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Abstract

The rapid evolution of wireless communication systems has increased the need for advanced waveform designs that can support higher data rates, lower latency, and better spectral efficiency. Among several candidates, Universal Filtered Multicarrier (UFMC) has emerged as a promising solution due to its ability to minimize out-of-band emissions and operate effectively in asynchronous and fragmented spectrum scenarios.

In this thesis, we evaluate UFMC in comparison to the conventional Orthogonal Frequency Division Multiplexing (OFDM), which has been the dominant waveform in 4G and 5G systems. The study includes a detailed simulation-based performance analysis using MATLAB. We investigate key performance metrics such as Power Spectral Density (PSD), Peak-to-Average Power Ratio (PAPR), Out-of-Band Emissions (OOBE), Bit Error Rate (BER), and Symbol Error Rate (SER) under various modulation schemes (4-QAM to 256-QAM) and a Rician fading channel. The Simulation results demonstrate that UFMC achieves better spectral containment, more stable PAPR behavior with high-order modulations, and improved OOBE suppression outperforming OFDM in several scenarios relevant to 5G and future 6G requirements. This work highlights UFMC's advantages and limitations and confirms its potential as a strong waveform candidate for next-generation wireless systems.

الملخص :

شهدت أنظمة الاتصالات اللاسلكية تطورًا سريعًا، مما زاد من الحاجة إلى تصاميم موجية متقدمة قادرة على دعم معدلات بيانات أعلى، وزمن كمون أقل، وكفاءة طيفية أفضل. ومن بين عدة موجات مرشحة، برزت تقنية المرشح متعدد الحوامل الشامل (UFMC) كحل واعد، بفضل قدرتها على تقليل الانبعاثات خارج النطاق الترددي والعمل بكفاءة في البيئات غير المتزامنة وذات الطيف المجزأ. في هذه المذكرة، نقوم بتقييم أداء UFMC مقارنةً بتقنية تقسيم التردد المتعامد (OFDM) التقليدية، والتي تُعد الموجة السائدة في أنظمة الجيل الرابع (G4) والخامس (G5). تتضمن الدراسة تحليلًا تفصيليًا قائمًا على محاكاة باستخدام برنامج MATLAB. ندرس من خلاله مؤشرات أداء رئيسية مثل: كثافة القدرة الطيفية (PSD)، نسبة الذروة إلى متوسط القدرة (PAPR)، الانبعاثات خارج النطاق (OOBE)، معدل خطأ البت (BER)، ومعدل خطأ الرموز (SER)، وذلك تحت تأثير مخططات التعديل المختلفة من QAM-4 حتى QAM-256، وضمن قناة Rician. تُظهر نتائج المحاكاة أن تقنية UFMC تحقق احتواءً طيفيًا أفضل، وسلوكًا أكثر استقرارًا لـ PAPR عند استخدام تعديلات مرتفعة الرتبة، بالإضافة إلى كفاءة أكبر في قمع الانبعاثات خارج النطاق، مما يمنحها تفوقًا على OFDM في عدة سيناريوهات مرتبطة بمتطلبات G5 وG6 المستقبلية. تُبرز هذه الدراسة مزايا وحدود UFMC، وتؤكد على إمكاناتها الكبيرة باعتبارها موجة مرشحة قوية للأنظمة اللاسلكية من الجيل القادم.

Résume :

L'évolution rapide des systèmes de communication sans fil a accru le besoin de conceptions d'ondes avancées capables de supporter des débits de données plus élevés, une latence plus faible et une meilleure efficacité spectrale. Parmi plusieurs candidates, l'Universal Filtered Multicarrier (UFMC) s'est imposée comme une solution prometteuse grâce à sa capacité à minimiser les émissions hors bande et à fonctionner efficacement dans des scénarios de spectre fragmenté et asynchrone. Dans ce mémoire, nous évaluons l'UFMC en comparaison avec l'Orthogonal Frequency Division Multiplexing (OFDM), qui a été la forme d'onde dominante dans les systèmes 4G et 5G. L'étude comprend une analyse de performance détaillée basée sur des simulations sous MATLAB. Nous étudions des indicateurs de performance clés tels que la Densité Spectrale de Puissance (PSD), le Rapport de Puissance Crête à Moyenne (PAPR), les Émissions Hors Bande (OOBE), le Taux d'Erreur Binaire (BER) et le Taux d'Erreur Symbole (SER) sous divers schémas de modulation (du 4-QAM au 256-QAM) et un canal à évanouissement de type Rician. Les résultats de simulation démontrent que l'UFMC offre un meilleur confinement spectral, un comportement PAPR plus stable avec des modulations d'ordre élevé, et une suppression améliorée des OOBE, surpassant l'OFDM dans plusieurs scénarios pertinents aux exigences de la 5G et des futures 6G. Ce travail met en évidence les avantages et les limitations de l'UFMC et confirme son potentiel en tant que candidate sérieuse pour les systèmes sans fil de prochaine génération.

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List of Abbreviations

Abbreviation	**Full Term**
1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
DAB	Digital Audio Broadcasting
dB	Decibel
DC	Dolph-Chebyshev
DFT	Discrete Fourier Transform
DVB-T	Digital Video Broadcasting - Terrestrial
EDGE	Enhanced Data for GSM Evolution
EP	Estimation Pilots
FBMC	Filter Bank Multi-Carrier
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
F-OFDM	Filtered Orthogonal Frequency Division Multiplexing
GFDM	Generalized Frequency Division Multiplexing
Gbps	Gigabits per second
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSPA	High-Speed Packet Access
HSPA+	Evolved High-Speed Packet Access
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IES/ISI	Inter Symbol Interference
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IoST	Internet of Space Things
IoT	Internet of Things
LTE	Long Term Evolution
LMDS	Local Multipoint Distribution Service
MIMO	Multiple Input Multiple Output

MMS	Multimedia Messaging Service
MMSE	Minimum Mean Square Error
mMTC	massive Machine Type Communications
NFV	Network Function Virtualization
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OOB/OOBE	Out-of-Band Emission
OCDM	Orthogonal Chirp Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
OQAM	Offset Quadrature Amplitude Modulation
OTFS	Orthogonal Time Frequency Space
OTSM	Orthogonal Time Sequence Multiplexing
P/S	Parallel to Serial
PAPR	Peak to Average Power Ratio
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surfaces
S/P	Serial to Parallel
SDN	Software Defined Networking
SER	Symbol Error Rate
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
THz	Terahertz
uMBB	Ultra-Mobile Broadband
UFMC	Universal Filtered Multi-Carrier
URLLC	Ultra-Reliable Low-Latency Communications
VLC	Visible Light Communications
WLAN	Wireless Local Area Network
ZF	Zero Forcing
ZP	Zero Padding

General introduction

General Introduction

The evolution of wireless communications has become one of the most transformative forces shaping today's digital society. It has progressed from voice-centric 1G systems to data-centric 4G capabilities, with each generation introducing large-scale technological advancements to meet growing user demands. With fifth-generation (5G) systems now deployed globally and initial research into sixth-generation (6G) technology underway, the focus has shifted toward achieving even higher data rates, ultra-low latencies, massive connectivity, and improved spectral efficiency. To meet these ambitious performance goals, innovation at the physical layer—particularly in waveform design—has become essential.

Waveforms define how data is transmitted over the radio interface and directly affect the efficiency, robustness, and adaptability of wireless systems in challenging environments. While Orthogonal Frequency Division Multiplexing (OFDM) has served as a core waveform in both 4G and 5G due to its simplicity and effectiveness in multipath propagation, it suffers from significant limitations, including high out-of-band emissions, sensitivity to synchronization errors, and a high Peak-to-Average Power Ratio (PAPR). These drawbacks reduce its suitability in increasingly dense and heterogeneous networks.

As a result, researchers have explored more efficient and flexible alternatives. Among these, the Universal Filtered Multicarrier (UFMC) waveform has emerged as a promising candidate. Unlike OFDM, which applies filtering at the whole-band level, UFMC introduces sub-band filtering, enabling better spectral localization and reducing reliance on cyclic prefixes.

These properties make UFMC particularly well-suited for asynchronous transmissions, fragmented spectrum access, and energy-constrained scenarios—conditions expected to become more prevalent in future wireless systems. In this thesis, we examine UFMC’s performance through a detailed simulation-based comparison with OFDM. Specifically, we evaluate Power Spectral Density (PSD) to assess spectral containment, Peak-to-Average Power Ratio (PAPR) for power efficiency, Out-of-Band Emissions (OOBE) to evaluate spectral leakage, and Bit Error Rate (BER) and Symbol Error Rate (SER) to measure robustness across varying modulation orders (4-QAM to 256-QAM).

These metrics provide a comprehensive analysis of the performance trade-offs between UFMC and OFDM in the context of next-generation wireless communication requirements.

➢ We have split this thesis into three chapters:

- **Chapter 1** provides an overview of the evolution of mobile networks from 1G to 6G and introduces enabling technologies such as MIMO, millimeter wave, and virtualization.
- **Chapter 2** covers the theoretical foundations of OFDM and UFMC, discussing their

principles, advantages, limitations, and applications in modern communication systems.

- **Chapter 3** presents a comparative evaluation based on MATLAB simulations,

highlighting the performance differences between OFDM and UFMC across various modulation schemes and channel scenarios.

Chapter 1:

Mobile Network Evolution and Waveform Development

1.1 Introduction

Mobile telephony has been under extremely dramatic and continuous development in the past few years, and all this as a direct answer to customers' growing demand for high-speed, reliable, and high-quality wireless connections. Each new generation of mobile telephony has to overcome some weaknesses of earlier generations while introducing entirely new features meeting ever-stronger user demands. From simple voice services in the early first generation (1G) to the advent of broadband internet with 4G [1] [2], mobile communication systems have transformed beyond recognition the way we live, work, and interact with the world around us. Throughout this chapter, we will outline a detailed history of the development of mobile telecommunication systems from the initial to the promising 5G and upcoming 6G standards. In addition, we will introduce the modulation and waveform techniques that have played a key role in enabling these systems, with an emphasis on those designed for application in 5G and 6G networks. This chapter introduces a framework to address knowledge on the key concepts and technology shifts that power the future of wireless communication.

1.2 Evolution of Mobile Network Generations to 4G

We are now seeing the implementation and deployment of fifth-generation (5G) networks, and they aim to not only better mobile broadband service but also make provision for novel forms of application such as Internet of Things (IoT), autonomous vehicles, smart cities, and remote operations.

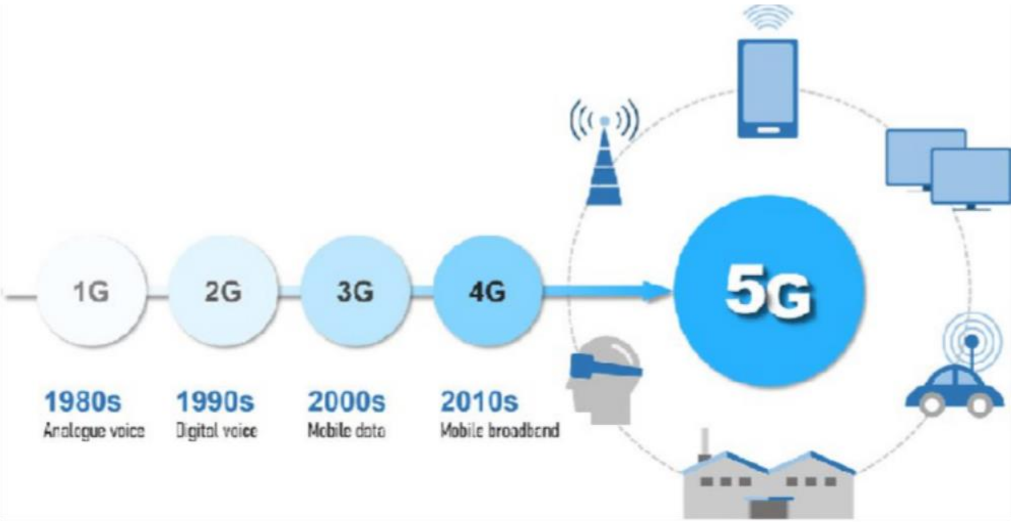


Figure 0.1: ***Evolution of mobile networks***

They call for ultra-high data rates, ultra-low delay, and quality connectivity to accommodate enormous numbers of devices and heavily mobile locations. Before giving an insight on 5G, let's start by reviewing the development of the telecommunication generations starting from the first one generation. [1] [3]

1.2.1 The First Generation (1G)

The first generation, known as 1G, appeared in the late 1970s and represented the earliest form of mobile communication systems. It was exclusively based on analog technology, providing voice-only services using Frequency Division Multiple Access (FDMA) to allocate different frequency bands for individual users.

Despite being a major step forward in mobile telephony, 1G networks suffered from several shortcomings. The quality of calls was often poor, prone to interference, and susceptible to eavesdropping due to the absence of encryption. Moreover, system capacity was limited, and operational costs were high, making these services accessible to a limited number of subscribers. The shortcomings of 1G systems made it necessary to develop a more advanced, digital-based solution. [1] [2]

1.2.2 The Second Generation (2G)

The second generation, or 2G, was launched around 1990 and introduced digital technology to mobile communications. This transition significantly improved the security and efficiency of voice services by implementing encryption mechanisms. The most prominent advancement was the introduction of Short Message Service (SMS) and later Multimedia Messaging Service (MMS), allowing users to exchange text and simple media messages.

2G systems initially supported data transmission rates up to 9.6 kbps. These networks later evolved through intermediate technologies:

GPRS (2.5G), which increased data speeds up to 171.2 kbps, enabling basic internet services such as email and web browsing.

EDGE (2.75G) further enhanced data transfer rates to 384 kbps, providing better support for mobile data applications.

Overall, 2G established a more secure, reliable, and efficient platform for mobile communication while introducing essential data services beyond voice. [1] [2]

1.2.3 The Third Generation (3G)

The third generation, known as 3G, emerged in the early 2000s and marked a significant milestone by offering high-speed data transmission alongside traditional voice services. With the adoption of technologies like Wideband Code Division Multiple Access (WCDMA), 3G networks provided initial data rates from 144 kbps up to 2 Mbps, depending on user mobility and network coverage conditions. [1]

3G enabled advanced mobile services such as video calls, mobile internet browsing, video streaming, and mobile TV. Subsequent enhancements included:

- HSPA (High-Speed Packet Access), achieving speeds up to 14.4 Mbps
- HSPA+ (Evolved HSPA), capable of theoretical peaks of 21 Mbps
- Dual-Carrier HSPA+, which could reach up to 42 Mbps

These developments made it possible for users to access rich multimedia services on mobile devices with considerably improved speed and performance. [1] [2]

1.2.4 The Fourth Generation (4G)

The fourth generation, or 4G, began to roll out in the early 2010s, aiming to provide very high-speed mobile internet and support for bandwidth-intensive applications. Based on Long Term Evolution (LTE) technology, 4G networks offered download speeds up to 150 Mbps, while LTE-Advanced pushed this further to 1 Gbps. [1]

4G dramatically transformed the user experience by enabling HD video streaming, large file downloads, high-quality video conferencing, and online gaming on mobile devices. It also introduced support for advanced network features such as Multiple-Input Multiple-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM), enhancing spectral efficiency and connection reliability.

The enhanced capacity and speed of 4G networks laid the groundwork for the development of the fifth generation, which would further address growing data demands and the emerging Internet of Things (IoT) ecosystem. [1] [4]

1.3 The Fifth Generation (5G) Mobile Network

With 5G rolling out globally, researchers and engineers have already begun to define the principles of sixth-generation (6G) networks. Next-generation 6G networks will aim to address problems that 5G did not and facilitate the ever-growing needs of smart systems, virtual reality and augmented reality services, and global communication networks. All this will be spearheaded by revolutionary technologies like Artificial Intelligence (AI), terahertz frequencies, and extremely dynamic waveform techniques.

Figure 1.2: The fifth generation 5G

1.3.1 Overview of the Fifth Generation

The fifth-generation wireless network, which is also called 5G, is a revolutionary technology in wireless communications. It was not only developed to improve the existing mobile broadband services but to support new forms of applications such as the Internet of Things (IoT), autonomous vehicles, smart cities, and remote health care services. These applications require extremely high data rates, ultra-low latency, and an extremely high density of connected devices. Unlike previous generations, 5G offers a new vision of wireless networks where heterogeneous services are integrated through a single infrastructure. These include high-speed multimedia services through eMBB, IoT billions of devices support through mMTC, and ultra-reliable and low-latency communications (URLLC) to serve mission- critical processes such as industrial automation and remote surgery.

In technology, 5G leverages different advances:

- Use of higher frequency bands, especially millimeter waves, to offer higher bandwidth and greater capacity for data.
- Massive MIMO (Multiple Input Multiple Output) technology to increase spectral efficiency tremendously by transmitting and receiving scores of antennas.
- New-generation waveform technologies like a refined OFDM and its variants, customized for 5G's different needs.
- Virtualized and software-based network topologies to improve scalability, flexibility, and power efficiency.
- In addition, 5G networks are characterized by their ability to accommodate densified small cells and beamforming techniques in order to supply cover and improve signal quality in densely populated urban areas.

