely to hack into telephone lines.

TACS (Total Access Communication System) is the European version of the AMPS model mentioned above. With a more powerful frequency band (900 MHz), this system was more widely used, particularly in England, and later in Asia (Hong Kong and Japan). Subsequently, in 1983, ETACS (Extended Total Access Communication System), an improved version of the TACS standard and AMPS, was developed in the United Kingdom using a larger number of communication channels.

The first-generation cellular networks, which operated on an analog communication system, did not achieve the expected success due to certain communication problems and the quality of mobile phones at the time [3].

- Technology: Analog
- Main Feature: Voice calls only

- Speed: Up to 2.4 kbps
- Limitation: Poor sound quality, no data services, low capacity
- Example: AMPS (Advanced Mobile Phone System)



**Figure 5:**Examples of 1G devices.

### **b) The Second Generation (2G)**

The second generation was 2G. Created in 1980, its cellular system relied on digital technology for both the connection and the voice signal. Analog technology was thus eliminated. It uses the following standards:

- GSM (Global System for Mobile Communications), the most widely used standard in Europe at the end of the 20th century, supported in the United States. This standard uses the 900 MHz and 1800 MHz frequency bands in Europe, a much higher range than that used for the first generation in the United States, where the frequency bands used were the 850 MHz and 1900 MHz bands. Tri-band mobile phones that could operate in both Europe and the United States were then called tri-band.

- CDMA (Code Division Multiple Access), using a spread spectrum technique to broadcast a radio signal over a wide range of frequencies. Thanks to the perfection of the 1G network and thus the creation of the 2G network, individuals can now communicate low-volume digital data. This includes sending SMS messages and various other multimedia messages such as MMS photos. This GSM standard, however, allows for a maximum data rate of 9.6 kbps (kilobits per second), which is low for our time, but a major advance in the past.

Following extensions, the GPRS (General Packet Radio Service) standard allows for more powerful theoretical data rates, reaching 40 kbps. Since this technology does not meet the future criteria of 3G, specialists have decided to dub it "2.5G."

Still not yet finished, the story of 2G continues with the EDGE (Enhanced Data Rates for Global Evolution) standard, which quadruples the previously made improvements, announcing a theoretical network speed of 384 kbps. This was named the “2.75G” [3]



Figure 6: GSM and GPRS standard

- Technology: Digital (GSM, CDMA)
- Main Feature: Voice + SMS (text messaging)
- Speed: Up to 64 kbps
- Advancement: Better call quality, encryption, roaming support
- 2.5G/2.75G: GPRS and EDGE introduced basic mobile internet

All these advances are only waiting to be improved over time...

### c) Third Generation 3G

The ITU's (International Telecommunications Union) IMT-2000 (International Mobile Telecommunications for the year 2000) specifications set out the criteria to be considered for 3G. Some of these characteristics are as follows:

- They aim for a high transmission rate of:
  - 144 Kbps with full coverage for mobile use,
  - 384 Kbps with medium coverage for pedestrian use,
  - 2 Mbps with a reduced coverage area for fixed use.
- Global compatibility to provide worldwide internet access.
- Compatibility of third-generation mobile services with second-generation networks, meaning they aim to maintain the parameters of previous generations (sending messages and multimedia content). The goal of 3G is to achieve speeds above 144 kbps, opening the door to multimedia uses such as video transmission, video conferencing, and broadband internet access. 3G networks use different frequency bands than previous networks. The main 3G standard in Europe is called UMTS (Universal Mobile Telecommunications System), and

the 5 MHz frequency band is used for voice and data transmission, with speeds ranging from 384 kbps to 2 Mbps [3].

- Technology: WCDMA, HSPA
- Main Feature: Voice + Internet (email, web browsing)
- Speed: 384 kbps to a few Mbps
- Advancement: Video calling, mobile internet, app stores



**Figure 7:**Standard UMTS.

#### **d) Fourth generation 4G**

This generation is the one currently in use. Expanding worldwide, 4G is currently only available in certain urban areas. This development guarantees greater data transfer, since the speed does not have to be shared as with 3G, where internet data and telephone conversations were separated.

4G speeds range from 100 Mbps to 1 GB/s. It offers significantly higher throughput than other generations of this network [3].

- Technology: LTE, LTE-Advanced
- Main Feature: High-speed mobile broadband
- Speed: 100 Mbps to 1 Gbps
- Advancement: HD video streaming, VoIP, low latency
- 4.5G: LTE-A Pro, better speed and capacity



**Figure 8:**4G standard logo.

### e) Fifth Generation 5G

5G technology is a "key technology" that could enable mobile telecommunications speeds of several gigabits of data per second: up to 1,000 times faster than mobile networks in 2010 and up to 100 times faster than 4G by 2020 [3].

- Technology: NR (New Radio), mmWave, Massive MIMO
- Main Features:
- eMBB: Enhanced mobile broadband
- URLLC: Ultra-reliable low-latency communication
- mMTC: Massive machine-type communication
- Speed: Up to 10 Gbps
- Latency: As low as 1 ms
- Use Cases: IoT, AR/VR, autonomous vehicles, smart cities



Figure 9:5G standard logo.

#### 1.4 Necessity of multicarrier modulation

Multicarrier modulation is crucial for 5G communication because it meets the strict needs for high data rates, efficient use of the spectrum, and strong performance in various channel situations. By splitting data into multiple subcarriers, it helps to reduce issues like multipath interference and adjusts to different network demands below are the key reasons for its necessity [4]:

- Mitigation of Multipath Fading and Interference

Techniques like Orthogonal Frequency Division Multiplexing employ cyclic prefixes to combat delays caused by multipath, ensuring dependable signal retrieval in both urban and indoor settings.

Filter Bank Multicarrier enhances the reduction of interference between carriers by using sophisticated filtering methods, which is ideal for traffic that is not time-synchronized and applications needing low latency.

- **Enhanced Spectral Efficiency**

While traditional OFDM struggles with a lot of out-of-band radiation, newer methods like Universal Filtered Multicarrier and Filter Bank Multicarrier offer better control of the spectrum. For instance, FBMC decreases out-of-band leakage by about 20 to 30 dB in comparison to OFDM.

Methods such as Generalized Frequency Division Multiplexing help to make better use of fragmented parts of the spectrum, which is vital for IoT and networks for machines.

### **1.4.1 Single-carrier modulation**

The information is transmitted via a radio frequency carrier. Consequently, a single carrier modulates the information in the form of symbol bits.

Next, we tackle the issue of baseband transmission of a digital message that consists of a series of  $S_q$  symbols sent at a rate of  $1/T$  symbols per second.

The transmitter output signal in a single-carrier transmission scenario looks like this:

$$s(t) = \sum x[q] \cdot h_{TX}(t - qT) \quad (1.1)$$

Where  $h_{TX}(\tau)$  is the transmit waveform (often a half-Nyquist filter) and  $T$  is the symbol duration. A propagation channel is then used to transmit the signal. [5]

### **1.4.2 Principle of multi carrier modulation**

When applied to a multipath channel, conventional modulation techniques are susceptible to ISI (inter symbol interference). Equalization procedures are employed to counteract this adverse effect. But putting them into practice has proven to be very difficult, particularly when the channel fluctuates a lot over time or is dependent on the signal's frequency. To solve this issue, Multicarrier modulation techniques have been developed, which simplify equalization and do away with ISI. After that, the data is dispersed among numerous subcarriers. Therefore, the system will still be able to recover the lost information on other carrier frequencies that have not been impacted in a transmission channel with multi-paths, where certain frequencies will be destroyed due to a destructive path combination. [6]

By splitting the frequency band  $f$  into  $N$  sub-bands based on frequencies known as sub-carriers, each modulated by a simple symbol sent in parallel, Multicarrier modulation creates frequency sub-bands that are smaller and narrower than  $B_c$ .

This corresponds to increasing the symbol duration  $T_s \geq \tau_R$  in the time domain. This reduces inter symbol interference. [7]

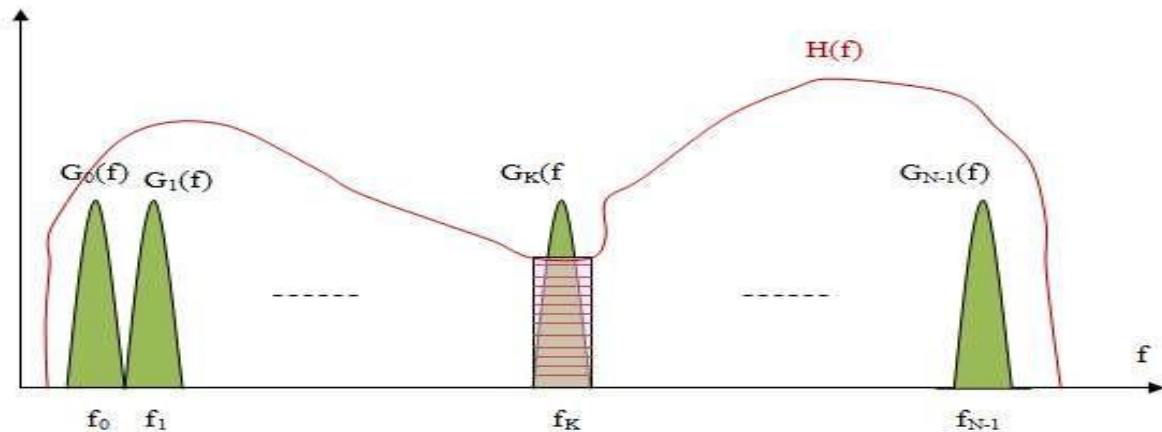


Figure 10: Spectrum of a Multi-carrier signal with channel response.

### 1.4.3 Use cases of multicarrier modulation in 5G and beyond [8]

#### 1.4.3.1 Enhanced Mobile Broadband (eMBB)

- Aims to deliver speeds up to gigabit to meet the needs of applications that require large amounts of data.
- MCM: Ensures high data throughput by enabling parallel transmission across multiple subcarriers.

#### 1.4.3.2 Ultra-Reliable and Low-Latency Communications (URLLC)

- Aims to facilitate critical activities such as autonomous vehicles and remote surgery.
- MCM: offers a variety of token numbers and short token durations to ensure highly reliable, low-latency communications.

#### 1.4.3.3 Massive Machine-Type Communications (mMTC)

- Aims to connect millions of low-powers IoT devices.
- MCM: narrowband MCM reduces spectrum and power consumption, like NB-OFDM.

### 1.4.3.4 Massive MIMO and Beamforming

- Aims to enhance spectrum efficiency and capacity in congested locations.
- Role of MCM: By using MIMO processing on individual subcarriers, MCM enables spatial multicasting.

## 1.5 Performances metrics in wireless communications [9]

### 1.5.1 Constellations diagram

Definition: A two-dimensional graphic representation of digitally modulated signals (such as QAM and PSK) that shows the signal points (symbols) in the I-Q (simultaneous and quadrature) plane.

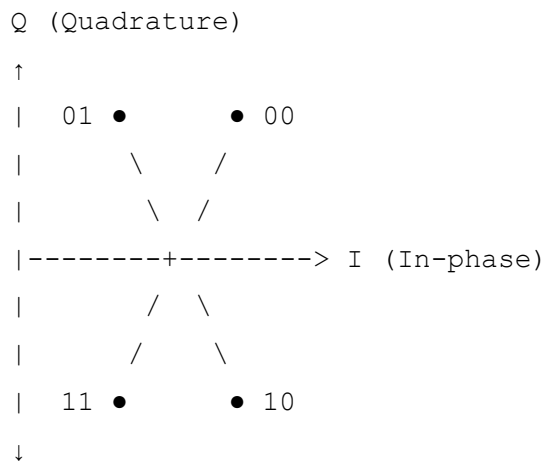
Purpose: Used to visualize modulation quality and detect signal distortions or noise. Well-clustered points indicate a high-quality signal.

Example of a Constellation Diagram: 4-QAM (Quadrature Amplitude Modulation)

Symbol Coordinates (Normalized for Unit Energy)

- 00:  $(1/\sqrt{2}, 1/\sqrt{2})$  (Phase:  $45^\circ$ )
- 01:  $(-1/\sqrt{2}, 1/\sqrt{2})$  (Phase:  $135^\circ$ )
- 11:  $(-1/\sqrt{2}, -1/\sqrt{2})$  (Phase:  $225^\circ$ )
- 10:  $(1/\sqrt{2}, -1/\sqrt{2})$  (Phase:  $315^\circ$ )

Graphical Representation:



### 1.5.2 Spectral efficiency

Definition: The quantity of data transmitted per unit of bandwidth, expressed in bits per second per hertz (bps/Hz).

Goal: It illustrates how effectively the spectrum is used. More data can be sent over the same bandwidth when the spectrum is more efficient.

The formula for spectral efficiency ( $\eta$ ) in wireless communications is:

$$\eta = \frac{C}{B} \text{ (in bps/Hz)} \quad (1.2)$$

Where:

$\eta$  = Spectral efficiency (bits/s/Hz)

$C$  = Channel capacity (data rate in bits/s)

$B$  = Bandwidth (Hz)

### 1.5.3 Bit Error Rate (BER) and Frame Error Rate (FER)

#### a) Bit Error Rate (BER)

- It is calculated by dividing the total number of transmitted bits by the number of incorrectly received bits.
- It shows how noisy or prone to errors the channel is while being transmitted.

The Bit Error Rate (BER) for BPSK is given by:

$$\text{BER}_{\text{BPSK}} = Q(\sqrt{2E_b / N_0}) \quad (1.3)$$

Where:

- $Q(x)$  is the Q-function:  $Q(x) = (1/\sqrt{2\pi}) \int_x^{\infty} e^{-t^2/2} dt$
- $E_b$  is the energy per bit.
- $N_0$  is the noise power spectral density.

This formula applies to BPSK modulation over an AWGN (Additive White Gaussian Noise) channel.

#### b) Frame Error Rate (FER)

- It is the proportion of error-containing frames (or packets) to all transmitted frames.
- Applications like real-time communications and video streaming require it.

The FER is the probability that at least one bit error occurs in a frame of length  $L$  bits:

$$\text{FER} = 1 - (1 - \text{BER})^L \quad (1.4)$$

- $L$  is the number of bits per frame
- This formula assumes independent bit errors and no error correction coding

### 1.5.4 Peak-to-Average Power Ratio (PAPR)

Definition: It is the ratio between the maximum power and the average power of a transmitted signal.

Purpose: This is critical in systems such as OFDM. A high peak-to-average power ratio (PAPR) can lead to distortion in power amplifiers, necessitating the use of mitigation techniques to improve power efficiency and signal integrity.

PAPR measures the ratio between the peak power and the average power of a transmitted signal. It is defined as:

$$\text{PAPR} = P_{\text{peak}} / P_{\text{avg}} \quad (1.5)$$

Where:

- $P_{\text{peak}}$  is the maximum instantaneous power.
- $P_{\text{avg}}$  is the average power over time.

