HASSIBA BENBOUALI UNIVERSITY OF CHLEF

Faculty of Technology

Department of Electronic

Master's Dissertation

Field : SCIENCE AND TECHNOLOGY

Major : TELECOMMUNICATIONS

Specialty : TELECOMMUNICATION SYSTEMS

Evaluation of modulation techniques for 5G wireless communications: Comparison of OFDM and UFMC performance.

BY

BEKHTI Nor El Houda

ZENATI Ikram

Supervisor:

Ms. FOUR Imane

Assistant professor «B » at UHBC

Co-supervisor:

SENHADJI Salima

PhD in Wireless Communication and Networks

Chlef, June 2025

UNIVERSITE HASSIBA BENBOUALI DE CHLEF

Faculté de Technologie

Département d'Electronique

MEMOIRE DE MASTER

Domaine	: SCIENCES ET TECHNOLOGIES
Filière	: TELECOMMUNICATIONS
Spécialité	: SYSTEMES DES TELECOMMUNICATIONS

Évaluation des techniques de modulation pour les communications sans fil 5G : Comparaison des performances de l'OFDM et UFMC.

Par

BEKHTI Nor El Houda

ZENATI Ikram

Encadrante:

Mme. FOUR Imane

Maitre Conférence «B » à l'UHBC

Co-encadrante:

SENHADJI Salima

Docteur en Communication et réseaux sans fil

Chlef, Juin 2025

Résume

Le système Universal Filtered Multi Carrier (UFMC) et met en avant ses avantages en tant que technique de modulation innovante pour les systèmes de communication sans fil de cinquième génération (5G). Bien que la modulation Orthogonal Frequency Division Multiplexing (OFDM) ait démontré son efficacité pour les réseaux de quatrième génération (4G), elle présente des limites significatives, notamment un rapport de puissance de crête à la puissance moyenne élevé (PAPR) et des fuites spectrales. Ces limitations compromettent sa capacité à prendre en charge les applications diversifiées et exigeantes prévues pour la 5G.

Étant donné que le trafic 5G aura des caractéristiques et des exigences très différentes de celles des technologies sans fil actuelles, des schémas accès multiple alternatifs, tels que UFMC, font objet de recherches actives. UFMC répond aux insuffisances connues de OFDM en offrant une meilleure efficacité spectrale et une réduction des interférences grâce au filtrage par sous-bandes. La simulation de ce travail sera effectuée à l'aide du logiciel MATLAB.

Mots clés : OFDM, UFMC, 5G, BER, PAPR.

Abstract

The Universal Filtered Multi-Carrier (UFMC) system is highlighted as an innovative modulation technique for fifth-generation (5G) wireless communication systems. Although Orthogonal Frequency Division Multiplexing (OFDM) has proven effective for fourth-generation (4G) networks, it has notable limitations, particularly a high Peak-to-Average Power Ratio (PAPR) and spectral leakage. These drawbacks hinder its ability to support the diverse and demanding applications envisioned for 5G.

Given that 5G traffic will have very different characteristics and requirements compared to current wireless technologies, alternative multiple access schemes such as UFMC are the subject of active research. UFMC addresses the known shortcomings of OFDM by providing better spectral efficiency and reducing interference through sub-band filtering. The simulation work in this study will be carried out using MATLAB software.

Keywords: OFDM, UFMC, 5G, BER, PAPR.

ملخص

يُعد نظام "الناقل المتعدد المرشح عالميًا (UFMC) تقنيةً مبتكرة في مجال التعديل، ويُبرز مزاياه كخيار واعد لأنظمة الاتصالات اللاسلكية من الجيل الخامس (5G) فعلى الرغم من أن تقنية "تعدد الإرسال بتقسيم التردد المتعامد (OFDM) أثبتت فعاليتها في شبكات الجيل الرابع (4G)، إلا أنها تعاني من بعض القيود المهمة، مثل ارتفاع نسبة الذروة إلى المتوسط في القدرة (PAPR) والتسرب الطيفي ، مما يحد من قدرتها على تلبية متطلبات التطبيقات المتنوعة والمعقدة المتوقعة في شبكات الجيل الخامس.

ونظرًا لأن حركة البيانات في شبكات 5G ستتسم بخصائص ومتطلبات تختلف كثيرًا عن تلك الخاصة بالتقنيات اللاسلكية الحالية، يتم البحث بنشاط عن أنماط وصول متعددة بديلة مثل UFMC حيث يُعالج UFMC أوجه القصور المعروفة في OFDM من خلال تحسين الكفاءة الطيفية وتقليل التداخل بفضل التصفية على مستوى النطاقات الفرعية.

ستتم محاكاة هذا العمل باستخدام برنامج MATLAB

الكلمات المفتاحية: UFMC، OFDM ، الجيل الخامس(5G) ، معدل الخطأ في البتات(BER) ، نسبة الذروة إلى المتوسط في القدرة(PAPR) .

Acknowledgments

As we bring this work to a close, we would like to express our heartfelt gratitude to all those who contributed to its completion.

First and foremost, we thank **Allah**, whose blessings gave us the strength, perseverance, and courage to explore this new field and see our work through to the end.

We are deeply grateful to our supervisors, **Ms. Four Imane** and **Ms. Sanhadji Salima**, for their unwavering support, insightful guidance, and thoughtful feedback throughout this journey. Their expertise and encouragement have been invaluable.

Our sincere thanks also go to the **president of the jury** and all **jury members** for taking the time to read, evaluate, and provide their reflections on our work.

We extend our appreciation to **Mr. Oumsalem**, Head of the Electronics Department, and to all the dedicated **faculty members** of the department, whose teaching and support have shaped our academic path.

Last but certainly not least, we are deeply grateful to our families and friends for their unwavering support, patience, and encouragement. Your presence and belief in us have made all the difference.

To everyone who helped us, directly or indirectly, **thank you.** We are truly proud of what we have accomplished.

Dedication

I dedicate this modest work to: My family, who raised me with care and gave me a good education.

To the most beautiful star in the universe, my dearest mother ABBED **Fatima,** to whom I wish a long life and good health.

To my beloved father **Mohammed,** who has always been by my side, encouraging me and supporting me throughout my studies. May God bless him with good health.

To my wonderful sisters **(Amira** and **Fathia**) and brothers (**Rida, Toufik,** and **Mouayade)**, and to my little niece **Ritadj** and **Oussayd**, for their constant encouragement and moral support.

To my dear friends, especially **Djihane** and **Fatiha,** who were always by my side.

To my dear project partner ***IKRAM,*** who was always with me through this journey.

And to everyone who helped me, directly or indirectly, during my studies.

Nor El Houda

Dedication

I dedicate this thesis to my beloved parents, **A & N** whose unwavering support and guidance have been my greatest source of strength.

To my dear grandmother **B.FADEL,** whose wisdom, love, and constant encouragements have shaped the person I am today. Your presence has been a source of comfort and inspiration throughout this journey.

To my dear brother **Ilyes** and sister **Jasmin,** the only siblings I have, thank you for always being by my side and encouraging me throughout this journey.

To the **Zenati** family, including my uncles and aunts. To my best friends **Marwa** and **Maryem**, your companionship and encouragement have made this experience more meaningful.

To my colleagues, your support and collaboration have been invaluable.

And to my project partner **Nor El Houda**, whose dedication and teamwork played a crucial role in bringing this work to life, I am truly grateful.

This achievement is not mine alone it belongs to all of you who have supported me.

IKRAM

Table of Contents

Chapter I: *Evolution of Network Systems.*

Chapter II: *Multi-Carrier Modulation Systems OFDM and UFMC*

Chapter III: *Simulation and Discussion of Results*

List of Figures

List of Tables

List of abbreviations

1G : First Generation

2G : Second Generation

3G : Third Generation

4G : Fourth Generation

5G : Fifth Generation

AC : Authentication Center

ADSL : Asymmetric Digital Subscriber Line

AMPS : Advanced Mobile Phone System

ASK : Amplitude Shift Keying

BER : Bit Error Rate

BSC : Base Station Controller

BSS : Base Station Subsystem

BTS : Base Transceiver Station

CDMA : Code Division Multiple Access

CP : Cyclic Prefix

DFT : Discrete Fourier Transform

DPSS : Direct-Sequence Spread Spectrum

EIR : Equipment Identity Register

eMBB : Enhanced Mobile Broadband

FDMA : Frequency Division Multiple Access

FDM : Frequency Division Multiplexing

FBMC : Filter Bank MultiCarrier

FSK : Frequency Shift Keying

FFT : Fast Fourier Transform

GGSN : Gateway GPRS Support Node

GMSC : Gateway Mobile Switching Center

GSM : Global System for Mobile communications

GUI : Graphical User Interface

HDSL : High-bit-rate Digital Subscriber Line

HLR : Home Location Register

ICI : Inter-Carrier Interference

IDFT : Inverse Discrete Fourier Transform

IEEE : Institute of Electrical and Electronics Engineers

IMSI : International Mobile Subscriber Identity

ISDN : Integrated Services Digital Network

ISI : Inter Symbol Interference

IFFT : Inverse Fast Fourier Transform

IOT : Internet of Things

KSP : Known Symbol Padding

LTE : Long Term Evolution

MIMO : Multiple Input Multiple Output

MMT : Multimedia Telephony

MN : Mobile Network

MCM : Multi-Carrier Modulation

MSC : Mobile Switching Center

MS : Mobile Station

MATLAB : Matrix Laboratory

NOMA : Non-Orthogonal Multiple Access

NSS : Network Switching Subsystem

OFDM : Orthogonal Frequency Division Multiplexing

OSS : Operation Support Subsystem

PAPR : Peak-to-Average Power Ratio

PSK : Phase Shift Keying

PSD : Power Spectral Density

PSTN : Public Switched Telephone Network

QAM : Quadrature Amplitude Modulation

RF : Radio Frequency

SC-FDMA : Single Carrier Frequency Division Multiple Access

SGSN : Serving GPRS Support Node

SNR : Signal-to-Noise Ratio

TDMA : Time Division Multiple Access

UMTS : Universal Mobile Telecommunications System

UFMC : Universal Filtered MultiCarrier

URLLC : Ultra-Reliable Low Latency Communications

VDSL : Very-high-bit-rate Digital Subscriber Line

VLR : Visitor Location Register

VPN : Virtual Private Network

Wi-Fi : Wireless Fidelity

ZP : Zero Padding

General introduction

General Introduction

Over the past decade, the field of mobile communications has experienced remarkable development, surpassing initial expectations. Nowadays, in a high-mobility world, the **capacity** and **speed** of transmission systems are essential factors to ensure connectivity and communication among people across all corners of the globe, unlike the old principle of communication and broadcasting.

This evolution has been marked by the transition from 1G to 4G, with a current focus on the development of 5G. The early transmission systems were based on the so-called single-carrier modulation technique, which offered very low data transmission rates. Generally, by decreasing the data symbol period, the bit rate of such broadcasting systems can be significantly increased. However, the presence of multipath channels introduces inter-symbol interference (ISI), which requires very complex equalization at the receiver side to combat it. These limitations eventually led to the abandonment of this modulation technique.

Today, 5G systems aim to provide even higher data rates. Among the techniques used, OFDM (Orthogonal Frequency Division Multiplexing), which played a key role in 4G, stands out for its high data rate and good spectral efficiency. However, it also has drawbacks, such as a high Peak-to-Average Power Ratio (PAPR) and significant out-of-band emissions. To overcome these limitations, UFMC (Universal Filtered Multi-Carrier), proposed for 5G, emerges as a promising alternative to OFDM.

The objective of this dissertation is therefore to study and evaluate the performance of OFDM and UFMC modulation, which is one of the serious candidates for 5G mobile communication systems.

This work is organised into three chapters:

- **Chapter One** presents the evolution of mobile network generations from 1G (AMPS) to 4G, highlighting their main characteristics, with a particular focus on the objectives and performance indicators of 5G.
- **Chapter Two** focuses on two modulation techniques: OFDM, used in 4G, and UFMC, proposed for 5G. OFDM is based on the use of orthogonal subcarriers, whereas UFMC involves grouping certain subcarriers into sub-bands, which are individually filtered.
- **Chapter Three** is dedicated to the simulation of both modulation schemes (OFDM and UFMC) and the analysis of their performance using several criteria: PAPR (Peak-to-

Average Power Ratio), which assesses the quality of the modulated signal, BER (Bit Error Rate), which evaluates transmission errors, PSD (Power Spectral Density), which measures how the signal's energy is distributed across frequency. The chapter concludes with a comparison between OFDM and UFMC. The dissertation ends with a general conclusion summarising the work presented.

Chapter I

Evolution of Network Systems

I.1 Introduction

Technological evolution and progress have reached a peak with the creation of the Internet and its spread across the four corners of the world. The latter plays an effective role in the rapid and free distribution and sharing of information. However, a gap can be observed in large-scale communication methods.

5G technology meets these needs by offering faster speeds, lower latency, and enhanced connectivity. It supports numerous connected devices, making it ideal for IoT and smart cities, while providing ultra-reliable low-latency communication for real-time applications such as autonomous vehicles and remote surgeries. By overcoming current network limitations, 5G paves the way for a more connected and efficient future.

In this chapter, we‘ll discuss the evolution of network systems.

I.2 Mobile Network (MN)

A mobile network (also known as a wireless network) transmits and receives communications via radio waves. It consists of base stations that each cover a specific area, or "cell." When connected together, these cells give radio coverage across a large geographic area. This allows a large number of portable transceivers (e.g., mobile phones, pagers, etc.) to communicate with each other as well as fixed transceivers and telephones anywhere in the network, even if some of the transceivers pass through many cells during transmission.

Mobile networks are quickly becoming as the primary means of delivering services for all purposes. The crucial concern is whether they can keep up with the underlying bandwidth requirements. The growing demand for mobile broadband has expedited the transition to LTE and LTE-Advanced. This latest mobile technology increases not only capacity but also quality requirements for the backhaul network. [1]

I.3 Evolutions of mobile cellular networks

The mobile wireless industry began in the early 1970s, yet it was not until the mid-1990s that cellular communication genuinely experienced rapid development. In a remarkably short timeframe, mobile system technology has evolved far beyond what anyone might have envisioned at its inception. Presently, over 5.03 billion individuals worldwide use the internet, with an extraordinary 180 million new users joining in the 12 months leading up to July 2022.

The progression from First Generation to Fifth Generation cellular innovation has been rapid, achieving remarkable advances in data-carrying capacity and reduced latency. As illustrated in Figure 1, the importance of cellular networks grows with technological changes and the evolution of new generations of technology. [2]

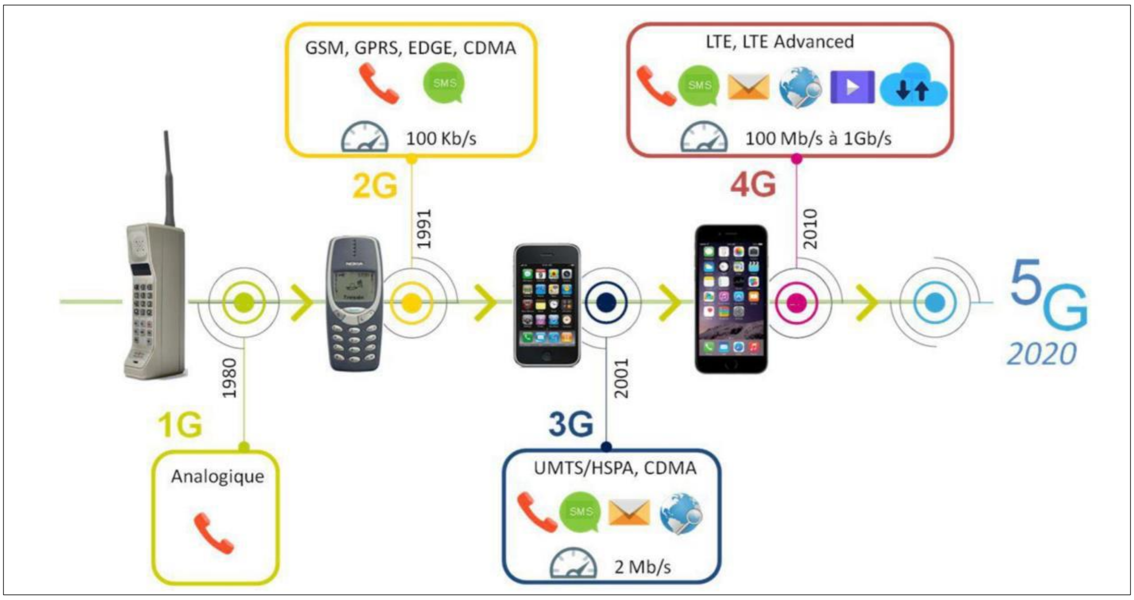


Figure I.1: Evolutions of Mobile Cellular Networks. [3]

I.3.1 The first-generation technology (AMPS)

Wireless mobile communication during the first generation operated as an analog system developed during the 1980s using for voice services a technology known as Advanced Mobile Phone System (AMPS).

The AMPS system was frequency modulated and used frequency division multiple access (FDMA) with a channel capacity of 30 KHz and frequency band of 824-894MHz.It supports a speed up to 2.4kbps.

AMPS obtained a new 10MHz bandwidth, known as Expanded Spectrum, in 1988, when Chicago became the first city to use this expansion for its service area of 2100 square miles. The United States introduced Advanced Mobile Phone System (AMPS) for the first time during 1982. [4]

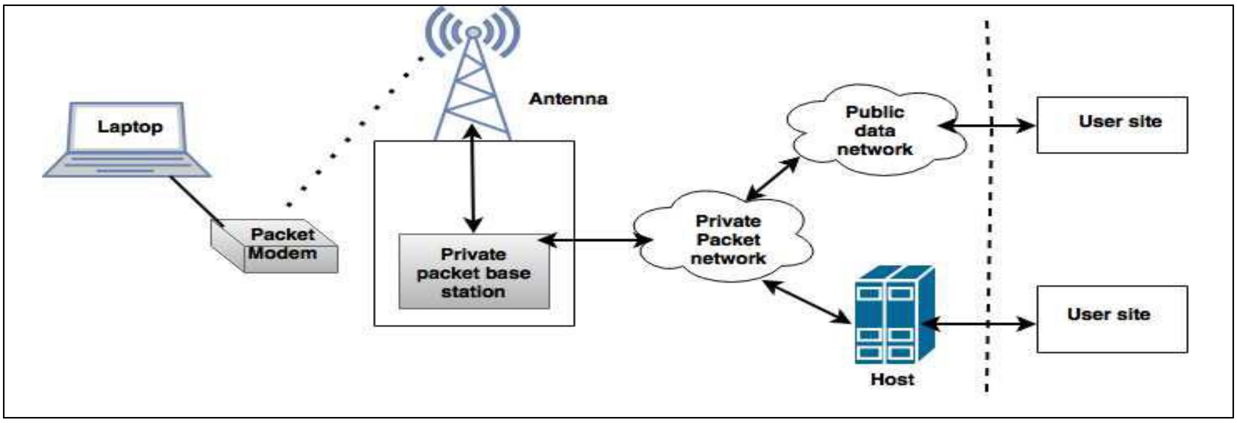


Figure I.2: 1G network architecture. [5]

I.3.1.1 Access technique (FDMA)

FDMA means Frequency Division Multiple Access, divides the frequency band in many channels. Each subscriber has a channel which can transmit voice. The number of channels depends on the bandwidth of each channel. The FDMA is used in analog systems. [6]

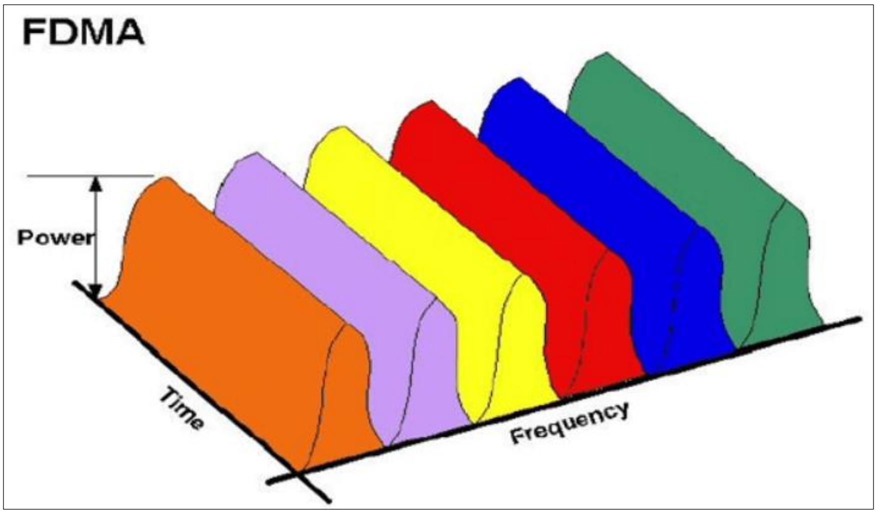


Figure I.3: Access technique : (FDMA). [6]

I.3.2 The second generation (GSM)

Global System for Mobile Communications or GSM is a set of protocols and standards governing the 2nd generation networks, better known as 2G networks. It operates on different frequency bands of 850 MHz, 900 MHz, 1800 MHz and 1900 MHz Developed and deployed in Europe, GSM of many functional units, namely [7] :

- MS or the Mobile Station.

- BSS or the Base Station Subsystem.
- NSS or the Network Switching Subsystem.
- OSS or the Operation Support Subsystem.
- The Public Network.

I.3.2.1 GSM architecture

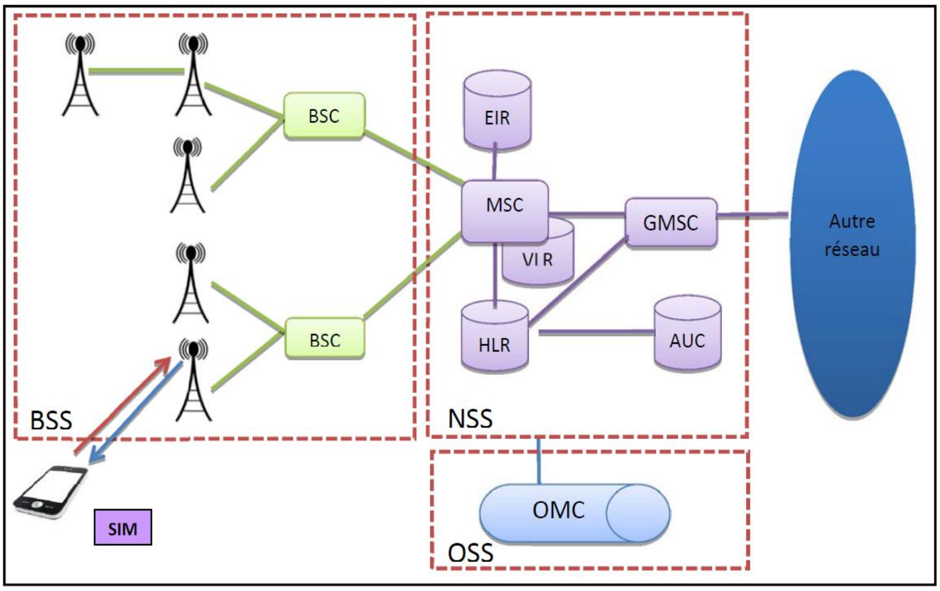


Figure I.4: GSM architecture. [7]

The GSM architecture consists of interconnected subsystems. It interacts with itself and the users with the help of certain network interfaces.