Therefore, 5G is going to revolutionize communication experiences through offering data rates of more than 10 Gbps, latency of below 1 millisecond, and the ability to connect up to one million devices per square kilometer. [1] [5]

1.3.2 Performance Indicators

The International Telecommunication Union (ITU) has defined eight key performance indicators (KPIs) to quantify and evaluate the performance characteristics of the IMT-2020 system within 5G networks. In addition, five new indicators have been proposed and are still under study, focusing on reliability, mobility interruption time, bandwidth, and spectral efficiency. [1] [5]

The eight primary KPIs include:

- Peak data rate
- User-experienced data rate
- Latency
- Mobility
- Connection density
- Network energy efficiency
- Spectrum efficiency
- Reliability

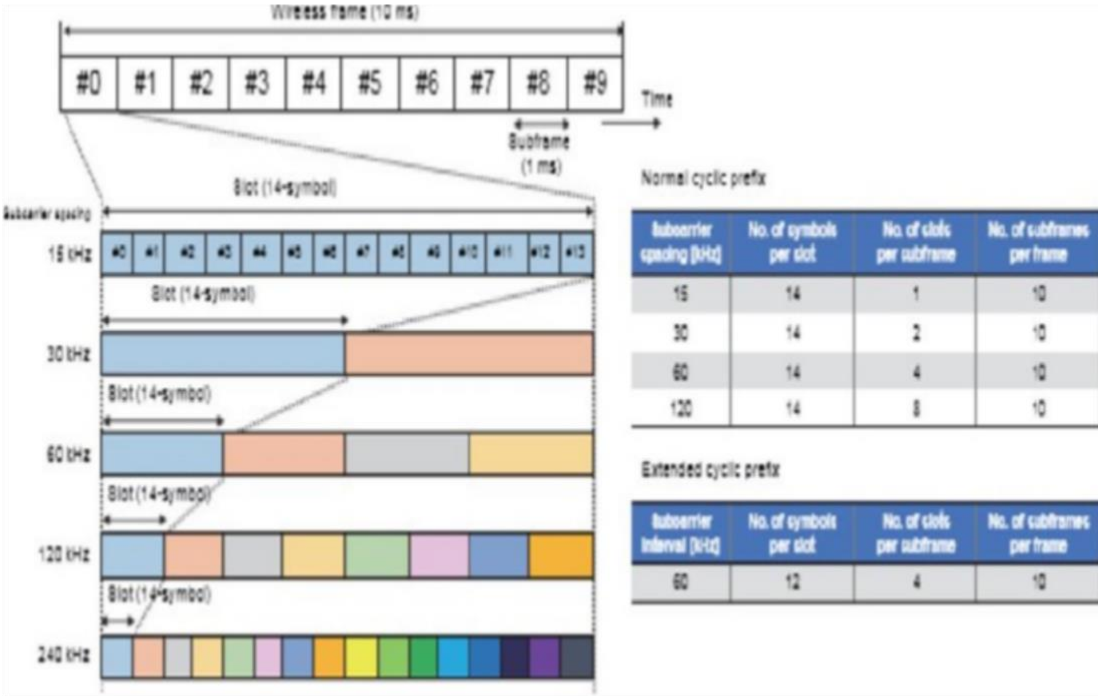
The table 1.1 gives a fair comparison of the eight performance indicators between 4G and 5G.

KPI	4G	5G
Peak Data Rate	1 Gbps	20 Gbps
User-Experienced Data Rate	10 Mbps	100 Mbps
Latency	10 ms	1 ms
Mobility	350 km/h	500 km/h
Connection Density	100,000 devices/km²	1,000,000 devices/km²
Energy Efficiency	1x	100x
Spectrum Efficiency	1x	3x
Reliability	99.99%	99.999%

Table 1.1: Comparison of the eight performance indicators between 4G and 5G

1.3.3 Frame Structure

In 5G New Radio (NR), both downlink (DL) and uplink (UL) transmissions are organized into frames of 10 milliseconds. Each frame is divided into 10 sub-frames, each lasting 1 ms. Unlike LTE, which uses a fixed subcarrier spacing of 15 kHz, 5G NR supports multiple subcarrier spacing, ranging from 15 kHz up to 240 kHz, to better adapt to different deployment scenarios. [5] [6]



Normal cyclic prefix

Subcarrier spacing (kHz)	No. of symbols per slot	No. of slots per subframe	No. of subframes per frame
15	14	1	10
30	14	2	10
60	14	4	10
120	14	8	10

Extended cyclic prefix

Subcarrier interval (kHz)	No. of symbols per slot	No. of slots per subframe	No. of subframes per frame
60	12	4	10

Figure 1.3: Frame organization in 5G-NR

1.3.3.1 NR Resource Block Structure

A resource block (RB) in 5G NR consists of 12 subcarriers in the frequency domain and typically 14 OFDM symbols in the time domain. In LTE, the bandwidth of a resource block was fixed at 180 kHz, but in NR, it varies according to the subcarrier spacing used. [6]

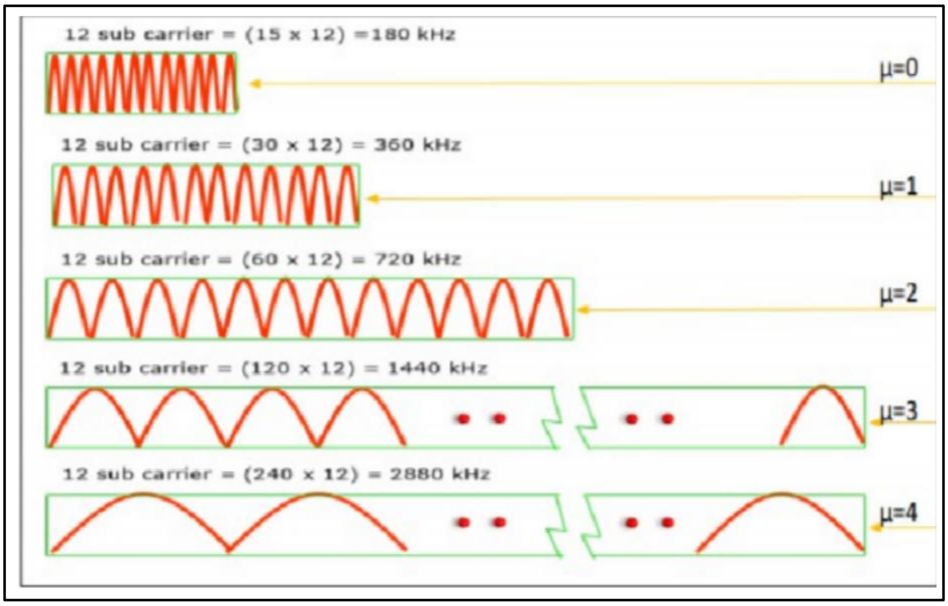


Figure 1.4: Subcarrier spacing for each numerology

1.3.3.2 5G NR Channel Bandwidth

5G NR supports very large channel bandwidths, especially in millimeter-wave bands. For frequencies below 6 GHz, the channel bandwidth reaches up to 100 MHz, and in mm Wave ranges, it extends to 400 MHz or more. Additionally, bandwidth efficiency has been improved, achieving up to 90% compared to LTE, where about 10% was reserved as guard bands. [5] [6]

The channel bandwidth can be calculated using the following formula :

$$CBW = N_{\{RB\}} \times N_{\{SP\}} \times \Delta f + 2 \times BG \qquad (1.1)$$

- CBW = Channel bandwidth
- $N_{\{RB\}}$ = Number of resource blocks
- $N_{\{SP\}}$= Number of subcarriers (typically 12)
- Δf = Subcarrier spacing
- BG = Guard band

An illustrative example of channel bandwidth and resource block allocation is given as following, in figure I.5.

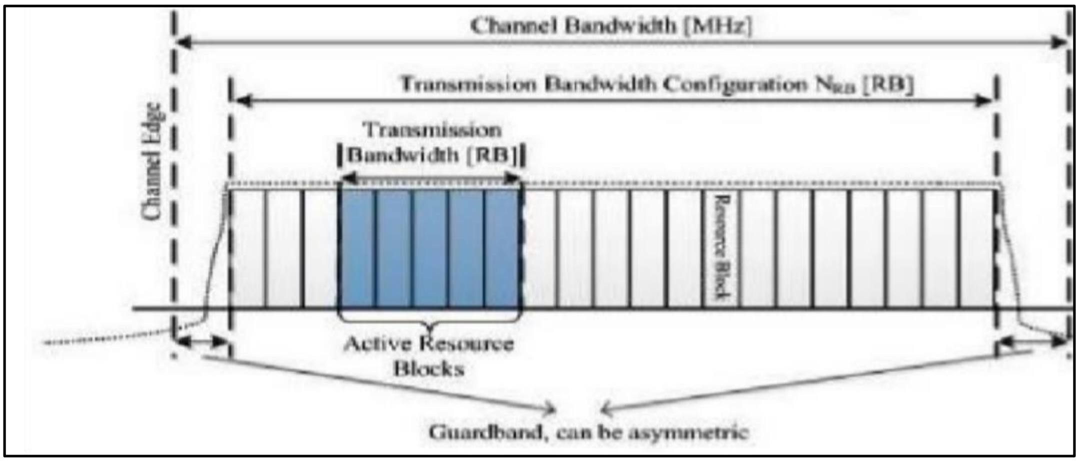


Figure 1.5: 5G channel bandwidth and resource block allocation

1.3.4 Network Architecture

The fifth-generation (5G) wireless network offers a new, more flexible, and very modular architecture that can deal with the performance demands of new applications and services. It provides for smooth support of enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC).

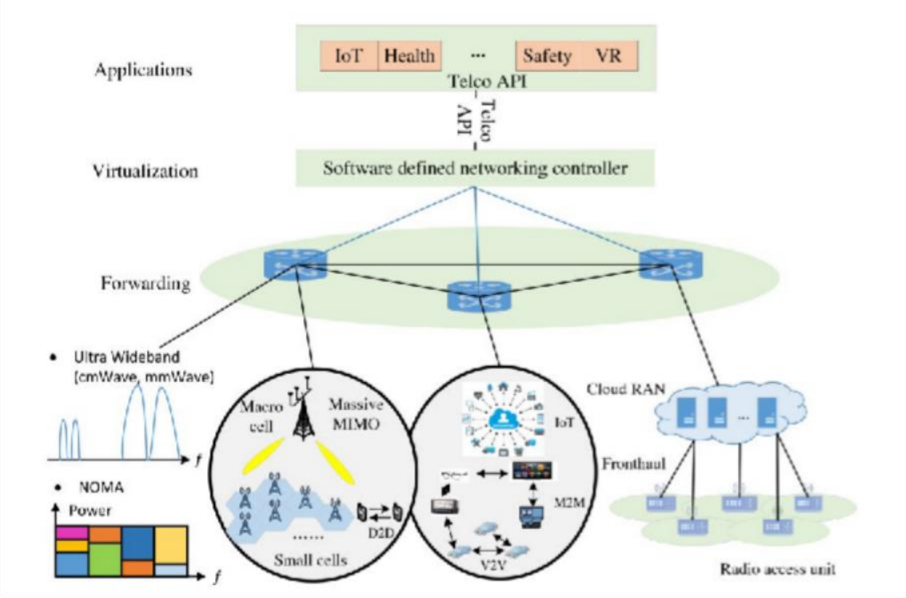


Figure 1.6: 5G network architecture with application, forwarding, and virtualization layers.

The overall architecture is organized in three horizontal layers:

- **Application Layer:** It allows for a broad range of services including IoT connectivity, high-definition video streaming, virtual and augmented reality, as well as real-time control services. It facilitates availability and reliability for a variety of applications.
- **Forwarding Layer:** Used as a control and switching domain, this layer handles routing, handling, and forwarding of data streams across the network. It integrates next-generation technologies such as Network Function Virtualization (NFV) and Software-Defined Networking (SDN) to enable dynamic and programmable network management.
- **Virtualization Layer:** This layer is placed at the infrastructure level and provides virtualized computing, storage, and radio resources. It optimizes resource usage and scalability by dynamically provisioning resources to handle changing requirements of different services.

Moreover, 5G architecture embraces sophisticated features such as Cloud- Radio Access Network (Cloud-RAN), where baseband processing functions are centralized in the cloud, ensuring more flexibility and centralized control. With Multi-Access Edge Computing (MEC) integrated, this approach reduces latency by processing data closer to end-users, which is crucial for mission-critical applications and real-time solutions.

Support for densified small cell installations and massive MIMO configurations is the other central element of 5G architecture. Such aspects provide increased network capacity and coverage, particularly in high-density city environments and indoor spaces. In addition, beamforming technologies dynamically beam out radio signals to specific users, reducing interference and increasing spectral efficiency.

This new, service-based, and virtualized architecture turns 5G into a highly versatile platform with the ability to respond to the rising and complex demands of future wireless communication services. [1] [7]

1.3.4.1 5G Applications

The fifth-generation (5G) network allows multiple types of application beyond traditional mobile broadband. The technology creates an instant, interconnected, multidimensional information ecosystem incorporating individuals and equipment as a coherent whole at all times and from everywhere. Several new and novel use cases are supported by the 5G network infrastructure using very high rates of data transmission, ultra-low latency, and high-density devices.

One of the most significant applications is ultra-high-definition (UHD) video streaming, one of the top services in 5G networks. This includes new applications like multi-view video streaming and even holographic communications. Furthermore, the combination of a higher available bandwidth and high reliability creates new services like remote robot control and critical Internet of Things (IoT) applications for healthcare, transportation, and smart cities.

Figure 1.7: The Top 5G Use Cases

The architecture allows uninterrupted connectivity across a wide spectrum of devices and applications, providing support for unified machine-to-machine (M2M) communication, large IoT deployments, and real-time control applications. This approach aims to realize the dream of a “global Wi-Fi zone” where everything is accessible through a mere push of a button, and every object is connected to a network. [5]

Ultimately, 5G is positioning the stage for interactive and immersive user experiences that will fundamentally transform the way people engage with digital content and control connected spaces in real time.

1.3.4.2 Future Services

The fifth generation (5G) network does not only provide fast data speeds and low-latency communications, but it also excels in introducing new and innovative services. With its advanced and differentiated infrastructure capabilities, 5G is well positioned to deliver stable, immersive, and high-quality user experiences.

One of the most forward-looking services is ultra-high-definition (UHD) video streaming, which is expected to become one of the leading services in the near future. This includes sophisticated forms such as multi-view video streaming and even holographic communication, offering virtual experiences far beyond conventional video.

Moreover, the massive reliability and ample bandwidth provided by 5G unlock new possibilities for remote robot control services and mission-critical Internet of Things (IoT) applications. These are particularly significant for sectors like smart healthcare, autonomous driving, and industrial automation. [5]

In addition, 5G services will create an uninterrupted, multidimensional information environment essentially a “global Wi-Fi zone” where information becomes instantly accessible and all systems and devices remain seamlessly interconnected. This hyper-connected world enables continuous, intelligent, and interactive experiences, reshaping how users engage with digital content and manage connected spaces.

These services form the foundation for the realization of a future digital society, enabling entirely new vertical industries such as smart cities, telemedicine, connected factories, and immersive interactive games. [5]

1.3.5 Enabling Technologies

1.3.5.1 Virtualization and Cloud-RAN

The fifth generation (5G) mobile network integrates advanced technologies such as Network Function Virtualization (NFV) and Software Defined Networking (SDN) to offer unprecedented flexibility and efficiency in network management. These concepts redefine network infrastructure by detaching traditional hardware-based operations and transforming them into software-driven virtual functions.

NFV allows network services, traditionally run on dedicated hardware, to operate on virtualized, commercial off-the-shelf servers. This transition not only reduces hardware dependency but also facilitates rapid deployment of services and dynamic adaptation to traffic demands. Its flexibility provides network operators with the ability to scale resources instantly and integrate new services without significant infrastructure modifications.

SDN complements NFV by centralizing network control through software, separating it from the data forwarding function. This logical separation enables dynamic network management, intelligent routing, real-time load balancing, and automated configuration adjustments. The synergy between SDN and NFV forms the backbone of modern, agile, and programmable 5G infrastructures.

An essential architectural advancement within this framework is the implementation of Cloud-Radio Access Networks (Cloud-RAN). Traditionally, baseband processing units were physically located at each base station. In Cloud- RAN architectures, these units are centralized and virtualized within a cloud infrastructure. Connected to distributed radio heads via high-speed optical links, this centralization improves network visibility, optimizes interference management, and enhances coordination between base stations.

This system architecture paves the way for smarter, software-managed, and service-centric networks, capable of supporting advanced applications like real-time video analytics, autonomous vehicle networks, and mission-critical IoT systems, all requiring ultra-low latency and high reliability. [7]

1.3.5.2 Millimeter Waves

The fifth generation (5G) radio technology is defined by the use of millimeter waves (mm-Waves), in frequency bands between 30 and 300 GHz. These frequencies offer a rich source of spectrum—almost 200 times larger than the collective low- frequency spectrum available in legacy mobile systems.

Among the most important advantages of mm-Waves is their ability to provide extremely high data rates and ultra-low latency. They are therefore ideal for data- intensive services such as ultra-high-definition (UHD) video streaming, real-time industrial control, and virtual reality applications. In the United States, five mm Wave bands are allocated for 5G use, combining both licensed and unlicensed spectrums. Of special importance is the LMDS band (27.5–31.5 GHz) and the E-band, which comprises several sub-bands totaling 12.9 GHz, enabling very high throughput communications.

However, these high frequencies also introduce certain propagation issues. mm Waves incur significant path loss, are highly susceptible to atmospheric absorption by water vapor and oxygen, and struggle to penetrate walls and heavy vegetation. These limitations constrain their effective range to a few hundred meters and necessitate intensive small cell deployments to ensure reliable coverage indoors and in dense urban environments.

An important operational advantage of mm-Waves lies in their potential for high-frequency reuse. As their signals attenuate rapidly over distance and are easily blocked by obstacles, it becomes feasible to reuse the same frequencies within neighboring cell clusters without interference. This characteristic greatly improves spectral efficiency in dense metropolitan deployments.

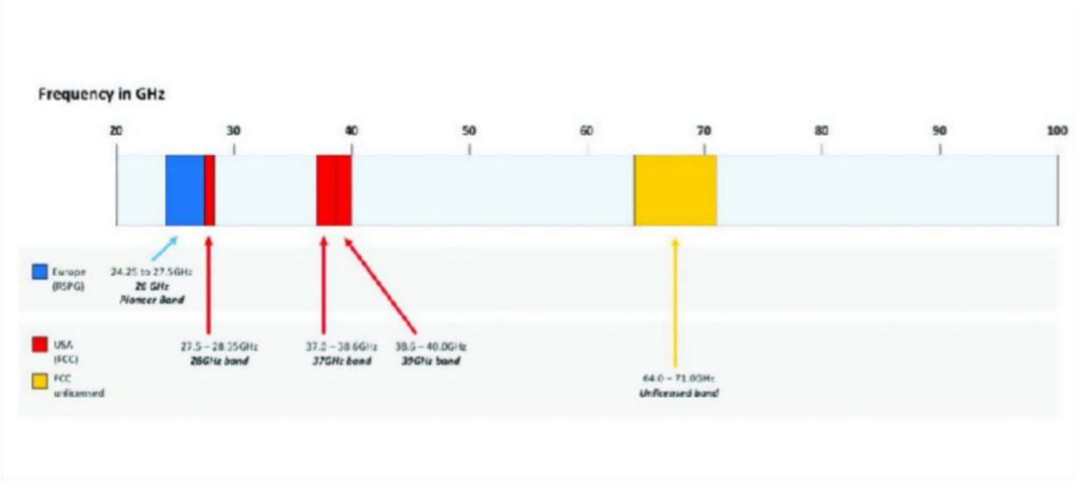


Figure 1.8: Examples of Millimeter Wave Bands for 5G Applications

In general, although mm-Waves present substantial technical and infrastructural challenges, their unmatched bandwidth and high data rate capacities make them essential for achieving the ambitious performance objectives set for 5G networks. [1] [5]

1.3.5.3 Limitations of Millimeter Waves

While there are numerous advantages that the millimeter waves (mm-Waves) offer for fifth-generation (5G) networks, high-frequency signals also have a number of limitations which pose operational as well as economic issues.