In decibels (dB), PAPR is expressed as:

$$\text{PAPR}_{\text{dB}} = 10 \cdot \log_{10} (P_{\text{peak}} / P_{\text{avg}}) \quad (1.6)$$

## 1.6 Conclusion

In this chapter provided a general overview of 5G telecommunications, highlighting key challenges such as multipath propagation, Doppler effects, and different types of interference. It traced the evolution from 1G to 5G, showing how technological demands led to the adoption of multicarrier modulation techniques. The necessity and advantages of multicarrier modulation were emphasized, particularly for improving spectral efficiency, managing interference, and combating channel fading. Lastly, important performance metrics like constellation diagrams, spectral efficiency, BER, FER, and PAPR were introduced to evaluate the efficiency and reliability of wireless systems. This foundation will support deeper discussions in the next chapters.

**CHAPTER 2**

**Multicarrier**

**Modulation**

**Techniques for 5G**

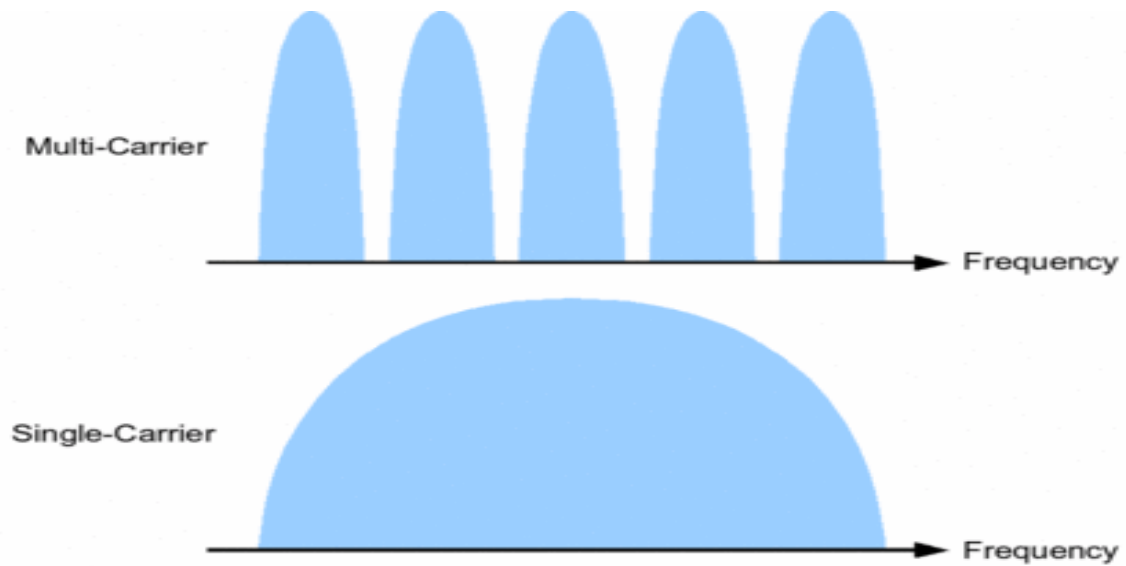
## **2.1 Introduction**

Multicarrier modulation techniques play a key role in achieving high data rates, low latency, and reliable communications, essential requirements for fifth generation (5G) networks. By dividing a wideband channel into multiple narrowband carriers, multicarrier modulation techniques can efficiently handle the complex and dynamic wireless environment that characterizes 5G networks. In 5G networks, these techniques are designed not only to improve spectrum efficiency but also to enhance multipath fading resistance, provide flexibility in frequency allocation and reduce the complexity of the equalization process. While orthogonal frequency division multiplexing (OFDM) remains the foundation, advanced variations and new multicarrier modulation methods, such as filter-bank multicarrier modulation (FBMC), generalized frequency division multiplexing (GFDM), and universally filtered multicarrier modulation (UFMC), are being explored to meet specific 5G requirements such as ultra-reliable, low-latency communications (URLLC) and massive machine-to-machine communications (MMTC). An insight on multicarrier modulation is presented in the following paragraph.

## **2.2 Overview of multicarrier modulation**

Digital data is transmitted using Multicarrier techniques by modulating it on numerous carriers at once. These are long-standing frequency division multiplexing techniques. When transmission occurs over a multipath channel, single-carrier modulation techniques are extremely susceptible to inter-symbol interference (ISI). When a symbol's duration is short compared to the channel's maximum delay or time dispersion, this interference becomes even more noticeable. In other words, if the useful symbol duration is longer than this channel parameter, single-carrier modulation is preferred. Multi-carrier modulation has the advantage of putting the data in a time-frequency window whose duration is significantly longer than the propagation channel's maximum time dispersion. Multi-carrier modulation has the advantage of placing information in a time-frequency window whose duration is significantly longer than the propagation channel's maximum temporal dispersion. This benefit, which is crucial for wireless communications, makes it a desirable option for cellular networks, radio local loops, and wireless local area networks, among other wireless broadband network types. In fact, Multicarrier modulation also has the benefit of recovering

the transmitted signal by converting the time-domain equalization step into a simplified frequency-domain equalization.



**Figure 11:**Multi-carrier modulations

## 2.3 Orthogonal Frequency Division Multiplexing (OFDM)

### 2.3.1 OFDM Principle

The OFDM technique appeared in the 1960s, it splits a frequency band into multiple sub-channels, named "carriers," separated by fixed-size zones (guard intervals), to transmit a signal. The System bandwidth is divided into many separate carriers, or subcarriers, then a symbol sent on one subcarrier can be demodulated without interference from nearby subcarriers in an ideal transmission scenario. The original data stream at bit rate  $R$  is multiplexed into  $N$  parallel streams at bit rate  $R/N$  in OFDM systems, which transmit data in blocks from the standpoint of digital implementation. Given that the data is being sent over  $N$  distinct channels, this is in fact frequency division multiplexing. Instead of sending data serially, this transmission is accomplished by introducing redundancy (also known as a guard interval) into the useful information, allowing for a simple (scalar) inversion of the propagation channel using Fourier transforms. This allows data to be transmitted in blocks rather than serially as single-carrier systems do. [10]

The digital signal to be transmitted is divided into numerous subcarriers according to the OFDM principle. It appears a multitude of separate transmission systems using various carrier frequencies are combining the signal to be transmitted. Orthogonal carrier frequencies are used in OFDM. Although the signals from various carriers overlap, they do

not interfere with one another because they are orthogonal. Therefore, the OFDM system will still be able to recover the information lost on other carrier frequencies that have not been destroyed in a transmission channel with multiple paths where some frequencies will be destroyed due to a destructive path combination. Modulations are used to modulate each carrier independently.

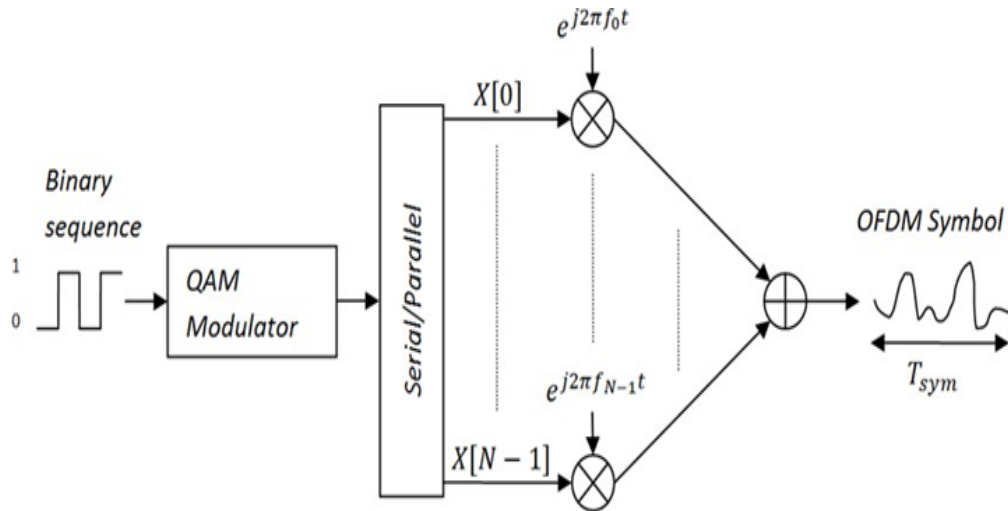


Figure 12: OFDM system principle.

### 2.3.2 Orthogonality

High spectral overlap between subcarriers is possible with the OFDM modulation technique. For the carriers to function properly, though, they must concurrently satisfy an orthogonality constraint in the frequency and time domains. When two adjacent frequencies are spaced apart by  $f_n = 1/T_n$ , orthogonality is attained (Figure 13). In fact, the cardinal sin, which is a rectangular window of time duration, represents the frequency spectrum of each symbol modulated by a carrier.

As a result, there is no interference from other subcarriers, allowing for optimal spectrum occupancy and carrier overlap.  $N$  is the number of subcarriers that must be selected to satisfy the two main requirements. For the channel to be considered flat,  $T_S \gg T_m$ , and  $T_s < 1/B_d$ , when it comes to maintaining a good separation between the subcarriers at reception, the OFDM solution is both straightforward and efficient.[11]

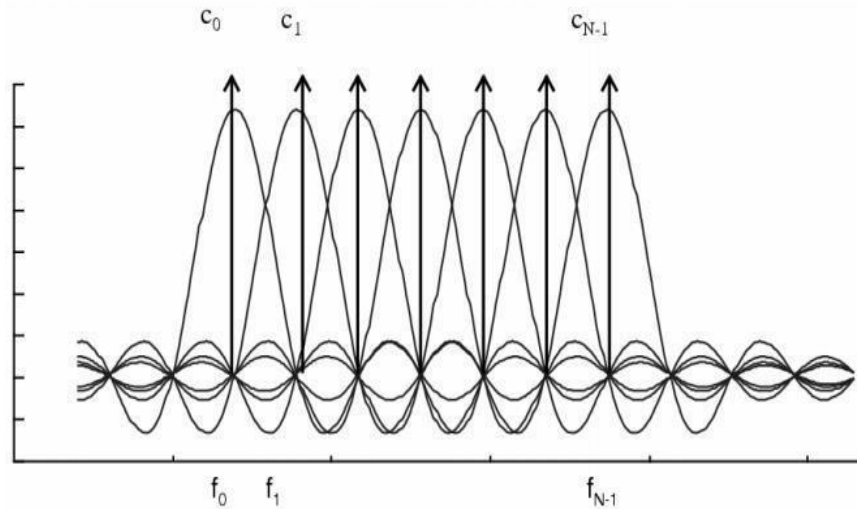


Figure 13: Spectrum at the output of the OFDM modulator.

### 2.3.3 OFDM system based on discrete Fourier transform

Figure 14 represents a complete OFDM system. It consists of a transmitter, a receiver and a channel through which the transmission takes place.

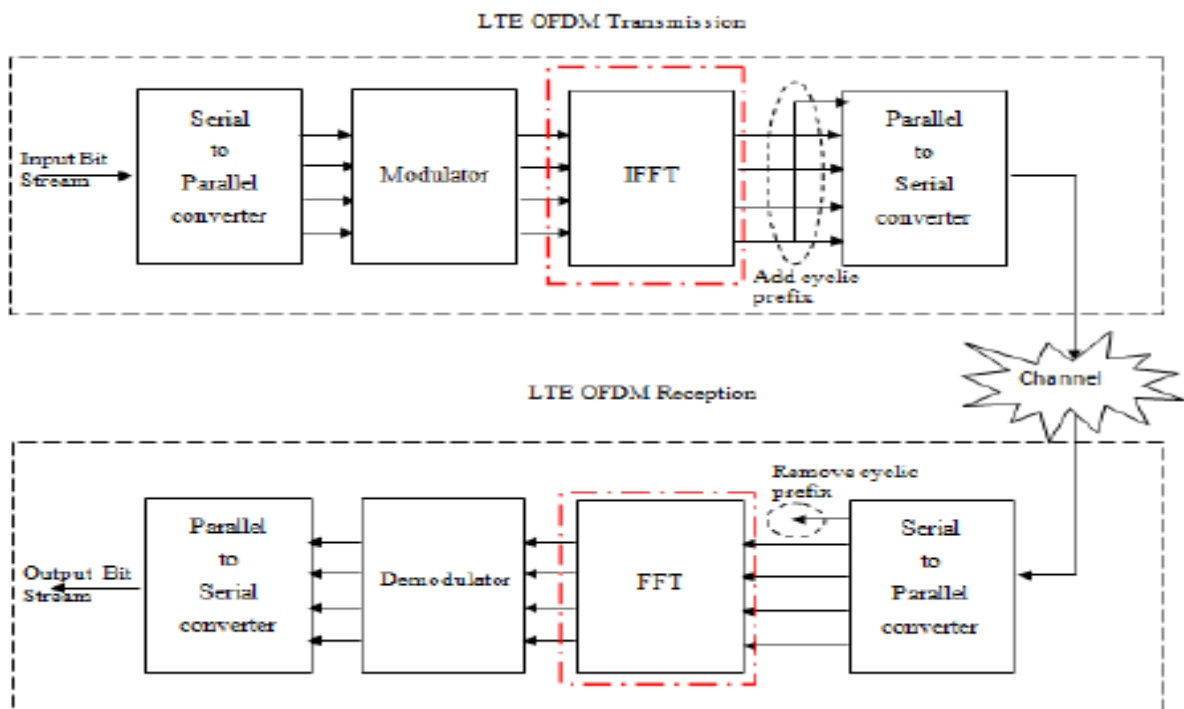


Figure 14: Block diagram of an OFDM-FFT system

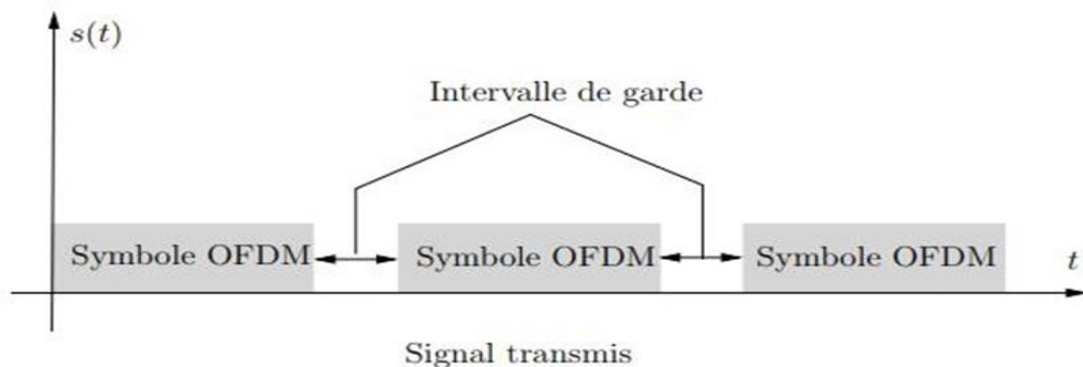
In the transmission chain, we generate a binary sequence representing, for example, voice, data, image, or information obtained from an analog-to-digital conversion. The binary data is distributed across various subcarriers and then modulated using a modulator (such as M-QAM). At the output of this device, the information is in a very specific constellation.

An inverse fast Fourier transform (IFFT) is then applied to each input to modulate the subcarriers. A parallel-to-serial conversion is then performed, followed by a guard period in the form of a cyclic prefix, ready for transmission.

At reception, the reverse process is performed. The cyclic prefix is first removed, then the signal is distributed across several different inputs (serial-to-parallel conversion). A fast Fourier transform (FFT) is applied to restore the signal to the frequency domain. The data is then demodulated, and a parallel-to-serial conversion is performed.