The GSM network can be broadly divided into four parts

- The Mobile Station
- The Base Station Subsystem (BSS)
- The Network Switching Subsystem (NSS)
- The Operation Support Subsystem (OSS)

➢ **The Mobile Station (MS)**

It consists of two parts:

- **Mobile equipment:** It is a portable, vehicle-mounted, handheld device that is uniquely identified by an IMEI number. Sending and receiving SMS, voice and data transmission are some of the perks of this equipment.

- **Subscriber Identity module(IMSI) :** Generally protected with a password or PIN, The sim basically allows the transmission of calls along with other services. It is a miniature chip containing the International Mobile Subscriber Identity (IMSI) number.

➢ **The Base Station Subsystem (BSS)**

Also known as the radio subsystem, it provides and handles radio transmission pathways between the mobile station and the Mobile Switching Centre (MSC). It also comprises of two parts:

- **Base Transceiver Station (BTS) :** It is responsible for encoding, encrypting, multiplexing, modulating, and feeding the RF signal to the antenna.
- **Base Station Controller (BSC) :** It is responsible for assigning frequency and time slots for all mobile stations in their respective area, along with handling call set-up, transcoding, and adaptation functionality handover for each MS radio power control.

➢ **The Network Switching Subsystem (NSS)**

It is the most significant part of the Mobile Switching Center (MSC). It is responsible for switching calls between mobile and other fixed or mobile network users, along with the management of mobile services.

It has the following elements:

- **Visitor Location Register (VLR) :**The Visitor Location Register is a database that contains the locations of all mobile subscribers in the area of service of the MSC.
- **Home Location Register (HLR) :**The Home Location Register is a database that contains all the pertinent data of subscribers authorized to use a GSM network.
- **Equipment Identity Register (EIR):** The Equipment Identity Register is a database that contains the record of all the allowed or banned persons in the network.
- **Authentication Center (AC):** Authentication Centre provides security against intruders in the air interface along with providing security triplets RAND, SRES, Ki. It also keeps a track of the authentication keys and algorithms.

➢ **Operation Support Subsystem (OSS)**

The implementation of the Operations and Maintenance Center (OMC) is called the Operation Support Subsystem. The Operation Support Subsystem is an integral part of the overall GSM architecture interlinked with the BSC and NSS components. It administrates commercial and network operations along with security management and maintenance tasks.

- **The Public Network**

The Public Network also comprises of two parts:

ISDN: Designed in the 1980s and improved in the 1990s, Integrated Services Digital Network is a set of international communication standards.

PSTN: The Public Switched Telephone Network is the database that contains all the information regarding the interconnected public telephone network worldwide. It was designed for analog calls, but now it is completely digital. **[7]**

I.3.1.2 Multiple access techniques in GSM

To facilitate efficient bandwidth sharing among multiple users, GSM employs or combines two major multiple access techniques:

- Frequency Division Multiple Access (FDMA).
- Time Division Multiple Access (TDMA).

- **Frequency Division Multiple Access (FDMA):**

The FDMA part, divides the available frequency spectrum into multiple narrower channels, assigning each user an exclusive channel for communication.

This prevents simultaneous transmission on the same frequency, minimizing interference. [8]

- **Time Division Multiple Access (TDMA):**

TDMA further divides each frequency channel into time slots, allowing multiple users to share the same frequency channel by occupying different time slots.

This maximizes spectrum utilization and allows more users to access the network simultaneously. [8]

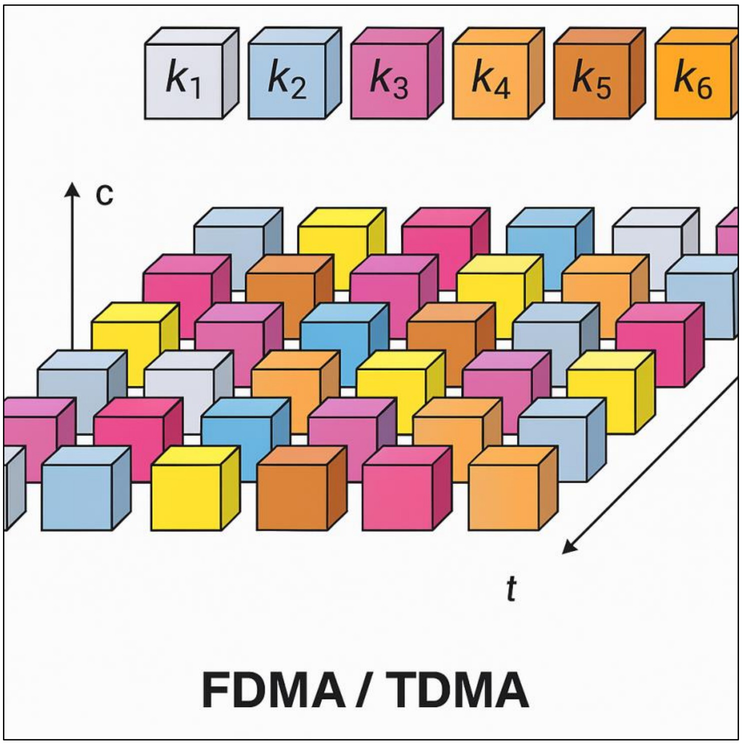


Figure I.5: Access technique: (TDMA). [8]

I.3.3 The third generation (UMTS)

3G uses a wideband wireless network that improves communication clarity. 3G telecommunication networks offer services with data transfer rates of at least 2 Mbps. With EDGE, high-speed data transfer was possible, but packet transmission over the air interface still behaved like a circuit-switched call.

As a result, part of the efficiency of packet-switched communication was lost in a circuit-switched environment. Additionally, network development standards varied across different regions of the world. Therefore, it was decided to create a network that could provide services independently of the underlying technology platform and follow globally standardized design principles. This led to the birth of 3G.

3G is not a single standard, but rather a family of standards designed to work together in harmony. An organization called the 3rd Generation Partnership Project (3GPP) was responsible for defining a mobile system that would meet these global requirements.

The technology which Europe identified as UMTS received its development direction from ETSI. The third-generation mobile system which the ITU-T names as IMT-2000 functions as a counterpart to the CDMA2000 network that operates as the American version of 3G. WCDMA functions as the air-interface technology which supports UMTS systems. The key system elements consist of Base Station (also known as Node B) combined with Radio Network Controller and Wideband CDMA Mobile Switching Center alongside SGSN/GGSN.

Under the guidance of ETSI UMTS (Universal Terrestrial Mobile System) operated as Europe's version while the ITU-T described this system as IMT-2000. ITU-T designated IMT-2000 as the official name for third-generation mobile systems but CDMA2000 presents the American implementation of these networks. The air-interface technology responsible for UMTS operations is WCDMA. The system consists of four main parts which include the Base Station (also named Node B) together with the Radio Network Controller (RNC) and Wideband CDMA Mobile Switching Center (WMSC) and SGSN/GGSN.

3G networks let providers extend their advanced services across bigger areas through bandwidth optimization to boost network quality. NTT DoCoMo introduced commercial 3G services as FOMA under W-CDMA technology through its network launch on October 1, 2001 in Japan. [9]

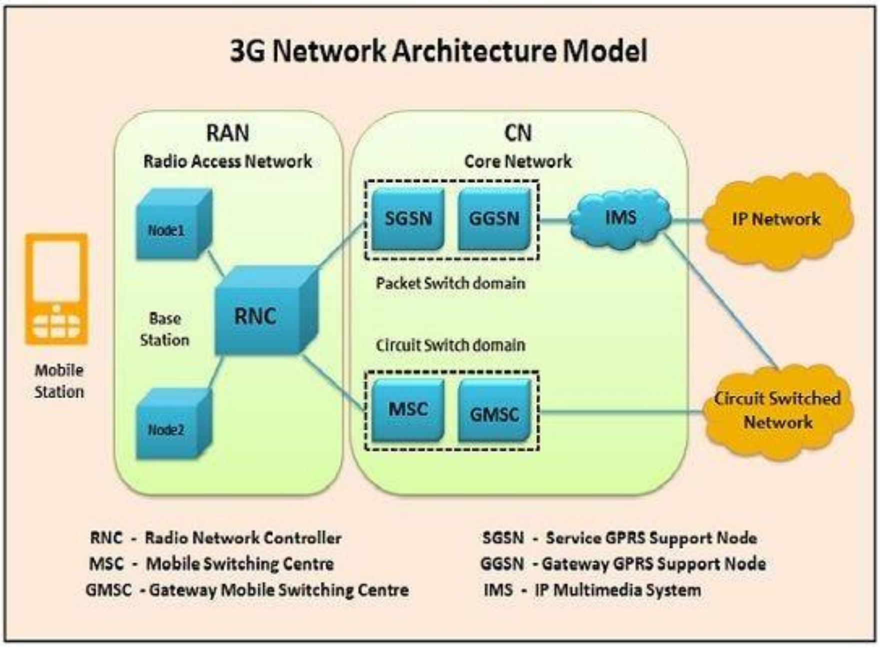


Figure I.6: 3G Core Network Architecture. [10]

3G Core Network has 4 main functions as it can be seen from figure above. These are [10]:

- **Circuit Switching**: It uses Circuit Switched Network in which dedicated link or channel is provided for a particular time slot to set of users. The two functions which are related with circuit switching part is:
  - ✓ **MSC** — Mobile Switching Centre manages circuit switched calls.
  - ✓ **GMSC** — Gateway MSC acts as an intermediary between external and internal networks.

- **Packet-switching:** It uses IP Network where IP's are responsible for transmitting and receiving data among two or more devices. The two functions which are related with Packet Switching is:
  - ✓ **SGSN(Serving GPRS Support Node):** The various functions provided by SGSN are mobility management, session management, billing, communication with other areas of the network.
  - ✓ **GGSN(Gateway GPRS Support Node):** It can be considered as a very complex router and handles the internal operations between the external packet switched networks and UMTS packet switched network.

I.3.3.1 Code -Division Multiple Access (CDMA)

UMTS has adopted a new CDMA system, called WCDMA, or Wideband CDMA, because it supports user data rates of up to 2 Mbit/s, compared to just a few tens of kilobits per second for previous systems.

The basic principle of CDMA is to assign the same frequency to all users communicating within the same cell at the same time, with discrimination between calls achieved through coding using a unique code for each user.

This encoding is the product of the signal to be transmitted and a pseudo-random sequence with a significantly higher rate (eight times in W-CDMA) than the signal. The original binary signal to be transmitted is simply encoded in NRZ (Non-Return-to-Zero) and then multiplied by the pseudo-random coding sequence. This results in a signal with a frequency equal to that of the pseudo-random sequence. This process is referred to as direct-sequence modulation. Additionally, a spectrum spreading operation is performed, since for a signal with a maximum frequency F, after modulation, the signal ready for transmission has a maximum frequency of nF, where n is the ratio between the rate of the coding sequence and that of the signal to be transmitted. This ratio is called the processing gain or spreading factor.

The receiver receives a multiplexed signal containing all the encoded sequences. By multiplying it with one of the coding sequences, it retrieves the original signal, while the others remain largely undecoded and imperceptible due to insufficient correlation. [7]

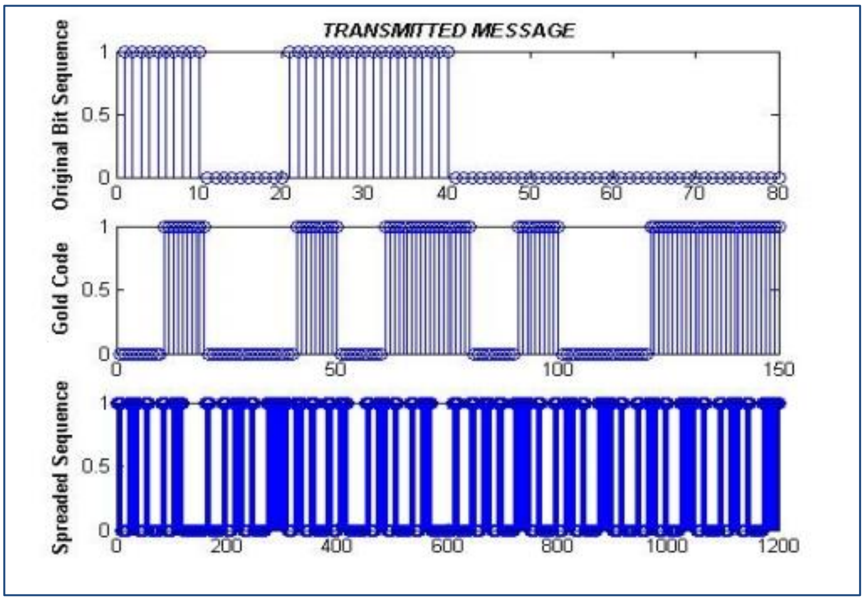


Figure I.7: Example of a CDMA signal [7]

I.3.4 The fourth generation (LTE)

We have now, for several years, been in the fourth-generation (4G) era of mobile communication, represented by the LTE technology. LTE followed in the steps of HSPA, providing higher efficiency and further enhanced mobile-broadband experience in terms of higher achievable end-user data rates. This was provided by means of OFDM-based transmission enabling wider transmission bandwidths and more advanced multi-antenna technologies. Furthermore, while 3G allowed for mobile communication in unpaired spectrum by means of a specific radio-access technology (TD-SCDMA), LTE supports both FDD and TDD operation, that's operation in both paired and unpaired spectra, within one common radio-access technology. By means of LTE the world has thus converged into a single global technology for mobile communication, used by essentially all mobile-network operators and applicable to both paired and unpaired spectra. The later evolution of LTE has also extended the operation of mobile-communication networks into unlicensed spectra. [11]

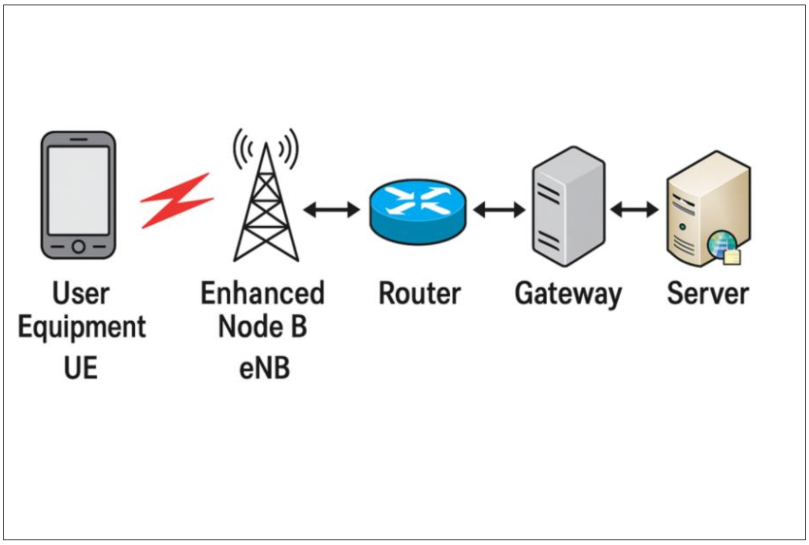


Figure I.8: General Presentation of the LTE System. [12]

I.3.4.1 LTE Network Access

LTE modulation is primarily based on the use of OFDM technology and associated access technologies, OFDMA used in downlink while SC-FDMA used in uplink.

I.3.4.1.1 OFDM (Orthogonal Frequency Division Multiplexing)

OFDM is a technique that involves dividing the transmission band into N sub-channels, leading to an increase in symbol duration. It is a multi-carrier modulation technique based on the Fast Fourier Transform, which allows the data stream to be transmitted to be divided into N parallel sub-data streams, which will be transmitted on different orthogonal sub-bands. This technique offers high efficiency in terms of spectrum and power utilization through the use of N orthogonal sub-carriers that are very close to each other. [13]

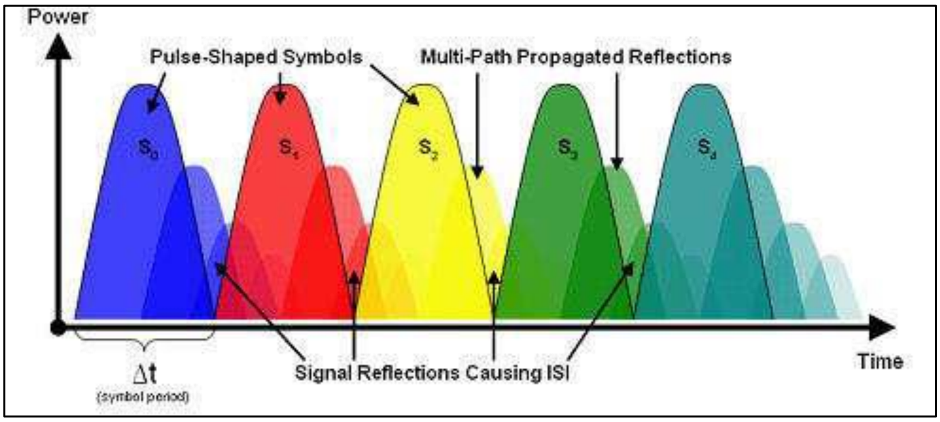


Figure I.9 : OFDM Modulation [13]

I.3.4.1.2 OFDMA (Orthogonal Frequency Division Multiple Access)

This hybrid technique combining OFDM, TDMA, and FDMA. It increases throughput by leveraging frequency diversity and enhancing robustness against multipath effects. This multiple access multiplexing technique involves distributing the signal across orthogonal subcarriers to transmit the signal independently at different frequencies.

LTE uses OFDMA in the downlink because it requires significant power amplification. While this is not an issue for fixed base stations, it is unsuitable for battery-powered transmitters (e.g., mobile terminals). For this reason, LTE uses SC-FDMA in the uplink, which is very similar to OFDMA but more energy-efficient. [13]

I.3.4.1.3 SC-FDMA (single carrier Frequency Division Multiple access)

SC-FDMA offers performance and overall complexity similar to OFDMA but uses a single-carrier frequency multiplexing technique. [13]

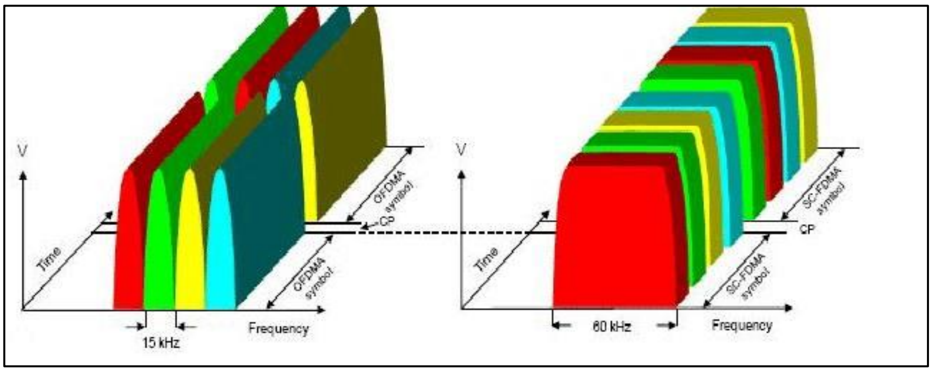


Figure I.10 : Difference between OFDMA and SC-FDMA. [14]

I.4 Conventional cellular systems –limitations

4G networks are insufficient to support many low-latency connected devices and achieve high spectral efficiency, critical for future applications. Heavy data transmission is challenging, and high-speed data requests can drain battery life and overload the core network. Traditional cellular networks use a single signalling mechanism for all traffic, creating substantial overhead for heavy loads. Additionally, base stations are underutilized during off-peak times, increasing network costs. Dual-channel assignment causes co-channel interference, hindering network densification. Heterogeneous wireless networks are not fully supported, limiting efficiency. [15]

5G technology aims to address these shortcomings, providing better support for diverse traffic types and efficient frequency spectrum use.

I.5 What is 5G?

Previous generations of mobile communications systems (1G to 4G) predominantly addressed consumer demands for mobile voice telephony and mobile broadband data services. 5G is the next generation of mobile communications systems [4]. It builds on the successes of the previous generations of mobile communications systems. 5G promises to deliver improved end-user experience and enable new services, new ecosystems, and new revenues.[11]

Figure I.11: Key features of 5G technology. [16]

The principle aspects of 5G technology include the following elements [16] :

- **Speed:**

The maximum data delivery speeds of 5G networks reach 10 Gbps, while remaining 100 times faster than 4G networks. Users experience instant access to high-quality videos and virtual reality content and games as well as quick cloud-based service usage because of 5G networks. Using 5G technology enables users to download 2-hour 4K resolution movies in less than 10 seconds whereas 4G users require approximately 7 minutes to complete the same operation.

- **Latency:**

The data journey time between points called latency will reach 1 millisecond in 5G networks that represents a 50-time reduction when compared to 4G networks. The rapid feedback capabilities allowed by 5G networks enable users to experience immediate interactions that are crucial for autonomous driving systems in addition to remote surgical operations and online video games and industrial control systems. The quick response of a driverless vehicle depends on 5G for near-instantaneous handling of traffic signals and obstacles rather than the slower 4G network response time.

- **Capacity:**

The amount of transmitted data and received data which 5G networks handle within a specific area or timeframe reaches up to 1000 times higher levels. This enhanced capacity enables simultaneous support for thousands of devices while maintaining performance standards. 5G network technology makes it possible for the Internet of Things (IoT) to support processing of billions of devices that autonomously exchange data through interconnected sensors. A 5G network holds space for 1 million connected devices in each square kilometer while the 4G network supports approximately 100,000 devices.

- **Reliability:**

The reliability aspect of 5G networks functions at 99.999% uptime because they deliver continuous uninterrupted service to critical sensitive applications. Moreover, 5G employs various technology combinations with different frequencies to optimize its performance across diverse settings. The 5G network has a dual-band capability by which it selects between sub-6 GHz and millimeter wave frequencies depending on spectrum use patterns. Additionally 5G utilizes network slicing to generate personalized virtual networks for different end users and services according to their unique specifications. A 5G network offers emergency services one specific slice while providing entertainment users with another slice and business users with a third slice each receiving different capabilities in speed latency capacity and security level.