One of the primary issues is signal attenuation due to atmospheric absorption. Certain frequencies within the mm Wave band are highly prone to absorption by atmospheric gases. For instance, 22 and 183 GHz frequencies are absorbed by water vapor, whereas 60 and 118 GHz are absorbed by oxygen molecules. This phenomenon results in severe signal quality degradation, particularly in humid conditions or during rain.

Another crucial limitation is that mm-Waves are unable to penetrate solid objects such as walls, concrete buildings, and even dense vegetation. Unlike lower frequency bands of previous generations, mm Waves can easily be blocked by physical barriers such as these, greatly reducing their effective distance of propagation to a few hundred meters.

This factor requires extensively deployed small cells and additional infrastructure within buildings in order to provide uniform coverage.

Additionally, mm-Waves are sensitive to the line-of-sight (LOS) environment. Even slight blocking of the line of sight between transmitter and receiver will cause a serious signal reduction or loss of connection. To avoid this, highly complex beamforming technologies and adaptive path handling need to be used in order to maintain constant links, in particular, under urban conditions as well as complicated indoor scenarios.

In addition, the expense of high deployment related to the extra number of small cells and antennas required to go around these confines remains a prominent economic consideration in network providers. However, the limitation is also partly offset by the reality that frequencies can be reused significantly in limited geographical environments due to rapid attenuation of signal with distance, enhancing spectral efficiency in the thick urban environment. [1]

1.3.5.4 Full-Duplex Communications

The Full-Duplex communication concept in 5G marks a fundamental evolution over traditional half-duplex systems. In previous generations, uplink and downlink transmissions were separated either by time (TDD — Time Division Duplexing) or (FDD — Frequency Division Duplexing). This required dedicated channels for sending and receiving data, leading to spectrum inefficiency and increased complexity. In contrast, 5G introduces Full-Duplex operation, which allows for the simultaneous transmission and reception of data over the same frequency band, at the same time, and on the same channel. This dramatically enhances spectral efficiency, reduces latency, and simplifies network architecture.

Full-Duplex systems address the challenge of self-interference, the phenomenon where a transmitter’s own signal interferes with its receiver through sophisticated interference cancellation mechanisms. Tests have demonstrated more than 113 dB of self-interference cancellation, resulting in a 90% increase in throughput in practical scenarios.

The implementation of Full-Duplex technology brings several advantages:

- Enhanced spectral efficiency
- Simpler filtering requirements
- New opportunities for relay-based systems
- Improved interference coordination, especially through active cancellation techniques
- Better resource utilization in dense urban networks

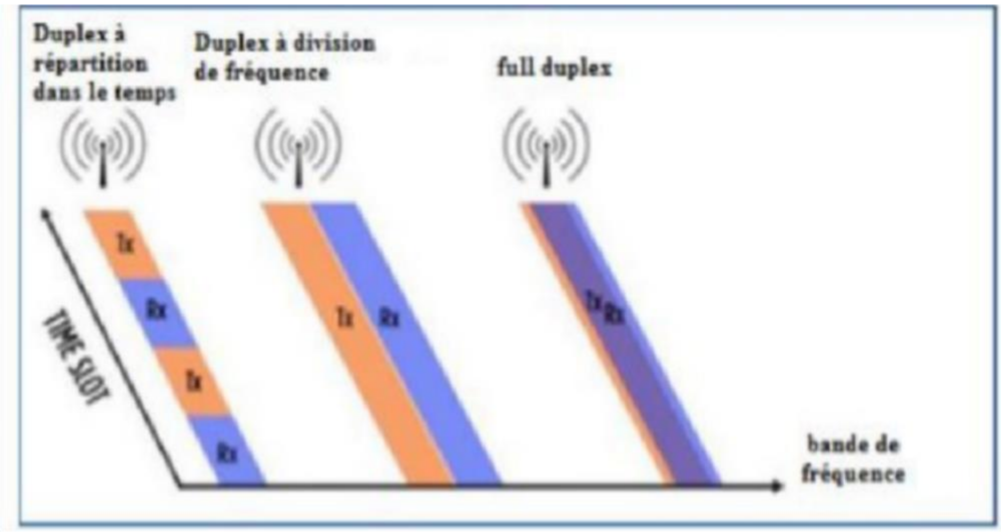


Figure 1.9: Full Duplex technology

This integral duplexing system has the potential to double wireless network capacity at the physical layer. Conceptually, it enables two-way simultaneous conversations much like two people talking and listening at the same time—cutting conversation time in half and starting the next exchange sooner. [1] [5]

1.3.5.5 Massive MIMO

Massive MIMO (Multiple-Input Multiple-Output) is one of the cornerstone technologies of 5G networks and a major leap from the multi-antenna systems deployed in earlier generations. This approach involves equipping base stations with a very large number of antennas-ranging from dozens to hundreds or even thousands- that operate coherently and adaptively.

The principal objective of Massive MIMO is to concentrate signal transmission and reception energy in highly localized spatial regions, significantly enhancing throughput and energy efficiency, particularly in scenarios with a large number of simultaneous users. Originally designed for Time Division Duplexing (TDD) systems, it can also be adapted for Frequency Division Duplexing (FDD) configurations. [5]

Key advantages of Massive MIMO include:

- Substantial spectral efficiency improvements: By directing narrow beams precisely to individual users, Massive MIMO enables up to 10 times greater spectral efficiency compared to conventional 4G MIMO setups.

- Enhanced energy efficiency: The ability to focus energy only where needed reduces power consumption and enhances overall system sustainability.
- Precise user tracking: Narrow beams facilitate accurate tracking of moving users, maintaining high signal quality and minimizing interference.

Moreover, in combination with beamforming technologies, Massive MIMO helps mitigate signal attenuation at high frequencies and reduces intercell interference through directional signal transmission. It not only increases network capacity but also improves link reliability and coverage quality in dense urban areas.

As future mobile networks migrate to even higher frequency bands such as terahertz ranges in 6G, Massive MIMO will remain a vital technology, potentially integrating over 10,000 antenna elements per base station for ultra-narrow beams and even more efficient high-capacity communication links.

1.3.5.6 Limitations of 5G

Despite the revolutionary potentials of 5G, several underlying limitations have surfaced, particularly with needs for high-level connectivity still escalating. Among the most obvious challenges is the low spectral efficiency of 5G systems in ultra-dense scenarios. Although 5G runs in both sub-6 GHz and mm-Wave frequencies, its capacity to efficiently manage spectrum in the presence of very high network loads remains limited. [8]

The other critical issue is latency, which although significantly lower than in previous generations, does not yet match the requirements of real-time applications such as holographic communication or remote robotic surgery. The one-millisecond standard achieved by 5G may still be too slow for certain industrial and medical applications.

In addition, 5G still suffers from energy inefficiency and sustainability. Cell densification and adding new hardware (e.g., Massive MIMO antennas) result in a drastic

increase in power consumption. Additionally, 5G network management systems are still not autonomous and lack native support for artificial intelligence-based decision-making.

There are also rural and remote area coverage gaps. Although 5G aims at massive connectivity through mMTC (massive Machine Type Communications), the deployment of dense networks in areas with low population density is often not economically viable.

Security-wise, 5G networks are more encrypted and authenticated, but still rely on centralized architectures, which can become bottlenecks or single points of failure. Emerging use cases in critical infrastructures demand end-to-end trust, privacy, and zero-trust architectures, pushing the boundaries of current 5G systems in secure design.

These limits provide a compelling case for R&D on sixth-generation wireless systems to not only overcome these limitations but to enable a new generation of intelligent, secure, and sustainable applications spanning the physical and cyber spaces. [8]

Feature	4G	5G	6G
Max Data Rate	1 Gbps	10 Gbps	>1 Tbps
Latency	~50 ms	<1 ms	<0.1 ms
Frequency Range	Sub-6 GHz	Sub-6 GHz, mmWave	Sub-THz, THz
AI Integration	No	Partial	Full
Energy Efficiency	Moderate	Improved	Optimized

Table 1.2: Comparison of 4G, 5G, and 6G

1.4 Sixth Generation (6G)

The future sixth-generation (6G) wireless telecommunication system will transform the digital era far beyond the reach of current 5G technology. It will be able to meet the exponentially increasing needs for data rate, latency, connectivity, and capacity required by future services like holographic communication, the Internet of Bio-Nano-Things, and highly autonomous vehicles.

6G is expected to operate on terahertz (THz) frequency bands, offering terabits- per-second (Tbps) data rates, 0.1 ms latency, and the ability to support over 10 million devices per square kilometer. It will enable applications that range from space communications to ultra-reliable, real-time control systems, including remote surgeries and tactile internet services.

Figure 1.11: 6G LOGO

Significant expected use cases for 6G include:

- Ultra-mobile broadband (uMBB) for ubiquitous global coverage.
- Ultra-reliable low-latency broadband communications (ULBC) for holographic-type services and immersive multi-sense experiences.
- Massive ultra-reliable low-latency communication (mULC) combining the features of URLLC and mMTC to support industrial and vertical markets.

6G will feature a distinctive, cell-free, multi-layered architecture composed of terrestrial, aerial, maritime, and satellite components to provide seamless global connectivity. This structure will extend reliable service to smart cities, rural and remote areas, deep-sea environments, and space communications.

Technologies expected to mature within 6G networks include:

- THz communications
- Visible Light Communications (VLC)
- Reconfigurable Intelligent Surfaces (RIS)
- Quantum communications
- AI-native network management
- Integrated space-air-ground-sea networks

1.4.1 Vision and Objectives

The sixth generation (6G) of wireless communication systems is expected to represent a remarkable evolution over the current 5G technology. With the growing demand for faster, more reliable, and highly efficient networks, the vision for 6G is to deliver communication systems that are capable of achieving unprecedented performance metrics. This includes offering peak data rates of up to 1 terabit per second (Tbps), reducing latency to less than 1 millisecond, and supporting a massive number of simultaneous connections in highly dense and dynamic environments.

6G networks are designed to go beyond traditional improvements in speed and capacity. The aim is to create a fully intelligent, interconnected infrastructure where artificial intelligence and machine learning are embedded at the core of network operation. These technologies will enable real-time, automated decision-making, self- optimization, and predictive management of network resources.

Another essential objective for 6G is to extend coverage and accessibility to regions and scenarios currently underserved by existing technologies. The integration of satellite-based communication systems and low Earth orbit (LEO) constellations will help achieve comprehensive global coverage, ensuring connectivity for rural, remote, and maritime environments, as well as for air and space applications.

In addition to enhanced connectivity, 6G aspires to support a wide range of advanced applications. These include immersive services such as holographic communications, augmented reality (AR), virtual reality (VR), and digital twin systems, which will require extremely high data rates and ultra-low latency to function effectively. Furthermore, the network is expected to be sustainable, with energy-efficient designs and environmentally friendly technologies forming a core part of its architecture.

The evolution towards 6G is not only about improving existing services but also about enabling entirely new capabilities that will reshape industries and daily life, bridging the gap between the digital and physical worlds. [1] [8] [9]

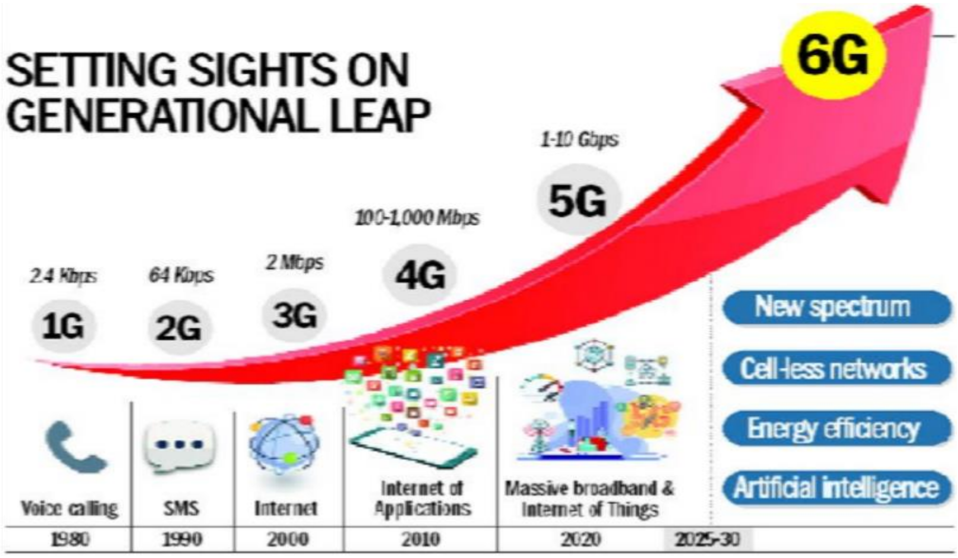


Figure 1.12: 6G vs Other generations

1.4.2 Key Applications and Features

The emergence of 6G wireless communication systems is necessitated by the demand for increasing demands for highly advanced applications beyond what existing networks can offer. The future applications will transform many industries through the establishment of new avenues for communication, automation, and smart services.

Among the most promising applications of 6G is the development of immersive and interactive technologies. Technologies such as holographic communication, digital twin worlds, and fully integrated extended reality (XR) systems will employ ultra-high data rates and extremely low latency to deliver smooth, real-time experience. These are going to transform sectors such as education, remote teamwork, entertainment, and industrial design. [8]

Simultaneously, autonomous vehicle networks and drone swarms will benefit from the low-latency, high-reliability characteristics of 6G. These systems require real- time, persistent data exchange to enable secure navigation, distributed control, and timely reaction in dynamic environments. Large-scale deployment of such technologies is expected to enhance transportation infrastructures, logistics, and emergency response.

Industrial automation is another area of utmost significance for 6G integration. Intelligent production lines and smart factories will leverage 6G to facilitate high-end machine-to-machine communication, predictive maintenance, and remote control of complex operations. This will enable improved efficiency, reduced downtime, and the development of highly flexible manufacturing processes. Further, 6G aims to address the age-old problem of connectivity gaps across the world, particularly in rural and remote regions. With the combination of satellite- based networks and Internet of Space Things (IoST), 6G networks will offer stable broadband coverage to locations that have been inaccessible so far, facilitating services such as telemedicine, online education, and disaster response.

The health sector shall also undergo significant changes through the utilization of 6G. Tele-surgery, patient monitoring in real time, and AI-based diagnostics will become more possible, offering improved access to healthcare and improving patient outcomes, especially in remote or intensive care conditions.

Furthermore, security and privacy will gain new aspects in 6G networks. Networks will increasingly adopt distributed, intelligent security architectures that actively counter threats and protect confidential data in heterogeneous, interconnected environments.

In summary, the anticipated use cases and functionality of 6G will reshape the interaction between digital systems and human activity through innovative services that seamlessly integrate the virtual and physical realms. [8] [9]. The following table summarizes the key performance metrics and technological advancements introduced in each wireless generation:

Feature	1G (1980s)	2G (1990s)	3G (2000s)	4G (2010s)	5G (2020s)	6G (2030s)
Technology	Analog	Digital	Packet-Switched	IP-Based	AI-Assisted	AI-Driven
Data Rate	2.4 kbps	64-200 kbps	Up to 2 Mbps	1 Gbps	10 Gbps	1 Tbps+
Latency	High (>100ms)	Moderate	~50ms	~10ms	<1ms	~0.1ms
Spectrum	<1 GHz	<2 GHz	2-3 GHz	3-6 GHz	24-100 GHz (mmWave)	0.1-10 THz (THz Band)
Key Features	Voice Calls	SMS, Encrypted Voice	Mobile Broadband	High-Speed Internet	Network Slicing, IoT	Quantum Security,AI-Optimized

Table 1.3: Comparison of Key Characteristics of 1G to 6G Wireless Networks

These performance enhancements demonstrate the continuous drive for higher efficiency, reliability, and intelligence in wireless communication systems. The next sections will delve deeper into the architecture and technologies that define 5G and 6G networks.

1.5 Evolution of Waveforms in Mobile Communication

The evolution of mobile communications waveforms has largely followed the successive demands of each generation of wireless systems. The initial mobile systems, beginning with 1G, were based on simple analog modulation techniques such as Frequency Division Multiple Access (FDMA). These systems were low in capacity and flexibility and offered basic voice service with very limited data capability.

As 2G arrived, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) technologies became popular with improved voice quality and the initial digital data services. With growing mobile data demands, 3G networks adopted more advanced techniques like Wideband CDMA (WCDMA) and Time Division Synchronous Code Division Multiple Access (TD-SCDMA) that supported higher data rates suitable for video calls and basic multimedia services. [10]

The introduction of 4G marked a watershed with the adoption of Orthogonal Frequency Division Multiplexing (OFDM) as the preferred waveform. OFDM divides the available bandwidth into a series of orthogonal sub-carriers and facilitates efficient parallel transmission of data streams. Its multipath fading tolerance and spectral efficiency made it apt for the high-speed, all-IP 4G networks.

However, despite its advantages, OFDM introduced some limitations such as high peak-to-average power ratio (PAPR) and sensitivity to frequency and timing offsets. This prompted researchers to devise several variants of OFDM and alternative waveforms to reduce these effects while paving the way for the demands of 5G and future systems.

Among the candidate waveforms for 5G, several stand out:

- CP-OFDM (Cyclic Prefix OFDM): Maintains simple frequency domain equalization and MIMO compatibility at the expense of high PAPR and out-of-band emissions.
- W-OFDM (Windowed OFDM): Reduces spectral leakage at the expense of decreased spectral efficiency.
- F-OFDM (Filtered OFDM): Offers flexible filter granularity and improved frequency localization at the expense of higher implementation complexity
- DFT-s-OFDM and its variants like ZT-DFT-s-OFDM and UW-DFT-s-OFDM: Traded PAPR reduction and spectral efficiency improvement at the cost of higher system complexity in most instances.
- FBMC (Filter Bank Multicarrier): Very good spectral efficiency and selectivity but still complex to realize, particularly for MIMO and IoT applications.
- UFMC (Universal Filtered Multicarrier): Exhibits a compromise between spectral efficiency and ease of implementation and is one of the popular candidates for enhanced mobile broadband.