### 2.3.4 Guard intervals

Guard intervals are necessary for orthogonality between carriers when the channel introduces multipath to the signal. These allow the creation of a buffer zone in which delayed versions likely to cause interference will accumulate. Several techniques exist for introducing guard intervals for OFDM. These involve either filling the guard space between two consecutive symbols with zeros (a technique used for some Ultra-Wide Band UWB transmissions) or introducing a cyclic extension of the OFDM symbol. The latter can be introduced in two different ways: one is called a cyclic prefix and the other a cyclic suffix.

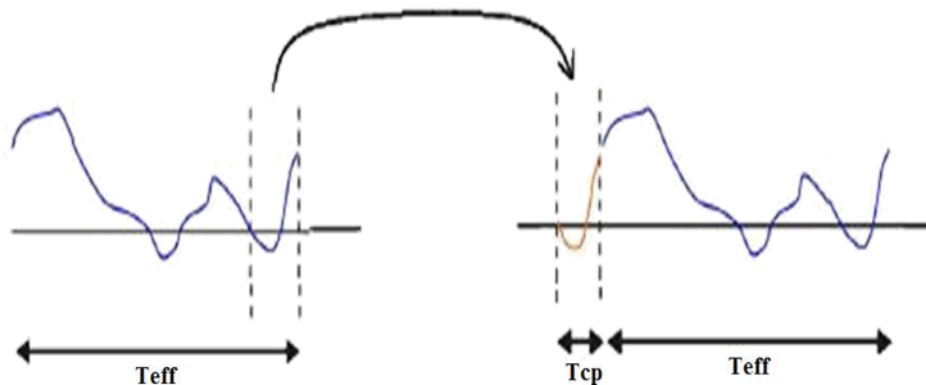


**Figure 15:**Guard intervals in an OFDM symbol

### 2.3.5 Cyclic prefix

The principle of the cyclic prefix is to copy the last samples of a symbol and place them at its beginning. By using this technique, continuity is maintained in the symbol. The cyclic prefix is a good method to combat interference between ISI symbols and between ICI carriers. Thanks to this extension, the symbol period is longer. Note that although the period is longer, this has no impact on the frequency spectrum of the signal. If the right number of samples are taken at reception anywhere in the extended symbol, orthogonality is

maintained, and interference is eliminated. Figure 16 gives a view of the principle of cyclic prefix insertion



**Figure 16:** Insertion of the cyclic prefix.

The length of the prefix that we add is added to the initial symbol, we obtain an OFDM symbol with a total length equal to:

$$T_{\text{total}} = T_{\text{cp}} + T_{\text{eff}}$$

It is important to note that the prefix length must be defined based on the maximum expected delays in the multipath channel. Indeed, the idea is not only to solve the interference problem by using the prefix, but also to make the most optimal use of the bandwidth. Repeated information in the prefix creates a waste of bandwidth that must be minimized as much as possible. Typically, the duration of the cyclic extension is between 1/4 and 1/10 of the number of subcarriers. This implies bandwidth losses ranging from 20% to 9%, respectively.

### 2.3.6 OFDM advantages

OFDM technique has several advantages, the main ones being:

- ✚ The Fast Fourier Transform (FFT) makes implementation simple.
- ✚ The ability to withstand multipath effects by employing a cyclic prefix (CP).
- ✚ Equalization is made simple by assigning a coefficient to each subcarrier.
- ✚ Good spectral efficiency, which permits the spectra of various subcarriers to overlap.
- ✚ Reduces the ISI caused by multipath propagation delay.
- ✚ The channel response is regarded as flat across each sub band, making the channels non-frequency selective.

### **2.3.7 OFDM limitations**

The OFDM modulation technique is straightforward and efficient, but its functionality is constrained by a few problems:

- Crest factor problems: The power amplifier is rapidly saturated by the large peaks in the OFDM signal envelope.
- OFDM is more sensitive to frequency shift and phase noise.
- Synchronization problems: Extremely exact synchronization is necessary for the demodulation procedure, and specifically for the decoding operation. It is necessary to ascertain the beginning and ending times of every OFDM symbol and to synchronize the transmitter and receiver frequencies; Synchronization errors can occur in OFDM systems.

## **2.4 Filtered and Filter Bank Multicarrier Modulation (FBMC)**

### **2.4.1 Filter Bank Multicarrier (FBMC)**

One type of onde candidate for 5G is the Filter Bank Multi-Carrier (FBMC) modulation. This technique is a development of OFDM; it is a little more complicated than OFDM, but its goal is to reduce interference and band-wide radiation by using a different modulation scheme based on filter banks. By enhancing its benefits and reducing its drawbacks, the FBMC technique maintains the same principles as OFDM modulation.

At the expense of more complicated implementation, FBMC Filter Bank Multi-Carrier Modulation is an improved sub band processing technique that addresses some of the drawbacks of OFDM while utilizing the main benefits of the original effective sub band processing based on Fast Fourier Transform.

### **2.4.2 FBMC Technique**

This modulation method gets past ICI and ISI interference. One of the biggest problems with network systems is inter-symbol interference. Filter Bank Multi-Carrier, or FBMC, is an adaptation of OFDM, or orthogonal frequency division multiplexing. Cyclic prefixes are employed in OFDM to increase signal robustness; however, there are some disadvantages to using cyclic prefixes in orthogonal frequency division multiplexing. FBMC is used to get around OFDM's drawbacks. It offers effective bandwidth. Modulation techniques are employed to handle this situation, and future developments will employ

additional novel approaches. Among these is FBMC, which offers higher efficiency than OFDM.

### 2.4.3 Architecture of the FBMC

FBMC is a Multicarrier technique that uses a network of filters at the transmitter and receiver, specific synthesis and analysis filters, and an inverse fast Fourier transform (IFFT) as a modulator and a fast Fourier transform (FFT) as a demodulator. A generic Multicarrier transceiver with filter banks is shown in Figure 17 below: [12]

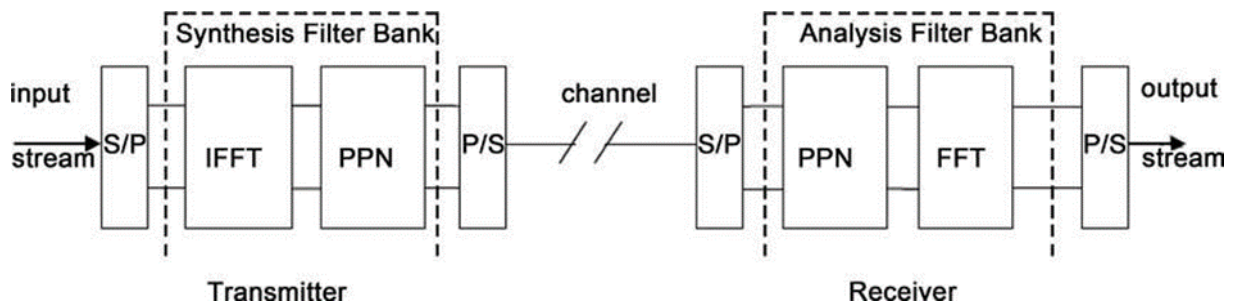


Figure 17: Architecture of the FBMC.

### 2.4.4 Filter bank

Unlike OFDM, FBMC uses filter banks which are considered as a table that groups  $M$  input signals on  $M$  lines and gives  $M$  output signals, as shown in Figure 18.

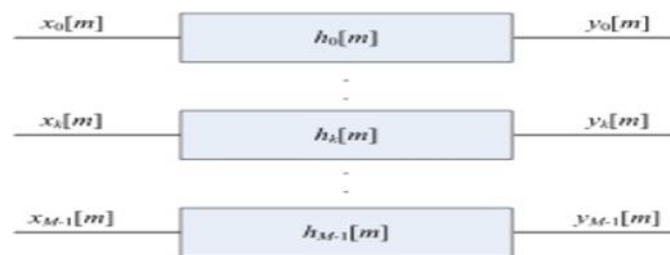


Figure 18: Architecture of a filter bank.

### 2.4.5 Filter Bank Principle

The system in Figure 19 (a) is called the analysis filter bank, and the filters  $H_k(n)$  (a) are the analysis filters. This bank decomposes the signal  $x(n)$  into  $M$  signals  $v_k(n)$  called sub band signals. The system in Figure 19 (b) is called the synthesis filter bank, and the filters  $F_k(n)$  are the synthesis filters. It combines the  $M$  signals  $w_k(n)$  into a single signal  $y(n)$ . [13]

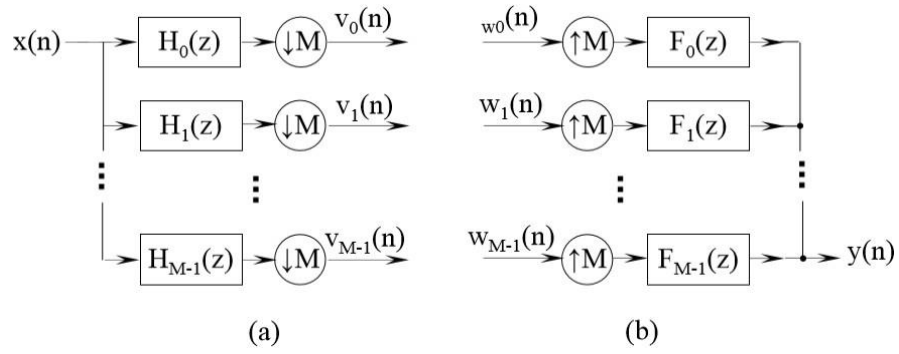


Figure 19: Synthesis/Analysis Filter Banks.

## 2.4.6 Filter types

### 2.4.6.1 PHYDYAS filter

The PHYDYAS prototype filter is the one used in the physical couch for the European project called "PHYDYAS: Dynamic Access to Spectrum and Radio Cognitive." It was Bellanger who introduced this prototype filter. The prototype filter is made using the frequency-based sampling technique. The basic idea behind this strategy is to use the formula for interpolating the desired response in frequency to determine the response in frequency  $G(f)$ . The physical layer for the European spectrum and cognitive radio uses the PHYDYAS prototype filter. Bellanger introduced this prototype filter in. The frequency sampling approach is used in the creation of the prototype filter. The primary goal of this technique is to create the desired frequency response to determine the frequency response  $G(f)$ . At the frequency locations  $FK = KT$ ,  $k$ , where  $K$  is the sampling factor and  $T$  is the symbol period, the  $GK$  samples are evenly distributed.

$$G(f) = \sum_k G(K) \frac{\sin(\pi(KTF - K))}{\pi(KTF - K)} \quad (2.1)$$

By performing an opposite Fourier transform operation on  $(f)$ , i.e.,  $g(t)$ , the prototype filter's continuous impulse response is obtained:

$$g(t) = \sum_k G(K) e^{j\frac{\pi kt}{KT}} \quad (2.2)$$

The frequency coefficients  $GK$  are selected based on Nyquist theory and tuned to provide maximum frequency selectivity and minimize the total interference resulting from the filter bench construction. The over-sampling factor for the PHYDYAS prototype filter is set at  $K = 4$ . For the PHYDYAS filter, the frequency coefficients  $GK$  selected are as follows:

$$\left\{ \begin{array}{l} G0 \\ G1 \\ G2 \\ G3 \end{array} \left| \begin{array}{l} 0 \\ 0.9716960 \\ 1/\sqrt{2} \\ \sqrt{(1 - G_1^2)} = 0.235147 \end{array} \right. \right\} \quad (2.3)$$

$$K = 0 \quad \text{pour } k > 3$$

$$Gk = G - k \quad \text{pour } k < 0$$

### 2.4.6.2 Hermite filter

The Hermite filter is made from linear combinations of Hermite-Gaussian functions. To meet the Nyquist criterion, passages to zero are provided by deforming the gaussian filter with the Hermite high-range functions. It has characteristics that are like those of the IOTA and provides an isotrope response. The design procedure proposed by Haas and Belfiore builds an isotropic filter according to the equation:

$$P(t) = \sum_{k=0}^L a_k h_k(t) \quad (2.4)$$

Where  $h_n$  is the set of hermit functions defined as:

$$H_n(t) = \frac{1}{\sqrt{n!}} e^{\pi t^2} \frac{d^n}{dt^n} e^{-2\pi t^2} \quad (2.5)$$

### 2.4.6.3 cosine filter

The cosine-raised square root (SRRC) filter is a reference filter that is well-connected in digital communication. for a transmission speed of  $F = 1 / T$ , the SRRC filter is defined in the frequency domain by:

$$G(f) = \begin{cases} \sqrt{T} & |f| \leq (1 - r) \frac{1}{2T} \\ \sqrt{T \cos\left(\frac{\pi}{2r} \left(T|f| - \frac{1-r}{2}\right)\right)} & \frac{1}{2T} < |f| \leq (1 \pm r) \frac{1}{2T} \\ 0 & (1 \pm r) \frac{1}{2T} < |f| \end{cases} \quad (2.6)$$

### 2.4.7 Benefits of FBMC

- Higher bandwidth compared to other orthogonal filters.
- No guard intervals or cyclic prefixes are required. Furthermore,
- no additional processing power is required to manage guard intervals and cyclic prefixes.

- Thanks to a well-localized filter design, lower spectral leakage
- can be ensured.
- In the case of FBMC, performance can be easily improved by integrating some of the compatible signal processing mechanisms such as diversity schemes and coding schemes.
- In FBMC, signal separation is achieved through filtering. There is no such critical need for perfect synchronization between users (an empty subcarrier is proposed as a guard band between two asynchronous users).
- FBMC modulation is a better choice for filling spectrum gaps.

### **The disadvantages of FBMC**

- Self-interference generated during asynchronous operating modes and/or in multipath channel conditions in terms of ICI, ISI, and ICSI.
- Excessive complexity and sometimes even incompatibility with receiver processing techniques when trying to find solutions to electrical distortion and multipath interference.

### **2.4.8 Limitation of FBMC**

- **Enhanced Complexity:** Compared to OFDM, FBMC systems necessitate more intricate filtering procedures (polyphase filter banks and prototype filters), which raises the complexity of transmitter and receiver implementation.
- **Latency:** Long prototype filters cause delay, which can be an issue for low-latency or real-time applications like control or voice systems.
- **MIMO Compatibility:** The inability of FBMC to support Multiple-Input Multiple-Output (MIMO) systems, particularly in comparison to OFDM, stems from issues with pilot design and channel equalization when a cyclic prefix (CP) is not present.
- **Lack of a Cyclic Prefix (CP):** In OFDM, the CP facilitates equalization and synchronization, whereas in FBMC, its absence enhances spectral efficiency.
- **Channel Estimation Challenges:** The overlapping nature of subcarriers and the absence of time-domain alignment make accurate channel estimation more difficult in FBMC.