I.5.1 mobile network architecture of 5G

Below Figure I.12 shows the system model that proposes design of network architecture for 5G mobile systems, which is all-IP based model for wireless and mobile networks interoperability. The system consists of a user terminal (which has a crucial role in the new architecture) and a number of independent, autonomous radio access technologies. Within each of the terminals, each of the radio access technologies is seen as the IP link to the outside Internet world. However, there should be different radio interface for each Radio Access Technology (RAT) in the mobile terminal. For an example, if we want to have access to four different RATs, we need to have four different accesses – specific interfaces in the mobile terminal, and to have all of them active at the same time, with aim to have this architecture to be functional. Applications and servers somewhere on the Internet. Routing of packets should be carried out in accordance with established policies of the user. [17]

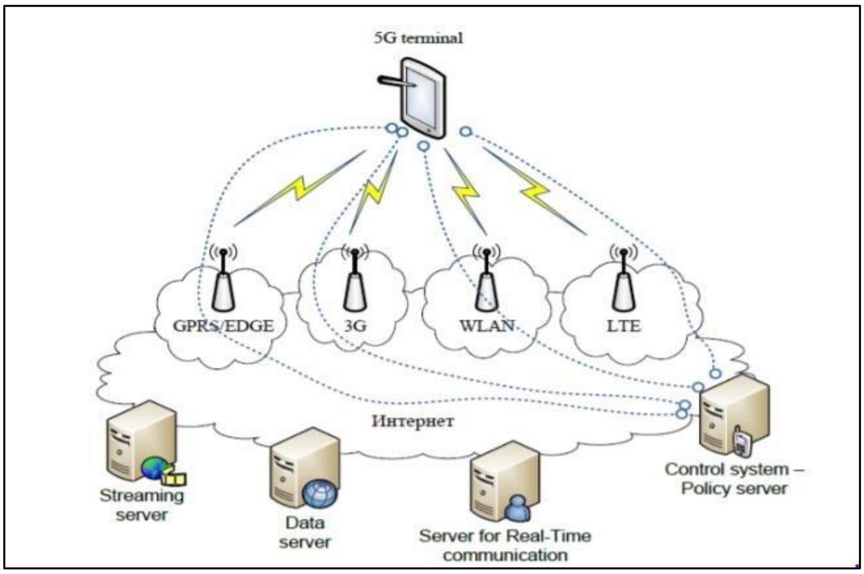


Figure I.12: functional architecture for 5G mobile network. [18]

I.5.2 Application of 5G

Three main use cases (defined by ITU, under IMT-2020), with their respective – and potentially mutually incompatible – demands are in the process of taking shape, and will make it possible to meet the sector-specific needs referred to in the introduction.

- **mMTC – Massive Machine Type Communications:** This application focuses on supporting an extremely high density of connected devices with diverse quality of service (QoS) requirements. It aims to address the exponential growth of connected objects in the Internet of Things (IoT).

  The IoT connects physical devices to exchange data over the internet, enabling automation and control across various systems. By leveraging 5G's ultra-low latency and massive connectivity capabilities—enhanced by technologies like Universal Filtered Multi-Carrier (UFMC) for efficient spectrum utilization and reduced interference—IoT ensures reliable communication for smart devices. This synergy drives innovations such as smart cities, industrial automation, and other applications, creating a connected and intelligent ecosystem that powers the future of mMTC.

- **eMBB – Enhanced Mobile Broadband:** This application delivers ultra-high-speed connection indoors and outdoors, with uniform quality of service, even on the edges of a cell.

- **uRLLC – Ultra-reliable and Low Latency Communications:** this application has stringent requirements for capabilities such as latency and packet-loss, to ensure increased reactivity. [19]

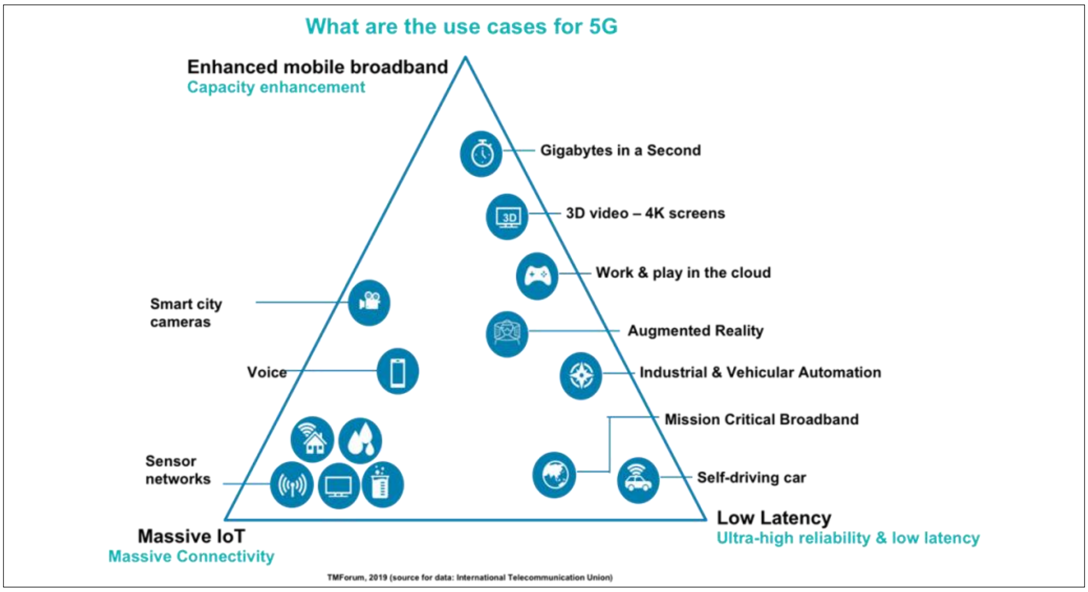


Figure I.13: 5G use cases. [20]

The first group (mMTC) primarily encompasses all Internet of Things related uses. These services require broad coverage, lower energy consumption and relatively slow transmission speeds. The 5G will deliver compared to existing technologies is the ability to connect objects that are spread out in a very dense fashion across a given area. Enhanced mobile broadband (eMBB) concerns all of the applications and services that require increasingly fast connections, for instance to watch ultra-high-definition (8K) videos or to stream virtual or augmented reality applications wirelessly. [19]

I.5.3 Advantages of 5G wireless communication system

The primary goal of fifth generation involves delivering numerous services quickly to end-users. The created applications demonstrate high user friendliness because they minimize communication requirements between the applications and their end users. Users will find application interfaces easier to use because standardized speech recognition capabilities integrate across their interfaces.

- 5G targets at providing a unified global standard which will facilitate global mobility and service portability.
- 5G stations and networks will provide common services independent of their capabilities. This is also called as service personalization.
- It is expected to provide wireless download speeds of above 1Gbps in local area network (LAN) and 500 Mbps in wide area network (WAN), about 40 times greater than the 4G wireless networks.
- Its focus at lower power consumption.
- It would provide users access to large repository of data and services where he would have flexibility to filter these data and services as per his preferences by configuring the operational mode of their devices.
- Better Network Convergence
- Provide Higher Bandwidth
- More effective and efficient
- Most likely, will provide a huge broadcasting data (in Gigabit), which will support more than 60,000 connections. [21]

I.5.4 Challenges of the 5^{th} G

Despite the capabilities and features that 5G provides, there are several challenges inherent in its implementation that researchers and industries must investigate.

These challenges are shown in Figure I.14 and can be summarized as follows [22] :

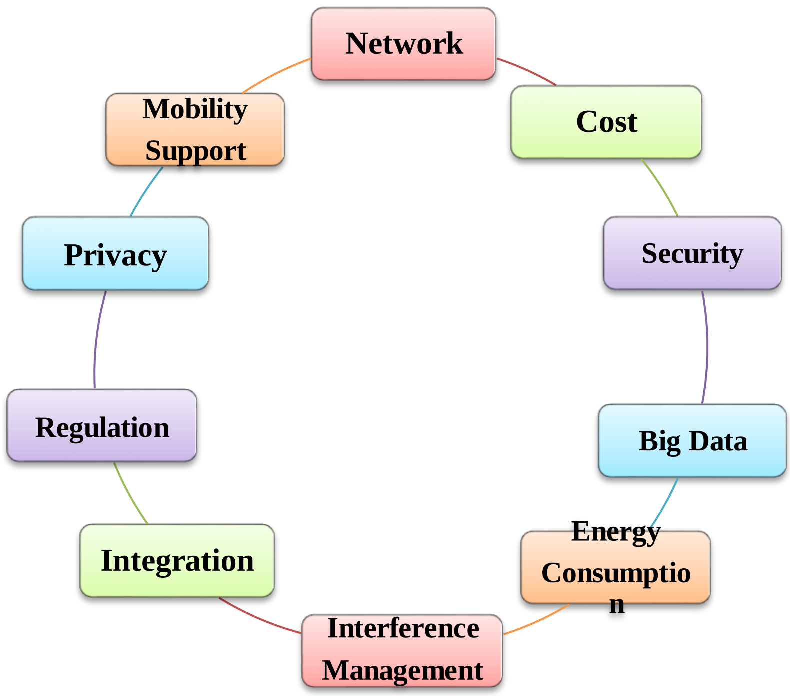


Figure I.14: Identified challenges in 5G systems.

- **Network Infrastructure:**

Upgrading to 5G requires substantial investment in new infrastructure, including more base stations and antennas.

- **Cost:**

Deploying 5G networks is expensive for service providers, which can result in higher costs for consumers.

- **Security:**

With more devices connected, the risk of cyber-attacks increases, necessitating robust security measures.

- **Big Data:**

The immense volume of data generated by 5G networks requires efficient data management and analysis solutions

- **Energy Consumption:**

5G networks may consume more energy due to higher data transmission rates and the need for constant connectivity.

- **Interfaces Management:**

Managing interfaces between different technologies and ensuring seamless connectivity is complex.

- **Integration:**

Integrating 5G with existing technologies and infrastructure poses technical challenges.

- **Regulation:**

Regulatory frameworks need to evolve to address the unique aspects of 5G technology.

- **Privacy:**

Protecting user privacy is crucial as the number of connected devices and data collection points increases.

- **Mobility Support:**

Ensuring consistent and reliable connectivity for mobile users, especially in high-speed scenarios, is challenging.

These challenges require careful planning and innovative solutions to fully realize the potential of 5G technology.

I.5.5 5G Multiple Access techniques

Wireless communication systems need Multiple Access (MA) techniques to allow numerous users to utilize the same frequency band at the same time. Several MA techniques operate within 5G (fifth-generation) networks to efficiently distribute the available spectrum bandwidth along with achieving high data rates and rapid response times and connecting vast numbers of devices**.** We'll provide an explanation about several significant 5G multiple access techniques [23]:

- **Orthogonal Frequency Division Multiple Access (OFDMA):**

- ✓ OFDMA is a widely used multiple access technique in 5G. It is based on the principles of Orthogonal Frequency Division Multiplexing (OFDM), which divides the available spectrum into multiple orthogonal subcarriers.
- ✓ In OFDMA, different users are allocated subsets of these subcarriers for simultaneous transmission. The orthogonality between subcarriers minimizes interference between users.
- ✓ OFDMA is suitable for both uplink and downlink communication, providing flexibility in resource allocation.

➢ **Non-Orthogonal Multiple Access (NOMA):**

- ✓ NOMA is a novel multiple access technique that allows multiple users to share the same time-frequency resources non-orthogonally.
- ✓ In NOMA, power and code domain multiplexing are used to distinguish signals from different users. Users are served at the same time and frequency resources, but with different power levels or using different coding schemes.
- ✓ NOMA enhances spectral efficiency and supports a varying number of users dynamically.

These multiple access techniques, among others, contribute to the diverse and efficient use of the spectrum in 5G networks, catering to the different requirements of enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC) use cases. The selection of a specific technique depends on the application's requirements and the characteristics of the communication environment.

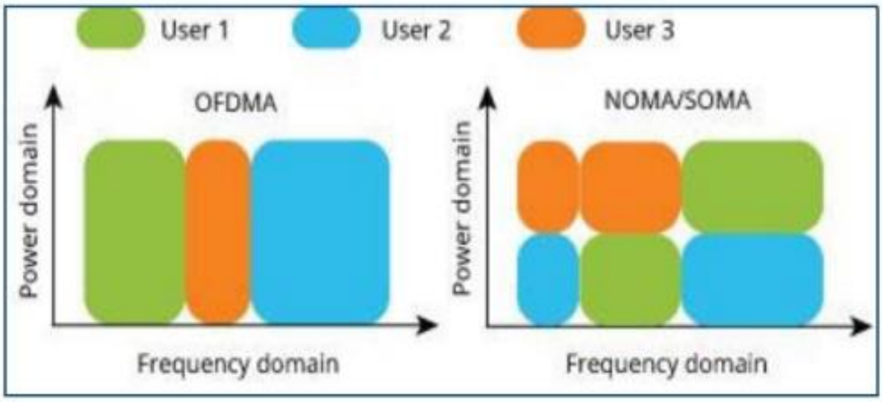


Figure I.15: illustration of power domain OFDMA and NOMA multiplexing. [24]

I.6 Comparison between 4G and 5G technology

Technical specifications of 4G and 5G networks differ greatly with regards to latency, transmission speed, base station layout, encoding methods, cell deployment, total connections, range of signals, and availability of bandwidth. The following table clearly defines the essential characteristics that distinguish the two generations of mobile communication technology.

Aspect	4G	5G
Latency	60-98 milliseconds	Less than 5 milliseconds
Speed	Up to 1 Gbps	Up to 10 Gbps
Base Stations	Traditional cell towers	Small cell technology for high-frequency bands, cell towers for lower frequencies
OFDM Encoding	Channels up to 20 MHz	Channels ranging from 100 MHz to 800 MHz
Cell Density	Lower density, limited to fewer users	Higher density, supports more users and devices
Connectivity Capacity	10,000 devices per square km	1 million devices per square km
Coverage	Good coverage in urban and suburban areas, some rural gaps	Wider coverage, improved service in urban, rural, and remote areas
Bandwidth	Limited bandwidth, up to 20 MHz per channel	Wider bandwidth, up to 400 MHz per channel, covering a broader frequency range (below 1 GHz to above 100 GHz

Table I.1: Comparison between 4G and 5G technologies [25]

I.7 Conclusion

The chapter is reflected in how mobile networks have advanced in speeding up to usher the arrival of 5G. Evolution from previous networks enables this new era to deliver significant improvements in speed, latency, and network bandwidth. By enabling access to a broader variety of next-generation applications, it changes the way wireless communication works around the globe.

As a result of the mobile networks that use radio waves for the transmission of signals, users, whether on the move or not, can remain online. The development of fast networks involves the incorporation of new, highly performing technologies. These developments are very strategic and economic in nature; they represent a strategic and economic value; particularly where lowering the production and operational cost is concerned.

Chapter II

Multi-Carrier Modulation Systems OFDM and UFMC

II.1 Introduction

The fifth-generation (5G) wireless technology has a significant impact on individuals' lives and work, and this impact is expected to continue increasing in the future. The Orthogonal Frequency Division Multiplexing (OFDM) method, which is currently used in fourth generation (4G) technology, has limitations in meeting certain criteria such as data rates and speed for the latest technology due to issues such as sideband leakages, high Peak-to-Average Power Ratio (PAPR), and poor spectrum utilization.

Additionally, the increasing demand for Internet of Things (IoT) and user-centric processing makes the OFDM method impractical; as a result, alternative technologies are being explored to meet these needs. Universal Filtered Multicarrier (UFMC) is among the contenders for 5G technology. In this chapter, we introduce two multicarrier schemes, OFDM and UFMC, explaining their concept, advantages, and disadvantages.

II.2 Single-Carrier Digital Modulation

In single-carrier transmission, data is transmitted sequentially over a single band around a carrier frequency, as shown in Figure II.1.

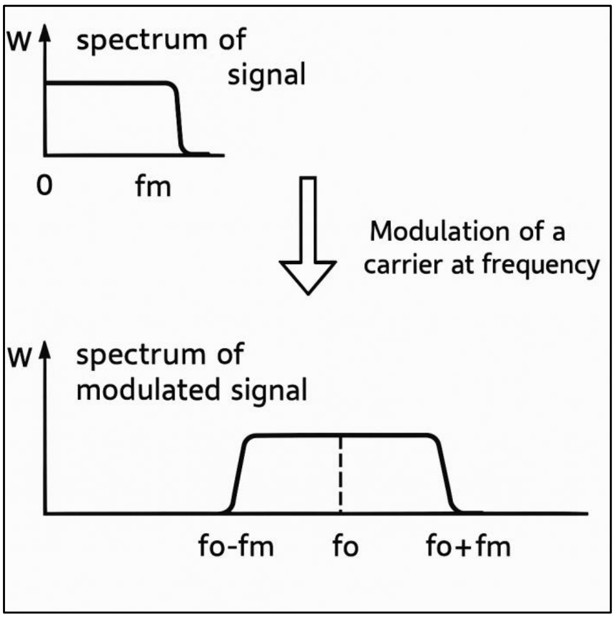


Figure II.1: Single-Carrier Modulation Format. [26]

The types of digital modulation are distinguished based on variations in the parameters of the carrier signal. The carrier signal parameters that can be modified are amplitude, phase, and frequency. Consequently, the digital modulation techniques are [26] :

- Amplitude Shift Keying (ASK).
- Frequency Shift Keying (FSK).
- Phase Shift Keying (PSK).

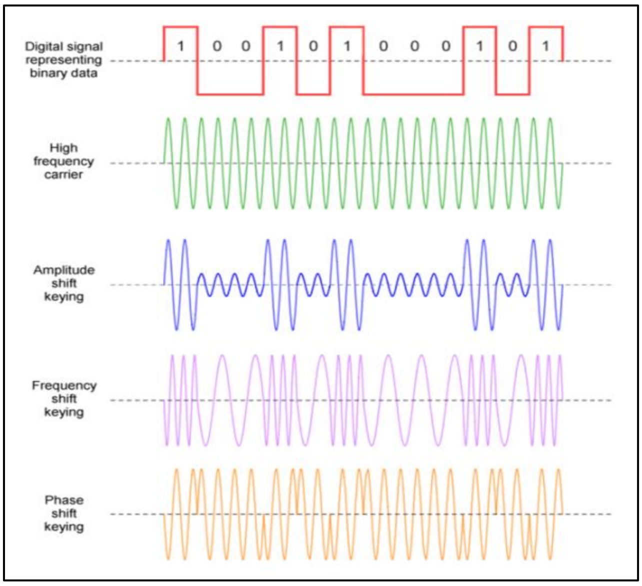


Figure II .2: ASK, FSK and PSK Modulation. [27]

II .2.1 Quadrature Amplitude Modulation (QAM)

Quadrature amplitude modulation with a quadrature carrier is a special case. This type of modulation, also called QAM (Quadrature Amplitude Modulation), is considered a two-dimensional modulation. The principle of QAM is to vary both the phase and amplitude of the carrier to transmit symbols. To achieve this, we have seen that the modulated signal m (t) can be expressed as [28] :

$$m(t) = a(t).\cos(\omega_0 t + \varphi_0) - b(t).\sin(\omega_0 t + \varphi_0) \quad (II.1)$$

Where:

- m (t) is The modulated signal, which is formed by combining two quadrature components.
- A (t) and b(t) are the Two signals that modulate the quadrature carriers.
- $\cos(\omega_0 t + \varphi_0)$ And $\sin(\omega_0 t + \varphi_0)$ are the quadrature carriers, where ω_0 is the angular frequency and φ_0 is the phase.

And the two signals a (t) and b (t) are expressed as [28] :

$$a(t) = \sum_k a_k\, g(t - KT) \text{ Et } b(t) = \sum_k b_k\, g(t - KT) \quad \text{(II.2)}$$

As a result, the modulated signal m (t) is the sum of two quadrature carriers, amplitude-modulated by the signals a (t) and b (t).

Where:

- a_k And b_k are the Coefficients that define the contributions of different components to the signals a (t) and b (t).
- $g(t - Kt)$ Is a function that shapes the signal components, often related to pulse shaping in communication systems.

II .3 Why multi-carrier modulation?

Multi-Carrier Modulation (MCM) is employed in modern communication systems due to several key advantages that address challenges in high-speed data transmission. [29]

First, the numbers of users who share the same resources and the development of new forms of telecommunications significantly increase the volume of information to be transmitted.

Then, since the transmitted signal is usually repeated on different carrier frequencies, in a multiple path transmission channel where certain frequencies may be destroyed because of the destructive combination of paths, the system will still be able to recover the lost information on other carrier frequencies which have not been destroyed.

Next, to overcome the loss of information due to channel selectivity, the idea is to distribute the information across a large number of carriers, thereby creating very narrow sub-channels for which the frequency response of the channel can be considered constant; These sub-channels are thus non-selective in frequency.

In the presence of a multi-path channel, classical modulation methods are very sensitive to inter-symbol interference (ISI), and it is even more important when the symbol duration is small compared to the maximum delay of the channel. In other words, simple demodulation is favoured if the duration of the useful symbols is large compared to the maximum delay time Tm of the propagation channel. [29]

II .4 Multi-Carrier Modulation Principle

Multi-carrier modulation techniques provide strong interference protection against Inter-Symbol Interference (ISI) as a result of the relatively long symbol durations, which are seen as a result of parallel transmissions of data over multiple overlapping subcarriers. The principal benefit that is seen from these modulation techniques is an improvement in the spectral efficiency of the data over the same frequency spectrum, which allows a better spectral overlap to be achieved. The implementation of modulation and demodulation using Fast Fourier Transform (FFT) is carried out through high-performance circuits. Multi-carrier modulation systems [30] :

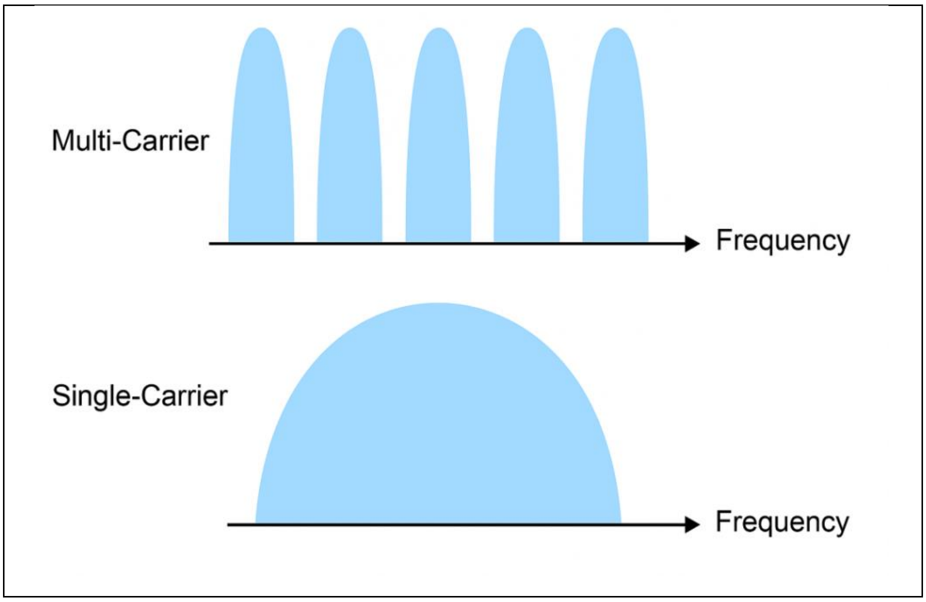


Figure II.3: Frequency Spectrum. [30]

The principle of multi-carrier modulation is based on the concept of Frequency Division Multiplexing (FDM). In an FDM system, signals from multiple transmitters are transmitted simultaneously during the same time interval, but on different frequencies. Each frequency range (or sub-band around a subcarrier) is independently modulated by a separate data stream. To avoid interference between adjacent subcarriers, guard bands are inserted between them.