As 6G research progressed, newer waveforms emerged to meet even more demanding requirements such as ultra-low latency, robustness to high Doppler shifts, and compatibility with massive MIMO and terahertz communications. These include:

- OTFS (Orthogonal Time Frequency Space): Maps time-varying multipath channels to a stable delay-Doppler domain for communication in high-mobility environments reliably.
- OCDM (Orthogonal Chirp Division Multiplexing): Offers robustness in frequency-selective and time-varying channels.
- OTSM (Orthogonal Time Sequence Multiplexing): Another novel modulation technique with future 6G installations in its sights.

This continuing waveform evolution and differentiation reflect the dynamic nature of mobile communication technologies. Each step in the development addresses specific technical challenges while laying the groundwork for the increasingly interconnected and complex systems envisioned for the decades ahead.

[10] [11]

1.6 Conclusion

The successive evolution of mobile communication networks from 1G through 6G represents a relentless pursuit of improved performance, broader coverage, and greater variety of services. Each generation has surmounted specific limitations of the earlier one while introducing new aspects that revolutionized how people communicate and interact with the digital world.

From 1G's voice services to 4G's high-speed, all-IP data transmissions, and 5G's promised smart, connected ecosystems, the progress in the fields of network architecture and waveform design has been immense. More specifically, the adoption of OFDM and its various enhancements was a turning point for modern broadband wireless systems, which offered multipath tolerance and high spectral efficiency.

As the industry is moving towards 6G, the expectations have broadened exponentially. The future networks are not just expected to deliver ultra-high data rates and low latency but also to support a new generation of applications such as holographic communications, brain-computer interfaces, and space-integrated networks. In order to meet these ambitious targets, candidate waveforms such as UFMC, FBMC, and OTFS are being seriously explored for their potential to overcome the limitations of the existing techniques.

This chapter gave an overview of the historical evolution of the generations of mobile networks, outlined the new demands and uses of 5G and 6G, and detailed the continuing development of waveform technologies that underpin these systems. The understanding obtained here provides a sound foundation for the more in-depth technical exploration to be developed in the coming chapters.

Chapter 2:

Candidate Waveforms For 5G and 6G Wireless Communication Systems

2.1 Introduction

The increasing need for wireless services has driven the evolution of wireless communication systems from one generation to the next with the prime focus on having greater capacity, greater data rate [1], and better quality of service. Over the years, several advances in technology have been made in an attempt to support these requirements with ensuing successive generations starting from 1G up to 4G. Nowadays, the introduction of 5G and the future introduction of 6G are a new leap in this evolution. These new generations are designed to provide very high data rates, very low latency, better reliability, and support for a large number of devices. To meet these goals, there is a need to implement new modulation techniques and optimize waveform methods to efficiently utilize the radio spectrum while limiting interference. [5]

Multicarrier modulation has become a significant technique in current wireless communication systems, particularly after the reference waveform for 4G and 5G has been Orthogonal Frequency Division Multiplexing (OFDM). Though successful, OFDM has certain drawbacks, such as vulnerability to synchronization error and high out-of-band emissions. This led to the development of improved alternatives like Universal Filtered Multi-Carrier (UFMC), [10] which involves sub-band filtering within the system to ensure improved spectral localization without losing the advantages of multicarrier transmission. The aim of this chapter is to overview the ideas and functioning of multicarrier modulation methods, especially OFDM and UFMC, and present other contender waveforms that are suggested for 5G and 6G systems. [11] [13]

2.2 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a digital modulation technique that enhances efficiency and reliability in mobile radio transmission channels, particularly in multipath environments. It has seen widespread use in wireless and cellular networks, as well as digital television systems. The core concept of OFDM involves transmitting data in parallel over a large number of subcarriers. The renewed interest in OFDM lies in its ability to improve spectral efficiency by ensuring the orthogonality of the carriers. [5]

2.2.1 Historical Background of OFDM

Multicarrier modulation, including OFDM, has been implemented in several European standards such as Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB). This technique attracted significant interest and has been proposed for various applications, including LANs and personal communication systems. The earliest multicarrier modulation systems date back to the 1950s, particularly in military HF systems. [12]

OFDM was introduced by Chang from Bell Labs in 1966 and patented in 1970. The idea was to use parallel data streams and Frequency Division Multiplexing (FDM), overlapping the spectra of different subcarriers to fully utilize the available bandwidth and eliminate the need for equalization to correct multipath distortions., [14]

In 1979, the advent of DSP processors allowed implementation of Discrete Fourier Transform (DFT) on digital circuits, making OFDM systems easier to develop. During the 1980s, OFDM was studied for high-speed modems and digital mobile communications. By the 1990s, it was widely adopted for broadband data transmission.

Today, OFDM is used in wired systems like ADSL, HDSL, and VDSL, and in wireless systems such as DAB and DVB. It also forms the basis of WLAN standards, particularly IEEE 802.11a. [20]

2.2.2 Interference Issues

2.2.2.1 Inter Symbol Interference (ISI)

In a multipath environment, a transmitted symbol arrives at the receiver with different delays through various propagation paths. From the receiver's point of view, the channel exhibits time dispersion in which the duration of the received symbol is spread out. Extending the symbol duration causes the symbol received at instant t to overlap with symbols received at other times. This is the phenomenon of Inter Symbol Interference (ISI). [22], To overcome this problem, OFDM uses a guard interval, which will be detailed later in this chapter.

In figure (2.1), it can be observed that in the presence of a multi-path channel, delayed versions of symbol n add up with each other and with symbols $(n-1)$, creating inter-symbol interference (ISI). The recovery of the symbol then becomes impossible. [23]

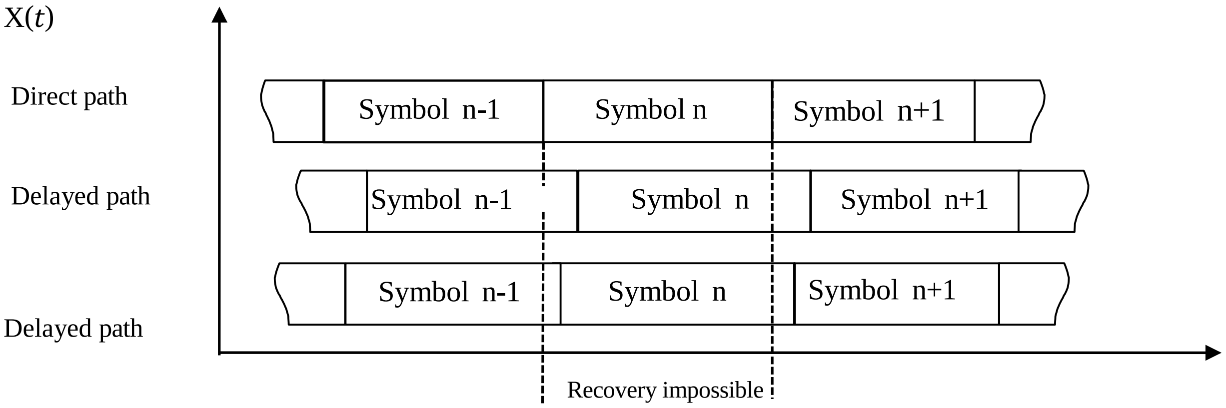


Figure 2.1: Effect of Multi-path on the OFDM Symbol

2.2.2.2 Inter Carrier Interference (ICI)

This type of interference (ICI) can appear in multicarrier transmission systems when the spectra of different subcarriers overlap. These interferences are mainly caused by a loss of orthogonality between adjacent subcarriers.

In order to eliminate these interferences, the notion of orthogonality which will be developed in paragraph (2.2.4) proves to be essential. In OFDM systems, the spectra of subcarriers overlap but remain orthogonal to each other. This means that at the maximum of each subcarrier spectrum, all the spectra of the other subcarriers are null. [22]

2.2.3 Interference Mitigation in OFDM Systems

As ISI mitigation and in order to absorb the symbol delay, a trick consists of extending the OFDM symbol with a cyclic prefix (CP) or guard interval (GI). Its duration is generally between 1/4 and 1/32 of the symbol duration. The useful data rate is reduced in the same proportions. Figure (2.2) [23] shows that thanks to the cyclic prefix, there is no longer any inter-symbol interference and symbol recovery becomes possible. [23]

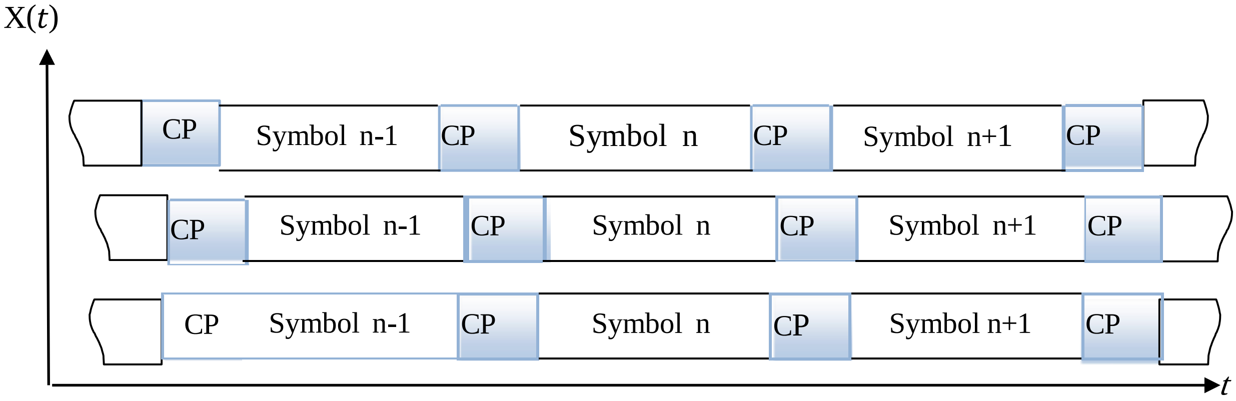


Figure 2.2: Effect of the Guard Interval on the OFDM Signal

The question that arises is: what should be placed in the guard interval to correctly decode symbol n ?

The answer is that it is necessary to restore the orthogonality of the subcarriers that has been lost. To do this, we copy the end of the symbol to its beginning as shown in the following diagram:

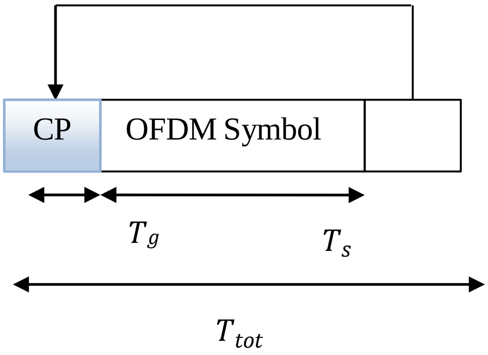


Figure 2.3: Insertion of the cyclic prefix

Let us reason with real carriers. Each OFDM subcarrier corresponds to an integer number of periods over the OFDM symbol (from 0 to : $N - 1$). By copying the end of the symbol into the guard interval, the signal is extended without creating discontinuity. This data is called the cyclic prefix (Figure 2.4). [23]

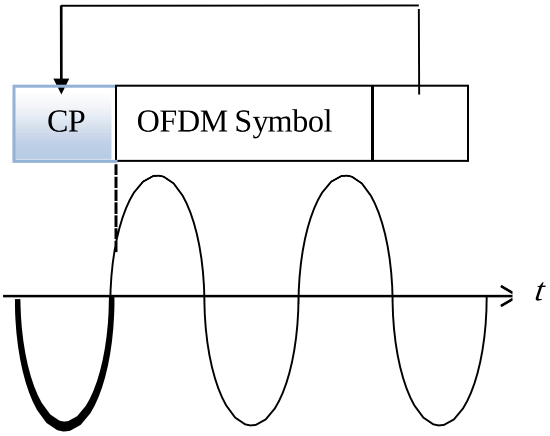


Figure 2.4: Restoration of the Carriers

The guard time can be a “blank” guard interval during which nothing is transmitted — this method is called ZP (zero padding) — but it is more commonly a copy of the end of the OFDM frame. [24]

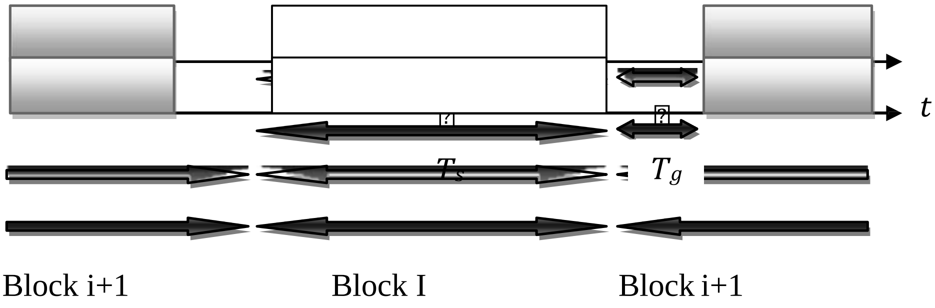


Figure 2.5: Insertion of zero padding

2.2.4 Orthogonality

Orthogonality is a property that allows multiple information signals to be transmitted over a common channel and to be detected without mutual interference. A loss of orthogonality results in inter-symbol interference (ISI) and a degradation in the transmission system's performance. [25]

Mathematically, the orthogonality between two functions f(t) and g(t) over the interval [a, b], is defined by the following relation:

$$\int_a^b f(t)g(t)dt = 0 \qquad (2\text{-}1)$$

There are two types of orthogonality:

- **Temporal Orthogonality.**
- **Frequency Orthogonality.**

2.2.4.1 Temporal Orthogonality

Let us first consider continuous signals, which are not yet sampled. In this case, an OFDM signal consists of a sum of N sinusoids of respective frequencies f_k , transmitted over a duration T_s, where k ranges from 1 to N, and defined by $f_{?} = \frac{k}{T_s}$, this condition ensures that each subcarrier contains an integer number of sinusoidal cycles over the duration T_s. Each real and unmodulated subcarrier $s_k(t)$ can be expressed in the form provided below .

Thus, two subcarriers$s_i(t)$ and $s_j(t)$ of respective frequenciesf_i and f_j, defined by expression (2-2), are orthogonal over the interval [0,T_s], as they satisfy equation (2-1). [25]

$$S_k(t) = \begin{cases} \sin\left(2\pi\frac{k}{T_s}t\right), & 0 < t < T_s \\ 0, & \text{otherwise} \end{cases} \text{ for } k \in [1, N] \qquad (2\text{-}2)$$

2.2.4.2 Frequency Orthogonality

One can also perceive the notion of orthogonality of the OFDM signal in the frequency domain. Indeed, if each subcarrierss_k(t) is transmitted during the duration T_s, this amounts to applying to the subcarrier a gate of duration T_s whose spectral envelope is a sinc function that cancels at the first frequencies $f_{-z} = f_k - 1/T_s$ and $f_{+z} = f_k + 1/T_s$ It is noted that these two frequencies are also respectively equal to f_{k-1} and f_{k+1}.Thus, we obtain the spectral envelope represented in figure (2.2),

where spectrum (a) is that of a subcarrier i, of bandwidth $\Delta f = N/T_s$ and spectrum (b) is that of an OFDM signal with N=4 subcarriers, which extends over B=N× Δf=N/T_s.

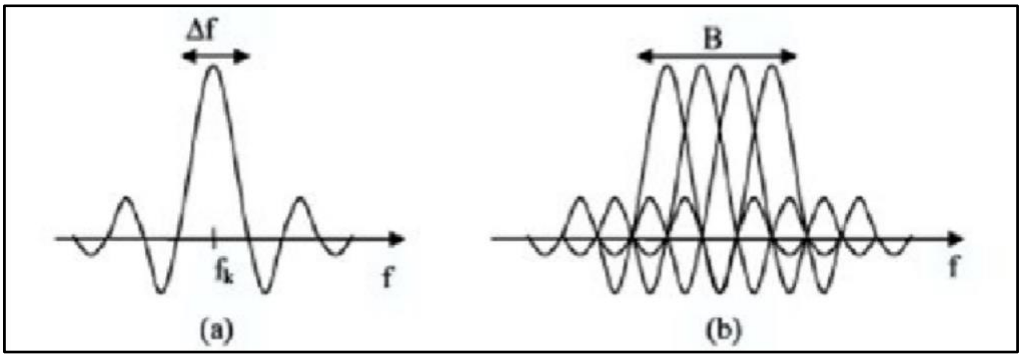


Figure 2.6: (a): Spectrum of a subcarrier (b): Spectrum of an OFDM signal.

Frequency orthogonality is achieved since the maximum of each subcarrier corresponds to a “zero” of the others. This condition therefore makes it possible to have an ideal spectral occupation and to avoid interference between subcarriers. [25]

2.2.5 OFDM System Transmitter and Receiver

The general diagram of an OFDM transmission system is divided into two parts: a transmission part and a reception part, as shown in figure (2.6).

At the transmission side, the bits from the binary source are modulated and generate complex symbols taking their values from a finite alphabet corresponding to a given digital modulation such as Quadrature Amplitude Modulation (QAM) or Phase-Shift Keying (PSK). These symbols c_k are distributed over the N subcarriers. The subcarriers in the frequency domain are spaced by .$\Delta f = 1/Ts$.

The Inverse Discrete Fourier Transform (IDFT) or Inverse Fast Fourier Transform (IFFT) is used to generate the signal in the time domain, consisting of N samples. Generally, all N subcarriers are modulated using data symbols, but some subcarriers are pilot carriers.