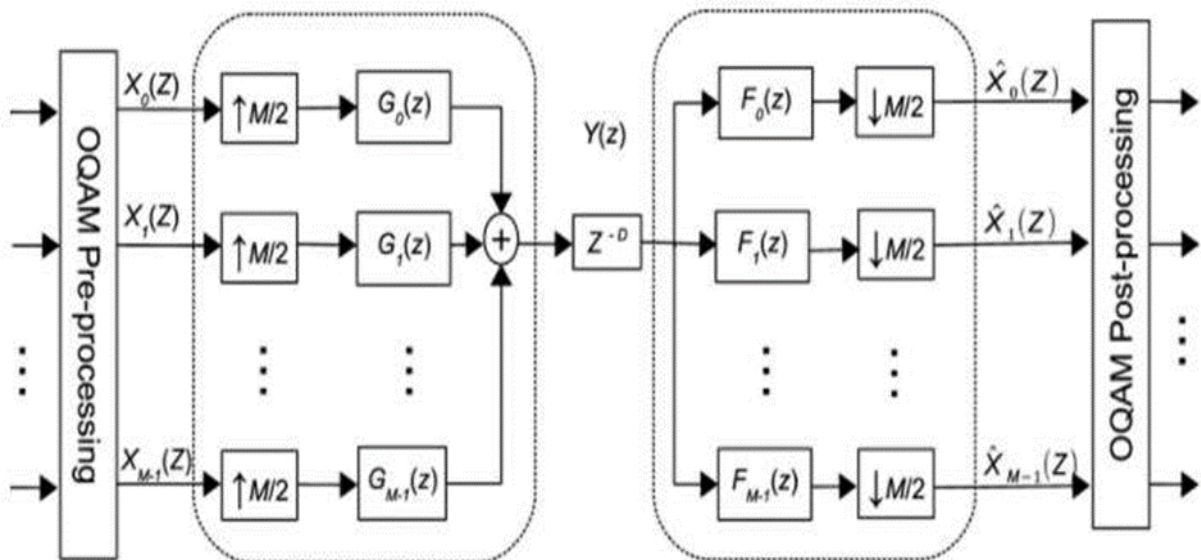
- **Standard Support and Ecosystem:** While FBMC is still largely a research topic with little commercial system deployment, OFDM has become more widely adopted in standards (such as LTE, 5G, and Wi-Fi).
- **Pilot Contamination:** FBMC's real-domain alignment, as opposed to OFDM's complex-domain alignment, complicates pilot placement and design, particularly in time-varying channels.

### 2.4.9 Principle of FBMC/OQAM modulation

The FBMC/OQAM modulation is positioned as an alternative to traditional OFDM modulation in 5G systems. FBMC/OQAM offers better spectral efficiency compared to OFDM, due to the lack of cyclic prefix usage, and it also exhibits low spectral uplift at the DSP level.

The FBMC-OQAM technique replaces conventional QAM modulation with OQAM modulation, where a shift of half a symbol period  $T/2$  is introduced between the real and imaginary parts of a given QAM symbol.

If the imaginary part is delayed by  $T/2$  on a subcarrier, the real part will be delayed on the subcarrier. Figure 20 shows the general structure of the FBMC/OQAM technique:



**Figure 20:** General structure of the FBMC/OQAM technique.

The structure of FBMC/OQAM can be divided into two parts: transmission part and reception part.

- Emission part.: At transmission, the SKN data symbols,  $K=0,1, \dots, M-1$ , which undergo QAM modulation, are sent by the serial/parallel conversion block and then undergo OQAM modulation, which involves introducing a time shift of half a period  $T/2$  between the real part and the imaginary part of the QAM symbol transmitted on a given subcarrier. This eliminates inter symbol interference.

The resulting signal passes through the synthesis filter block, which contains two blocks: The first block is the fast inverse Fourier transform. The second block is the polyphase filter ( $zn$ ). At the output of the synthesis filter bank, a parallel/serial conversion is performed, and the final output signal can be expressed as follows:

$$r(m) = \sum_{k=0}^{M-1} \sum_{n=-\infty}^{+\infty} dk(n) \phi_k(n) Bk(n) p(m - n \frac{m}{2}) e^{j \frac{2\pi}{M} km} \quad (2.7)$$

Where  $m$  is the sample index at the SFB/AFB input/output, and  $M$  is the number of subcarriers in the filter bank.

The block diagram of the FBMC/OQAM transmitting section is shown in Figure 21:

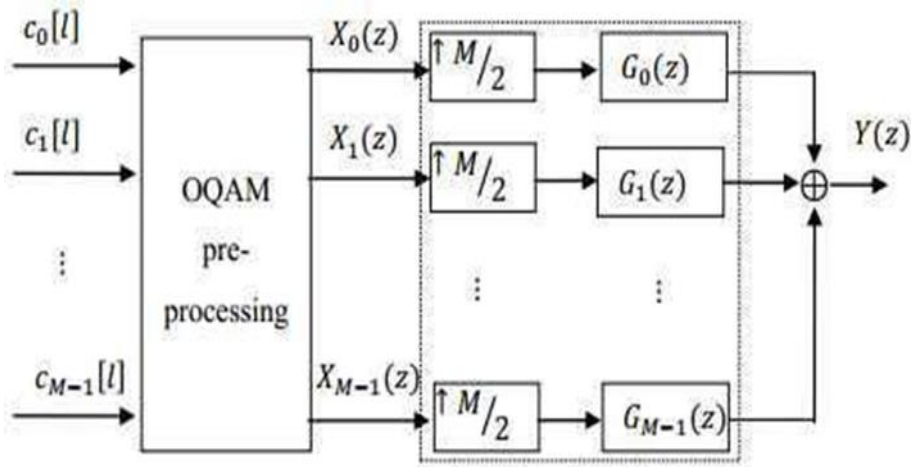


Figure 21: Emission part.

- Receiving part: The signal passes through the wireless channel and can be expressed as follows:

$$rk(m) = yk(m)h k(m) + Wk(m)$$

$h(m)$  is a complex fading process evaluated on the subcarrier for the FBMC / OQAM symbol,

$(m)$  is an additive white Gaussian noise (AWGN) process.

The processes of  $(m)$  and  $k=0,1, \dots, m-1$  are assumed to be mutually independent. They are zero-mean complex Gaussian processes with a distribution identical and equal variances. After processing the received signal  $(m)$  with the analysis filter bank block.

The block diagram of the FBMC/OQAM reception section is shown in Figure 22:

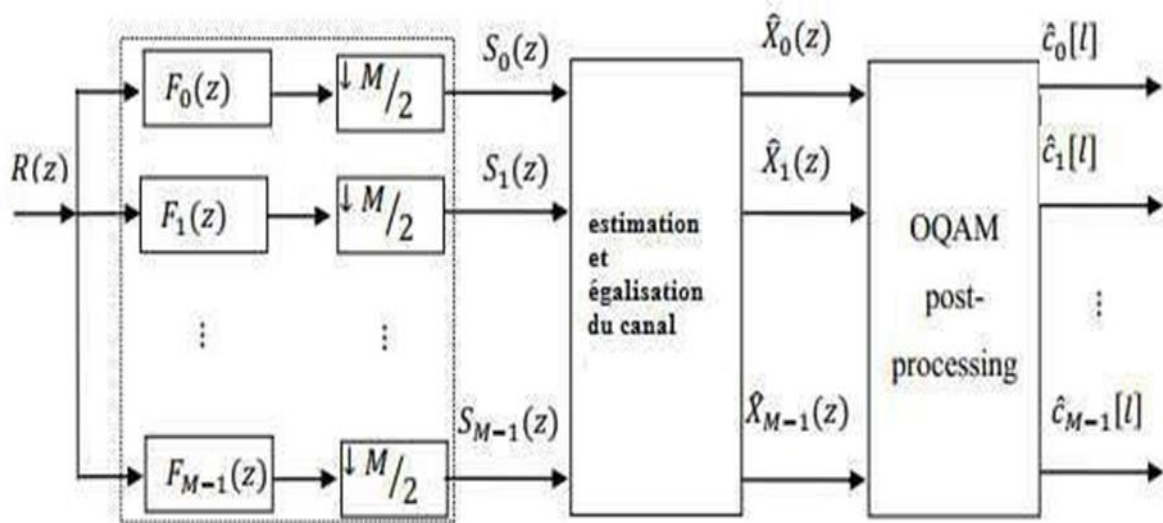


Figure 22: Reception section.

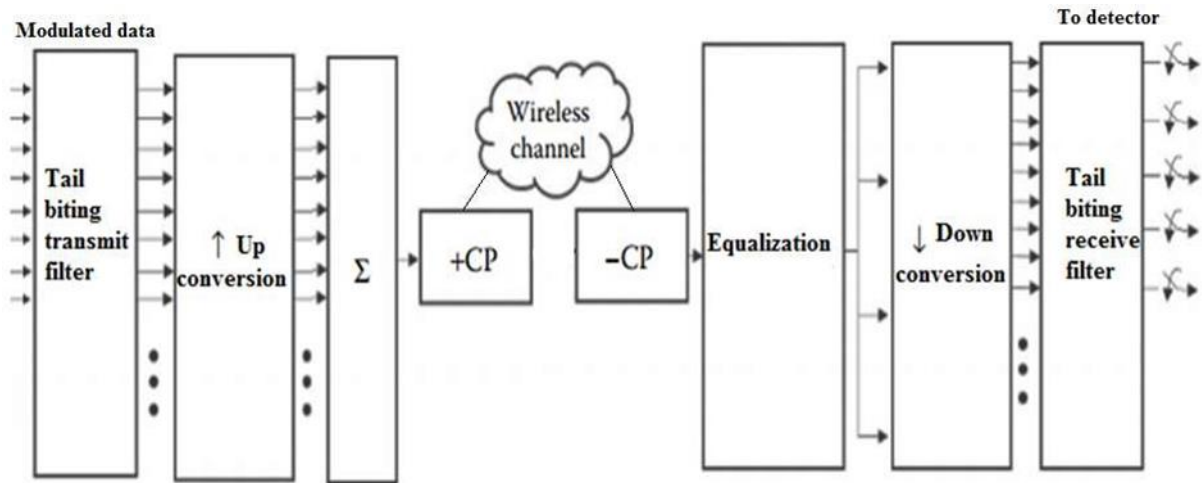
## 2.5 Generalized Frequency Division Multiplexing (GFDM)

### 2.5.1 Interest of GFDM Technique

By employing a variety of filters, the non-orthogonal modulation system known as GFDM (Generalized Frequency Division Multiplexing) provides additional degrees of freedom. An

adjustable shaping filter is applied to each carrier to control out-of-band radiation from the transmitted GFDM signal. Both the number of carriers and the time durations can be changed for each block of data symbols that make up the GFDM data structure. Because the block size is adjustable, long filters or a reduction in the overall number of subcarriers can be implemented. Like OFDM, GFDM fights ISI by using a cyclic prefix; however, the cyclic prefix is applied for every block, and the length of the cyclic prefix is used less frequently than in OFDM because each block can be multiple times the symbol period.[14]

## 2.5.2 GFDM Transmitter and receiver



**Figure 23:** Overall Diagram of GFDM transceiver. [15]

The diagram shows a system for transmitting and receiving data in wireless communications using Multicarrier technology (such as OFDM), and the brief explanation is as follows:

### On the sending side:

- Tail Biting Transmit Filter: A filter that reduces inter-symbol noise.
- Up Conversion: Converts the signal to a higher frequency (the carrier frequency).
- $\Sigma$  (Summation): Combines all sub-signals into a single signal.
- +CP (Cyclic Prefix Addition): Added to reduce the effect of channel interference.

### Wireless Channel:

- Carries the signal but may introduce noise or interference (multipath).

### On the reception side:

- -CP (Cyclic Prefix Elimination).
- Equalization: Balancing out the negative effects of a channel.
- Down Conversion: Converting the signal from the carrier frequency to the base frequency.
- Tail Biting Receive Filter: Receive filter to remove interference.
- To Detector: Sending data to a processor or detector for decoding.

### 2.5.3 Principle of GFDM

In contrast to traditional OFDM multiplexing, the new flexible multi-port transmission concept known as generalized frequency division multiplexing (GFDM) introduces additional degrees of freedom.

In GFDM, the emission signal's out-of-band is controlled by a filter that produces controllable impulses that are applied to individual subcarriers. Additionally, a two-dimensional data structure is introduced to group data symbols across multiple subcarriers and time slices into blocks. Block size is a variable parameter that enables the implementation of long filters or the reduction of the overall number of subcarriers. These blocks are treated using a low level of pique digital filters that preserve the circulatory properties in the temporary and frequent domains. Like OFDM, in GFDM a cyclic prefix can be used to combat ISI in a multipath channel. Subcarrier filtering, which can produce non-orthogonal subcarriers and lead to both inter-symbol interference (ISI) and inter-carrier interference (ICI), is one of the technique's drawbacks. Two block diagrams, one depicting a GFDM transmitter and the other a comprehensive GFDM modulator, are displayed in Figures 24 and 25.[16]

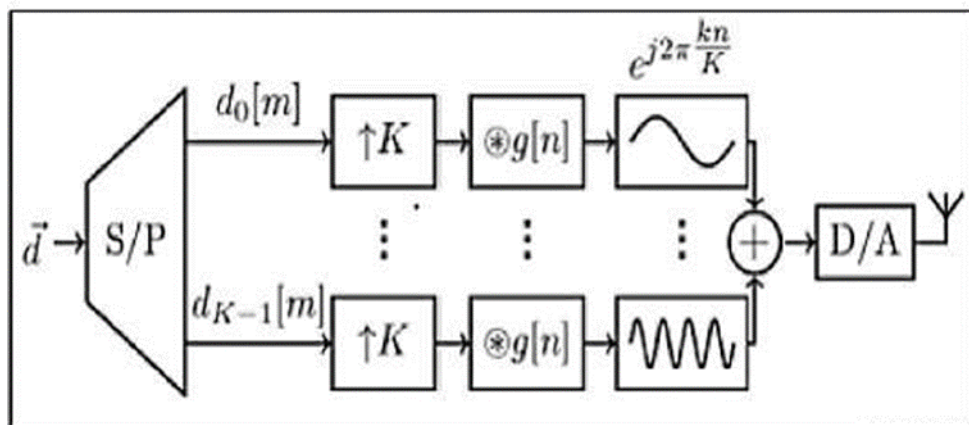


Figure 24:GFDM transmitter block diagram.[16]

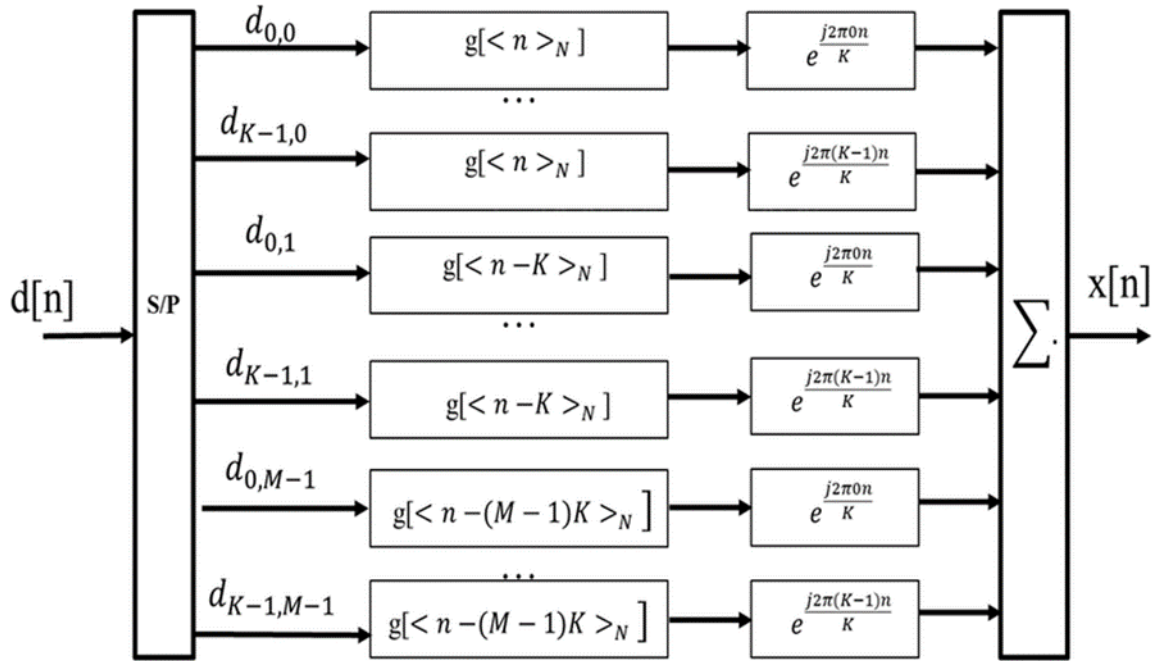


Figure 25: detailed GFDM modulator block diagram.[14]

#### 2.5.4 Advantages of GFDM modulation [17]

The adaptability of GFDM makes this type of wave suitable for a 5G future communication system. The characteristics of GFDM techniques are summarized as follows:

- Reasonable energy use.
- High spectral efficiency and quick response.
- A well-located emission impulsion frequency makes the system resilient to frequency dispersion (Doppler effect).
- A well-located impulsion provides robustness against time dispersion.
- The maximum power rate for GFDM, or PAPR, is lower than that of OFDM.
- Multi-port flexible modulation with dynamic spectrum allocation that can be obtained without significantly interfering with the service or other users.
- Petite has gone one step further by adding a single CP to the entire block that has multiple sub-symbols to lower energy consumption and achieve the GFDM is a non-orthogonal wave form that reduces complexity through transmission and reception diversity.