II .4.1 Multi-Carrier Modulation Systems

Several forms of multi-carrier modulation techniques are being studied for future applications. Some of the well-known systems are summarized below [30] :

- Orthogonal Frequency Division Multiplexing (OFDM)
- Filter Bank-based Multi-Carrier (FBMC)
- Universal Filtered Multi-Carrier (UFMC)

II .4.2 Orthogonal Frequency Division Multiplexing (OFDM) modulation

For high-speed applications, the issues of source bandwidth limitation and Inter-Symbol Interference (ISI) generation arise quickly. To best address these problems, an OFDM-type modulation (Orthogonal Frequency Division Multiplexing) can be used. This modulation is based on the principle that data is transmitted over multiple channels simultaneously using different subcarriers. As a result, the duration of each symbol corresponding to each subcarrier is significantly longer than its equivalent for a single carrier, which helps to considerably reduce the impact of ISI while optimizing bandwidth. The introduction of a guard time also helps to reduce interference between subcarriers. The major advantage lies in the ability to perform very simple equalization during reception. [31]

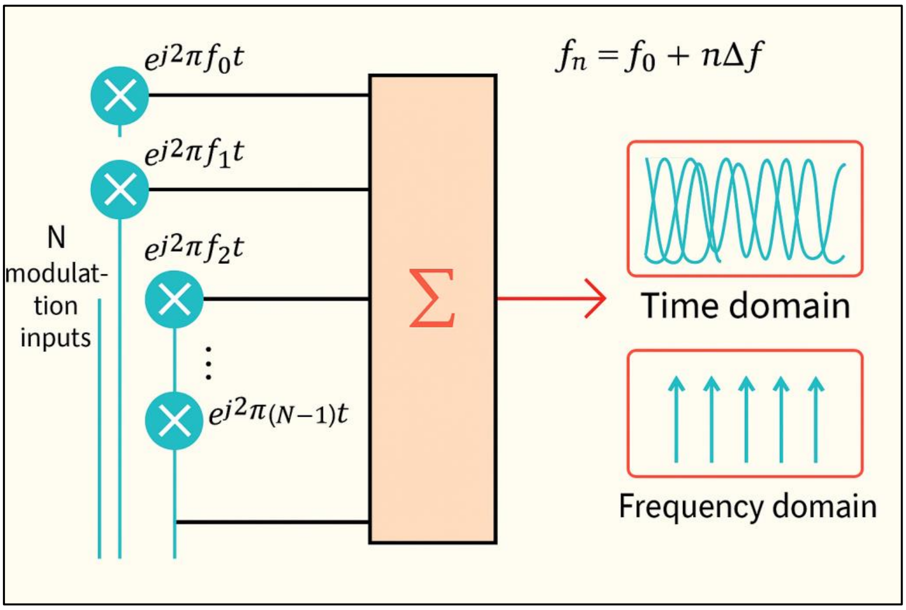


Figure II.4: OFDM Modulation. [31]

- **Mathematical Development of OFDM**

Generally, an OFDM signal consists of N subcarriers with frequencies given by [31] :

$$f_l = f_0 + l\Delta f \tag{II.3}$$

These subcarriers are used to ensure the parallel transmission of N elementary input symbols S_l ,which can be of type M-PSK or QAM.

At the receiver, to demodulate an OFDM signal, it only requires a demodulation operation based on the N subcarriers. Figure II.4 illustrates the most basic configuration of an OFDM modulator.

The OFDM time-domain signal is expressed as follows [31] :

$$S(t) = \sum_{l=0}^{N-1} S_l \, e^{j2\pi f_l t} \tag{II.4}$$

- **Digital Implementation**

Currently, wireless communication systems all use digital transceivers due to their efficiency. By defining $t = nT_{sm}$, where T_{sm} is the sampling period, the digital OFDM signal at the transmitter is expressed as:

$$s(nT_{sm}) = \sum_{l=0}^{N-1} S_l \, e^{j2\pi f_l n T_{sm}} \tag{II.5}$$

Furthermore, when the carrier frequencies are regularly spaced by $f_l = l\Delta f$, we can write:

$$s(nT_{sm}) = \sum_{l=0}^{N-1} S_l \, e^{j2\pi l \Delta f n T_{sm}} \tag{II.6}$$

Where $\Delta f = \frac{1}{NT_{sm}}$ describes the minimum spacing that ensures orthogonality between subcarriers, the OFDM signal is expressed as [31] :

$$S(nT_{sm}) = \sum_{l=0}^{N-1} S_l \, e^{\frac{j2\pi n l}{N}} = \text{IDFT}\,(S_l) \tag{II.7}$$

The analysis and development carried out show that the OFDM modulator at transmission can be implemented using an Inverse Discrete Fourier Transform (IDFT).

The digital implementation of an OFDM modulator/demodulator can be efficiently performed using a simple Inverse Fast Fourier Transform (IFFT) for modulation and a Fast Fourier Transform (FFT) for demodulation, respectively .

II .4.2.1 OFDM Orthogonality

The efficient and strategic use of frequency spectrum has turned OFDM into a top choice multicarrier communication system. The orthogonality property in OFDM creates a mathematical relationship between communication system subcarriers so they can overlay without causing disturbances between adjacent sub-channels. Any OFDM system uses N equally spaced subcarriers which create an orthogonal relationship by placing them with their specific frequency spacing throughout the designated frequency spectrum. [32] :

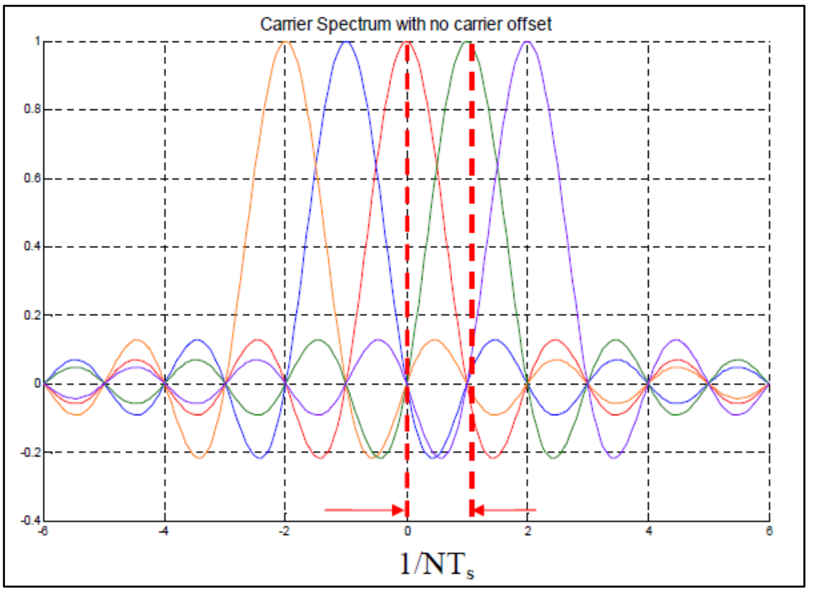


Figure II.5: The frequency spectrum of an OFDM signal. [32]

$$\Delta f = 1/(N.Ts) \qquad \text{(II.8)}$$

Where: N. Ts = Symbol duration.

This mathematical relationship creates a sine frequency response for all these N subcarriers where each one of them has maximum amplitude at a point, whereas others have nulls. Figure II.5 shows how OFDM operates based on the orthogonality principle. The

mathematical proof, which shows there is no interference between signals if spaced as in equation (II.12) [32] :

$$\int_0^{NT_S} X_k(t) X_1{}^*(t) = \begin{cases} 0\,, & k \neq 1 \\ C\,, & k = 1 \end{cases} \qquad \text{(II.9)}$$

Where, C is constant. Equation (II.9) shows that out of 5 OFDM subcarriers, shown in Figure II.5, the amplitude of only one subcarrier can be non-zero value at a frequency of multiples of 1/(N.Ts) while the remaining ones should have zero amplitudes.

As a result of this orthogonality aspect, the spectral inefficiency problem has been taken care of as it has been shown in Figure II .6. Considering that the system frequency bandwidth is the most valuable component in any communication system, OFDM system has met the aim of occupying the communication system spectrum efficiently.[32]

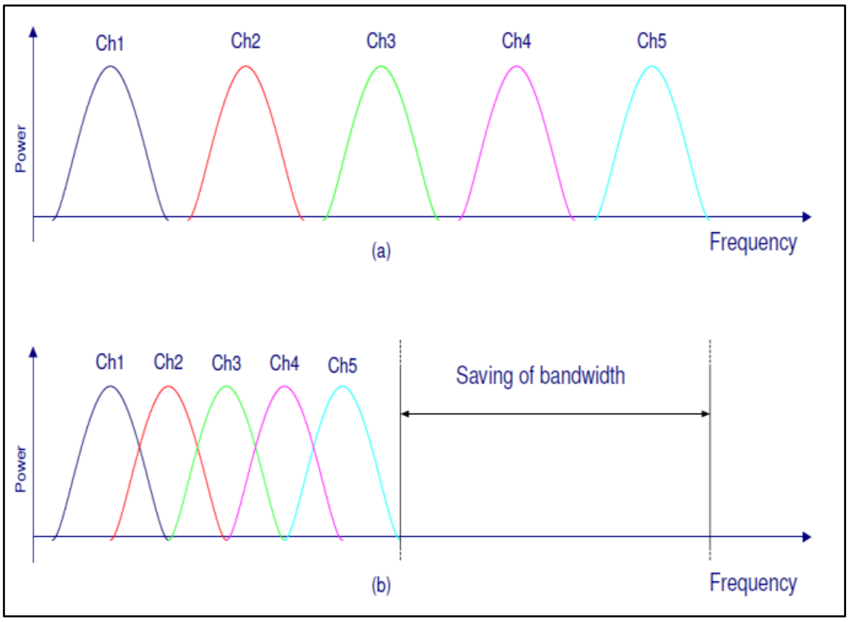


Figure II .6: Comparison between conventional FDM and OFDM. [33]

II .4.2.2 OFDM System Theory Diagram

The OFDM system theory diagram is shown as Figure II .7. The bits stream of 0 and 1 emitted by information source maps as QPSK or QAM signals in groups after M-ray modulation, and the bit stream of 0 and 1 is set equally distributed. [34]

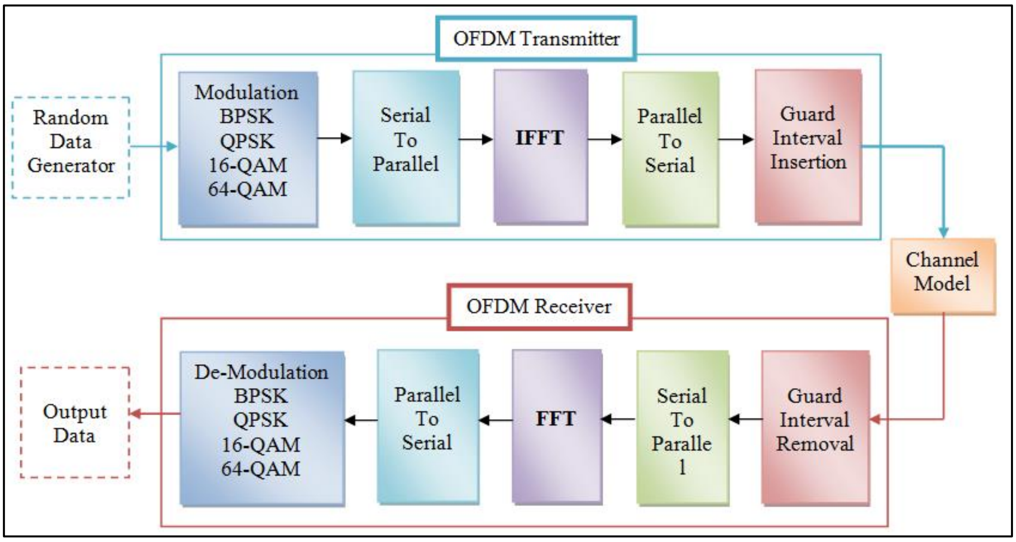


Figure II .7: The OFDM system theory diagram. [35]

After the conversion between series connection and parallel connection, the bit stream turns into a number of parallel signals. Then after inserting pilot, all the parallel frequency domain signals turn into time domain signals through IFFT conversion. Inserting guard interval (CP), we can get [34] :

$$X_g(n) = \begin{cases} x(N+n) & n = -N_g, -N_g+1, \dots, -1 \\ x(n) & n = 0,1,\dots,N-1 \end{cases} \quad \text{(II.10)}$$

In formula (II.10), N is the number of sub-carriers, N_g is the sampling points contained in the guard interval (i.e.C). Then, emitting the signals through multi-path fading channel with AWGN frequency selectivity, when they reach at the receiving end, converting them with FFT, then the frequency domain sequence Y (k) can be obtained.

Trasmitter part

- **Random Data Generator**

Generates uniform random data within the range (0, M-1).

- **Modulation of Data**

Data is differentially encoded based on previous symbols and mapped using Phase Shift Keying (PSK) or Quadrature Phase Shift Keying (QPSK). PSK maintains constant amplitude, which helps minimize issues caused by fading.

- **Serial to Parallel Converter**

Converts serial data into parallel format for transmission.

- **IFFT (Inverse Fast Fourier Transform) -Frequency-Domain to Time-Domain Conversion**

The orthogonality of the subcarrier is maintained and the frequency domain signals are converted into a time domain .This process converts the parallel subcarrier signals into a single time-domain waveform.

- **Parallel to Serial Conversion**

The final stage in the implementation must undo the first stage. A switch is used to time-division multiplex the four individual bit signals into a single sequence. [36]

Converts serial data into parallel format for transmission. Each subcarrier is assigned a unique symbol, then phase mapped according to the modulation scheme. OFDM allows adaptive modulation, choosing methods like QPSK or 16-QAM based on channel conditions. Transmission is optimized after channel estimation at the transmitter. [37]

- **Guard Interval**

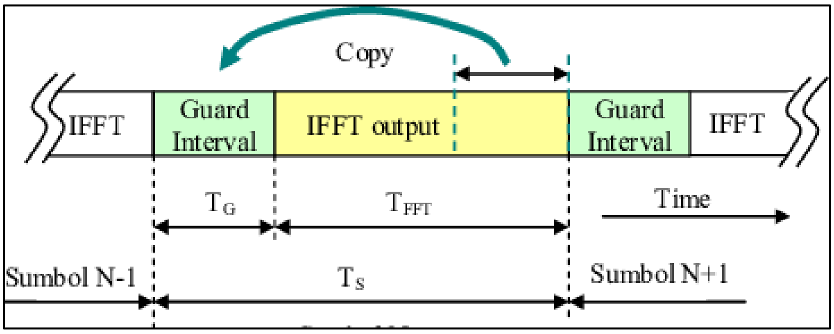


Figure II. 8: Guard Interval. [38]

There are Three Different Guard Intervals [37] :

- ❖ **Cyclic Prefix (CP):** This technique includes adding a copy of the information block that will be broadcast at the start of the frame. More specifically, a piece of the information is extracted and put at the beginning of the frame, known as the cyclic prefix (CP-OFDM) [14] (Figure II.7). This is the guard interval used in OFDM modulation.

- **Zero-Padding (ZP):** This method uses zeros instead of a guard interval, and no signal is transmitted during the guard interval. This is referred to as zero-padding (ZP) OFDM, 'Known Symbol Padding'.
- **Known Symbol Padding (KSP):** The guard interval consists of pilot symbols. This guard interval technique can help resolve timing synchronization difficulties that occur with other guard interval strategies.

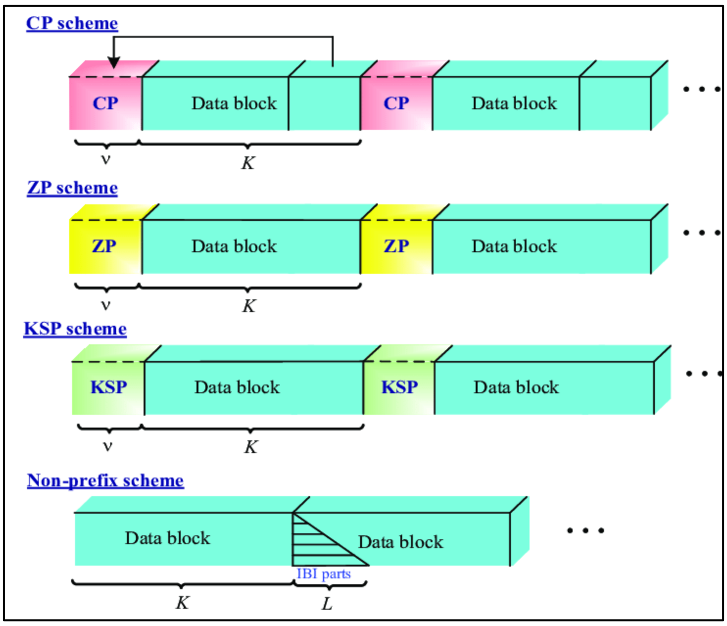


Figure II.9: The Different Guard Intervals [39].

Receiver

The receiver reverses the transmitter's operations by removing the guard period. The FFT is applied to extract the original spectrum from transmitted symbols. Phase angles are analysed and demodulated to reconstruct the data. The decoded words are then combined to match the original data size. [36]

II .4.2.3 Interference problem

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

OFDM signals are transmitted at equal intervals and must travel a certain path to reach the receiver. In the case of a multipath channel, a transmitted symbol experiences different delays upon arrival due to multiple propagation paths, leading to temporal spreading. The extended duration of symbols causes them to overlap, resulting in Inter-Symbol Interference (ISI). [40]

- **Inter-Carrier Interference (ICI)**

Orthogonality in an OFDM system means that at the peak of each subcarrier's spectrum, the spectra of all other subcarriers are zero. As a result, the subcarrier spectra overlap but remain orthogonal to each other. Inter-Carrier Interference (ICI) is caused by a loss of frequency orthogonality due to a frequency offset, which leads to the presence of data symbols from adjacent subcarriers in the current subcarrier. [40]

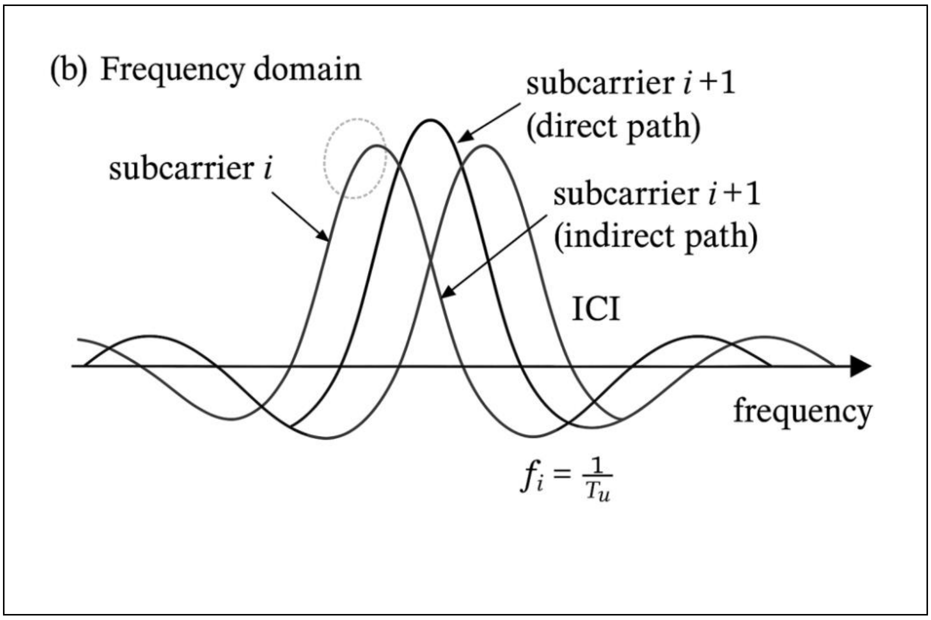


Figure II.10: Carrier Interference in the Frequency Domain. [40]

II .4.2.4 OFDM variants

OFDM (Orthogonal Frequency Division Multiplexing) is a crucial technology in wireless communication systems. It divides a wide channel into multiple narrowband sub-channels, improving data transmission efficiency and resilience against interference. OFDM has evolved into various types, each optimized for specific challenges and scenarios.

- **COFDM (Coded OFDM):**

COFDM combines forward error correction (FEC) coding and OFDM to improve reliability in noisy settings. Redundancy improves fault resilience, making it perfect for digital television (DVB-T) and radio (DAB). While it operates effectively in low-SNR environments, the additional coding adds system complexity.

- **Flash-OFDM (F-OFDM)**

This technology uses quick frequency hopping to reduce interference and improve security. Optimized for mobile broadband, it provides low latency and high-speed data transmission, making it ideal for IoT and real-time applications. Despite its benefits, it has received little adoption due to competition from LTE and 5G.

- **VOFDM (Vector OFDM)**

VOFDM extends OFDM to MIMO (Multiple Input Multiple Output) systems that use multiple antennas to provide spatial diversity. It broadcasts several OFDM streams at the same time, which increases wireless communication capacity and robustness. It is commonly employed in 4G LTE and 5G networks, and it provides faster data speeds but necessitates complicated antenna systems.

- **WOFDM (Wavelet OFDM)**

WOFDM is a technique that uses the Wavelet Transform instead of the Fourier Transform to generate orthogonal subcarriers. This decreases sidelobe interference while increasing spectrum efficiency, making it appropriate for cognitive radio and power-line communication. However, it has a larger computational complexity than classical OFDM.

Types of OFDM	**COFDM**	**Flash OFDM**	**VOFDM**	**WOFDM**
Characteristics	1. Error correction coding. 2. Excellent performance on frequency selective channels. 3. Capable of handling very strong echoes. 4.More immune to impulse noise	1. Frequency hopping for CCI reduction, reuse 1.25 to 5.0 MHz BW. 2. Mobility support fast wireless broadband technology. 3. Supports high data rates at very low packet and delay losses.	1. MIMO Technology. 2. Standard for broadband wireless Internet services. 3. Upto 20 Mbps speed.	1. 2.4 GHz Bandwidth 2. 30-45 Mbps speed 3. Large tone width(for mobility, overlay) 4. Low-power, multipoint radio networks
Adopted for technologies	High-bit-rate digital subscriber lines [HDSL(**1.6** Mbps)], Asymmetric digital	IEEE 802.20 wireless broadband standard Wi-Fi networks.	Long distance telephony services, Virtual Private Network (VPN)	IEEE 802.11a/g/n technologies, 4G Applications

	subscriber lines [ADSL**(1.536** Mbps)], Very high-speed digital subscriber lines [VHDSL (lOOMbps)], digital audio broadcasting (DAB), digital television and HDTV terrestrial broadcasting.			