The pilots (Estimation Pilots (EP)) are known at both the transmitter and receiver sides and are used for channel estimation. The number of pilots inserted between the data depends on the channel and the precision required for the channel estimation. The pilot symbols can be distributed over several consecutive OFDM symbols. [12]

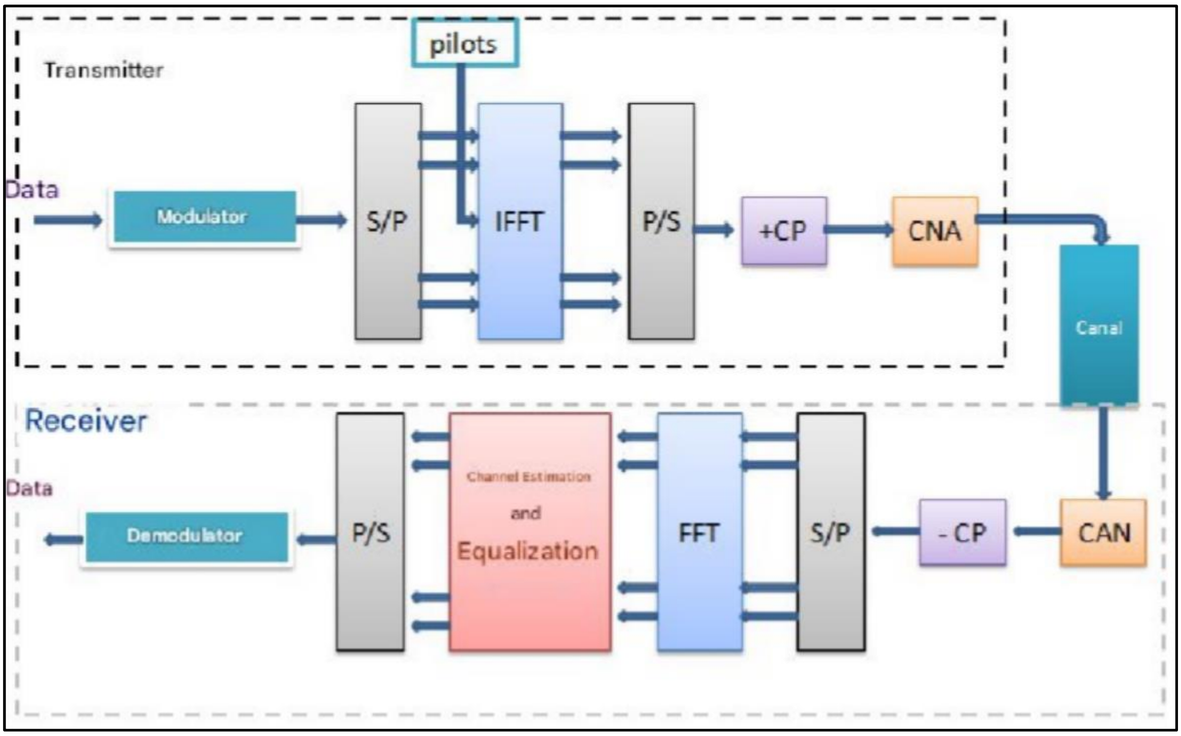


Figure 2.7: Block diagram of an OFDM transmission system.

After the IDFT function, a cyclic prefix (CP) of length: is added to eliminate inter-symbol interference while maintaining orthogonality between subcarriers. The OFDM symbol is then transmitted to the radio-frequency stage involving digital-to-analog conversion and translation onto a carrier frequency.

At the reception side, the CP — which may present interference with adjacent symbols — is removed, and the OFDM symbol is passed to the demodulator. This demodulator performs a Fourier Transform (FFT) which converts the OFDM symbols, carrying useful data and/or pilots, from the time domain to the frequency domain.

Due to the distortions induced by the transmission channel, its correction consists of applying a weighting on each subcarrier. The weighting coefficients are obtained thanks to the pilot symbols whose values are known at the receiver side. Channel equalization consists, from the channel coefficients H(k), of generating the equalization coefficients to compensate for the effects of the channel. Equalization is performed in the frequency domain.

There exist different equalization techniques, the most commonly used being Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) methods. [5], [10], [12]

2.2.5.1 Modulation in an OFDM System

Let us consider the complex symbols C_k which are defined from binary elements according to an M-QAM or M-PSK constellation. These symbols are grouped into packets of N elements corresponding to the N carriers. This packet of N elements C_1, C_2,…, C_{N-1} constitutes the OFDM symbol. The N symbols are transmitted in parallel and modulate the N subcarriers: f_0, f_1 ,…, f_{N-1} The subcarriers are separated by Δf=1/T_s , Or $f_k = f_0 + K.\Delta f$ with K=0,1,…, N-1, to guarantee orthogonality between adjacent subcarriers. [20]

The signal resulting from the modulation of the data stream is expressed in the following complex form:

$$P_n(t) = C_k e^{j2\pi f_k t} \qquad (2\text{-}3)$$

The total signal s(t) corresponding to all the data of an OFDM symbol is the sum of the individual signals:

$$S(t) = \sum_{k=0}^{N-1} C_k e^{j2\pi f_k t}, t \in [0, T_s] \qquad (2\text{-}4)$$

Where is the duration : T_s of the OFDM symbol :

$$S(t) = e^{j2\pi f_0 t} \sum_{k=0}^{N-1} C_k e^{j2\pi \frac{k}{T_s} t} \qquad (2\text{-}5)$$

By discretizing this signal and digitizing it at baseband at instant t=nTs. we obtain an output S_n in the form:

$$S_n = \sum_{k=0}^{N-1} C_k e^{j2\pi \frac{kn}{N}} \qquad (2\text{-}6)$$

This analytical development shows that OFDM modulators at the transmitter side can be implemented by an Inverse Discrete Fourier Transform (IDFT) or by an Inverse Fast Fourier Transform (IFFT) C_k .The Fast Fourier Transform (FFT) is a fast algorithm for computing the discrete Fourier transform of a digital signal. The IFFT allows transforming the complex input blocks C_n into a time-domain signal.

To apply the Fourier transform to a signal or a data block, it is enough to divide it into ‘n’ small blocks, with n being a power of two. [5] The expression of the inverse discrete fast Fourier transform is given by equation : (2-6). We denote S[n] as the Fourier transform of the digital signal C_k and ‘N’ the number of samples. [20]

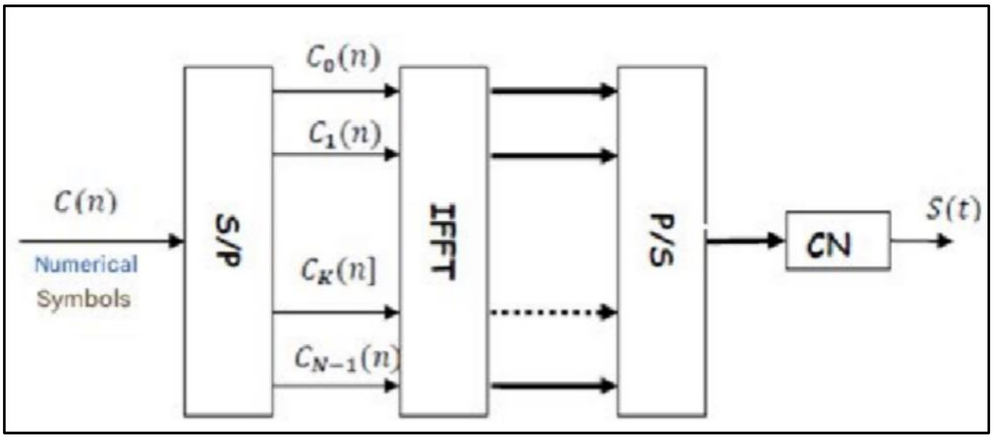


Figure 2.8: Principle of an OFDM modulator

The spectrum of the OFDM signal is the sum of the subcarriers, as shown in figure (2.5):

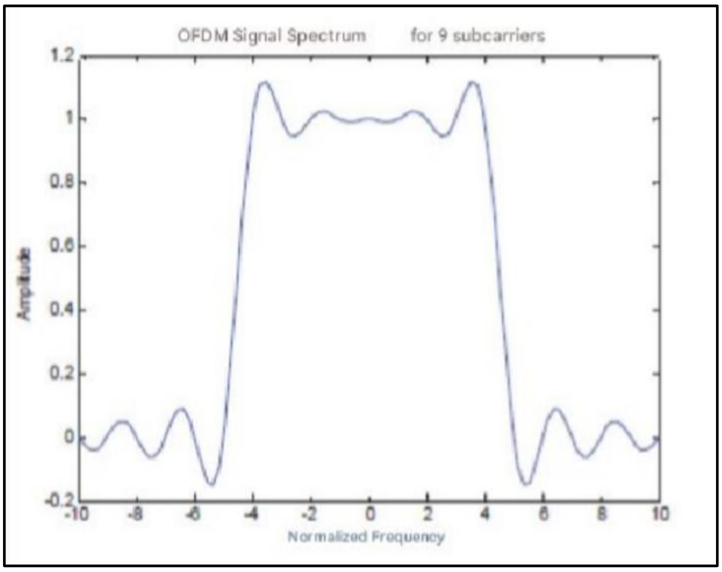


Figure 2.9: Spectrum of the sum of OFDM subcarriers.

2.2.5.2 Demodulation in an OFDM System

The received discretized signal takes the following form:

$$Z_n = \sum_{k=0}^{N-1} C_k H_k e^{j2\pi\frac{kn}{N}} \quad (2\text{-}7)$$

H_k(t) is the transfer function of the channel around the frequency f_k and at instant t. This function varies slowly and can be assumed constant over the period T_s. Z_n is the inverse discrete Fourier transform of $C_k H_k$. Therefore, demodulation consists of performing a Discrete Fourier Transform (DFT), or a Fast Fourier Transform (FFT). [5], [19], [20] ,The diagram for an OFDM demodulator is depicted in figure 2.9. [6] [10]

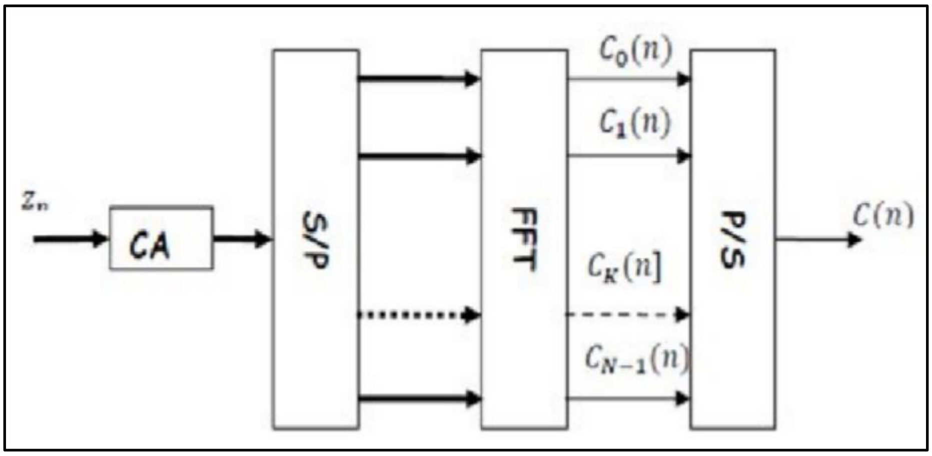


Figure 2.10: Block diagram of an OFDM demodulator

2.2.6 Digital Modulation Techniques in OFDM-Based Systems

In multicarrier communication systems such as OFDM, digital modulation techniques play a crucial role in determining both data rates and system robustness. In these systems, the total data stream is divided into several parallel lower-rate streams, each transmitted on a separate subcarrier. [18], To transmit these data streams, each subcarrier must be modulated using an appropriate digital modulation scheme.

The choice of modulation order is made dynamically based on the transmission channel conditions, allowing for adaptive modulation that balances throughput and resilience to noise. In OFDM-based systems, the most commonly used modulation schemes include:

- Binary Phase Shift Keying (BPSK)
- Quadrature Phase Shift Keying (QPSK)
- Quadrature Amplitude Modulation (QAM)

These digital modulation techniques directly affect the spectral efficiency, data throughput, and robustness of the system.

2.2.6.1 Quadrature Amplitude Modulation (QAM)

Quadrature Amplitude Modulation (QAM) is one of the most widely used digital modulation schemes in OFDM systems, especially in modern wireless communication standards such as 4G, 5G, and 6G. QAM involves direct modulation on the channel, often referred to as baseband transmission. This modulation technique increases the data rate by combining variations in both the amplitude and phase of the transmitted signal. The modulation formats used in 5G mobile communication systems include 16QAM, 64QAM, 256QAM, and 1024QAM. [18]

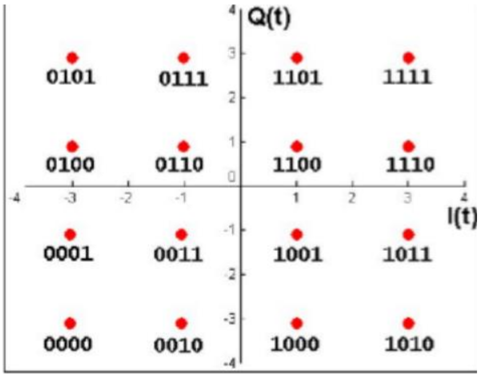


Figure 2.11 : Example of a constellation diagram for 16-QAM modulation

QAM is considered a high-order modulation when the modulation index exceeds 64. As the modulation order increases, the data throughput also increases, although this improvement comes at the expense of reduced noise resilience. For instance, 256QAM is only used when the link quality is very good, whereas the system adapts by downgrading to 64QAM, then 16QAM, and so forth, as the link quality deteriorates. This represents a trade-off between robustness and data rate.

Table 2.1 gives an Illustration of the gain in spectral efficiency provided by the various states of QAM modulation.

N	Modulation Order (M)	Modulation Scheme	Bit Rate	Spectral Efficiency
1	2	BPSK	D	η
2	4	QPSK	2D	2η
4	16	16-QAM	4D	4η
6	64	64-QAM	6D	6η
8	256	256-QAM	8D	8η

Table 2.1: Illustration of the gain provided by QAM modulation

where D is the data rate and η is the spectral efficiency.

2.2.7 Applications of the OFDM Technique [27]

OFDM is a predominant technique; it is used in the European project for digital radio broadcasting (Digital Audio Broadcasting DAB), digital television broadcasting (Digital Video Broadcasting DVB), and in high-speed wireless local area networks (High Performance Radio Local Area Network type 2 HiperLAN2 from ETSI) or 802.11a and 802.11g. OFDM is perfectly suited for mobile communications and seems unavoidable for future communication standards.

- **ETSI HiperLAN II Standard**

HiperLAN2 is a European standard developed by ETSI (European Telecommunications Standards Institute), supported by the H2GF (HiperLAN2 Global Forum) founded in 1999 by Bosch, Dell, Ericsson, Nokia, Telia, and Texas Instrument. At the physical level, the HiperLAN2 standard uses a frequency band between 5.15 and 5.25GHZ, which is divided into 9 carriers of 200MHZ each (with a spacing of : 20MHZ provided between the carriers). This second version offers a peak data rate of : 54 Mbps and uses, at the physical level, the OFDM (Orthogonal Frequency Division Multiplexing) protocol, in the same way as 802.11a.

- **IEEE 802.11a (Wi-Fi 5)**

The IEEE 802.11a proposal originates from studies conducted within the framework of HiperLAN standardization by ETSI. IEEE 802.11a is an extension of IEEE 802.11 that improves transmission speed by offering data rates ranging from 6 to 54Mbit/s. This standard operates in the UNII (Unlicensed National Information Infrastructure) band (5GHz), a frequency band that does not require a usage license.

- **IEEE 802.11g**

The 802.11a standard offers a fairly high data rate, but its range is shorter, and its outdoor use is often restricted. To address these issues, IEEE developed the new 802.11g standard, offering the same data rate as Wi-Fi 5 while remaining compatible with Wi-Fi 2 (operating in the 2.4 GHz band). This standard also aims to replace Wi-Fi 2 on the 2.4 GHz band but with a higher throughput that can reach 54Mbits/s, it uses the OFDM modulation technique.

- **Digital Audio Broadcasting (DAB)**

DAB (Digital Audio Broadcasting) is a standard for the digital transmission of radio signals. This standard is deployed in Europe and worldwide as the first one using OFDM modulation. The goal is to ensure reception under the most challenging propagation conditions (on board reception in dense urban areas, resistance to Doppler effects). Broadcasting modes have been defined using various frequency bands to transmit the signal (VHF, 1,5 GHz band, 2,3 GHz band).

- **Terrestrial Digital Video Broadcasting System (DVB-T)**

Terrestrial digital television systems allow users to enjoy a greater number of TV programs, better image quality, and wider reception coverage. The first terrestrial digital TV system standardized in Europe is the DVB-T system (Digital Video Broadcasting – Terrestrial). The OFDM (Orthogonal Frequency Division Multiplex) modulation was adopted by this standard for its implementation simplicity and robustness against frequency-selective channels.

2.2.8 OFDM Technique Variants in Modern Communication Systems

➢ **C-OFDM (Coded-OFDM):**

- Offers a real advantage in the presence of isolated narrowband interference signals.

➢ **MIMO-OFDM (Multiple Inputs, Multiple Outputs-OFDM):**

- Uses multiple antennas to transmit and receive radio signals.

➢ **V-OFDM (Vector-OFDM):**

- Increases subscriber coverage.
- Reduces provisioning and infrastructure deployment costs.
- Creates a robust processing technique for multi-path and narrowband interference.

➢ **W-OFDM (Wideband OFDM):**

- Invented by Wi-LAN.
- Features large spacing between carriers.

2.2.9 Advantages and Disadvantages of OFDM

Advantages:

- The OFDM technique is robust against impulsive noise since each subcarrier is affected by noise independent from the others, so the loss of a symbol due to significant noise does not impact the remaining symbols — unlike single-carrier modulations, where noise can affect multiple transmitted symbols.
- Inter-symbol interference (ISI) and inter-carrier interference (ICI) can be avoided at transmission
- and corrected at reception.
- By choosing an appropriate guard interval duration, OFDM allows for very simple elimination of multi-path effects, which is a major issue in single-carrier systems as transmission rates increase.
- The simplicity of implementation through IFFT/FFT algorithms has made this technology a promising alternative in broadcasting and digital communications.
- Efficient use of frequency resources helps avoid channel overlap and maintain perfect orthogonality.

Disadvantages:

- Flexibility: Cyclic prefixes reduce spectral efficiency.
- OFDM is also highly vulnerable to frequency offset and synchronization issues. In the first case, frequency offset introduces inter-carrier interference that can destroy orthogonality between

carriers. In the second case, synchronization errors introduce phase shifts in the received symbols.