## 2.6 CONCLUSION

The various Multicarrier modulation types used in 5G systems, referred to as FBMC and GFDM, were examined in this chapter. Although OFDM is frequently utilized in wireless networks, its efficiency is limited. FBMC is one of the future 5G networks under consideration. Unlike OFDM, FBMC suppresses inter-carrier interference with small guard bands and does not require a cyclic prefix. It has low side lobes and uses the full symbol period. Compared to OFDM, it is far less sensitive to changes in time. We will start our experimental section in the following chapter, simulating transmission chains using MATLAB's OFDM and FBMC techniques for comparison.

**Chapter 3**

**Simulation and**

**Performance**

**Analysis**

### 3.1 Introduction

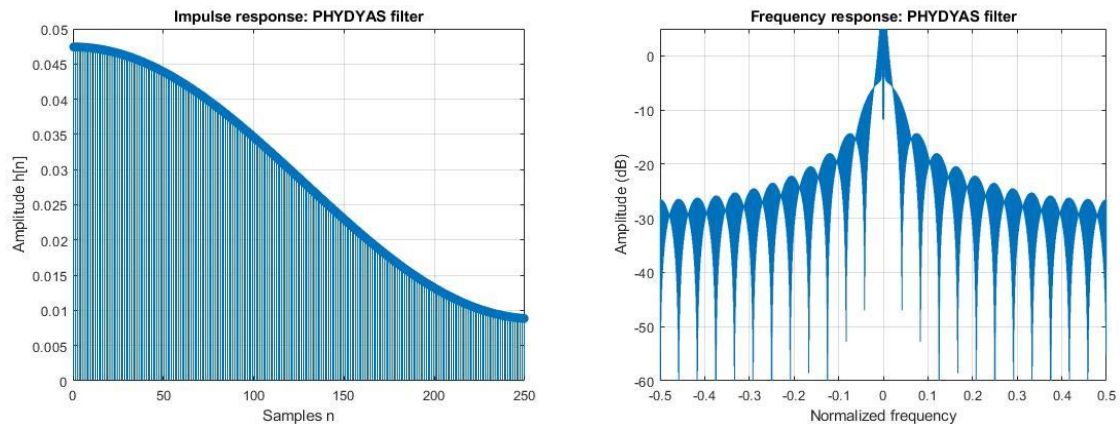
This chapter examines the simulation and performance analysis of Filter Bank Multicarrier (FBMC) and Orthogonal Frequency Division Multiplexing (OFDM) systems for 5G telecommunications. It explores prototype filter characteristics, including PHYDYAS, Raised Cosine Root (RRC), and Hermite filters, and their impact on FBMC performance. The analysis covers the FBMC transmission/reception systems, assessing metrics like power spectral density (PSD), Peak-to-Average Power Ratio (PAPR), and Bit Error Rate (BER). Through simulations, we compare FBMC and OFDM performances; we highlight their strengths and weaknesses to optimize 5G communication systems.

### 3.2 Prototype filters characteristics

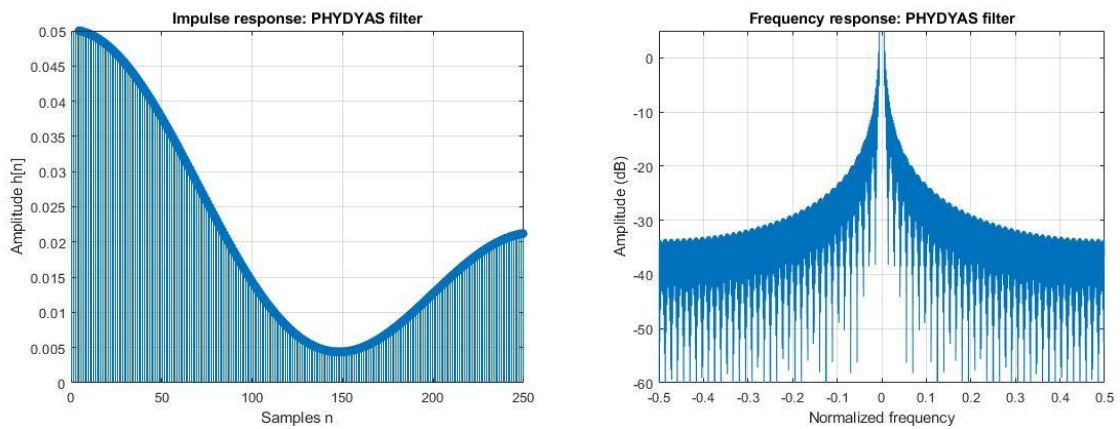
In this section we perform filters characteristics, namely the impulse response and frequency response for the prototype filters. We use PHYDYAS, Raised Cosine Root (RRC), and Hermit as prototype filters.

#### 3.2.1 PHYDYAS Filter characteristics

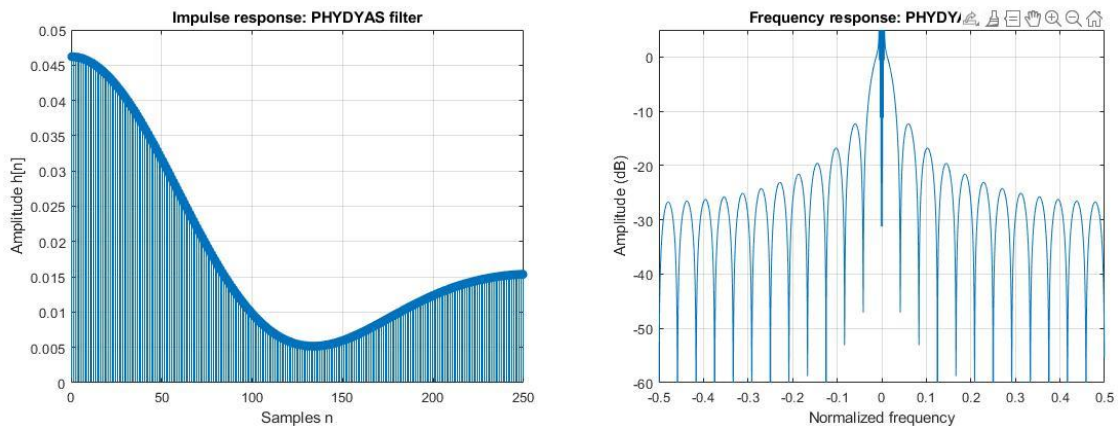
The PHYDYAS filter, tailored for FBMC, provides excellent spectral containment. Its impulse response is symmetric, with increasing time-domain spread as  $K$  increases from 2 to 4, enhancing orthogonality in Offset Quadrature Amplitude Modulation (OQAM) systems. Figure 26 give the impulse and frequency responses for PHYDYAS filter, varying the overlapping factor;  $k=2$  part (a),  $k=3$  part (b) and  $k=4$  part (c) respectively.



(a)



(b)



(c)

**Figure 26:**PHYDYAS Filter Impulse and Frequency Responses  $k=2$  part (a),  $k=3$  part (b) and  $k=4$  part (c)

The impulse response (part (a),  $k=2$ ) shows a rapid decay from amplitude of 0.045 to near zero over 250 samples, indicating a compact time-domain response suitable for minimizing inter-symbol interference. The frequency response peaks at 0 dB with

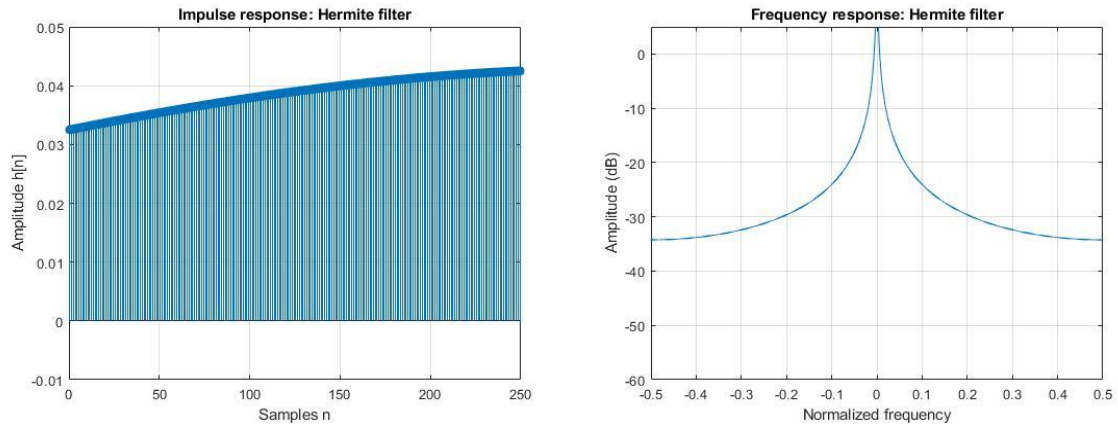
oscillations between -10 dB and -60 dB, reflecting good spectral containment but with noticeable side lobes that may cause minor interference at normalized frequencies from -0.5 to 0.5.

For (part (b),  $k=3$ ), the impulse response extends slightly longer than  $K=2$ , suggesting a trade-off between time-domain compactness and filter sharpness. The frequency response shows reduced side lobe amplitudes compared to  $K=2$ , improving spectral efficiency and reducing out-of-band interference.

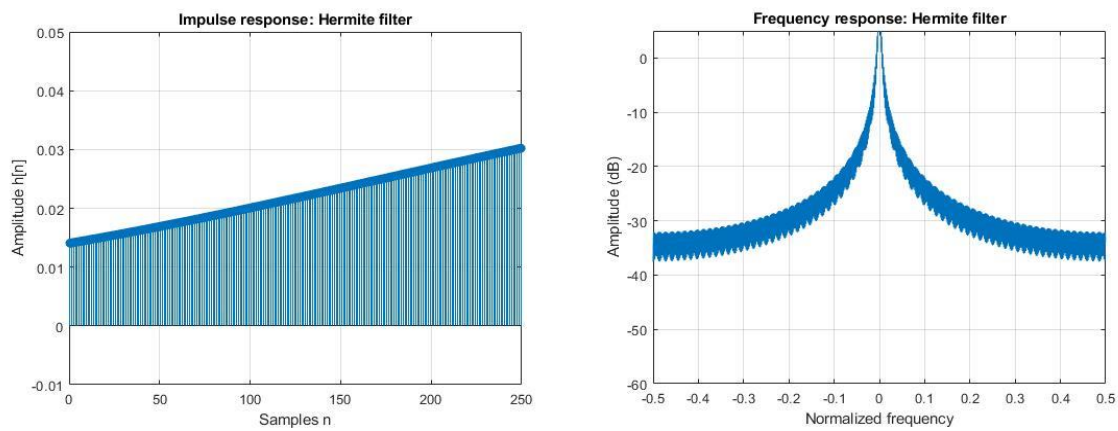
For (part (c),  $k=4$ ), the impulse response is more spread, indicating a longer filter length that enhances frequency selectivity. The frequency response exhibits the lowest side lobe levels among the PHYDYAS configurations, achieving better spectral confinement, ideal for dense 5G spectrum environments.

### **3.2.2 Hermite Filter**

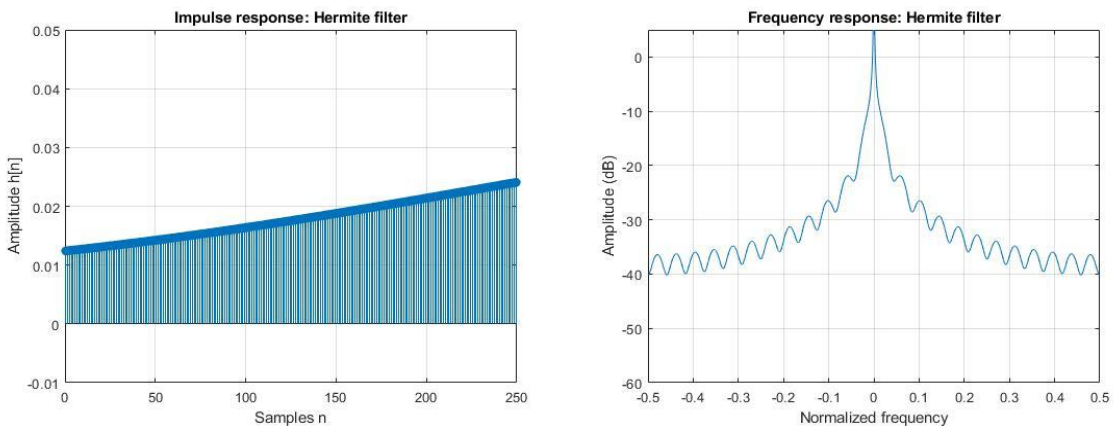
The Hermite filter, based on orthogonal polynomials, provides compact impulse responses and low sidelobes, ideal for low-latency applications. Its impulse response is symmetric, with increasing time-domain spread as the overlapping factor  $K$  increases from 2 to 4, enhancing frequency selectivity in Offset Quadrature Amplitude Modulation (OQAM) systems. Figure 27 shows the impulse and frequency responses for the Hermite filter, varying the overlapping factor:  $K=2$  part (a),  $K=3$  part (b), and  $K=4$  part (c).