Tableau II .1: OFDM types. [41]

II.4.2.5 Advantages and disadvantages of OFDM

The OFDM technique is widely used in various standards, which can be explained by the advantages it offers despite certain limitations.

a) Advantages of OFDM [36] **:**

- OFDM makes resourceful utilization of the spectrum by overlapping. By dividing the channel into narrowband, flat-fading subchannels, OFDM is more resistant to frequency-selective fading than single-carrier systems.
- It can easily adapt to severe channel conditions without complex time-domain equalization.
- It reduces ISI and ICI through use of a cyclic prefix and fading caused by multipath propagation.
- Using sufficient channel coding and interleaving lost symbols can be recovered.
- Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.
- OFDM is computationally capable by using FFT techniques to implement the modulation and demodulation functions.
- It is less sensitive to sample timing offsets than single carrier systems are.
- It is robust against narrow-band co-channel interference.
- Unlike conventional FDM, tuned sub-channel receiver filters are not required.
- It facilitates single frequency networks (SFNs); i.e., transmitter macro diversity.

b) The disadvantages [36]

- The OFDM signal has noise-like amplitude with a very large dynamic range; hence, it requires RF power amplifiers with a high peak-to-average power ratio.
- It is more sensitive to carrier frequency offset and drift than single carrier systems are due to leakage of the DFT.
- It is sensitive to Doppler shift.
- It requires linear transmitter circuitry, which suffers from poor power efficiency.
- It suffers the loss of efficiency caused by the cyclic prefix.

II.4.3 Universal Filtered Multi-Carrier (UFMC)

Universal Filtered Multi-Carrier (UFMC) is a multi-carrier modulation format considered as a modification of the well-known 4G waveform CP-OFDM. Instead of applying a cyclic prefix (CP), UFMC applies filtering to group subcarriers. Defining K as the total number of subcarriers, we assume that these K subcarriers are divided into B distinct groups. Although groups can consist of different numbers of subcarriers, for simplicity, we propose that each group is composed of N subcarriers, so that K = N × B [42].

II.4.3.1 UFMC system model

a) UFMC transmitter

The figure presents a block diagram of the UFMC system, which enhances spectral localization compared to traditional OFDM by filtering groups of subcarriers (sub-bands) rather than individual subcarriers or the whole band.

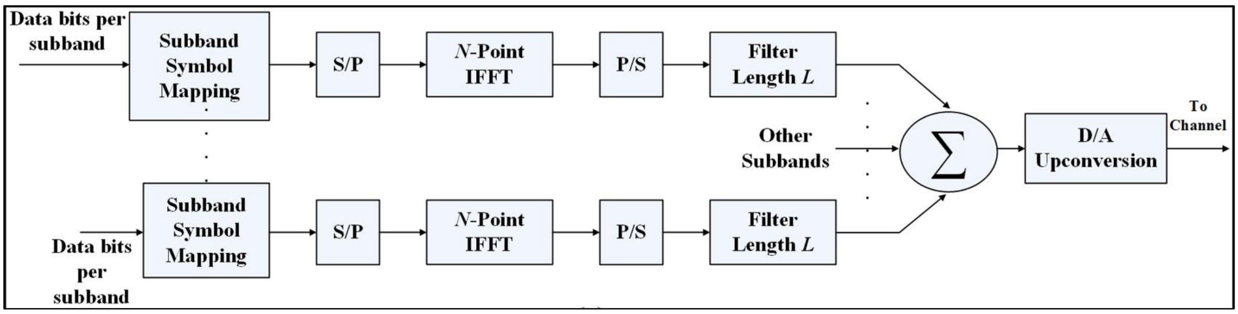


Figure II.11: UFMC Transmitter. (b) [43].

The total system bandwidth, comprising N orthogonal subcarriers, is partitioned into B distinct sub-bands. Each sub-band contains K contiguous subcarriers (K≤N), with the flexibility to leave some sub-bands unassigned. This allows dynamic allocation based on spectral availability or traffic demands.

Only a subset of sub-bands is activated for transmission. Unused sub-bands remain idle, enhancing spectral flexibility. [43] Within each active sub-band, data symbols are mapped to its *K* designated subcarriers.

The remaining N−K subcarriers in the sub-band are padded with zeros, ensuring orthogonality and confining energy to the allocated K-subcarrier block.

N-point Inverse Fast Fourier Transform (IFFT) is computed for each active sub-band. This converts the zero-padded frequency-domain symbols into a time-domain signal of length N.

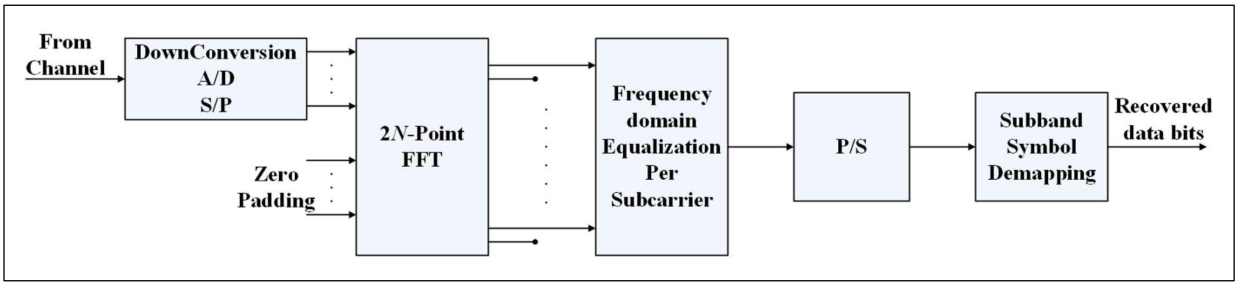


Figure II.12: UFMC Receiver block. [43]

Upon receiving the signals, radio frequency (RF) operations, including down-conversion, are employed to translate the band-pass signals to baseband. This step is critical to mitigate noise interference and facilitate digital signal processing. The baseband conversion ensures compatibility with subsequent demodulation stages, where precise recovery of the transmitted information is feasible.

To prepare for demodulation, a zero-padding process is applied to the received time-domain signal. Specifically, a defined number of zeros is appended to the received signal, extending its length from *N* to 2*N*. This interpolation in the time domain enhances frequency resolution by increasing the number of samples available for the Fast Fourier Transform (FFT).

The 2N-point FFT operation then transforms the zero-padded signal into the frequency domain, enabling accurate subcarrier separation and channel characterisation. Equalisation is performed to counteract channel-induced distortions (e.g., multipath fading, frequency selectivity). [43]

II.4.3.2 Principles of UFMC

UFMC (Universal Filtered Multi-Carrier) is a multicarrier modulation scheme employing orthogonal subcarriers. It is capable of mitigating the loss of orthogonality at the receiver side, which may occur due to frequency and time misalignments (see Figure II.13). [44]

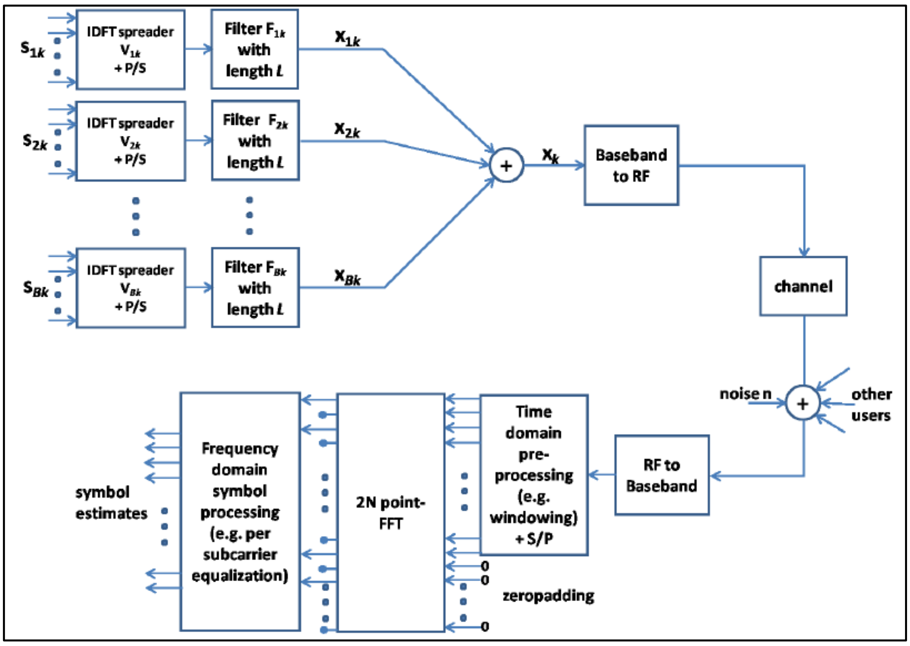


Figure II.13: Functional diagram of the UFMC system.[44]

This is due to improved spectral properties compared to OFDM . Figure III.2 from the previous chapter shows the functional diagram of the transmitter-receiver, with the receiver applying FFT (Fast Fourier Transform) detection.

Compared to OFDM, additional sub-band filters are introduced, which reduce the spectral levels of the side lobes outside this sub-band. This increases robustness against any source of interference between carriers and improves suitability for fragmented spectrum. These properties of UFMC open up the possibility of managing synchronous traffic and transmissions with relaxed synchronization in the same band at neigh boring frequencies. Note that relaxed synchronization does not necessarily mean complete asynchrony, as open-loop synchronization based on downlink signals is still possible.

Compared to OFDM, the cyclic prefix is removed, and its additional symbol duration is used to introduce sub-band filters. Note that these filters are much shorter—on the order of an OFDM cyclic prefix. This property also improves the ability to communicate in short bursts

[50]. Thus, UFMC can be more or less interpreted as a generalization of filtered OFDM (F-OFDM). [44]

a. UFMC Transmitter Structure:

The UFMC transmits a signal X in the time domain, which is the sum of the signals from all sub-bands and can be represented using the following expression [44] :

$$X = \sum_{i=1}^{B} F_i \, V_i \, S_i \tag{II.11}$$

Or: S_i Is a vector of QAM symbols from $i^{éme}$sub-band.

V_i Represents columns of IDFT (N×n_i) dimensions corresponding to the position of the $i^{éme}$ sub-band within the overall frequency range.

F_i It is a Toeplitz matrix of dimension ((N+L-1) ×N), which implements the convolution of the signal with the filter characteristic.

The signal can be rewritten without summation in the following forms:

$$\bar{F} = [F_1 \, F_2 \dots \, F_B] \tag{II.12}$$

$$\bar{V} = diag(V_1, V_2, \dots., V_B) \tag{II.13}$$

$$\bar{F} = [S_1, S_2 \dots, S_B]^T \tag{II.14}$$

These equations enable the column wise assembly of filter matrices, allowing the generation of a block diagonal IDFT matrix and the integration of all data symbols into a single column .

B: Number of sub-bands.

n_i **:** (Block size) Number of sub-carriers in sub-band i.

N: Total number of sub-carriers.

Filter i: length / pass band**,** filter characteristics defined by FIR filter coefficients (finite impulse response filter).

Figure III-3 below illustrates an example of the baseband structure of the UFMC transmitter with B sub-bands.$i^{éme}$ The UFMC sub-module.

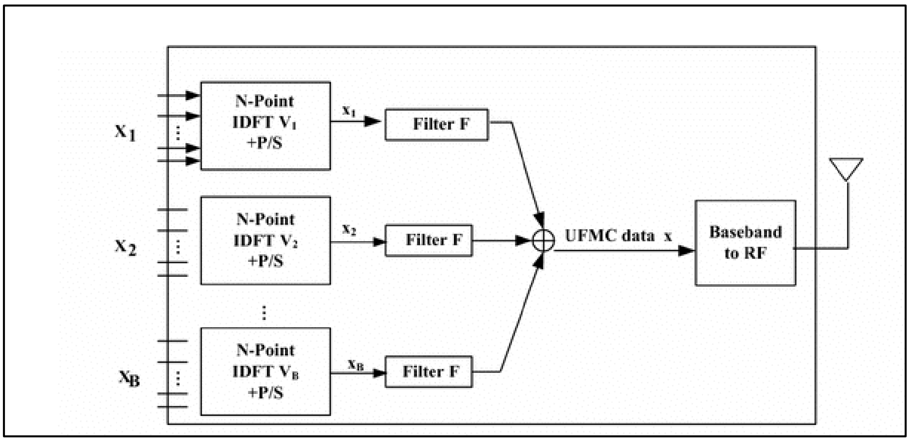


Figure II. 14: transmitter structure. [44]

b. Receiver structure:

The UFMC reception is carried out as shown in Figure II.14 below.

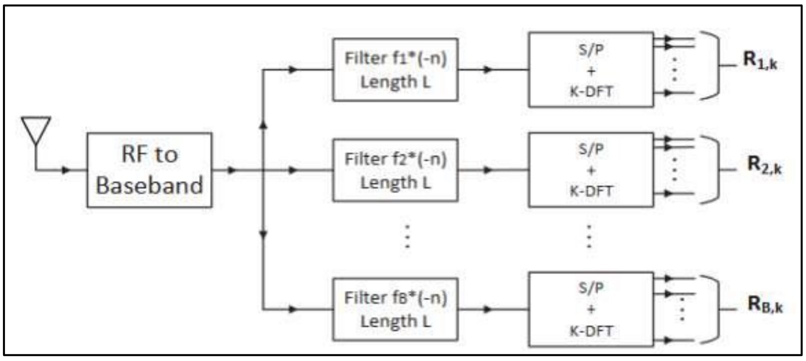


Figure II.15: Receiver structure. [44]

The UFMC signal received can be represented using the following expression [44] :

$$R = Hx + n = H\,\bar{F}\,\bar{V}\,\bar{S} \qquad \text{(II.15)}$$

R is the vector of the received signal after propagation through the channel. **H** represents the convolution matrix with a TOEPLITZ structure, modified by the channel impulse response in the time domain, **n** represents the noise.

II.4.3.3 Purpose of Filtering

The filter shapes the sub-band's spectrum, suppressing sidelobes and reducing OOB emissions caused by abrupt transitions (e.g., rectangular windowing in conventional OFDM). This is critical for coexistence with adjacent frequency bands.

The filtered outputs from all active sub-bands are coherently summed to form the final transmitted signal. This composite signal retains the spectral efficiency of multi-carrier systems while achieving superior OOB suppression.

II.4.3.2 Prototypes filters

Prototypes filters are designed to control the shape of the subcarrier signals in UFMC systems. Unlike traditional OFDM, UFMC applies filtering at the sub-band level, which means that groups of subcarriers are filtered together. This approach reduces out-of-band emissions, minimizes inter-subcarrier interference, and improves system robustness against noise and fading. [45]

- **Dolph-Chebyshev filter**

The Dolph-Chebyshev filter, as it was developed by Dolph (1946), aims to improve the main lobe while reducing the amplitude of secondary lobes. When this window is used and the filter configuration is adjusted to obtain a narrower transition region, the filter can be expressed mathematically as follows [45] :

$$\mathrm{w}_{\mathrm{cheb}} = \frac{\cos\left\{N\cos^{-1}\left[\frac{\pi k}{N}\right]\right\}}{\cos[N\cosh^{-1}(\beta)]} \quad ;\ k=0,\ 1,\ 2\ldots.N-1 \tag{II.16}$$

Where:

$$\beta = \cosh\left[\frac{1}{N}\cosh^{-1} 10^{\alpha}\right], \alpha \cong 2,\ 3,\ 4 \tag{II.17}$$

- N is the total number of filter coefficients
- k is the index of the coefficient
- α is the design parameter
- β is the parameter that controls the sidelobe attenuation

The Chebyshev filter has a distinctive characteristic: all its side lobes retain equal amplitudes, regardless of the frequency. This property is visually represented in Figure (II.16) below.

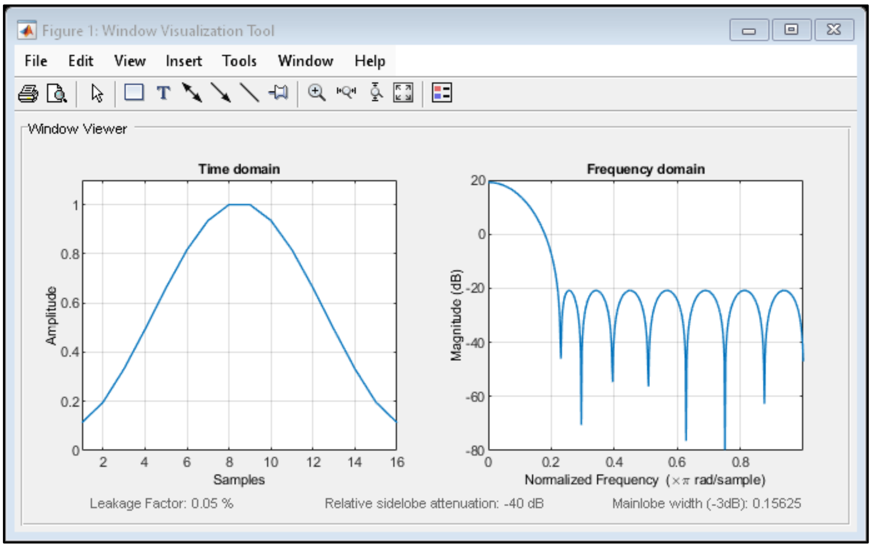


Figure II.16: time and frequency domain of the Chebyshev filter. [46]

The major advantage of UFMC lies in the use of the "Chebyshev" filter. Thanks to the properties of this filter, it becomes possible to significantly reduce the spectral effects of side lobes on adjacent subcarriers, a problem frequently associated with OFDM. Consequently, the requirement for a guard band becomes superfluous, since other UFMC symbols will no longer be disturbed by interference emanating from the side lobes.

- **Kaiser filter**

The Kaiser window, also known as the Kaiser-Bessel window, was developed by James Kaiser while working at Bell Laboratories. Kaiser introduced a new set of windowing functions that provide a level of control in the frequency domain, allowing users to balance the width of the main lobe and the amplitude of the side lobes by adjusting a parameter called β. This offers a versatile tool for tailoring spectral analysis characteristics.

The Kaiser window is particularly notable because it closely approximates the discrete prelate spheroidal sequence (DPSS), which is known for its exceptional energy concentration in the main lobe. However, the DPSS window can pose computational challenges. The Kaiser window serves as an accessible alternative, maintaining a narrow main lobe width while allowing for significant attenuation of side lobes, as illustrated in Fig. II.17.

The general form of the Kaiser window is expressed as follows [45] :

$$w_{kaiser} = \begin{cases} \frac{I_0(\beta)}{I_0(\alpha)} & |n| \leq \frac{N-1}{2} \\ 0 & \text{otherwise} \end{cases} \tag{II.18}$$

Where:

$$\beta = \alpha\left[1-\left(\frac{2n}{N-1}\right)^2\right]^{0.5} \tag{II.19}$$

$$I_0(z) \cong 1+\sum_{i=1}^{20}\left(\frac{\left(\frac{z}{2}\right)^I}{I!}\right)^2 \tag{II.20}$$

- $I_0(z)$ Represents the modified Bessel function of the first kind.
- N is the total number of filter coefficients.

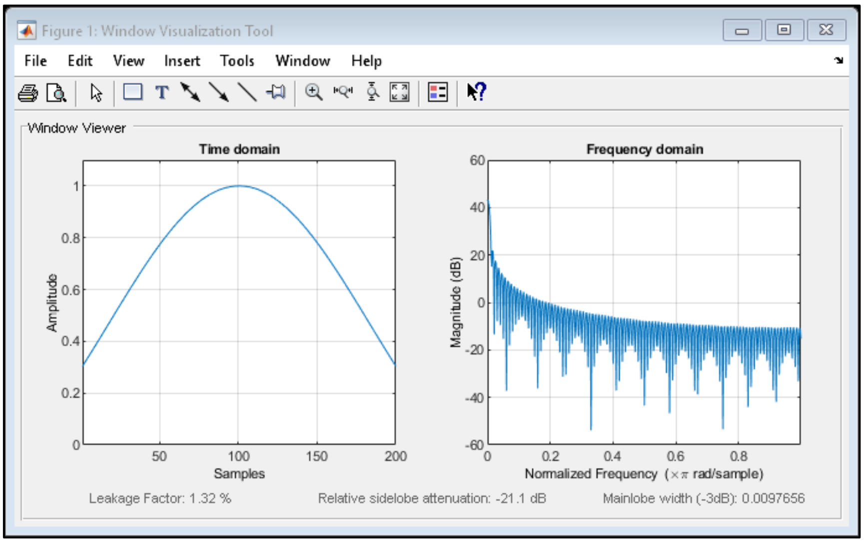


Figure II.17: time and frequency domain of the Kaiser filter. [46]

- **Parson Filters**

Parson windows have an approximately cubic shape, with their side lobes covering 1/4 of the window width. Essentially, they can be described as piecewise cubic windows, resulting from the convolution of two half-length triangular windows or four quarter-length rectangular windows, as explained in reference.

Figure II.18 illustrates the time-domain and frequency-domain representation of the Parzen window, and its mathematical expression is presented as follows [45] :

$$W_{parzen} = \begin{cases} 1-6\left(\frac{|n|}{\frac{N}{2}}\right)^2+6\left(\frac{|n|}{\frac{N}{2}}\right)^3 & ,0\le|n|\le(N-1)/4 \\ 2\left(1\frac{|n|}{N/2}\right)^3 & ,(N-1)/4<|n|<(N-1)/2 \end{cases} \tag{II.21}$$

- $|n|$ is the absolute value of the index, used to determine the filter's shape.
- N is the total number of filter coefficients.

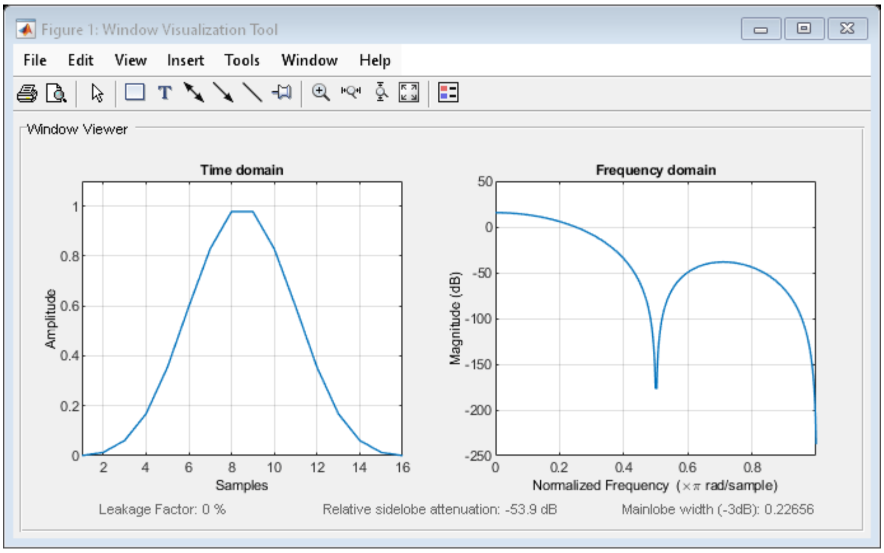


Figure II.18: time and frequency domain of the Parzen filter. [46]

Most UFMC (Universal Filtered Multi-Carrier) systems traditionally use the Chebyshev window to shape signals, serving as a conventional filter within the UFMC framework. However, a notable drawback of the Chebyshev window is its tendency to increase spectral leakage due to out-of-band emissions, which result from the window's constant side lobe decay rate.