- Envelope fluctuation: OFDM signals present high envelope fluctuations, resulting in a high Peak-to-Average Power Ratio (PAPR). This demands high linearity from the transmission chain, especially at the power amplifier stage, which leads to poor efficiency — incompatible with power-optimized mobile applications.
- Rapid transmission: Very difficult to handle short symbols with channel delay.

2.3 Universal Filtered Multi-Carrier (UFMC)

Universal-Filtered-Multi-Carrier (UFMC) is a new multi-carrier modulation incorporating filters for sub-bands, which aims to replace OFDM (Orthogonal Frequency Division Multiplexing) modulation. The objective of UFMC is to eliminate the strict synchronization constraints of OFDM. [18]

As previously mentioned, OFDM suffers from two major issues: the Peak-to-Average Power Ratio (PAPR) and the synchronization problem. The Out Of Band (O.O.B) radiations of this waveform also cause significant losses. This has driven researchers to consider new waveform forms to replace the OFDM technique in future mobile radio systems. [10]

UFMC is a technique initially proposed by Alcatel-Lucent & Bell laboratories [28], it is also referenced under the name UF-OFDM in the literature.

UFMC is a combination of ZP-OFDM (traditional CP-OFDM, with the CP replaced by Zero Padding (ZP)) and a filtered OFDM. Each OFDM symbol at the output of the IDFT is filtered, and the ZP is used to absorb the transient response of the filter. In the absence of a multipath channel, UFMC preserves the orthogonality of the subcarriers. Nevertheless, orthogonality is no longer maintained as the channel's time spreading increases, and only soft protection against multipath effects is possible at the receiver.

At reception, multi-user interference resulting from time and frequency asynchrony is first reduced by applying a window to the received UFMC block symbols. It should be noted that this processing destroys the subcarrier orthogonality, even if the channel is perfect. Finally, an FFT of a size twice that of the IFFT used during transmission is applied to the received OFDM block symbols, and only the subcarrier indices are retained. [18]

It is important to note that the receiver complexity can be reduced by collecting additional samples corresponding to the length of the ZP and using an overlap-and-add method to obtain the circular convolution property. In this case, the required FFT size is identical to the IFFT size used during transmission. The functional diagram of UFMC is illustrated in Figure 2.11.

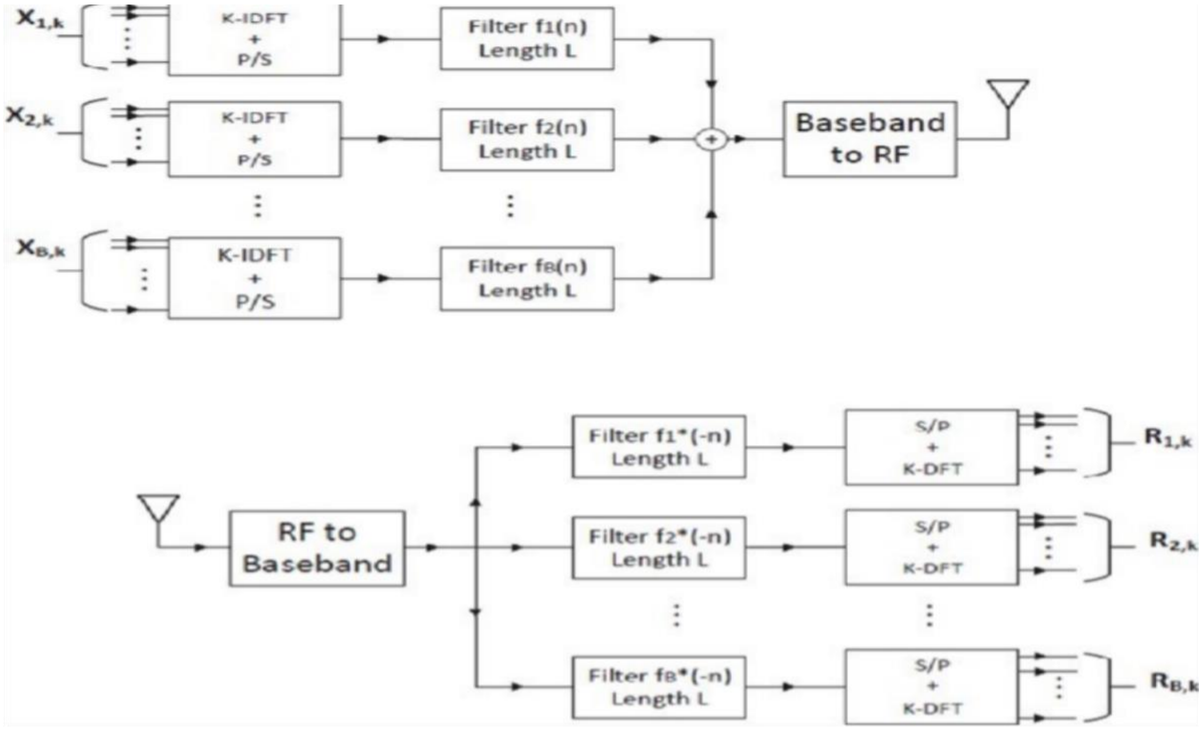


Figure 2.12: Architecture of a UFMC Transmitter/Receiver

2.3.1 Principle and Operation of UFMC

The figure 2.12 illustrates the operation of UFMC. In the transmitter part, a group of k complex input data symbols are mapped into sub-bands B, where each sub-band is composed of $M = K/B$ subcarriers. The symbol assigned to the k-th subcarrier of the j-th sub-band is $X_{(j,k)}$. For each sub-band, the time domain symbols x_j are obtained by applying an IFFT at point k on $X_{(j,k}$ More precisely, the group of subcarriers in the j-th sub-band is shifted by inserting Θj zeros at the beginning; likewise, zeros are inserted at the end to account for unallocated subcarriers. [18]

$$x(l) = \frac{1}{M}\sum_{k=0}^{M-1} X(j,k)e^{j2\pi\frac{(k+\Theta_j)l}{K}} \quad (2\text{-}8)$$

With $l = 0, \ldots, K-1$ and $\Theta_j = (j-1).M$. Each sub-band sequence $x(l)$ passes through a finite impulse response filter $fj(l)$ of length L to reduce out-of-band emissions. The filter $f(l)$ is modulated at the appropriate frequency by multiplying a prototype $f\ (l)$ with an exponential sequence, as shown in equation:

$$f_j(l) = f(l)e^{j2\pi\frac{(\Theta_j+M-1)l}{K}} \quad (2\text{-}9)$$

The prototype filter (l) is obtained from the Dolph-Chebyshev window with adjustable side lobe attenuation. output of the j-th sub-band after the FIR filter is expressed by:

$$y(l) = x_j(l) * f_j(l) = \sum_{l'=0}^{K-1} x_j(l')f_j(l-l') \qquad (2\text{-}10)$$

with * denoting discrete-time convolution and index $l = 0, \ldots, (K + L - 2)$. The different sub-band signals $y(l)$ are then added, resulting in:

$$y(l) = \sum_{j=1}^{B} y_j(l) \qquad (2\text{-}11)$$

Finally, the discrete-time baseband signal $y(l)$ is converted into an analog signal for transmission by analog shaping and RF conversion. [18]

At reception, the received signal is denoted (l).. For each of the sub-bands B, the received signal (l) is convolved with the time-reversed and complex conjugate of the corresponding sub- band filter $f_j(l)$. The resulting time-domain signal $r_j(l)$ is expressed by :

$$r_j(l) = r(l) * f_j^*(-l) = \sum_{l'=0}^{K+L-2} r(l')f_j^*(l'-l) \qquad (2\text{-}12)$$

Where only the samples with index $l = 0, \ldots, K - 1$ are retained. For each sub-band, the signal $r_j(l)$ is mapped into the frequency domain by applying an FFT despreading operation. [18]

More precisely, the estimated symbol corresponding to the k-th subcarrier and the j-th sub-band is expressed by:

$$R_j(k) = \sum_{l=0}^{M-1} r_j(l)e^{-j2\pi\frac{(k+\Theta_j)l}{K}} \qquad (2\text{-}13)$$

With k=0, . . ., M – 1.

2.3.2 Advantages and Disadvantages of UFMC Modulation

- **Advantages:**
  - UFMC has better spectral efficiency compared to OFDM, as UFMC does not insert a cyclic prefix like in OFDM.
  - There is no repetition of the same bits, so it efficiently uses the entire allocated spectrum.
  - Fewer side lobes than OFDM; as the side lobes decrease, interference on adjacent subcarriers also decreases.
  - PAPR is lower for UFMC compared to OFDM, because in OFDM the signal is composed of a large number of independently modulated subcarriers which can lead to a high PAPR when they are added in phase. In UFMC, the total bandwidth is divided into sub-bands. Since the probability of a large number of subcarriers adding up in phase is lower in UFMC, the maximum power decreases.
- **Disadvantages:**
  - The complexity of implementing this technique.
  - High PAPR (Peak-to-Average Power Ratio).

2.4 Other Candidate Waveforms

2.4.1 Filter Bank Multicarrier

Filter Bank Multicarrier (FBMC) is a multicarrier modulation technique that uses a bank of filters to achieve better spectral containment than OFDM. It is an alternative technique to CP-OFDM that avoids the use of the cyclic prefix, thereby allowing for increased spectral efficiency. In the FBMC system, each subcarrier is shaped using a prototype filter, and data symbols are modulated and transmitted with an offset in time between the in-phase and quadrature components (QAM real/imaginary parts), referred to as OQAM (Offset QAM).

2.4.1.1 FBMC operating principle

The operating principle of FBMC consists of using a series of digital filters that divide the bandwidth into several sub-bands, each corresponding to a subcarrier. These subcarriers are modulated by QAM symbols. A synthesis filter bank is used at the transmitter to shape each subcarrier and avoid inter-symbol interference (ISI) and inter-carrier interference (ICI). At the receiver, an analysis filter bank is used to demodulate the received signal and extract the transmitted symbols.

The modulation of a symbol is done by applying a time and frequency offset, which makes it possible to separate the subcarriers without requiring a guard interval or cyclic prefix. This approach leads to excellent spectral confinement.

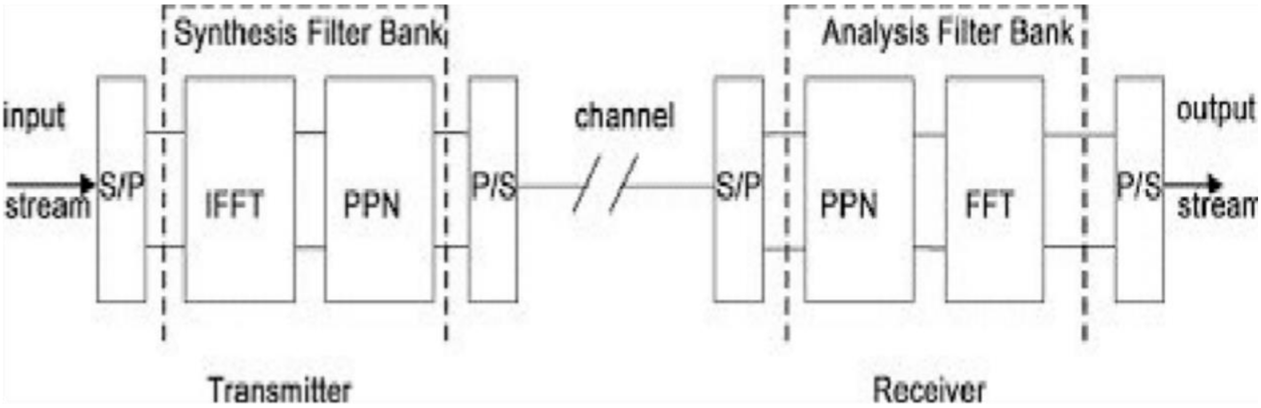


Figure 2.13: The FBMC transmission chain

2.4.1.2 Advantages and disadvantages of FBMC

➢ **Advantages of FBMC**

- Better spectral efficiency due to the absence of the cyclic prefix.
- Excellent spectral containment, which reduces out-of-band emissions.
- No need for synchronization between users.
- More resistant to frequency dispersion and suitable for asynchronous communication systems.

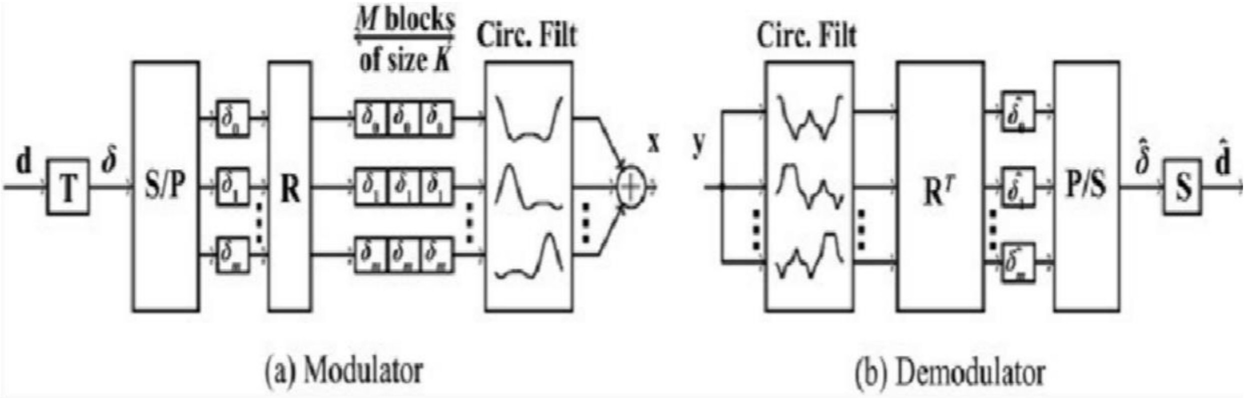
➢ **Disadvantages of FBMC**

- Higher complexity in implementation, especially for the receiver.
- More complex equalization process.
- Difficult integration with MIMO systems.
- Higher latency due to filter length.

2.4.2 Generalized Frequency Division Multiplexing

Generalized Frequency Division Multiplexing (GFDM) is a multicarrier modulation technique designed to be more flexible than OFDM. It is based on the transmission of blocks where each subcarrier is filtered by a prototype filter. In GFDM, the data to be transmitted is divided into several blocks, each composed of multiple subsymbols spread over several subcarriers.

Each GFDM block is generated by applying a filtering process to each subcarrier, using a circular convolution with a prototype filter. The system employs a time-frequency grid where each time slot corresponds to a subsymbol and each frequency slot corresponds to a subcarrier. The GFDM modulation process thus allows for better control of time and frequency localization.



(a) Modulator (b) Demodulator

Figure 2.14: Block diagram of GFDM modulator and demodulator

2.4.2.1 Characteristics of GFDM

Generalized Frequency Division Multiplexing (GFDM) is a flexible multicarrier modulation scheme characterized by its block-based structure, where each block consists of multiple subsymbols transmitted over several subcarriers. Unlike traditional OFDM, GFDM employs circular pulse shaping, allowing each subcarrier to be individually filtered with a prototype filter. This approach leads to a non-orthogonal waveform, introducing inter-carrier interference (ICI) that necessitates more complex receiver designs for effective signal detection. Additionally, GFDM utilizes a single cyclic prefix for the entire block, enhancing spectral efficiency by reducing redundancy. The modulation scheme's inherent flexibility in filter design and block configuration makes it adaptable to various transmission requirements, positioning it as a strong candidate for next-generation wireless communication systems.

2.4.2.2 Advantages and disadvantages of GFDM

- **Advantages of GFDM**
  - Flexibility in the choice of filters and parameters.
  - Good spectral containment (low OOB emissions).
  - Better adaptation to fragmented spectrum.
  - Lower latency than OFDM.
- **Disadvantages of GFDM**
  - Non-orthogonal modulation, which complicates the receiver design.

- Higher complexity in equalization.
- Residual interference between subcarriers (inter-carrier interference).

2.5 Candidate Waveforms for 6G

5G technology has been deployed since 2020, and research to make it more latency-efficient and ultra-reliable is actively ongoing. However, this technology will not be able to meet the demand for high-speed data transmission in high-mobility scenarios, especially with the large-scale use of artificial intelligence in the coming decades. Consequently, research has been launched for the development of the sixth generation of mobile communication systems capable of meeting these emerging challenges. This future generation of mobile networks is expected to rely on various techniques to provide high energy efficiency, permanent global coverage, data rates of up to (1 Terabits per second), and environmentally friendly operation. [29]

To satisfy these requirements, new waveforms that are highly flexible and robust must be invented or adapted from existing ones.

OFDM supporting machine learning and deep learning techniques has been proposed as a waveform suitable for the Radio Access Network (RAN) of 6G networks,

An hybrid modulation technique named OFDM-HNIM for (OFDM Hybrid Number and Index Modulation). OFDM-HNIM modifies the indices and number of active subcarriers in each OFDM sub-block, achieving improvements in spectral efficiency, power efficiency, reliability, and complexity reduction. the most cited in the literature is Orthogonal Time Frequency Space (OTFS) modulation, we give an insight on this wave form in the following paragraph. [29]

2.5.1 Orthogonal Time Frequency Space (OTFS)

Orthogonal Time Frequency Space (OTFS) modulation is another promising waveform, which is characterized by its capability to handle high mobility at very high frequencies. OTFS transforms the time-varying multipath channel into a two-dimensional, time-independent channel in the Delay-Doppler domain, thus effectively addressing the challenges of tracking time-varying fading in high-speed vehicular communications.

OTFS is capable of extracting full channel diversity over time and frequency and demonstrates linear throughput scaling with the number of antennas in moving vehicles.