(a)



(b)



(c)

**Figure 27:** Hermite Filter Impulse and Frequency Responses  $k=2$  part (a),  $k=3$  part (b) and  $k=4$  part (c)

The impulse response (part (a),  $K=2$ ) exhibits a symmetric, bell-shaped decay, with amplitude dropping from 0.05 to near zero over 200 samples, indicating excellent time domain compactness suitable for minimizing inter-symbol interference. The frequency response peaks at 0 dB, with side lobes oscillating between -20 dB and -50 dB, reflecting

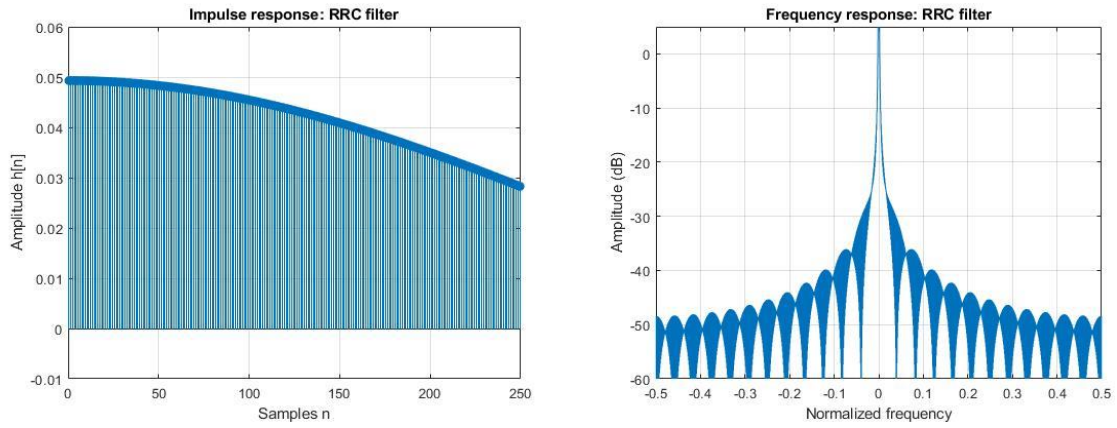
moderate spectral containment but with noticeable out-of-band leakage at normalized frequencies from -0.5 to 0.5.

For (part (b),  $K=3$ ), the impulse response extends slightly longer than  $K=2$ , suggesting a trade-off between time-domain compactness and frequency resolution. The frequency response shows reduced side lobe amplitudes compared to  $K=2$ , improving spectral efficiency and reducing out-of-band interference.

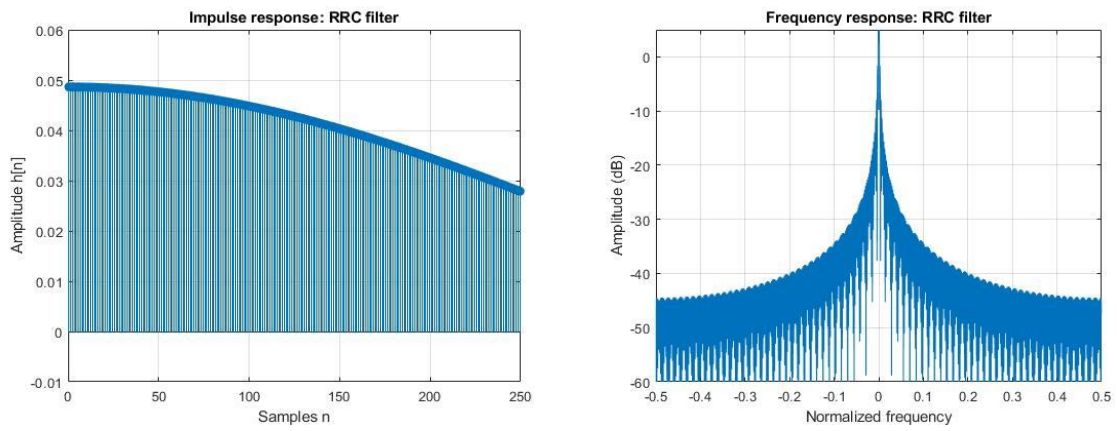
For (part (c),  $K=4$ ), the impulse response is more spread, indicating a longer filter length that enhances frequency selectivity. The frequency response exhibits the lowest side lobe levels among Hermite configurations, achieving better spectral confinement, ideal for dense 5G spectrum environments, though still with slightly higher out-of-band emissions compared to PHYDYAS.

### **3.2.3 Raised Cosine Root (RRC) Filter**

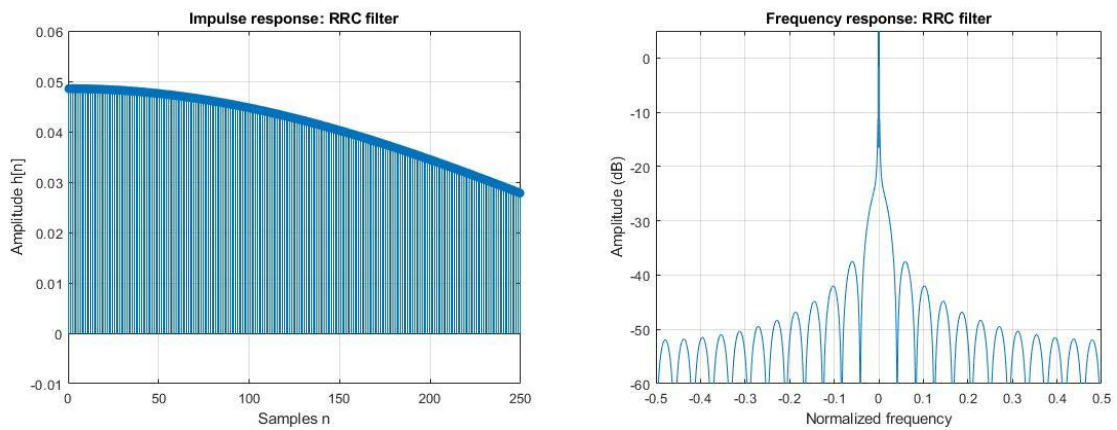
The Root Raised Cosine (RRC) filter provides a smooth frequency roll-off, with a wider impulse response compared to PHYDYAS, balancing time-frequency localization. Its impulse response is symmetric, with increasing time-domain spread as  $K$  increases from 2 to 4, improving frequency selectivity in OQAM systems. Figure 28 shows the impulse and frequency responses for the RRC filter, varying the overlapping factor:  $K=2$  part (a),  $K=3$  part (b), and  $K=4$  part (c).



(a)



(b)



(c)

**Figure 28:**RRC Filter Impulse and Frequency Responses  $k=2$  part (a),  $k=3$  part (b) and  $k=4$  part (c)

With numFFT=512, the impulse response (part (a), K=2) shows a smooth decay from an amplitude of 0.04 to near zero over 300 samples, effective for reducing inter-symbol interference. The frequency response peaks at 0 dB, with side lobes between -15 dB and -40 dB, indicating decent spectral efficiency but more out-of-band interference compared to PHYDYAS at normalized frequencies from -0.5 to 0.5.

For (part (b), K=3), the impulse response extends further than K=2, balancing time and frequency domains. The frequency response shows improved side lobe suppression compared to K=2, reducing interference, though it remains less efficient than PHYDYAS.

For (part (c), K=4), the impulse response is the longest, optimizing frequency resolution. The frequency response exhibits the best side lobe suppression among RRC configurations, closely rivalling Hermite but still trailing PHYDYAS in spectral containment.

We recapitulate prototype filter characteristics for (K=4) in Table 1

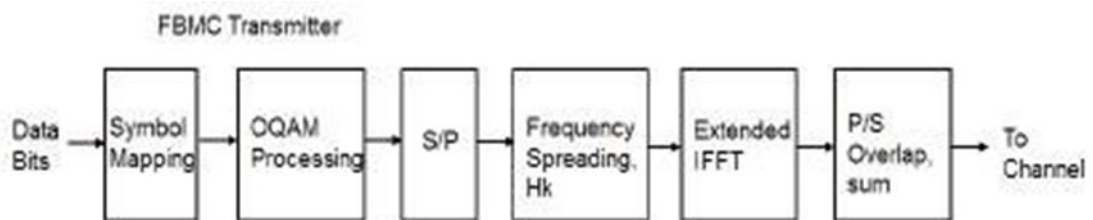
**Table 1:** Comparison of Prototype Filter Characteristics (K=4).

Filter	Frequency Roll-off	Impulse Response Width	Side-lobe Suppression
<b>PHYDYAS</b>	Sharp	Moderate	<b>High</b>
<b>RRC</b>	Moderate	Wide	<b>Moderate</b>
<b>Hermit</b>	<b>Compact</b>	<b>Narrow</b>	<b>High</b>

Hermit is best for FBMC due to its compact frequency roll-off, narrow impulse response width, and high side-lobe suppression, optimizing performance and efficiency.

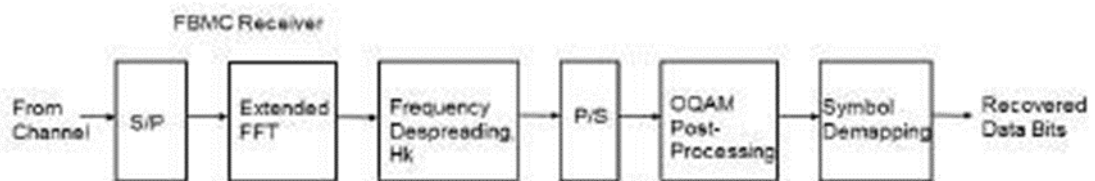
### 3.3 FBMC Transmission/Reception system

In our simulation we adopt the flowing FBMC system. OQAM modulation is used with optimized polyphase filtering to enhance subcarrier orthogonality.



**Figure 29:** FBMC structure of the transmission chain in transmission.

The FBMC transmitter structure depicts the data flow from input bits through modulation, filtering, and transformation. The Symbol Mapping block maps input bits to modulation symbols, typically using Quadrature Amplitude Modulation (QAM). The Offset Quadrature Amplitude Modulation (OQAM) Processing block separates the real and imaginary components of the symbols, introducing a time offset of half symbol duration to maintain orthogonality. The Serial-to-Parallel (S/P) converter prepares the data stream for parallel subcarrier processing. Next, the Frequency Spreading block applies subcarrier-specific filtering using a prototype filter ( $H_k$ ) to enhance spectral shaping. The Extended IFFT then converts the frequency-domain signal into its time-domain representation. Finally, the Parallel-to-Serial (P/S) block overlaps and sums the filtered time-domain signals to form the transmitted waveform, minimizing spectral leakage and inter-symbol interference.



**Figure 30:**FBMC structure of the transmission chain in reception

The FBMC receiver structure shows the signal processing from channel input to data recovery, with an added post-filtering step after the FFT to enhance noise rejection.

The transmission process begins with input data bits undergoing symbol mapping to assign modulation symbols. These are processed using Offset Quadrature Amplitude Modulation (OQAM) to separate real and imaginary components, improving spectral efficiency. The serial-to-parallel (S/P) conversion prepares data for frequency spreading with prototype filters (e.g., PHYDYAS), followed by an Inverse Fast Fourier Transform (IFFT) to convert the signal to the time domain. Overlap and add operations combine subcarriers, and parallel-to-serial (P/S) conversion prepares the signal for channel transmission. In reception, the reverse occurs: the signal is converted to parallel streams, processed with a Fast Fourier Transform (FFT), filtered to remove noise, and demodulated via OQAM to recover the original data bits, ensuring robust performance in 5G environments.

### 3.3.1 Simulation Parameters

In Table 2, we give an insight on simulation parameters.

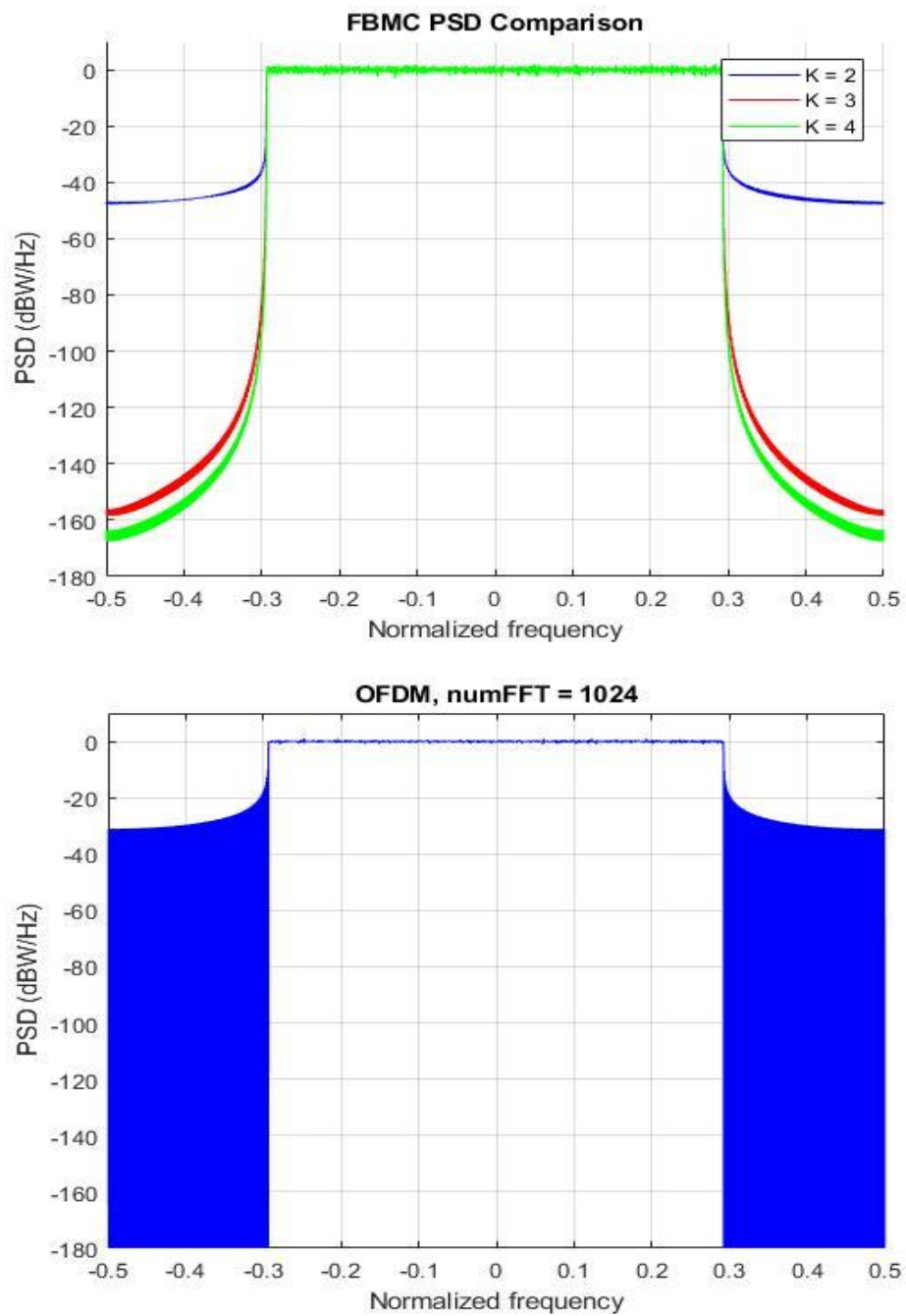
**Table 2:**Simulation Parameters for FBMC System Analysis