As is generally understood, windowing is a method used to isolate the desired frequency range while effectively eliminating signals outside of it . In this thesis, we introduce the use of specific windows, particularly Flat Top windows, for the UFMC system. These choices are motivated by their distinct advantages, such as lower Bit Error Rate (BER) and reduced Peak-to-Average Power Ratio (PAPR) compared to the conventional Chebyshev window and other proposed windows, such as, Parzen, Kaiser, etc.

II.4.3.3 IoT and UFMC "Advancing Connectivity for the Future"

The Internet of Things (IoT) represents a dynamic network where interconnected devices share data to enable smarter operations and automation across diverse domains such as healthcare, industrial systems, and smart cities [15]. To support the ever-growing number of connected devices and ensure efficient communication, Unified Filtered Multi-Carrier (UFMC) offers significant advantages. UFMC enhances spectral efficiency and minimizes interference, making it ideal for dense IoT environments. By integrating UFMC into IoT systems, seamless data transmission and robust connectivity become achievable, laying the groundwork for scalable solutions and advancements in 5G-enabled technologies. This integration strengthens the IoT ecosystem, addressing the challenges posed by dense device networks and ensuring reliable communication for future applications.

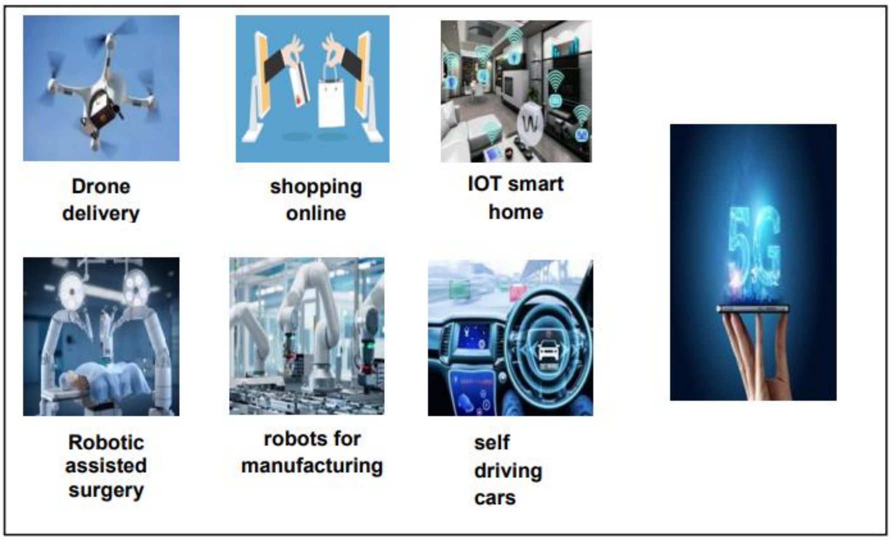


Figure II.19: Application of IoT and UFMC in advanced Technologies.

II.4.3.4 UFMC advantages and disadvantages

a) The advantages

Universal Filtered Multi-Carrier (UFMC) offers several advantages over other multicarrier techniques like OFDM, making it a strong candidate for 5G and beyond.

- **Better spectrum Use:** reduces interference between signals and allows for more efficient use of available frequencies.
- **Low latency:** Fast data transmission. This makes it ideal for real-time applications such as gaming and self-driving cars.
- **Flexibility:** works well in a variety of environments, including high mobility scenarios (such as fast-moving vehicles).
- **Improved reliability:** reduces errors caused by interference or synchronisation issues.
- **Energy Efficiency:** uses less energy. This is ideal for IoT devices and green technology.
- **Easy Integration:** can be added to an existing system with minimal changes.

b) The disadvantages are as follows

- The complexity of implementing this technique.
- High PAPR (Peak-to-Average Power Ratio). [47]

II.5 Comparison between OFDM and UFMC

To assess multi-carrier modulation techniques in wireless communication, it's important to analyse how each method meets specific performance demands. OFDM and UFMC are two prominent approaches, each offering distinct benefits and drawbacks. The table below presents a comparative summary, providing clarity on their strengths and potential applications.

Aspect	OFDM	UFMC
Technique	Divides the spectrum into orthogonal subcarriers with a cyclic prefix.	Filters a group of subcarriers (sub-bands) to reduce out-of-band emissions.
Cyclic prefix	Requires a cyclic prefix to combat inter-symbol interference (ISI).	Does not require a cyclic prefix, leading to improved spectral efficiency.
Spectral efficiency	Moderate due to overhead from the cyclic prefix.	Higher spectral efficiency, as it avoids CP and applies better filtering.
Out-of band-emission	Relatively higher due to the abrupt transitions of subcarriers.	Reduced out-of-band emissions due to the filtering of sub-bands.
Latency	Higher latency because of the cyclic prefix and guard intervals.	Lower latency, as it minimizes overhead and filtering is localized.
Suitability for 5 G	Widely used in LTE but less suited for 5G requirements.	A potential candidate for 5G, thanks to better flexibility and efficiency.
Complexity	Lower implementation complexity.	Slightly higher complexity due to filtering operations for sub-bands.
Interference management	Prone to inter-subcarrier interference without accurate synchronization.	Handles interference better, especially in asynchronous scenarios.

Table II .2: Comparison between OFDM and UFMC**.** [48],[49]

II.6 Conclusion

This chapter discussed the transition from traditional OFDM technology to UFMC as a potential alternative for 5G. While OFDM has improved spectral efficiency and reduced multipath interference, it faces limitations such as high PAPR, poor spectrum utilisation, and sensitivity to frequency offsets.

UFMC offers promising solutions to these challenges through enhanced filtering techniques and adaptability, making it more suitable for the demands of future applications like the Internet of Things (IoT). Overall, the chapter emphasises the importance of evolving communication technologies to effectively address emerging needs.

Chapter III

Simulation and Discussion of Results

III.1 Introduction

In this chapter, we describe the key aspects of the UFMC (Universal Filtered MultiCarrier) system and highlight the advantages of this new modulation technique for emerging fifth-generation (5G) wireless communication systems. Orthogonal Frequency Division Multiplexing (OFDM) has proven to be an excellent choice for fourth-generation (4G) systems. However, 4G modulation methods suffer from a high Peak-to-Average Power Ratio (PAPR). Side-lobe leakage is another significant issue in OFDM. Our current 4G systems rely on the OFDM waveform, which is not capable of supporting the wide range of applications introduced by 5G.

Our study encompasses both UFMC and OFDM, evaluating and comparing their performance through simulations, with a focus on key metrics such as Power Spectral Density (PSD), Peak-to-Average Power Ratio (PAPR), and Bit Error Rate (BER).

III .2 General Presentation of MATLAB

MATLAB is both a computational software and a high-level programming language. It is paid software, but there are two free alternatives [50] :

-Octave is software that uses the MATLAB language and can therefore use functions written in MATLAB. It is slower and somewhat less visually appealing.

-Scilab is developed by INRIA and its syntax differs slightly from that of MATLAB, but the overall concept is the same. In my opinion, it is even less convenient than MATLAB.

Matlab is numerical computation software, not symbolic computation software, unlike Maple. It can only solve numerical equations. The name Matlab comes from Matrix Laboratory. In MATLAB, all objects are matrices by default. A real variable is therefore seen by MATLAB as a 1×1 matrix. The default multiplication is matrix multiplication, so one must be careful.

The type of variables is not very important. Matlab can add a Boolean to a real number, or multiply an integer by a complex number without any issues. To launch Matlab, you simply run the Matlab command in a terminal. This opens Matlab's main window. You can directly execute command lines there, but most of the time you will use the Matlab editor, which allows you to create scripts and functions. [50]

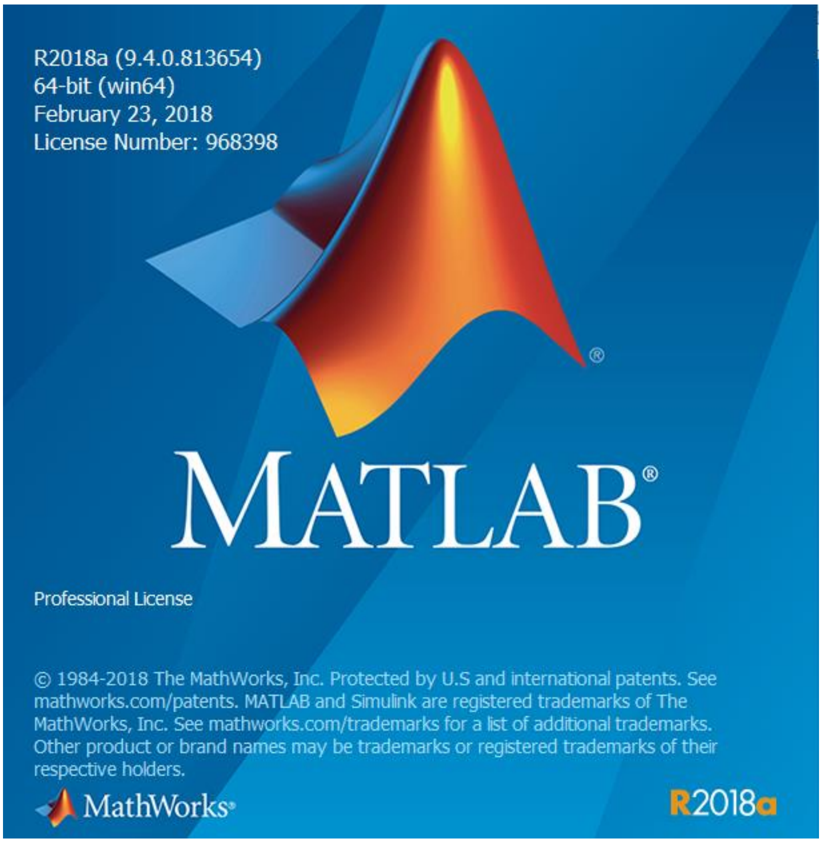


Figure III.1: Overview of MATLAB 2018. [46]

III.2.1 MATLAB Features

MATLAB supports interactive activities both through the command-line mode and through programming mode, while always allowing graphical visualisations. Ranked among the top programming languages (such as C or Fortran), MATLAB offers the following advantages compared to those languages [50] :

- Easy programming,
- Continuity between integer, real, and complex values,
- Wide range of numeric precision and value representation,
- A highly comprehensive mathematical library,
- Integrated graphical tools including GUI functions and interface utilities,
- Possibility of interfacing with other classical programming languages (C or Fortran).

III.3 Evaluated parameters

To achieve key technical objectives such as high data transfer rates and reliable network connectivity, 5G networks employ essential modulation techniques. These techniques ensure fast data transmission, low latency, and dependable signal delivery to support advanced communication systems.

The evaluation of modulation schemes like OFDM and UFMC relies on key performance metrics including Power Spectral Density (PSD), Peak-to-Average Power Ratio (PAPR), Signal-to-Noise Ratio (SNR), and Bit Error Rate (BER) which collectively provide a comprehensive assessment of modulation efficiency under varying transmission conditions.

III.3.1 Power Spectral Density PSD

PSD represents the distribution of signal power across different frequencies and is considered an essential tool for evaluating bandwidth utilisation efficiency in modulation techniques. PSD shows the signal intensity over a specific time duration to determine the frequency range capable of transmitting data without errors. [51]

Through simulation, the PSD of UFMC is compared with OFDM, where the graphs illustrate differences in spectral distribution. Maximum modulation efficiency is achieved when the signal intensity reaches its peak within the normalised frequency range. PSD is primarily used in the design of 5G systems to enhance power distribution and reduce interference. The formula of PSD is given by Equation (III.1) as [52] :

$$S(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) e^{-j2\pi f t} dt \right|^2 \qquad \text{(III.1)}$$

III.3.2 Peak-to-Average Power Ratio (PAPR)

The Peak to Average Power Ratio is the relation between the maximum powers of a sample in a transmitted symbol divided by the average power of that symbol. PAPR occurs when the different subcarriers in a multicarrier system are out of phase with each other. In a multicarrier system there are a large number of independently modulated subcarriers, which are out of phase concerning each other. If more than one subcarrier achieves the maximum value at the same time, the output envelope will increase, causing a peak in the output, and when these peaks are added up for transmission, a large peak value is reached that is very large compared to the average value of the sample. PAPR is defined by the following equation [53] :

$$PAPR = \frac{\max\{x|[n]|\}^2}{E\{|x[n]|\}^2} \tag{III.2}$$

Where,

$|x[n]|$ The amplitude of x [n] and E is the expectation of the signal.

Higher PAPR level causes the power amplifier to act in the saturation region, leading to increases in errors and also increases in out-of-band radiation (OOB). In the study of signal performance on the basis of power level, complementary cumulative distribution function (CCDF) curves are known to have great performance. CCDF is the probability that PAPR exceeds a given PAPR threshold. [53]

$$\mathrm{CCDF(PAPR)} = \mathrm{Pr_{PAPR}} > \mathrm{Pr_{PAPR0}} = 1 - (\mathrm{Pr_{PAPR}} > \mathrm{Pr_{PAPR0}})$$

$$= 1 - (1 - e^{-\eta})^N \tag{III.3}$$

With: $\eta = PAPR0$.

III.3.3 Bit Error Rate (BER)

BER represents the ratio of incorrectly received bits to the total number of transmitted bits over a given period. It serves as a critical metric for evaluating transmission accuracy. In 5G environments characterised by high-frequency and high-speed communication the reliability of the system is closely tied to BER. A lower BER indicates improved performance, as it reflects fewer errors during data transmission.

Evaluating BER accurately is essential to ensure data integrity, particularly in dynamic and noisy conditions typical of 5G networks. The resistance of a modulation technique to signal impairments is often judged by its BER performance under varying conditions. [52]

$$BER = \frac{\text{Number of Bits Error}}{\text{Total Number of Transmitted Bits}} \tag{III.4}$$

III.3.4 Signal-to-Noise Ratio (SNR)

SNR shows the relation between signal powers against the noise power within a system. It is a fundamental element to evaluate signal quality in received signals. The signal quality enhances with an increased SNR. [52]

Several performance parameters help evaluate the modulations when noise levels change across different environments. In the SNR plays a critical role to determine 5G connection reliability and data rate capabilities in the current communication framework.

SNR encompasses particular importance in tightly packed urban environments as well as conditions with intense interference levels. The calculation of SNR occurs as depicted in Equation (III.2). The calculation indicated by Equation (III.5) produces results that operators present in units of decibels. [52]

$$SNR_{dB} = 10log_{10}\left(\frac{P_S}{P_n}\right) \qquad \text{(III.5)}$$

Where,

P_S is average signal power and P_n is average noise power.

III.4 Simulation Results

This section studies the performance of each waveform and compares the results of OFDM and UFMC. The BER, PAPR, and PSD are the metrics used to evaluate the performance.

We explore the capabilities of UFMC compared to conventional OFDM through computer modelling. A MATLAB simulation was designed to test these modulation techniques under varying conditions, simulation parameters are shown in Table III-1.

Parameter	Value
FFT/IFFT Size	128, 256, 512,1024
Sub band Size	20
Number of sub bands	10
Sub band offset	156
Filter Length (Dolph-Chebyshev)	43
Side lobe Attenuation (dB)	20,40,60,80
Bits per Subcarrier (QAM)	4QAM, 16QAM, 64QAM, 256QAM
Cyclic Prefix Length (CP-OFDM)	72
Number of Symbols (CP-OFDM)	100
Guard Bands (CP-OFDM)	156
Subcarrier Spacing	156

Table III-1: simulation parameter**s.**

III .4.1 Simulation of Power Spectral Density PSD

Figure III.2 illustrates the PSD of UFMC and OFDM waveforms, both systems use an FFT size of 512 and a modulation order of 6-QAM. For UFMC we have used 20 subcarriers grouped into 10 sub-bands. It can be observed that the UFMC waveform exhibits significantly reduced out-of-band (OOB) emissions compared to the OFDM waveform. Specifically, the side lobe attenuation for UFMC reaches approximately -80 dB, whereas for CP-OFDM, it is limited to around -30 dB.

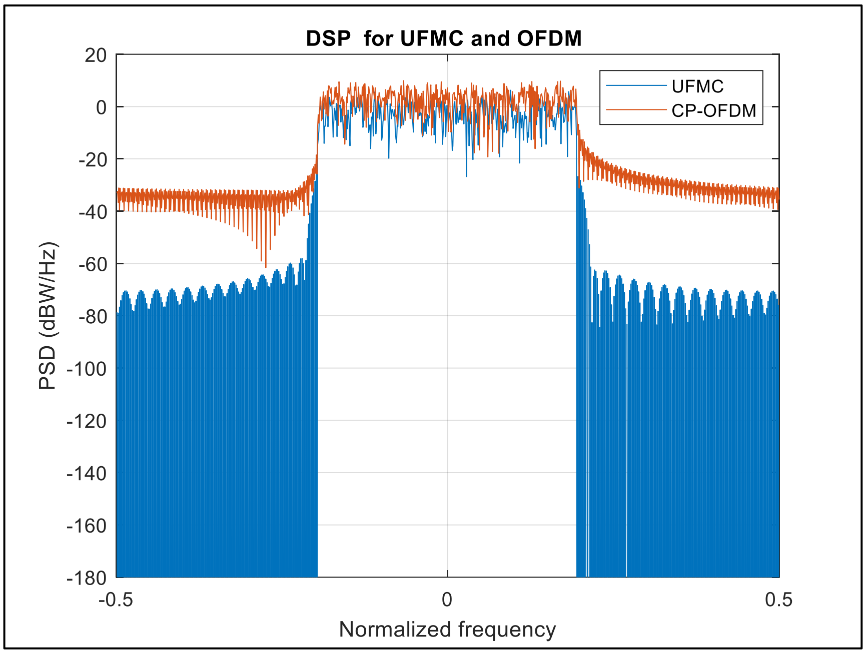


Figure III. 2: PSD of UFMC and OFDM.

III.4.1.1 Impact of QAM modulation orders

In this section, we present the PSD of the UFMC and CP-OFDM signal using the same parameters fixed in Table III-1, while varying the QAM modulation order.

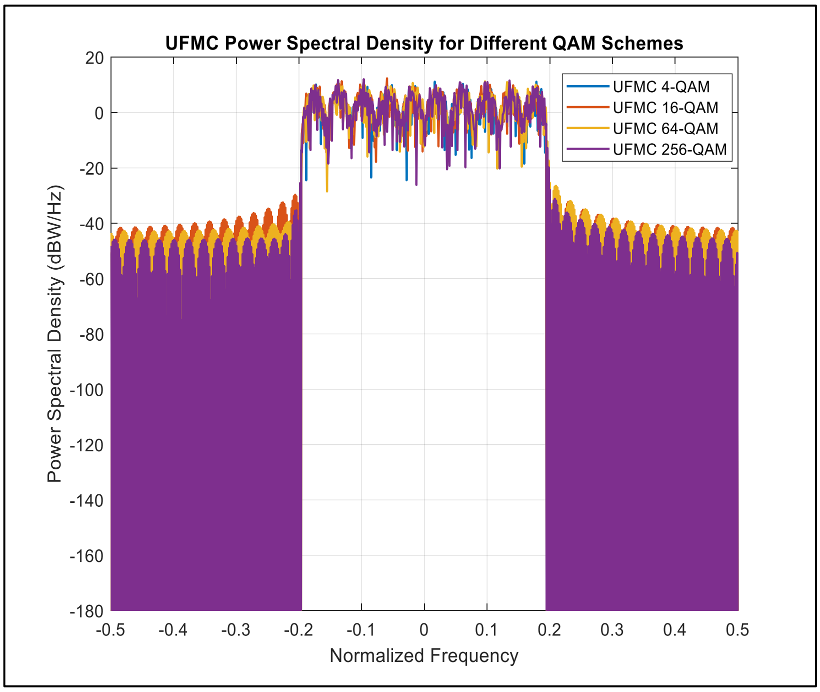


Figure III. 3: PSD of UFMC for different QAM order.

Figure III.3 illustrates the PSD of UFMC signals for various QAM modulation orders: 4-QAM, 16-QAM, 64-QAM, and 256-QAM. It is observed that all modulation schemes demonstrate comparable spectral containment. The PSD values lie within the range of approximately –42 dBW/Hz to -45 dBW/Hz. This consistency across different modulation orders indicates that the QAM order has a limited impact on the spectral distribution of UFMC signals.

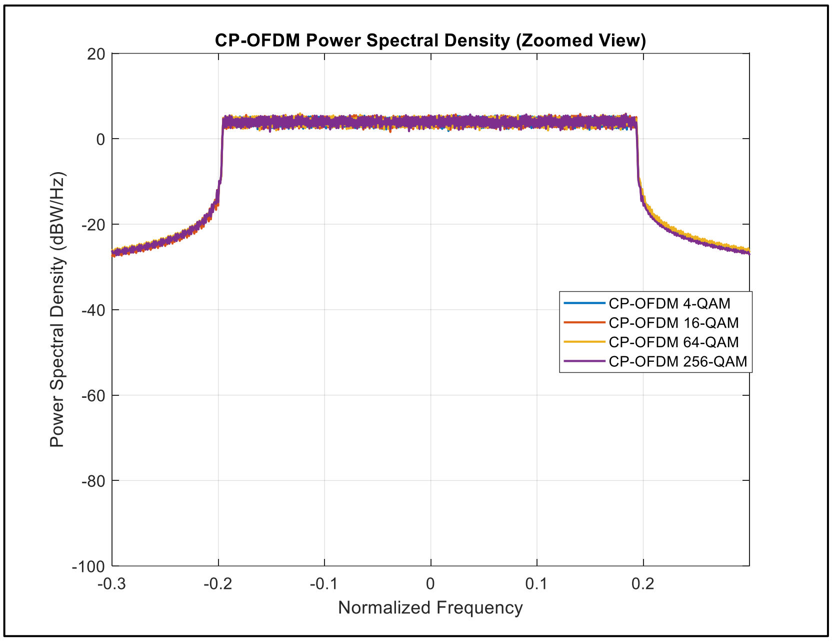


Figure III.4: PSD of CP-OFDM for different QAM.

Figure III.4 shows the PSD of CP-OFDM signals for QAM modulation orders 4, 16, 64, and 256. All modulation levels exhibit similar spectral behaviour, with PSD values ranging from -25 dBW/Hz to -28 dBW/Hz. Therefore, spectrum leakage will be less felt when we use UFMC. The PSD results show that the impact of QAM modulation order on the spectral shape is limited. All orders maintain nearly the same spectral characteristics with slight variations in peak PSD values.

III.4.1.2 the Impact of Side lobe Attenuation in UFMC and CP-OFDM

The figure shows the Power Spectral Density (PSD) as a function of normalized frequency, comparing the UFMC technique with different side lobe attenuation levels (20, 40, 60, and 80 dB) to the CP-OFDM technique using 64-QAM modulation. The same simulation settings were applied in all cases, as previously indicated in Table III.1.