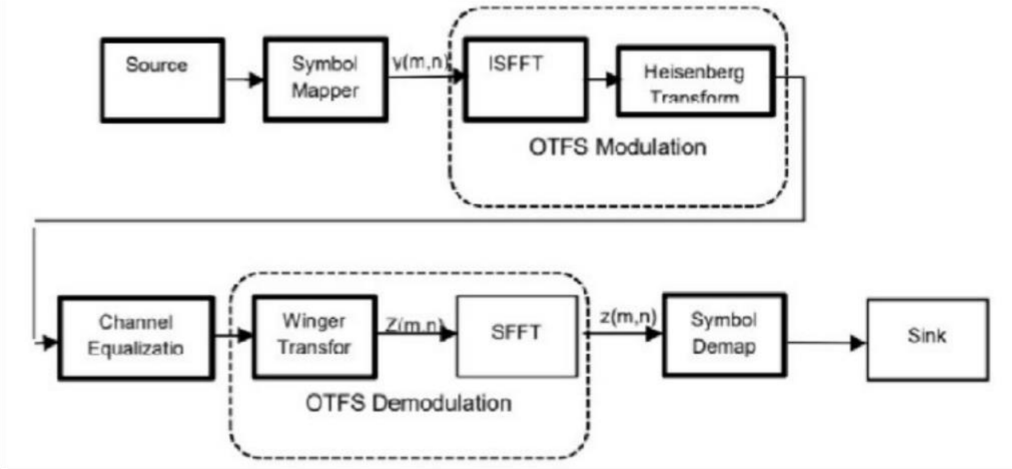


Figure 2.15: OTFS modulation scheme

Different types of transforms are used for performing the domain transformation. From one domain to another domain and from 1D to 2D domain. They are Symbol Mapper and demapper, Inverse Symplectic Finite Fourier Transform (ISFFT) and Symplectic Finite Fourier Transform (SFFT), Heisenberg and Wigner transform.

Additionally, the Delay-Doppler channel representation is compact, enabling dense and flexible stacking of reference signals. These signals are critical for supporting large antenna arrays in massive MIMO systems. A key advantage of OTFS is its ability to convert a channel that randomly fades in the time-frequency domain into a stationary, deterministic, and non-fading channel between the transmitter and receiver.

The OTFS modulation process involves applying a 2D Inverse Fourier Transform to signals in the Delay-Doppler domain to convert them to the frequency domain, followed by a Heisenberg transform to obtain the time-domain transmit signal. At the receiver, the Wigner transform and Fourier transform are applied. [29]

OTFS offers several advantages, including efficient management of high Doppler effects and strong support for massive MIMO architectures. Due to its complexity, ongoing research focuses on designing less complex detection schemes. Variants of OTFS were also proposed such as:

- Circular Pulse Shaped OTFS (CPS-OTFS)
- Circular Dirichlet Pulse Shaped OTFS (CDPS-OTFS),
- OTFS, Orthogonal Time Frequency Space Modulation
- Discrete Fresnel Transform (DFnT) and Discrete Fourier Transform (DFT),
- Orthogonal Chirp Division Multiplexing (OCDM).
- Affine Frequency Division Multiplexing (AFDM)
- Additionally, a new non-orthogonal waveform (NOW)

2.5.2 Characteristics comparison of the candidate waveforms [29]

The characteristics comparison between the various candidate waveforms is summarized in table 2.1:

Waveform	Advantages	Inconveniences
OFDM and its variants	• Selective fading immunity • Resilience to interferences • Spectrum efficiency • Resilient to ISI and narrowband effects • Simple channel equalization	• High PAPR • Sensitive to offset and drift • Unsuitable for high mobility communications
FBMC	• High spectral efficiency and selectivity • Strong band isolation • Reduced side lobes	• Symbol overlapping • Difficult to use in MIMO • Requires very long filters • Not ideal for IoT and M2M applications
OQAM-FBMC	• Optimal frequency localization • High spectral efficiency • Suitable for asynchronous transmission and high mobility	• No ISI resistance (no guard or CP) • Complex hardware • High implementation complexity • High energy consumption
UFMC	• Strong OOBE suppression • Good frequency localization • Filter shorter than subcarrier • MIMO compatible	• High PAPR • Complex receiver design (due to OQAM) • No ISI immunity • High receiver complexity
GFDM	• Effective OOB suppression • Average PAPR reduction • Good frequency localization • Flexible structure	• Difficult ISI/ICI management • Modulation complexity • Discontinuities between blocks • High latency • MIMO integration challenges • High complexity
OTFS	• Handles strong Doppler channels • Utilizes frequency diversity • Efficient user multiplexing	• High implementation complexity • Suboptimal equalization techniques

Table 2.1: Candidate waveforms for future mobile communications networks.

2.6 Performance Measurement and Evaluation Metrics

2.6.1 Peak-to-Average Power Ratio (PAPR)

The Peak-to-Average Power Ratio (PAPR) represents the ratio between the maximum instantaneous power and the average power of a transmitted signal. In multicarrier systems like OFDM, PAPR quantifies how extreme the peaks are in a waveform, which can affect the efficiency of power amplifiers.

PAPR is expressed in decibels (dB) and is calculated as follows:

$$\text{PAPR} = \frac{\max|x(t)|^2}{\frac{1}{T}\int_0^T |x(t)|^2 dt} \qquad (2\text{-}14)$$

High PAPR values indicate significant power fluctuations, which can lead to inefficiencies in power amplifiers. Therefore, reducing PAPR is crucial for enhancing the efficiency of power amplifiers in wireless communication systems. [26]

2.6.2 Complementary Cumulative Distribution Function (CCDF)

To evaluate the statistical behavior of PAPR in a system, the Complementary Cumulative Distribution Function (CCDF) is widely used. The CCDF provides the probability that the PAPR of a transmitted signal exceeds a specified threshold value. It effectively quantifies how frequently high PAPR events occur within a given signal, offering a valuable tool for designers to assess the suitability of different modulation and waveform schemes under varying system conditions. In general, a waveform with a lower CCDF at a given PAPR threshold is considered more power-efficient and favorable for practical implementations in wireless communication systems.

2.6.3 Bit Error Rate (BER)

The Bit Error Rate (BER) is a key parameter used to evaluate the performance of digital communication systems. It quantifies the rate at which errors occur in a transmitted data stream over a communication channel.

BER is defined as the ratio of the number of bit errors to the total number of bits transmitted:

$$\text{BER} = \frac{\text{Number of Bit Errors}}{\text{Total Number of Bits Transmitted}} \qquad (2\text{-}15)$$

A lower BER indicates a more reliable communication system. Factors such as noise, interference, and signal distortion can increase the BER, affecting the overall system performance. [26]

2.6.4 Symbol Error Rate (SER)

The Symbol Error Rate (SER) quantifies the probability that a symbol is incorrectly decoded in a digital communication system. Unlike the Bit Error Rate (BER), which measures errors on a per-bit basis, SER considers the entire symbol, which may represent multiple bits depending on the modulation scheme. the SER is defined as:

$$\mathrm{SER} = \frac{\text{Number of Symbol Errors}}{\text{Total Number of Transmitted Symbols}} \qquad (2\text{-}16)$$

A higher-order modulation scheme, while increasing data throughput, may also lead to a higher SER due to the closer spacing of symbol points, making them more susceptible to noise and other impairments. [26]

2.6.5 Out-of-Band Emissions

Out-of-Band Emissions (OOB) refer to the spectral components of a transmitted signal that fall outside its designated frequency band. These emissions are unintended and can cause interference with adjacent channels or systems.

In multicarrier modulation schemes like OFDM, OOB emissions are primarily caused by the abrupt transitions between symbols, leading to spectral leakage. Managing OOB emissions is crucial to ensure spectral efficiency and to minimize interference with neighboring frequency bands.

Regulatory bodies, such as the European Conference of Postal and Telecommunications Administrations (CEPT), define specific limits for OOB emissions to ensure coexistence of multiple services within the radio spectrum. [26]

2.7 Conclusion

In this chapter, we explored in detail the fundamental principles, architectures, and performance aspects of multicarrier modulation schemes, with a particular focus on the candidate waveforms for 5G and 6G wireless communication systems. We began by revisiting the historical development and theoretical foundations of Orthogonal Frequency Division Multiplexing (OFDM), analyzing its strengths such as spectral efficiency and robustness against multipath fading, as well as its limitations, including sensitivity to synchronization errors and high Peak-to-Average Power Ratio (PAPR). We also discussed critical concepts like inter-symbol and inter-carrier interference, the role of the cyclic prefix, and the orthogonality conditions that ensure optimal signal demodulation.

Furthermore, we examined the transmitter and receiver architectures of OFDM-based systems and highlighted the integration of digital modulation schemes such as Quadrature Amplitude Modulation (QAM). Building on this foundation, we introduced Universal Filtered Multicarrier.

(UFMC) as an advanced waveform designed to overcome specific drawbacks of OFDM. Its operation, prototype filtering approach using Dolph-Chebyshev filters, and its performance advantages were discussed, emphasizing its enhanced spectral containment and better suitability for short-burst transmissions.

We also presented other prominent waveform candidates including Filter Bank Multicarrier (FBMC) and Generalized Frequency Division Multiplexing (GFDM), outlining their principles of operation, unique characteristics, and comparative advantages and disadvantages. These alternatives highlight the ongoing innovation aimed at addressing diverse requirements such as low latency, high spectral efficiency, and flexible waveform configurations in next-generation networks.

The chapter concluded with an overview of performance evaluation metrics such as PAPR, Bit Error Rate (BER), Symbol Error Rate (SER), and Out-of-Band Emissions, which are essential for objectively comparing modulation techniques and assessing their feasibility in practical deployments.

Ultimately, this comprehensive analysis provides a solid foundation for understanding the technical evolution from OFDM to more advanced modulation schemes like UFMC, FBMC, and GFDM, which are paving the way toward efficient and flexible 5G and 6G communication systems. The next chapter will implement simulations to evaluate and compare the performance of some of these waveforms under various channel conditions using MATLAB.

Chapter 3:

MATLAB-Based Simulation And comparative analysis of UFMC and OFDM

3.1 Introduction

With the emergence of next-generation wireless communication systems such as 5G and future 6G, the need for high-speed, low-latency, and spectrum-efficient technologies is increasing. Among the potential candidates for the development of multicarrier modulation schemes is the Universal Filtered Multicarrier (UFMC) technique. Unlike traditional Orthogonal Frequency Division Multiplexing (OFDM), which suffers from high out-of-band emissions and high sensitivity to synchronization errors, UFMC offers good spectral containment and enhanced robustness to time and frequency dispersion. [16]

This chapter presents a simulation-based comparison of Universal Filtered Multicarrier (UFMC) and conventional Orthogonal Frequency Division Multiplexing (OFDM) in MATLAB, focusing on key metrics such as Power Spectral Density, Peak-to-Average Power Ratio, Out-of-Band Emissions, Bit Error Rate, and Symbol Error Rate. The simulation considers different modulation schemes and analyzes prototype filters for UFMC. The findings are crucial for guiding waveform design and optimization in future 5G and 6G wireless networks.

3.2 Orthogonal Frequency Division Multiplexing (OFDM)

Modern wireless communication systems use OFDM modulation to transmit data. QAM and FDM are combined in OFDM to produce a system that offers high data rates. Different types of modulation are referred to as QAM. By delegating a slice of the frequency spectrum to each channel, FDM basically allows multiple communication channels to coexist. A range of subcarriers can be created using OFDM in order to transmit data over a wide range of frequencies. [10]

4G LTE is currently using OFDM, the data rate of LTE devices is 1 Gpbs and bandwidth lies between 1.4 – 20 MHz A packet switch is used in LTE. An OFDM method is a more efficient and less time-consuming way to model 5G networks. High PAPR is one of the main disadvantages of OFDM. [10]

OFDM split the whole spectrum into sub-bands and transmits those employing cyclic prefixes (CP), time, and frequency synchronization. A CP frame is added between OFDM symbols before transmission in order to prevent interference between symbols on the receiver, such that the CP time duration exceeds the channel delays time. [10]

Multi-carrier OFDM is a widely used waveform for RF systems and LTE downlink communications. It allows for high spectral efficiency in channels with limited bandwidth and significantly boosts data rates. OFDM's robustness to both phase noise and time selective channels can be determined by the spacing between its subcarriers. By using multiplexing, data is grouped in packages of M for frequency multiplexing, which is known as OFDM symbol, a different carrying is modulated simultaneously on each data. M data points are considered (S_0, S_1, …., S_{M-1}), M data is divided into two sequences by time T_s. A signal at the frequency fk is present in each data through the S_k module. A complex form $S_k\ e^{2j\pi f_k t}$ is used to represent each signal. [10] The signal x(t) for all M symbols can be calculated as follows:

$$x(t) = \sum_{k=0}^{M-1} S_k e^{j2\pi f_k t} \qquad (3\text{-}1)$$

Multiplexing is orthogonal, if the spacing frequency is $1/T_k$, then $f_k = f_0 + k/T_s$. Then, we can write the overall signal as:

$$x(t) = e^{j2\pi f_0 t} \sum_{k=0}^{M-1} S_k e^{j2\pi k \Delta f t} \qquad (3\text{-}2)$$

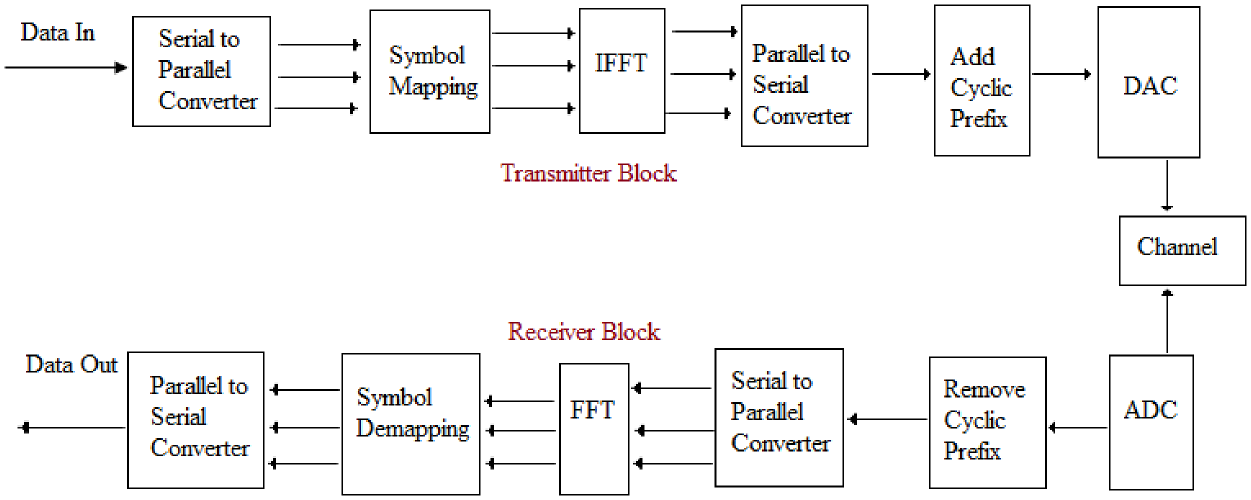


Figure 3.1: OFDM Transceiver

3.3 Universal Filtered Multicarrier (UFMC)

A new waveform candidate for future wireless systems, the UFMC, was introduced, to get improved spectral efficiency, minimized out-of-band emissions and reduced latency. A version of the technology is also called Universal Filtered OFDM. It offers much more efficient usage of radio resources since the UFMC system is equipped with a spectral containment signal. This eliminates the need for CP. UFMC offers several advantages over OFDM. [10]

The bandwidth is separated into many sub- bands, according to UFMC. There are several subcarriers for each sub-band. The sub-bands are filtered during transmission, binary data streams are divided into sub- streams based on their data speeds. [10]

A base band modulator generates the complex symbols for user K in the UFMC system. A block of streams is formed by converting the parallel signals to serial signals using the IFFT spreader. It will then be passed on to the filter. Each block's output is filtered and then added together and sent to the baseband and RF sections. The signal will be processed by the domain pre-processing window in the receiver section after it has been routed through the RF to baseband link. There is no interference through this window.

A point stream of 2N is generated as a result of this process. There are N sub-carriers in those streams, which are parallel streams. Symbol de-mappers are also known as frequency domain symbol processers. De- mapping of symbols occurs here. Symbols are demodulated using a QPSK demodulator, which uses the bits of data in the symbols to retrieve them. [10]

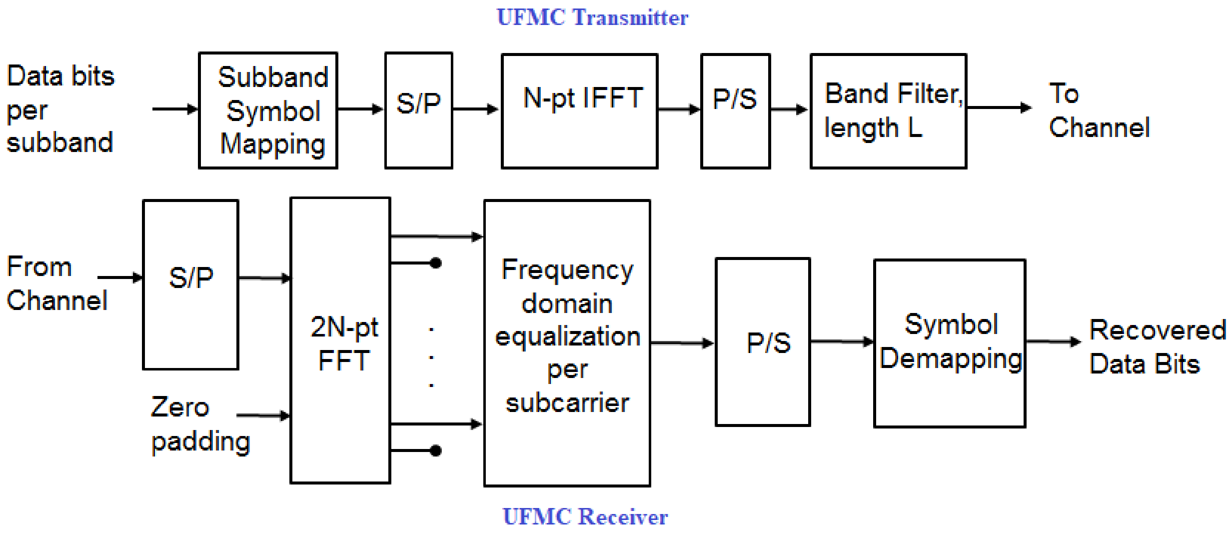


Figure 3.2: UFMC Transceiver

3.3.1 Prototype filters characteristics

Prototype filters are electronic filter designs used as a template for modified filter designs tailored to a specific application. They constitute a dimensionless design example from which the desired filter can be transformed. [19]

The choice of the prototype filter is particularly important. Indeed, it offers possibilities for adaptation relative to OFDM. Prototype filters can thus be constructed to meet certain objectives, such as localization in time and frequency, regularity, etc.