Parameter	Value
FFT Size (numFFT)	512, 1024
Overlapping Factor (K)	2, 3, 4
Guard Bands	100,212,300
Modulation Scheme	OQAM
Filter Types	PHYDYAS, Hermit, RRC
Sampling Frequency	15.36 MHz
Channel Model	AWGN, AWGN+Rayleigh
Simulation Iterations	1000
Signal-to-Noise Ratio	0 to 30 dB

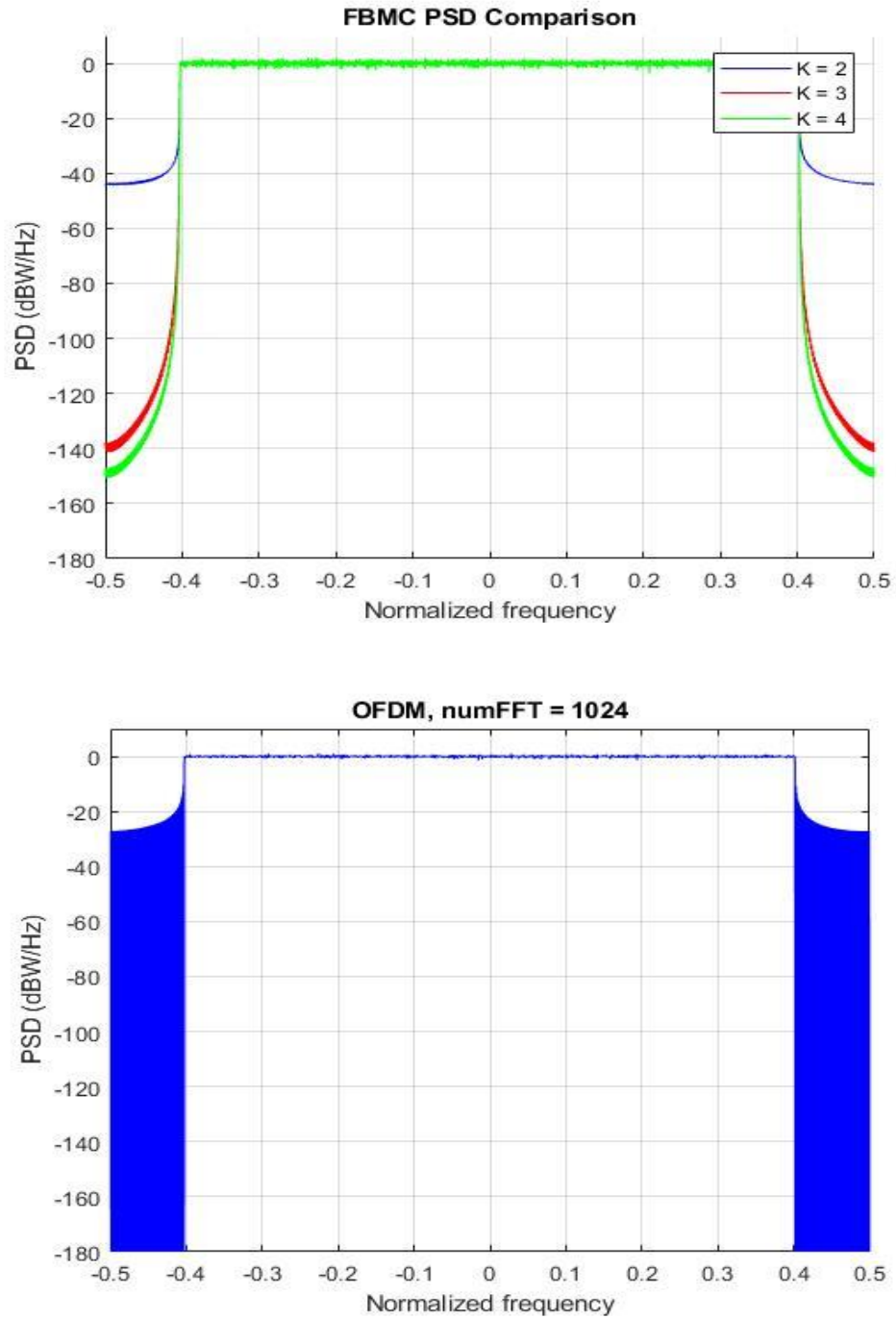
### 3.3.2 Power Spectral Density performance

In this section we present the PSD of OFDM and FBMC with different values of the overlapping factor ‘k’, different values of ‘numGuards’ and different length of FFT. We observe the effect of varying those parameters on the PSD.

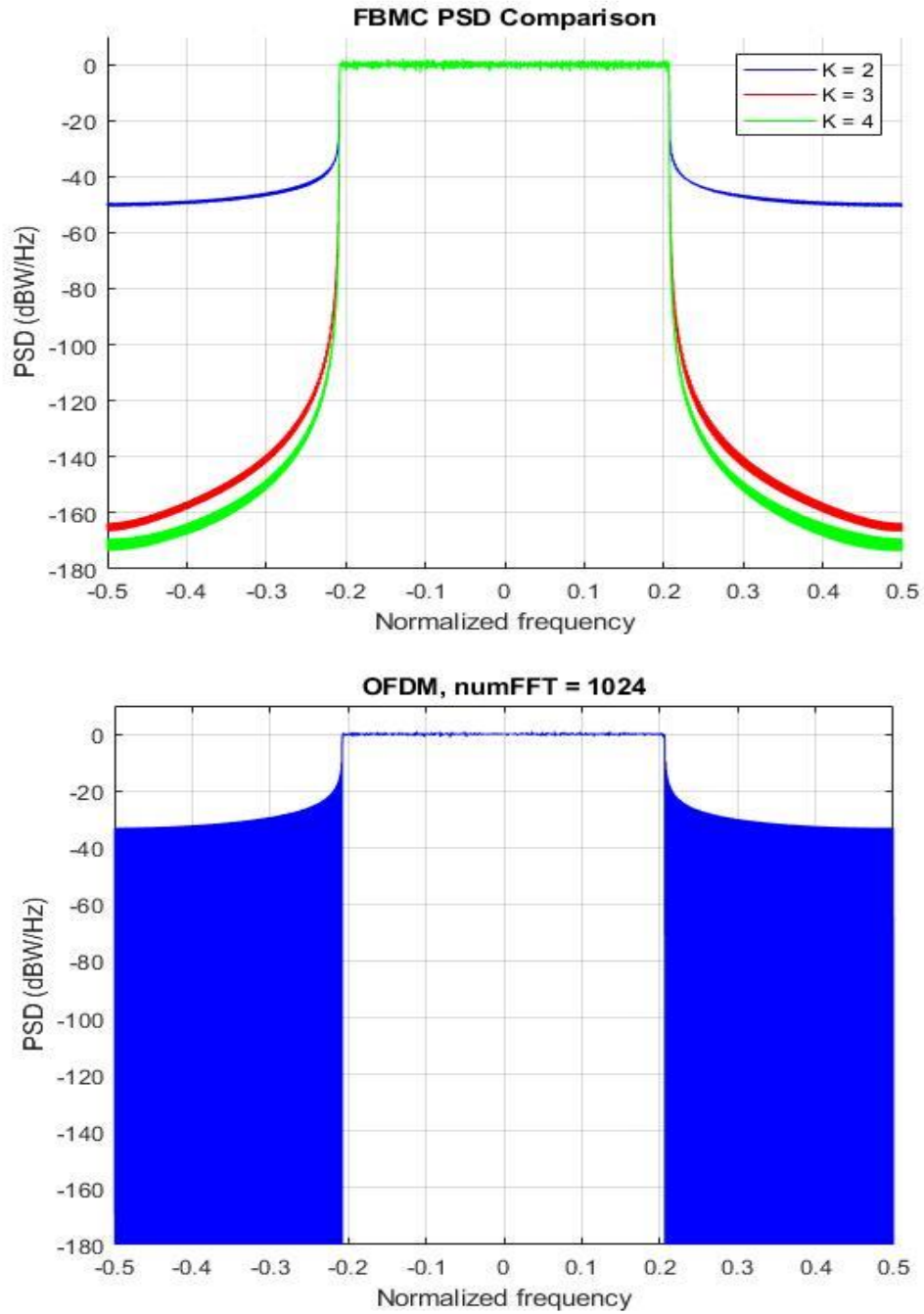
✚ Effect of varying 'k' and 'numGuards' with fixed NFFT=1024



**Figure 31:** PSD of FBMC and OFDM; (numFFT=1024, numGuards = 212)

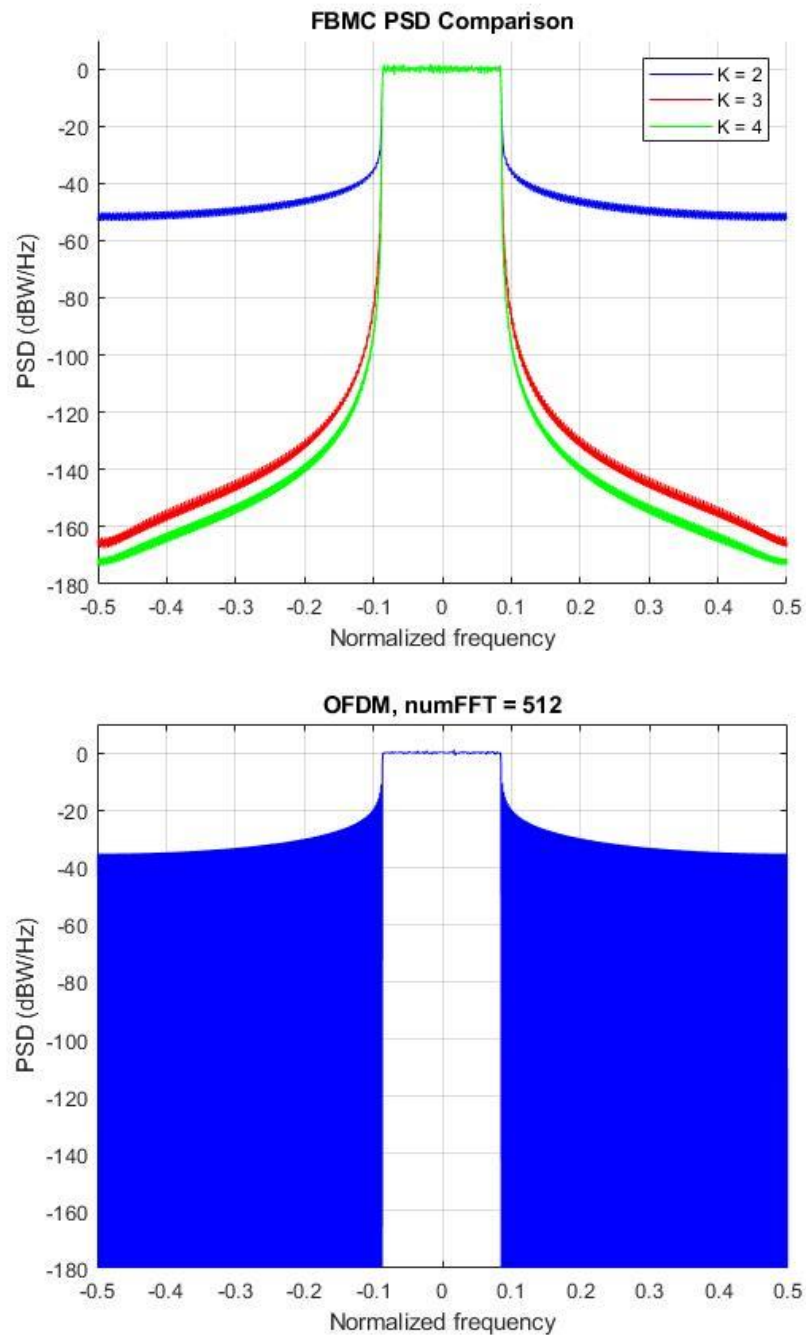


**Figure 32:** PSD of FBMC and OFDM; (numFFT=1024, numGuards = 100)

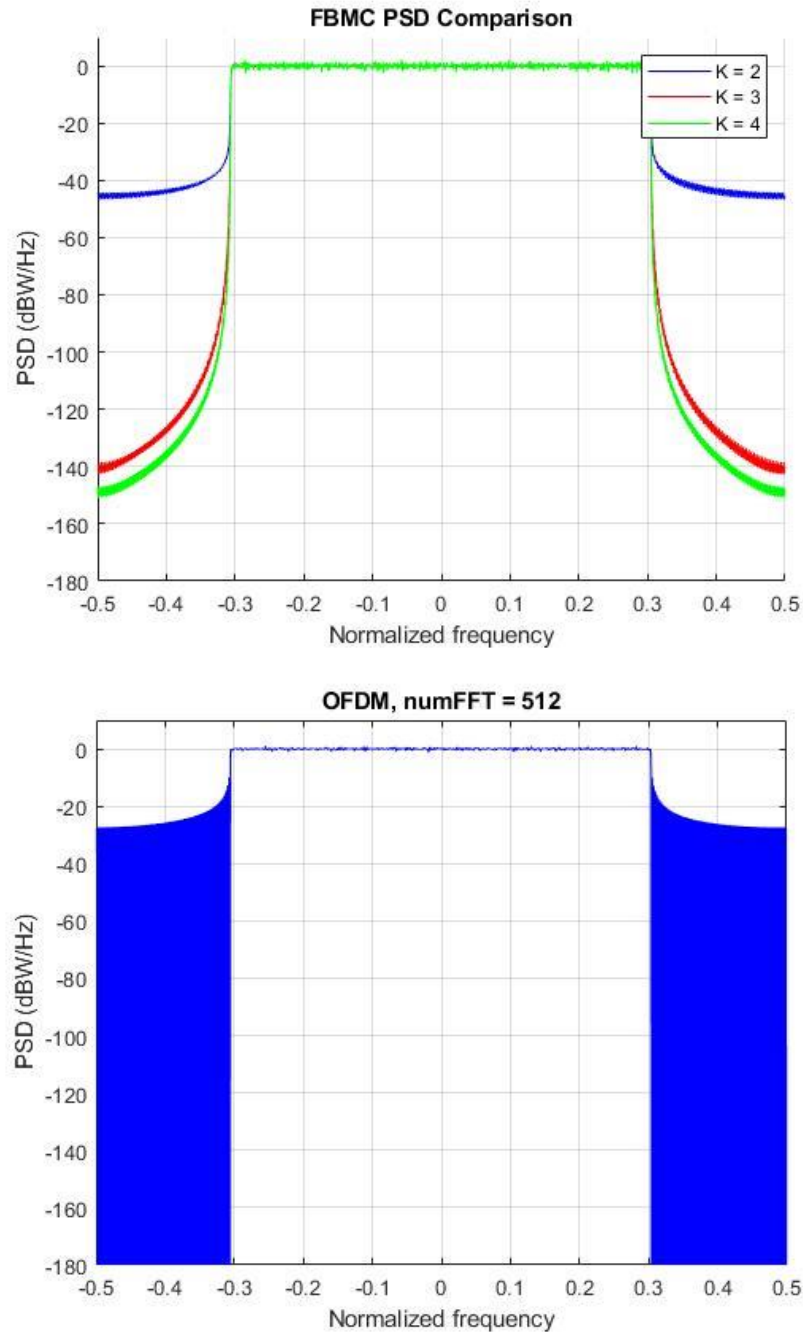


**Figure 33:** PSD of FBMC and OFDM (numFFT=1024, numGuards=300)

## ✚ Effect of varying 'k' and 'numGuards' with fixed NFFT=512



**Figure 34:** PSD of FBMC and OFDM (numFFT=512, numGuards=212)



**Figure 35:** PSD of FBMC and OFDM (numFFT=512, numGuards=100)

The PSD figures collectively demonstrate FBMC's superior spectral efficiency over OFDM across various configurations (numFFT=512 or 1024, numGuards=100, 212, or 300). FBMC consistently exhibits sharper roll-off and lower side lobes, reducing out-of-band emissions and improving bandwidth utilization, which is critical for 5G systems. The overlapping factor ( $K$ ) in FBMC enhances spectral containment, with higher  $K$  values (e.g.,  $K=4$ ) showing tighter spectra. OFDM, while simpler, suffers from higher side lobes and broader spectral spread, leading to less efficient spectrum use, even with increased guard

bands. These results highlight FBMC's potential for 5G applications requiring high spectral efficiency, though OFDM's simplicity may still be preferred in less constrained scenarios.