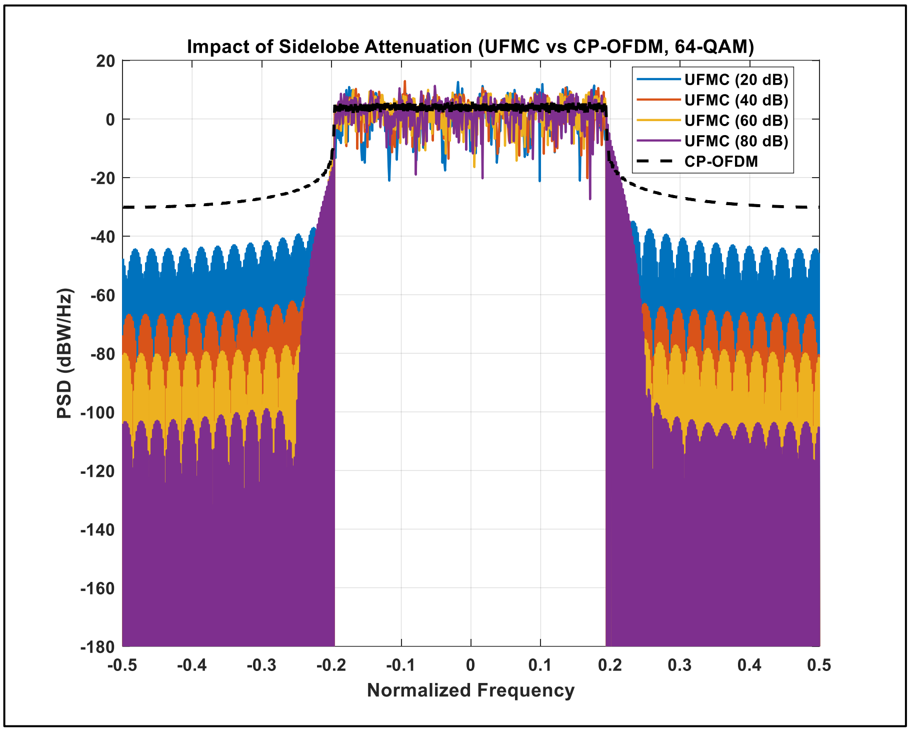


Figure III.5: PSD of CP-OFDM and UFMC for different side lobe attenuation.

According to Figure III.5, OFDM exhibits a slower PSD, with significant side lobes reaching approximately -30 dBW/ Hz. In contrast, UFMC demonstrates better side lobe suppression, with performance improving as attenuation increases (from 20 to 80 dB). Specifically, at an attenuation level of 80 dB, UFMC reaches around -120 dBW/ Hz in the out-of-band regions, representing an improvement of approximately -90 dBW/ Hz compared to CP-OFDM, with UFMC demonstrating superior spectral containment compared to CP-OFDM.

III.4.1.3 Impact of filters

The same simulation settings were applied in all cases, as previously indicated in Table III.1. Figure III.6 shows the Power Spectral Density (PSD) of the UFMC system using three different filters: Chebyshev, Kaiser, and Parzen. It can be seen that the Parzen filter gives the best performance in terms of spectral confinement, with side lobe levels reaching around -140 dBW/Hz, compared to -100dBW/Hz for Kaiser and -80dBW/Hz for Chebyshev.

This strong attenuation helps reduce out-of-band emissions (OOBE), which is very important for multiband systems. In short, the Parzen filter is the most effective at limiting interference between frequency bands.

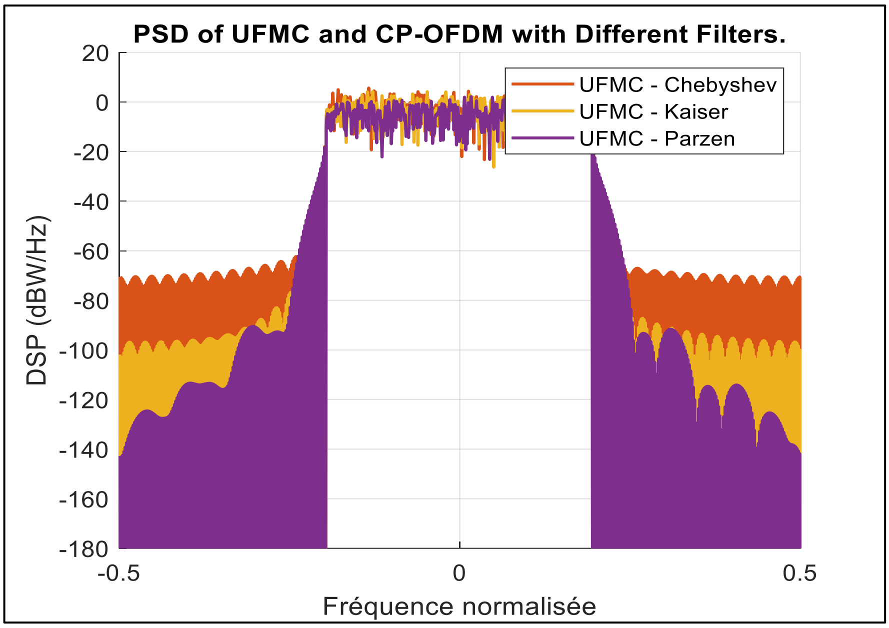


Figure III.6: PSD of UFMC and CP-OFDM with Different Filters.

III.4.2 Simulation of Peak-to-Average Power Ratio PAPR

In this section, we evaluate the PAPR performance of the UFMC system and compare the results with those of the OFDM system. The Simulations are conducted based on the setup parameters outlined in Table III-1.

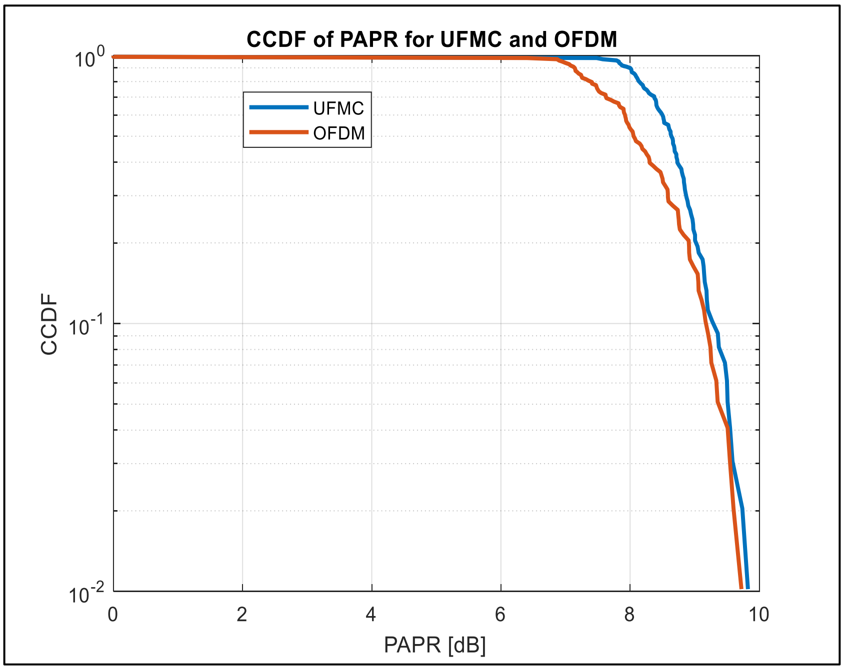


Figure III.7: CCDF of PAPR for UFMC and OFDM.

According to the figure, the PAPR level for both systems OFDM and UFMC reaches a close value. In a detailed way, we can observe that at a probability of 10^{-2}, UFMC reveals a PAPR level of 9.9 dB, while OFDM demonstrates a PAPR level of 9.8 dB for the same probability 10^{-2}. The PAPR of OFDM is approximately 0.1 dB lower than that of UFMC. This is due to the filtering process by sub-band in UFMC not like in OFDM no filtering process just a simple IFFT and CP operations. Filtering introduces temporal smoothing, but when multiple sub-bands overlap or are summed, their time domain signal can constructively interfere, increasing the peak amplitude. These measurement results show that both OFDM and UFMC waveforms exhibit high PAPR values. We conclude that both waveforms need PAPR reduction.

III.4.2.1 Impact of QAM modulation orders

In the following figure III.8, we will present the PAPR measurements for different modulation orders (4-QAM, 16-QAM, 64-QAM, and 256-QAM) for both modulation systems OFDM and UFMC.

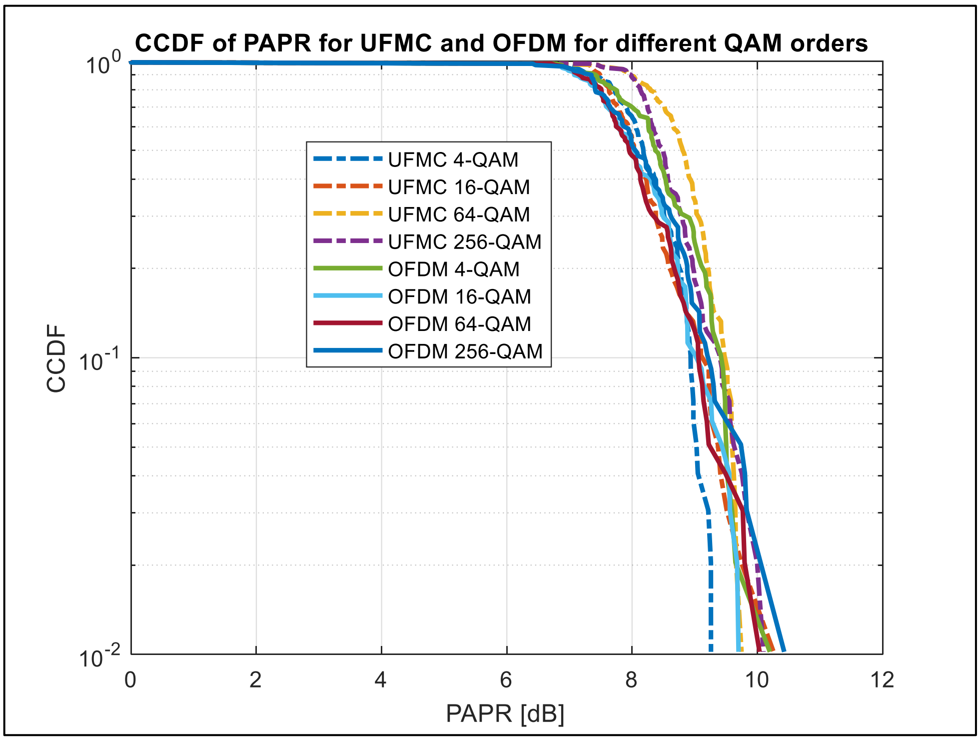


Figure III.8: PAPR Comparison of UFMC and OFDM with different QAM.

This figure illustrates the estimated PAPR using the CCDF for UFMC and OFDM modulations across various QAM orders (from 4-QAM to 256-QAM). For a CCDF probability of 10^{-2}, the PAPR ranges from 9.2 dB to 10.4 dB. Both systems show nearly PAPR levels. Among the two systems, lower PAPR values are reached when we use a small QAM order. Moreover, the PAPR value tends to decrease as the QAM modulation order increases in both systems.

III.4.2.2 Impact of filters

The same simulation settings were applied in all cases, as previously indicated in Table III.1. Figure III.9 presents the CCDF curves of PAPR for a UFMC signal filtered using three windows; Parzen, Kaiser (β = 8), and Dolph-Chebyshev (40 dB attenuation). At a CCDF level of 0.1, the Parzen filter achieves the lowest PAPR (approximately 9.4 dB), followed by Kaiser (10.3 dB), while Dolph-Chebyshev records the highest value (10.4 dB). The Parzen filter stands out for its effective PAPR reduction capability, enabling better signal linearity and more efficient use of the power amplifier. As a result, the energy efficiency of the UFMC system is significantly improved.

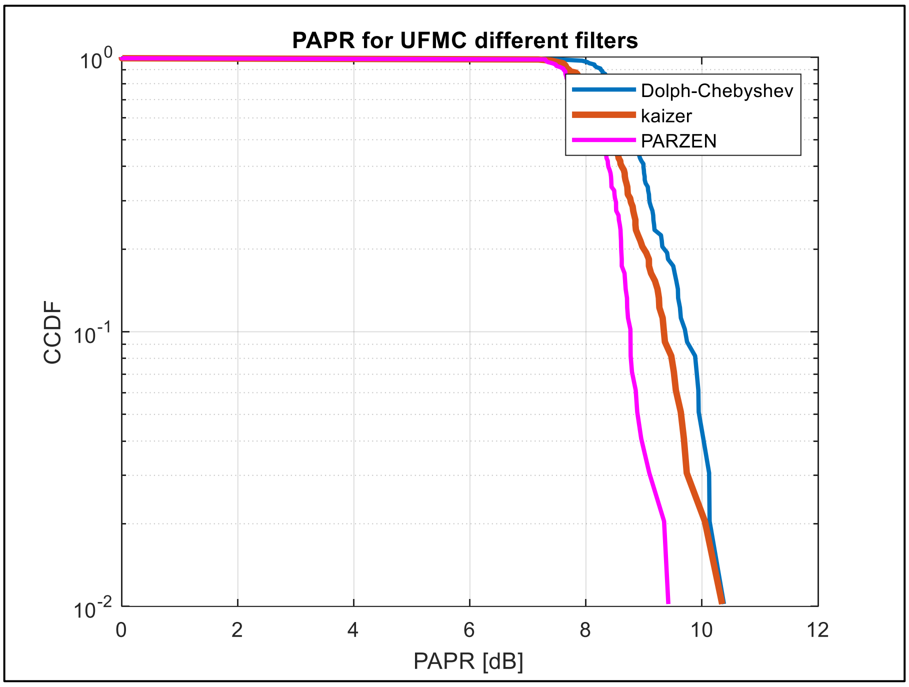


Figure III.9: PAPR CCDF for UFMC Modulation with Different Filters.

III.4.2.3 PAPR with variation in FFT size

In this section we compare the PAPR of UFMC and OFDM for different number FFT points with Dolph_chebyshev filter for 4-QAM modulation.

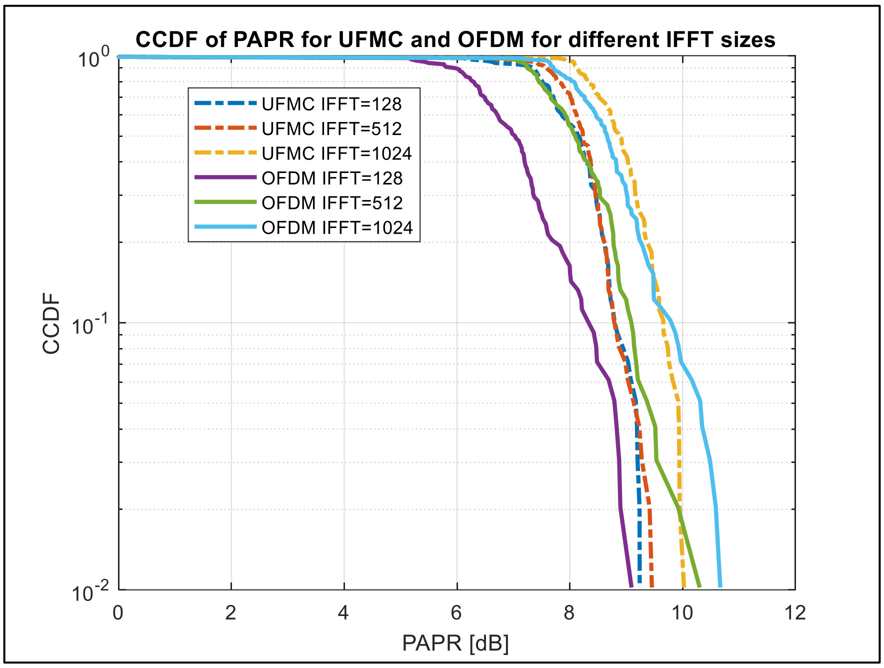


Figure III.10: PAPR variations for 64QAM UFMC modulation.

Based on the previous CCDF graphs of PAPR for UFMC and OFDM with different FFT sizes, here's Table III.2 represent the data; these values are approximated from the CCDF graphs at the probability 10^{-2} level.

Number of points in FFT	PAPR of UFMC	PAPR of OFDM
128	9.2	9.1
512	9.5	10.3
1024	10.0	10.7

Table III.2: PAPR with variation in FFT size.

According to the figure III.10 and table III.2**,** at a CCDF level of 10^{-2}, it is observed that both techniques show a competitive value of PAPR. When the FFT size increases from 128 to 1024, the PAPR rises for OFDM and UFMC systems. This progression indicates that increasing the FFT size increase the peak dynamic in OFDM and UFMC this is logical due to large number of summed subcarriers.

III.4.3 BER comparison

In this section, we evaluate the performance of the UFMC system and compare the results with those of the OFDM system. The simulations are conducted based on the setup parameters outlined in Table III.1. Additionally, the BER is computed to assess the error performance of both systems under different SNR.

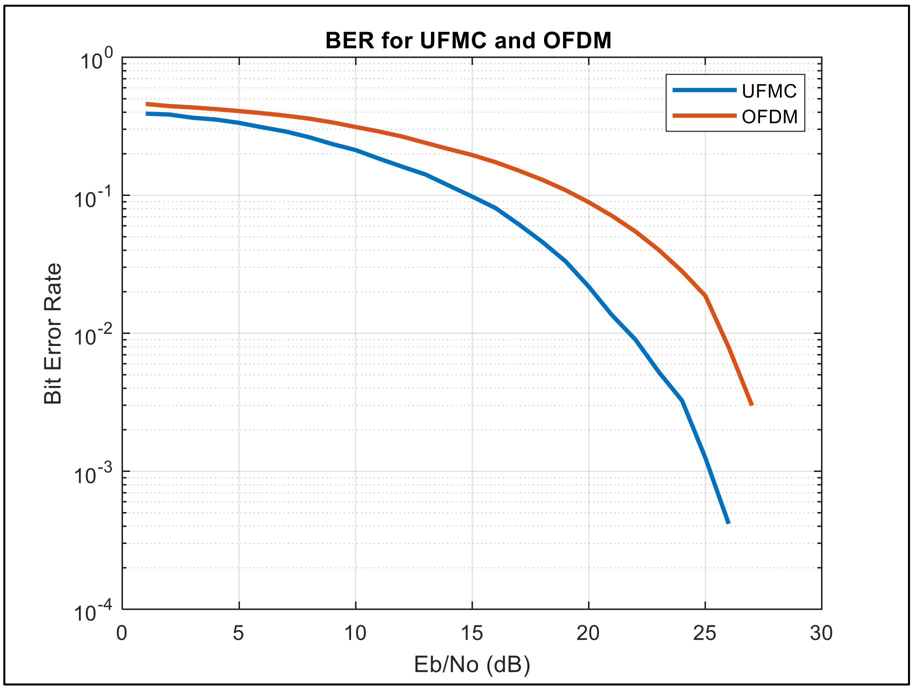


Figure III.11: BER for UFMC and OFDM.

In the results shown in the figure III.11, we present the influence of the Eb/No parameter on the BER. From these results, we observe that the BER decreases as Eb/No increases. UFMC achieves a BER of 10^{-2} at approximately 22.7 dB of SNR, while OFDM does not reach this level even at 26 dB. Based on the simulation results comparing the BER performance of OFDM and UFMC, it is evident that UFMC performs better at high SNR values.

III.4.3.1 Impact of QAM modulation

In this section, we present the BER of the UFMC and OFDM signal using the same value noted in table III.1, while varying the QAM modulation order.

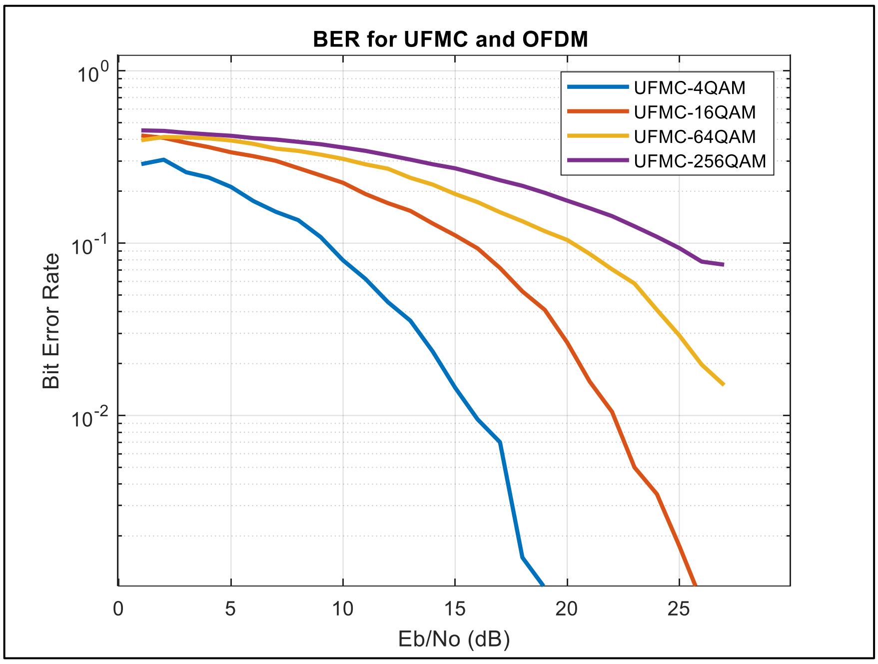
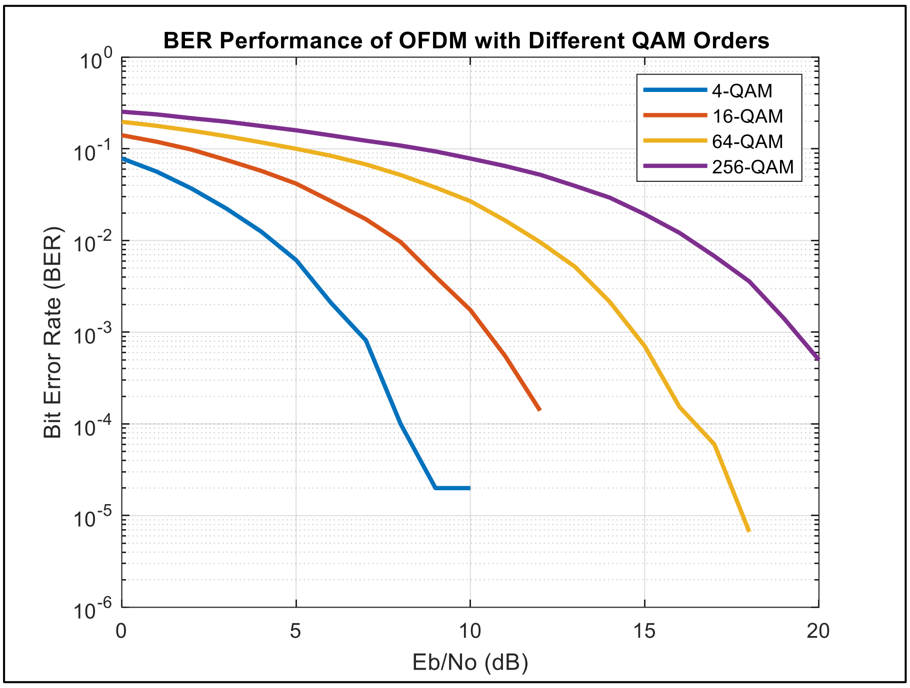


Figure III.12: BER performances of UFMC with Different QAM orders.

This graph illustrates the performance of the UFMC system in a differential QAM context as the SNR increases. A significant decrease in the bit error rate (BER) is observed with rising SNR, confirming the system's effectiveness for various QAM modulations (from 4 to 256). The analysis highlights the inverse relationship between modulation order and error robustness. These results demonstrate the system's ability to adapt to varying requirements in data rate and reliability. The table III.3 below shows estimated values from the graph where the BER is around 10^{-1}.

Modulation Scheme	BER (Bit Error Rate)	Eb/No (dB)
4QAM	10^{-1}	8.8
16QAM	10^{-1}	15
64QAM	10^{-1}	20
256QAM	10^{-1}	24.5

Table III.3: BER performances of UFMC with variation in QAM modulation.



FigureIII.13: BER performance of OFDM with different QAM orders.

This graph shows how the BER changes with the Eb/No in an OFDM system using different QAM modulation levels. It shows that lower-order modulations like 4-QAM work better in noisy conditions, while higher-order modulations like 256-QAM need a higher SNR to keep errors low. This shows the balance between sending more data and resisting noise. It also highlights the need to adjust the modulation depending on the channel quality. The table III.4 below shows estimated values from the graph where the BER is around 10^{-3}.

Modulation Scheme	BER (Bit Error Rate)	SNR (dB)
4QAM	10^{-3}	6.8
16QAM	10^{-3}	10.5
64QAM	10^{-3}	14.8
256QAM	10^{-3}	19

TableIII.4: BER of OFDM with variation in QAM modulation.

III.4.3.2 Impact BER for UFMC with different side lobe Attenuation

Figure III.14 presents the BER for the UFMC technique varying side lobe attenuation levels (20, 40, 60, and 80 dB). All scenarios were simulated under identical conditions, as detailed earlier in Table III.1.

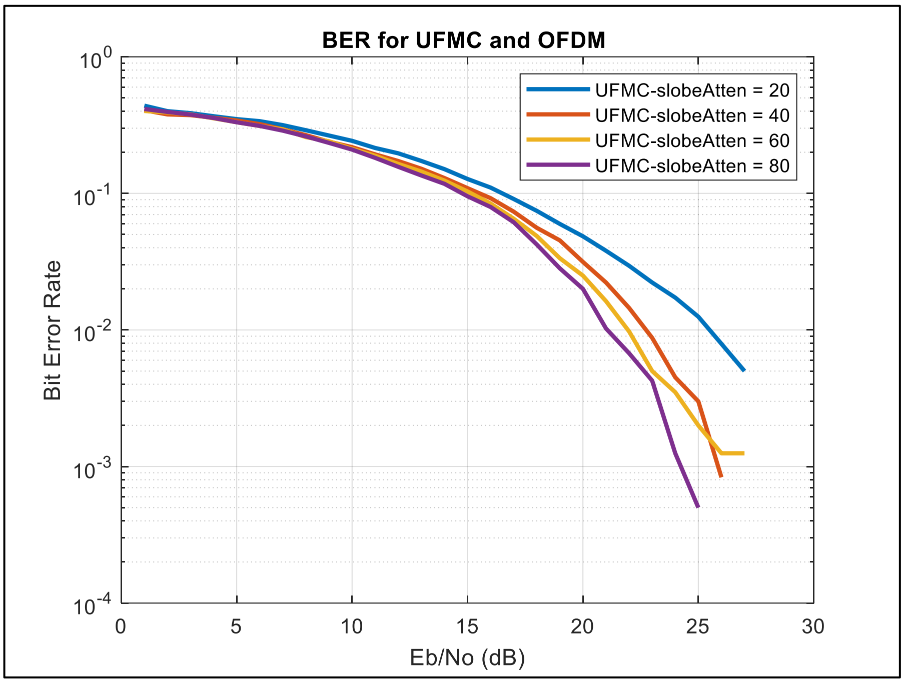


Figure III.14: BER for UFMC with Different Side lobe attenuation.

The figure shows the BER performance of UFMC systems using the Dolph-Chebyshev filter with different side lobe attenuation levels. As the attenuation increases, the BER clearly improves, especially at high Eb/No values, showing the filter's ability to reduce interference. This highlights the importance of strong attenuation for better communication quality.

Side lobe attenuation (dB)	BER	Eb/No(dB)
20	10^{-2}	25.8
40	10^{-2}	22.2
60	10^{-2}	22
80	10^{-2}	21.6

Table III.5: BER with variation in side lobe attenuation.

III.4.3.3 Impact of filters

The same simulation settings were applied in all cases, as previously indicated in Table III.1. The figure illustrates a comparison of the Bit Error Rate (BER) performance for the UFMC modulation scheme using three different filters: Chebyshev, Kaiser, and Parzen. It is evident that the Parzen filter provides the best performance, particularly beyond 5 dB, where its BER curve decreases more rapidly. The Chebyshev filter exhibits intermediate performance, while the Kaiser filter shows the highest BER across all Eb/No values. The superior performance of the Parzen filter can be attributed to its better frequency localization and lower out-of-band energy. A detailed summary of these results is presented in Table III.6.

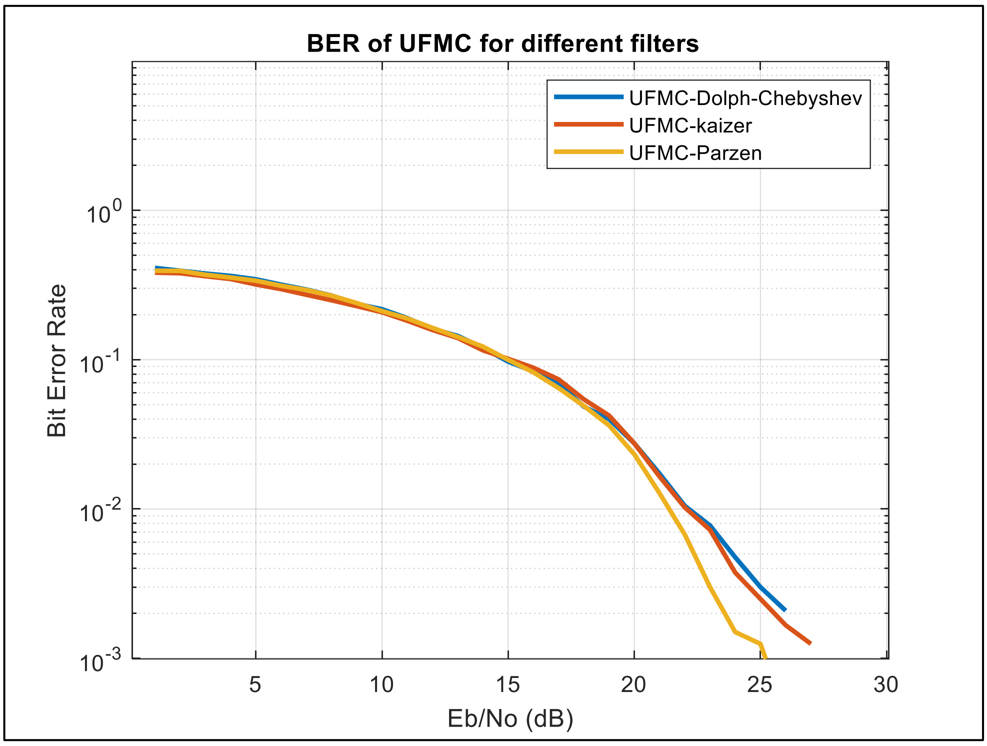


Figure III.15: BER for UFMC with Different filters.

Number of points in FFT	BER	Eb/No (dB)
Parzen	10^{-2}	21.7
Dolph-Chebyshev	10^{-2}	22.9
Kaiser	10^{-2}	22.7

Table III.6: BER with different filters.

III.5 Comparison between CP-OFDM and UFMC

In order to clearly distinguish and evaluate the performance differences between CP-OFDM and UFMC, we made a simple comparison based on some key technical points. CP-OFDM uses a Cyclic Prefix (CP) to reduce interference between symbols, but this reduces how efficiently the spectrum is used. On the other hand, UFMC filters small groups of subcarriers, which helps use the spectrum better and reduce interference. CP-OFDM is easier to process and less complex, while UFMC needs more calculations because of the filters it uses.

UFMC also works better in fast-changing channels because it can reduce interference between users more effectively. The table below shows a clear comparison between CP-OFDM and UFMC in terms of efficiency, interference, and how stable they are in changing conditions.

The table below highlighted the key differences between OFDM and UFMC:

Metrics	OFDM	UFMC
PSD	• High side-lobe leakage, leading to lower spectral efficiency • Needs of guard bands.	• Lower side-lobes due to sub-band filtering • improving spectral efficiency by reducing out-of-band emissions
PAPR	• High PAPR due to constructive interference between subcarriers. • Affect power amplifier efficiency and increases power consumption	• Slightly better PAPR thanks to sub-band filtering. • Still a challenge; requires PAPR reduction techniques
BER	• Sensitive to synchronisation errors and Doppler shift. • Higher BER in multipath channels.	• More robust due to sub-band filtering. • Improved power efficiency.

Table III.7: The comparison between CP-OFDM and UFMC

III.6 Conclusion

In this chapter, we conducted a comprehensive analysis of two prominent multicarrier modulation schemes, UFMC (Universal Filtered Multi-Carrier) and OFDM (Orthogonal Frequency Division Multiplexing) to evaluate their suitability for 5G wireless communication systems.

Using MATLAB-based simulations, we assessed key performance metrics such as Power Spectral Density (PSD), Peak-to-Average Power Ratio (PAPR), and Bit Error Rate (BER) under various system conditions. The simulation parameters included different FFT sizes, QAM orders, and filtering options like Dolph-Chebyshev within UFMC.

Our results indicate that UFMC offers notable advantages over OFDM for 5G applications. Its strong frequency location, the spectral containment achieved through filtering minimizes interference and improves spectral efficiency. UFMC also demonstrates better BER performance at high SNRs, implying increased reliability and data integrity. However, it suffers as all multicarrier systems from high PAPR.

While both schemes support high data rates and reliable communication, UFMC's spectral efficiency, and BER performance position it as a more promising candidate for future 5G and beyond wireless systems. Nonetheless, further optimization and real-world testing are required to address practical implementation challenges.

General conclusion

The work presented in this dissertation adopts an analytical approach to evaluate the performance of modulation techniques used in next-generation mobile networks. The study primarily focuses on comparing OFDM (Orthogonal Frequency Division Multiplexing) with UFMC (Universal Filtered Multi-Carrier), the latter being a promising evolution of OFDM that is better suited to meet the requirements of 5G.

A comprehensive review of the evolution of cellular networks from 1G to 5G was conducted, addressing architectures, multiple access protocols, as well as major technological innovations.The fifth generation of mobile networks (5G) marks a major technological breakthrough, offering very high data rates, reduced latency, and efficient management of a large number of connected devices. The simulations performed enabled the assessment of both OFDM and UFMC techniques based on key performance indicators, namely PSD, PAPR and BER.

The obtained results demonstrate that UFMC offers better spectral efficiency, good BER measurements; however it suffers from high PAPR as OFDM. This highlights the potential of UFMC as a suitable solution for 5G systems, while emphasising the need for further analysis under real-world propagation and mobility conditions.

The main conclusions drawn from this work are as follows:

UFMC modulation, with its enhanced features compared to OFDM, demonstrates better performance in terms of PSD, PAPR and BER, making it suitable for 5G network requirements. As we know 5G systems, are up to ten times faster than 4G, paves the way for numerous advanced applications, including high-definition video conferencing, virtual reality, autonomous vehicles, and the Internet of Things (IoT). The 5G does not merely represent a speed improvement but constitutes a complete transformation of the digital ecosystem, capable of meeting future needs for smart connectivity and massive communications.

As future perspectives, it would be relevant to explore other modulation techniques suited to 5G, such as FBMC and GFDM, and to evaluate their performance in real-world environments. The integration of artificial intelligence for adaptive optimisation also represents a promising direction.

References

References

[1] Dialogic Inc., "Mobile Network (MN)," Glossary, accessed April 29, 2025.

[2] Kharel, Ujjwal. Evolution of Mobile Wireless Communication Networks to 5G Revolution. Bachelor's thesis, Metropolia University of Applied Sciences, 2022.

[3] Boufeken, Houda. " Étude et implémentation des formes d'ondes multi-porteuses candidates pour la 5G. " Master's thesis, University 8 mai 1945 – Guelma, 2022

[4] Ms. Anju Uttam Gawas "An Overview on Evolution of Mobile Wireless Communication Networks: 1G-6G." International Journal on Recent and Innovation Trends in Computing and Communication, Volume 3, Issue 5, May 2015, pp, 3130–3133. ISSN: 2321-8169.

[5] Krishn Kumar Gupt, Vinay Kumar Singh. " Evolution of Modern Communication Systems". International Journal of Advanced Research in Computer and Communication Engineering, vol. 5, issue 6, June 2016. Zakir Husain Delhi College, New Delhi, India.

[6] Http://www.What is CDMA? - Electrical eLibrary.Com

[7] Ouassim Ouleha and Salahdine Didouna, " Etude des performances de modulation UFMC Pour le réseaux 5G ", Master's thesis, University 8 May 1945 - Guelma, June 2019.

[8] Http://www.Networking: Multiple Access Techniques Applied by GSM - Too Abstractive.Com"

[9] Pankaj Sharma,"Evolution of Mobile Wireless Communication Networks-1G to 5G as well as Future Prospective of Next Generation Communication Network.",International Journal of Computer Science and Mobile Computing, vol. 2, no. 8, August 2013, pp. 47–53.

[10] Http://www.Core Network Evolution: 3G vs 4G vs 5G - Sarp Koksal on Medium.Com

[11] Erik Dahlman, Stefan Parkvall, and Johan Sköld, " 5G NR: The Next Generation Wireless Access Technology", 2nd edition, Academic Press, 2020.

[12] Allel Moncef and Amraoui Zakaria. " Conception de nouveau système d'antennes MIMO pour le standard 5G",Master's thesis, University 8 May 1945 - Guelma, 2021.

[13] Tassist Mohamed Houssam, Omari Abderrahmane, " Analyse et Optimisation de l'Accessibilité du Réseau LTE", Master's thesis, University Yahia Fares of Medea, 2020.

References

[14] Http://www.Difference entre OFDMA et SC-FDMA - Ahmed Roumane on ResearchGate.Com

[15] Bhushan.B, Sharma.S.K, Kumar.R, and Priyadarshini.I, (Eds.), " 5G and Beyond" Springer Tracts in Electrical and Electronics Engineering, Springer Nature Singapore Pte Ltd, 2023. ISBN: 978-981-99-3667-0 (print), ISBN: 978-981-99-3668-7 (eBook).

[16] Http://www.Introduction To 5G Technology – FasterCapital.Com

[17] Smruti Ranjan Dash, Sumit Ghosh, and Subhashree Ray, " Network Architecture for 5G Mobile Technology ", International Journal of Engineering Research & Technology (IJERT), Volume 3, Issue 25, Special Issue - NCRAEEE-2015 Conference Proceedings, ISSN: 2278-0181, 2015.

[18] Hadj Mekhnache Khadidja and Reguibi Racha, " Étude et Implémentation des Modulations Multiporteuses pour la 5G ", Master's thesis, University 8 Mai 1945 – Guelma, July 2019.

[19] Arcep, " 5G: Issues & Challenges", Report, March 2017, Regulatory Authority for Electronic Communications and Postal Services, French Republic.

[20] Http://www.Arming 5G Private Networks with Altran - Arm Community Blog.Com

[21] Menal Dahiya, " Need and Advantages of 5G Wireless Communication Systems" International Journal of Advance Research in Computer Science and Management Studies, Volume 5, Issue 6, June 2017, Pages 48–51.

[22] Majid H. Alsulami, " Challenges Facing the Implementation of 5G ", Journal of Ambient Intelligence and Humanized Computing, Volume 14, Pages 6213–6226, 2023.

[23] Http://www.5G Multiple Access Techniques - Telecom Trainer.Com

[24] Bendahmane Amira Meriem and Ghermoul Rania," Étude de méthodes de beamforming à maximisation du rapport signal sur bruit pour des systèmes FBMC ", Master's thesis, University Abou Bekr Belkaïd - Tlemcen, June 2018.

[25] Http://www.4G vs 5G - The Knowledge Academy Blog.Com

[26] R. Boukara and A. Tair, " Etude d'un système de transmission multi-porteuses", Graduation Thesis, University 8 May 1945 – Guelma, Faculty, Department of Electronics and Telecommunications, June 2021.

References

[27] Http://www.TechnologyUK.net, Digital Modulation Techniques (Part One), Telecommunications Principles.Com.

[28] L.Ghaib and Z.Ferrouani, "Modulation avancée pour les systèmes de télécommunications optiques", Master's thesis, , University Abou-Bekr Belkaid, Tlemcen, Algeria, Sep. 2020.

[29] Benani Mohamed Nadjib, and Benyahia Yasser, " Principe et simulation d'une transmission de type OFDM. ",Master's thesis, University Abdelhamid Ibn Badis de Mostaganem, 2017/2018.

[30] A. Benyahia and H. Mouaici, " La technique OFDM dans les communications satellitaires", Master's thesis, University Blida 1, Algeria, 2018.

[31] W. N. E. Nabli and A. Hallaci, " Etude et évaluation des performances d'un système de communication par lumière visible dans les applications Indoor", Master's thesis, Univercity 8 Mai 1945 – Guelma, Algeria, Jun. 2024.

[32] Albogame, M.M, and Elleithy, K. M, " Enhancement Orthogonal Frequency Division Multiplexing (OFDM) in Wireless Communication Network by Using PTS (Partial Transmit Sequences) Technique.", University of Bridgeport, CT, USA.

[33] Wu, Zhongshan, " MIMO-OFDM communication systems: channel estimation and wireless location.", LSU Doctoral Dissertations, 2605, 2006. Louisiana State University Scholarly Repository.

[34] Xiaomin Li, Hui Yang, Xin Ning, Guangchun Fu and Tao Xu. " Research on Synchronization Algorithms of OFDM Reliability Engineering.", Systems Engineering Procedia,_ vol. 2, 2011, pp. 278-286. Published by Elsevier B.V., Henan Institute of Science and Technology, Xinxiang, China. Open access under CC BY-NC-ND license.

[35] Http://www.ResearchGate, "OFDM Block Diagram," Fig. 1.Com

[36] Sravya.Y, Manasa.M, Jagadeesh.B, and Kumar, J. A, " Comprehensive Analysis of UFMC and OFDM for 5G Communications.", Bachelor of Engineering in Electronics & Communication Engineering, Department of ECE, Andhra University, Visakhapatnam, ANITS.

[37] Daoud, Khedidja " Simulation Comparative Des Techniques Fbmc Et Ofdm Pour Les Reseaux 5g.", Master's Thesis, University of Tlemcen, Faculty of Technology, Department of Telecommunications, June 2016.

[38] Http://www.ResearchGate, "Addition of a Guard Interval to an OFDM Signal," Fig. 3.

[39] Http://www.Google Search, " The Different Guard Intervals." Available.Com

[40] H. Ait Saadi and Y. Ait Bachir, " Réduction du Facteur de Crète d'un signal OFDM par la méthode PTS," M.S. thesis, Univercity Mouloud Mammeri de Tizi-Ouzou, Algeria, 2010.

[41] N. Chide, S. Deshmukh, P. B. Borole, and N. Chore, " An Overview of OFDM Variants and Their Applications", International Journal of Electronics Communication and Computer Engineering, vol. 4, no. 2, REACT-2013, pp. 1–6, 2013.

[42] N. Kerriche and M. Kedidah, " Comparaison de la modulation UFMC de la 5ème génération avec la modulation multi-porteuses OFDM ", Master's thesis, University SAAD DAHLAB de BLIDA, Algeria, 2018.

[43] azan Alkhlefat, Sevia M.Idrus and Farabi M. Iqbal, " Numerical analysis of UFMC and FBMC in wavelength conversion for radio over fiber systems using semiconductor optical amplifier ", Alexandria Engineering Journal, Volume 61, Issue 7, 2022, Pages 5371-5381,

[44] Y. Boumechache and F. Messaoudi," Etude de la communication sans fils multi porteuse UFMC ", Master's thesis, University Mohamed Larbi Ben M'hidi, Oum El Bouaghi, Algeria, 2021.

[45] AL QUDAMI Dheya and Alhaq Ahmed Hamood Abdullah,"Contribution au Développement de Formes d'Ondes Multi-porteuses et Techniques de Précodage Avancées pour les Systèmes Large MIMO", Doctoral Thesis, Université 8 Mai 1945 Guelma, Algeria, 2024.

[46] MATLAB (R2018a), The MathWorks Inc., 2018.

[47] Younes Boumechache and fares Messaoudi, " Étude de la communication sans fil multi porteuse UFMC," Master's thesis, University of Mohamed Larbi Ben M'hidi, Oum El Bouaghi, Algeria, 2021.

[48] MathWorks,"UFMC vs. OFDM Modulation" ,Communications Toolbox Documentation.

[49] C. An, B. Kim, and H.-G. Ryu,"Waveform Comparison and Nonlinearity Sensitivities of FBMC, UFMC and W-OFDM Systems", in Proceedings of NETCOM, NCS, WiMoNe, GRAPH-HOC, SPM, CSEIT - 2016, pp. 83–90, 2016. DOI: 10.5121/csit.2016.61508.

[50] A. A. Zerrouki and M. Taki Allah, "Etude et réalisation d'un système de reconnaissance de faces humaines par la méthode des faces propres," Master's thesis, Univercity Saad Dahlab de Blida, Algeria, 2016.

[51] P. V. Yellala and E. S. Rao,"Performance Analysis of Various Modulation Schemes for 5G Technology", National Journal of Antennas and Propagation, vol. 6, no. 2, pp. 33-41, Oct. 2024. doi: 10.31838/NJAP/06.02.05.

[52] Evaluation of Modulation Techniques for 5G Wireless Communication,"A Performance Comparison of OFDM, F-OFDM, UFMC and FBMC in terms of PSD, BER and SNR Metrics".

[53] M. R. Abou Yassin, H. Abdallah, H. Issa, and S. Abou Chahine," Universal Filtered Multi-Carrier Peak to Average Power Ratio Reduction", Journal of Communications, vol. 14, no. 3, pp. 243-248, Mar. 2019. doi: 10.12720/jcm.14.3.243-248.