### 3.3.3 Peak-to-Average Power Ratio (PAPR)

In this part of simulation, we present the study of the Peak-to-Average Power Ratio (PAPR) versus SNR for various QAM modulation order in noisy environment materialised by AWGN and a noisy fading environment materialised by AWGN plus Rayleigh.

**Table 3:**Peak to Average Power Ratio (PAPR) of OFDM and FBMC versus QAM order, AWGN Channel

QAM	4	16	64	256
PAPR (dB)				
FBMC	<u>10.674</u>	11.175	11.3345	11.5648
OFDM	10.9634	10.9828	10.4994	10.5332

**Table 4:**Peak to Average Power Ratio (PAPR) of (OFDM; FBMC) versus QAM order, (AWGN+ Rayleigh) Channel.

QAM	4	16	64	256
PAPR (dB)				
FBMC	<u>15.3971</u>	18.634	17.613	17.5107
OFDM	15.4231	14.1085	16.9303	14.7197

For the AWGN channel, FBMC's PAPR vary from 10.674 dB to 11.5648 dB, It increases with QAM order. Although OFDM's PAPR vary from 10.9634 dB to 10.5332 dB slightly decreases. A lower PAPR of 10.674 is only performed by the FBMC at 4QAM

compared to 10.9634 performed by OFDM. For All QAM order FBMC exhibits a high PAPR when compared to OFDM (e.g., 11.5648 dB vs. 10.5332 dB at 256 QAM).

For the severe environment materialised by AWGN plus Rayleigh, PAPR rises significantly due to fading, with FBMC (15.3971 dB to 17.5107 dB) exceeding OFDM (15.4231 dB to 14.7197 dB) at 16 QAM and 256 QAM (e.g., 18.634 dB vs. 14.1085 dB), indicating OFDM’s better performance in fading at higher modulations.

Overall, FBMC excels in stable AWGN at low QAM order while OFDM is more robust in fading channels, especially at higher modulation orders.

### 3.3.4 Bit Error Rate (BER)

In this part of simulation, we present the study of the Bit Error Rate (BER) versus SNR for various QAM modulation order and overlapping factor ‘k’. We consider noisy environment materialised by AWGN and a noisy fading environment materialised by AWGN plus Rayleigh.

#### a) Bit Error Rate in AWGN channel

✚ BER performance of OFDM and FBMC in AWGN channel and K=4

**Table 5:**Bit Error Rate (BER) versus SNR, AWGN Channel; 4 QAM (OFDM; FBMC)

SNR (dB)	0	4	8	12
<b>BER</b>	<b>0</b>	<b>4</b>	<b>8</b>	<b>12</b>
<b>FBMC</b>	0.092101	0.019402	0.000489	0
<b>OFDM</b>	0.096817	0.018583	0.000533	<b>0</b>

**Table 6:**Bit Error Rate (BER) versus SNR, AWGN Channel; 16 QAM (OFDM; FBMC)

SNR (dB)	0	4	8	12	16
<b>BER</b>					
<b>FBMC</b>	0.228361	0.133777	0.051966	0.006966	0
<b>OFDM</b>	0.228258	0.133846	0.053133	0.007788	0

**Table 7:**Bit Error Rate (BER) versus SNR, AWGN Channel; 64 QAM (OFDM; FBMC)

SNR (dB)	0	4	8	12	16	20	24
<b>BER</b>							
<b>FBMC</b>	0.316709	0.232796	0.144928	0.074505	0.020531	0.001280	0
<b>OFDM</b>	0.317056	0.232311	0.145847	0.075306	0.020792	0.001386	0

The BER tables compare FBMC and OFDM across different modulation schemes (4 QAM, 16 QAM, 64 QAM) for overlapping factors  $K=4$ . in AWGN channel:

- For 4 QAM: FBMC generally shows slightly lower BER than OFDM at lower SNRs (0–4 dB) for  $K=4$  yielding the lowest FBMC BER. At higher SNRs (8–12 dB), both systems achieve near-zero BER, with minor differences.
- For 16 QAM: FBMC and OFDM have comparable BERs, with FBMC slightly better at lower SNRs (e.g., 0.228361 vs. 0.228258 at 0 dB for  $K=4$ ). At higher SNRs, performance converges, with both reaching zero BER at 20 dB.
- For 64 QAM: BER differences are minimal, but FBMC slightly outperforms OFDM at intermediate SNRs (e.g., 0.144928 vs. 0.145847 at 8 dB for  $K=4$ ). Both achieve zero BER at 24–28 dB.

### b) Bit Error Rate in AWGN + Rayleigh channel

In the same manner we present the study of BER for a fading environment materialised by AWGN + Rayleigh channel.

- ✚ BER performance of OFDM and FBMC in (AWGN + Rayleigh) channel;  $K=4$

**Table 8:**Bit Error Rate (BER) versus SNR, AWGN + Rayleigh channel; 4 QAM

(OFDM; FBMC)

SNR (dB)	0	4	8	12
<b>BER</b>				
<b>FBMC</b>	0.092373	0.018678	0.00056159	0
<b>OFDM</b>	0.096175	0.01895	0.00046667	0

**Table 9:**Bit Error Rate (BER) versus SNR, AWGN + Rayleigh Channel; 16 QAM

(OFDM; FBMC)

SNR (dB)	0	4	8	12	16	20
<b>BER</b>						
<b>FBMC</b>	0.22811	0.13361	0.05221	0.0074094	9.058e-05	0
<b>OFDM</b>	0.22777	0.13407	0.053271	0.0076	6.25e-05	0

**Table 10:**Bit Error Rate (BER) versus SNR, AWGN + Rayleigh Channel; 64 QAM

(OFDM; FBMC)

SNR (dB)	0	4	8	12	16	20	24
<b>BER</b>							
<b>FBMC</b>	0.31898	0.2331	0.14492	0.074396	0.020423	0.0012923	0
<b>OFDM</b>	0.31932	0.2329	0.14583	0.075267	0.021036	0.0012611	0

The BER tables compare FBMC and OFDM across different modulation schemes (4 QAM, 16 QAM, 64 QAM) for overlapping factors  $K=4$  in (AWGN+ Rayleigh) channel:

- 4 QAM: FBMC shows lower BER at lower SNRs  $K=4$  (e.g., 0.092373 vs. 0.096175 at 0 dB for  $K=4$ ), OFDM slightly outperforms FBMC at 8 dB (0.00060833 vs. 0.00031915). Both reach zero BER at 12 dB.
- 16 QAM: FBMC and OFDM have similar BERs, with FBMC slightly better at lower SNRs (e.g., 0.22811 vs. 0.22777 at 0 dB for  $K=4$ ). At 16–20 dB, both converge to zero BER, with minor variations.
- 64 QAM: BERs are nearly identical, with FBMC slightly better at intermediate SNRs (e.g., 0.14492 vs. 0.14583 at 8 dB for  $K=4$ ). Both systems reach zero BER at 24–28 dB, with OFDM occasionally showing a slight edge at 24 dB.

✚ **Impact of K (Overlapping Factor):** Higher  $K$  values (e.g.,  $K=4$ ) generally improve FBMC's BER at lower SNRs across all modulations, particularly in AWGN + Rayleigh channels, due to better spectral containment. However, the improvement is marginal, and OFDM sometimes matches or slightly outperforms FBMC at specific SNRs (e.g.,  $K=4$  QAM at 8 dB).

✚ **Modulation Complexity:** As modulation order increases (4 QAM to 64 QAM), BER increases for both systems at lower SNRs, requiring higher SNRs to achieve zero BER (e.g., 12 dB for 4 QAM, 20 dB for 16 QAM, 24–28 dB for 64 QAM). This trend is consistent across both channels and  $K$  values.

✚ **Overall Comparison:** FBMC shows slight BER advantages over OFDM at lower SNRs, particularly with  $K=4$ , due to its superior spectral efficiency and reduced interference from optimized filters. However, differences are small, and OFDM's performance is comparable, especially at higher SNRs or with simpler modulations (4 QAM). In AWGN + Rayleigh channels, the fading effect slightly amplifies BER differences at lower SNRs, but both systems converge at higher SNRs.

These results suggest FBMC's potential for 5G systems in scenarios requiring robust performance at low SNRs, while OFDM's simplicity may still be advantageous in high-SNR or less complex environments. Further optimization of  $K$  and filter design could enhance FBMC's edge.

### 3.4 Conclusion

This chapter provided a simulation-based comparison of FBMC and OFDM systems, focusing on prototype filter effects on PSD, PAPR, and BER. FBMC with optimized filters (PHYDYAS, RRC, and Hermit) showed improved spectral efficiency and lower PAPR compared to OFDM, though BER performance varied with channel conditions. OFDM's simplicity remains advantageous, but its higher PAPR and side lobes are limitations. These findings suggest FBMC's potential for 5G, with future research needed to enhance filter adaptability and integrate both techniques for optimal performance.

# **General Conclusion and Perspectives**

## General Conclusion and Perspectives

The demand for new wireless services and applications, along with the increasing number of users, is rapidly growing, imposing significant throughput constraints. Among the solutions studied to address these challenges are Multicarrier modulations: Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multicarrier (FBMC). The primary objective of this project is to develop a comparative simulation of FBMC and OFDM techniques for 5G networks.

The simulations conducted highlight the benefits of OFDM modulation, as detailed in Chapter 2, focusing on key transmission chain parameters such as the number of carriers, choice of constellation (e.g., 4-QAM, 16-QAM, 64-QAM), and various modulation types, which are adjusted based on channel conditions and data requirements, as outlined in Chapter 1. Chapter 3 further elaborates on these findings through performance analysis, demonstrating OFDM's simplicity and effectiveness in multipath and interference scenarios.

The performance comparison between the widely used OFDM and the innovative FBMC, explored in Chapters 2 and 3, is based on their operating principles. Simulation results from Chapter 3 show that FBMC offers performance improvements over OFDM in specific metrics, such as lower Peak-to-Average Power Ratio (PAPR) and enhanced Power Spectral Density (PSD) efficiency, particularly with optimized filters like PHYDYAS. However, these improvements are not universal across all parameters; for instance, Bit Error Rate (BER) performance is comparable between the two, with FBMC showing slight advantages only at lower Signal-to-Noise Ratios (SNRs) in AWGN and AWGN + Rayleigh channels. Thus, FBMC emerges as a promising candidate for future 5G development, though not definitively superior in all aspects.

In future work, we aim to expand our study of the FBMC technique, as suggested in Chapter 3, to investigate other critical factors such as spectral masking, not covered here, to conduct a more comprehensive analysis. Additionally, other technologies like Generalized Frequency Division Multiplexing (GFDM), introduced in Chapter 2, are under consideration as potential 5G candidates. This approach opens new avenues for advancements in wireless communications, building on the foundational insights provided throughout this study.

# **REFFERENCES**

- [1] Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C., & Zhang, J. C. (2014). *What will 5G be?* IEEE Journal on Selected Areas in Communications, 32(6), 1065–1082.
- [2] J. G. Proakis and M. Salehi, \*Digital Communications\*, 5th ed. New York: McGraw-Hill, 2007.
- [3] « Téléphonie mobile : l'évolution du réseau de la 1 à la 5G », consulté le 20 Mars 2019
- [4] Taha, H. J., & Salleh, M. F. M. (2009). Multi-carrier transmission techniques for wireless communication systems: A survey. *Wseas transactions on communications*, 8(5), 457-472.
- [5] Khedidja, D. A. O. U. D. (2016). Simulation Comparative des Techniques FBMC et OFDM pour les Réseaux 5G. *mémoire de master, département de télécommunication, université de Tlemcen*, 17-20.
- [6] DAACHI Dalila. « Étude des systèmes MIMO-OFDM communication sans fil » ; UNIVERSITE ABDERRAHMANE MIRA DE BEJAIA FACULTE DE TECHNOLOGIE DEPARTEMENT DE GENIE ELECTRIQUE ; 2011-2012.
- [7] BENSENOUCI Salima, BENSABER. Habiba Bochra, " Evaluation d'un système de communication FBMC", Université ABOUBAKR BELKAÏD– Tlemcen – Faculté de TECHNOLOGIE, Année 04 ; juillet 2019.
- [8] Dahlman, E., Parkvall, S., & Skold, J. (2020). *5G NR: The next generation wireless access technology*. Academic Press.
- [9] Goldsmith, A. (2005). *Wireless communications*. Cambridge university press.
- [10] HACINI Khaled, ABADELIA Anes, « Egaliseur LTE-LMS avec différentes Modulations», Thèse de MASTER, Département d'Electronique et Télécommunications, Systèmes de Télécommunications, Université du Guelma, 2019.
- [11] BENSENOUCI Salima, BENSABER Habiba Bochra, Evaluation d'un système de Communication FBMC, Thèse de MASTER, Télécommunications, Réseau et Télécommunications, Université Aboubakar Belkaïd– Tlemcen, 2019.
- [12] BENDAHMANE Amira Meriem ; Ghermoul Rania. (2017 /2018) Etude de méthodes de beamforming à maximisation du rapport signal sur bruit pour des systèmes FBMC''Mémoire, université de Tlemcen.
- [13] ARI VIHOLAINEN, MAURICE BELLANGER, and MATHIEU HUCHARD, "Prototype filter and structure optimization," website: [www.ict-phydyas.org](http://www.ict-phydyas.org): Document D5.1 deliverable, 2009.
- [14] Marwa CHAFII. "Étude d'une nouvelle forme d'ondes multi porteuses à PAPR réduit".

THÈSE DE DOCTORAT d'École doctorale Matisse. ANNÉE 2016,

[15] MAHARIMANANA Léonie Elsa. "ETUDE DE LA MODULATION GFDM ET DE LA TECHNIQUE D'ACCES NOMA DU RESEAU 5G". Thèse de Master d'Université D'ANTANANARIVO\_ECOLE SUPERIEURE POLYTECHNIQUE. Année mardi 28 mars 2017.

[16] BENAZOUT Nassiba. "Etude et simulation de la technique multi porteuses GFDM". Thèse de Master d'Université SAAD DAHLAB\_ BLIDA Faculté de Technologie. Année 2018.

[17] SADOU Bachir, ALQUDAMI Dheya Alhaq. "Etude des techniques de modulation pour les réseaux mobile 5G et 6G de nouvelle génération". Thèse de Master. Année 2020.