However, it is necessary for the prototype filter to satisfy an orthogonality constraint. This additional filtering, associated with the IFFT operation, forms a filter bank structure in which the prototype filter is designed to suppress inter-symbol interference. [19]

➢ **Common examples of prototype filters include:**

- **Dolph-Chebyshev Filter:** Offers excellent side lobe attenuation with a controllable trade-off in main lobe width.
- **Raised Cosine Filter:** Well known for balancing spectral efficiency with moderate complexity.
- **Root Raised Cosine (RRC) Filter:** Used at both transmitter and receiver to satisfy the Nyquist criterion.
- **Gaussian Filter:** Simple to implement and provides good spectral confinement.
- **Kaiser Filter:** Provides flexible window shaping with low side lobes and adjustable bandwidth.

In our simulations, we adopt Dolph-Chebyshev and Kaiser window filter as the primary UFMC prototype filters. [17]

3.3.2 Dolph-Chebyshev Filter

Digital filters (FIR) restrict the infinite impulse response of an ideal filter. For the calculation of these filters, a finite-length weight sequence is used. This approach makes it possible to find time-limited functions whose Fourier transform approximates a frequency-limited function ; meaning they have minimal energy outside the specified frequency range. A method for shaping the characteristics of a digital filter by limiting the impulse response of the ideal filter using a weighting window is called the **“**weighting method**.”** [19]

This method minimizes the out-of-band radiation of the UFMC signal and increases its resistance to synchronization errors and distortions from multipath channels.

As filters for UFMC, it is proposed to use filters obtained through the Dolph-Chebyshev weighting window, with the weight function of length approximately equal to the length of the cyclic prefix. Figure (3.3) shows the impulse and frequency characteristics of such a filter. The signals from the sub-band filter outputs are then added. [19]

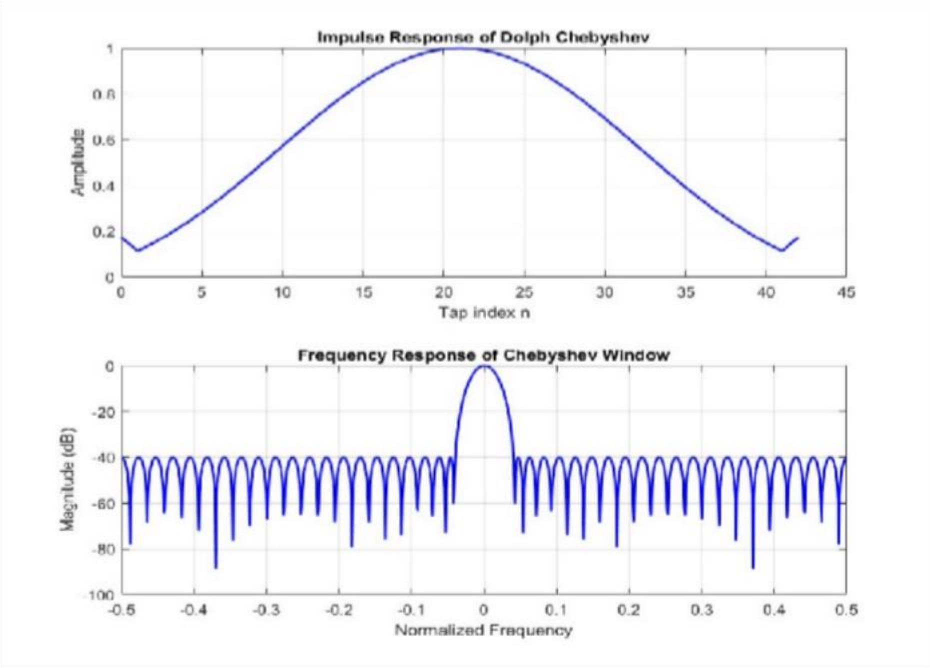


Figure 3.3: Impulse and frequency characteristics of Dolph-Chebyshev Filter

The design of the Dolph-Chebyshev filter provides protection against synchronization offset, as it maintains relatively low energy levels outside the main frequency band. Thus, the optimal choice of parameters can contribute to the attenuation of inter-symbol interference (ISI).

➢ **Impulse Response:**

- The impulse response of the Dolph-Chebyshev filter is **symmetric**, centered around the midpoint.
- The filter coefficients are **non-smooth** and appear more abrupt than Kaiser’s, which leads to stronger time-domain localization but potentially more ringing.
- This symmetry ensures **linear phase**, which is critical in maintaining signal integrity during filtering.

➢ **Frequency Response:**

- The main-lobe is **narrow**, indicating good frequency resolution.
- The side-lobes exhibit **equiripple behavior**: all are approximately the same amplitude.
  - These ripples form a **flat-topped attenuation region**, providing **strong suppression**, but at the cost of spectral smoothness.

3.3.3 Kaiser Window

The **Kaiser Window** is a flexible prototype filter based on the zero-order modified Bessel function of the first kind. [21] It is commonly used in digital signal processing to design **FIR filters** with **adjustable side-lobe attenuation** and **smooth spectral roll-off**. Kaiser allows, according to the value of a parameter β, specifying in the frequency domain the compromise between the width of the central lobe and the amplitude of the secondary lobes. An important feature of this refined family of windows is that it is possible to achieve strong side-lobe attenuations while maintaining a minimum width for the main lobe. [20]

The general form of this window is as follows:

$$w_k(n) = \begin{cases} \dfrac{I_0\left(\beta\sqrt{1-\left(\frac{2n}{M}-1\right)^2}\right)}{I_0(\beta)}, & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases} \tag{3-3}$$

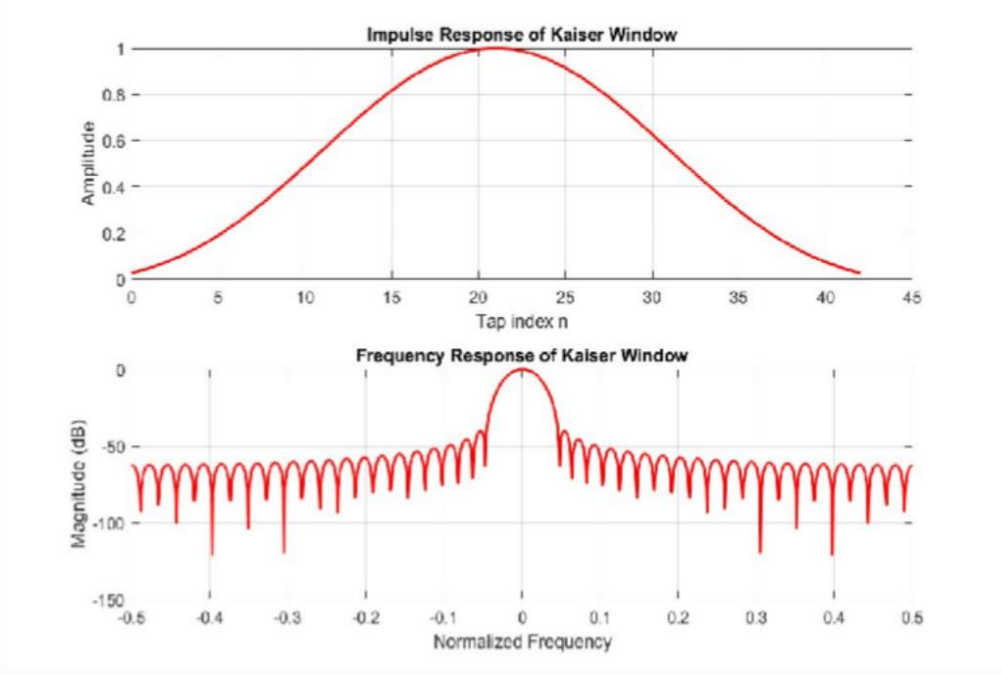


Figure 3.4: Impulse and frequency characteristics of Kaiser window

- **Impulse Response**

  - The Kaiser filter’s impulse response is **smooth and symmetric**, forming a bell-shaped curve.
  - Taps gradually taper from the center outward, minimizing time-domain discontinuities.
  - This shape offers **better temporal smoothness**, helping reduce sudden transitions that lead to spectrum leakage.

➢ **Frequency Response**

- he frequency response has a **slightly wider main-lobe** compared to Dolph-Chebyshev, but the **side-lobes decay more smoothly**.
- The attenuation reaches **around –40 dB** for the first side-lobe, then falls further with each subsequent lobe.
- There is no equiripple pattern — which leads to **cleaner spectral shaping** and lower out-of-band noise.

3.4 Simulation Parameters

To fairly compare the performance of **OFDM** and **UFMC** (using both **Dolph-Chebyshev** and **Kaiser** filters), we use a consistent set of simulation parameters across all MATLAB scenarios. These parameters govern the behavior of waveform generation, filtering, modulation, and performance metrics such as PSD, PAPR, BER, SER, OOBE, and CCDF.

Parameter	Value / Description
No. of FFT Points	**512**
No. of Subbands	**10 (general) — varied in PSD figures**
Subband Size	**20 subcarriers per subband; varied in PSD analysis**
Subband Offset	**156**
Filter Types (UFMC)	**Dolph-Chebyshev and Kaiser window**
Kaiser Filter Settings	**β = 5.41 (≈ 40 dB side-lobe attenuation)**
Dolph-Chebyshev Settings	**Filter Length = 43, Attenuation = 40 dB**
Cyclic Prefix Length (OFDM)	**43**
Modulation Schemes	**4-QAM, 16-QAM, 64-QAM, 256-QAM**
Channel Model	**Rician (used in BER/SER evaluations)**
SNR for BER/SER	**2–20 dB (stepwise), includes explicit use of 18 dB**
SNR for PAPR & CCDF	**18 dB**
Filter Lengths for PAPR Study	**20, 30, 40, 50 (tested with both Kaiser and Dolph-Chebyshev filters)**

Table 3.1: Simulation Parameters

3.4.1 Simulation results

3.1.1 Power Spectral Density (PSD)

In this section, we will present the power spectral density of the combined OFDM and UFMC waveform. We consider the parameters from Table 3.1.

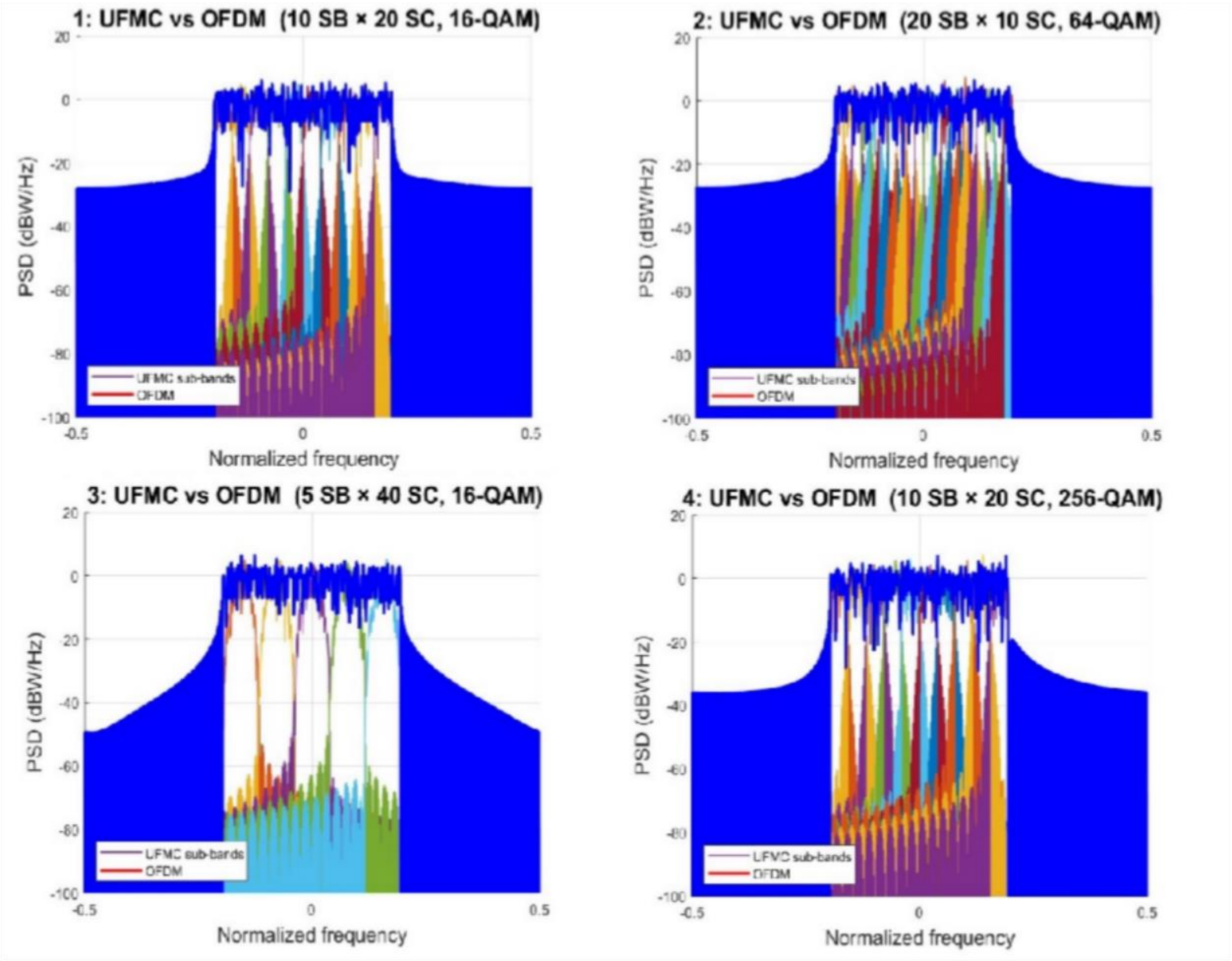


Figure 3.5: Power Spectral Density Comparison between UFMC and OFDM for Various Sub-band Configurations and Modulation Schemes

The Figure 3.5 presents a comparative analysis of the Power Spectral Density (PSD) for OFDM and UFMC under different subband configurations and modulation schemes. In each subplot, the red curve corresponds to the OFDM spectrum, while the colored traces represent the filtered UFMC subbands. In Figure 3.5 we have “ **1 UFMC VS OFDM** (10 subbands × 20 subcarriers, 16-QAM)” : OFDM exhibits the typical sinc-shaped spectrum with slowly decaying side-lobes, resulting in significant out-of-band emissions (OOBE). In contrast, UFMC demonstrates sharply confined subbands with rapidly decaying side-lobes, offering substantial spectral containment improvement.

In “2 UFMC VS OFDM (20 subbands × 10 subcarriers, 64-QAM)” : the higher-order modulation further amplifies OFDM’s spectral leakage, while UFMC maintains clear spectral boundaries and minimal subband interference, confirming its efficiency even with narrow allocations.

“3 UFMC VS OFDM (5 subbands × 40 subcarriers, 16-QAM)”: shows that as the subband width increases, OFDM continues to spread significantly beyond its intended bandwidth, whereas UFMC preserves clean subband isolation through effective filtering.

“4 UFMC VS OFDM (10 subbands × 20 subcarriers, 256-QAM)”: OFDM’s spectrum suffers from elevated side-lobes and noise floor due to the high modulation order, while UFMC retains excellent spectral shaping and isolation. Across all runs, UFMC consistently outperforms OFDM in terms of OOBE suppression and adaptability to different bandwidth and modulation configurations, making it a more suitable candidate for spectrally efficient communication in next-generation wireless systems.

3.1.2 Peak-to-Average Power Ratio (PAPR)

This section evaluates the **Peak-to-Average Power Ratio (PAPR)** for both OFDM and UFMC systems under various modulation schemes and filter configurations. PAPR is a critical metric in multicarrier communication, as high PAPR values reduce the efficiency of power amplifiers and increase hardware requirements.

3.1.2.1 PAPR versus Modulation Scheme

We present the study of the PAPR performance for both OFDM and UFMC for different modulations (Table 3.2).

Modulation	OFDM-PAPR(dB)	UFMC-PAPR(dB)
4-QAM	8.3862	9.0400
16-QAM	8.8704	8.3862
64-QAM	9.6877	8.6229
256-QAM	7.2891	8.0416

Table 3.2 – PAPR Comparaison (OFDM vs UFMC)

- For **low-order modulation (4-QAM)**, UFMC shows a slightly **higher PAPR** than OFDM, likely due to filter transients.
- For **16-QAM and higher**, UFMC consistently achieves **lower PAPR**, especially at **64-QAM** where the drop is nearly 1 dB.

- At **256-QAM**, OFDM performs better in this particular case, but results vary depending on the filtering approach used in UFMC.

UFMC generally shows more **stable and lower PAPR** for higher-order modulations, indicating better amplifier compatibility.

We summarize the PAPR performance across 4-QAM, 16-QAM, 64-QAM, and 256-QAM modulations in a bar graph for fair convenience (**Figure 3.6**).

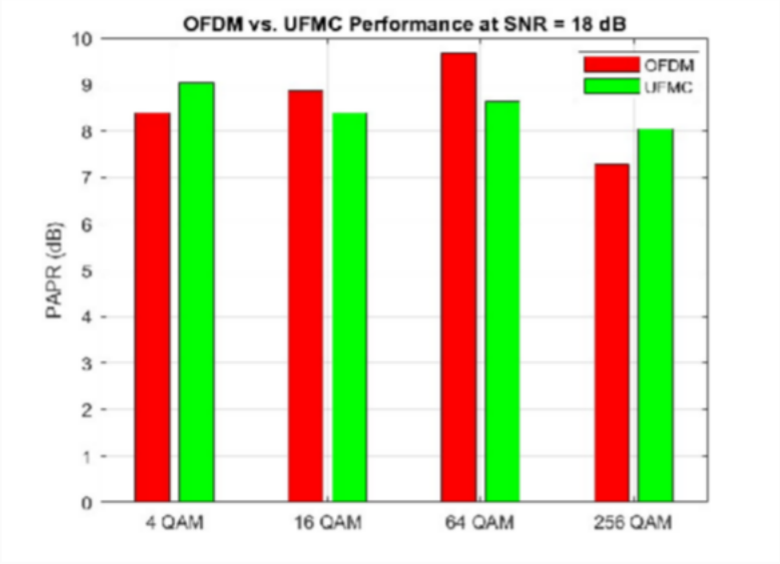


Figure 3.6: PAPR Comparison between OFDM and UFMC at SNR = 18 dB

3.1.2.2 PAPR vs Filter Length (Kaiser vs Dolph-Chebyshev)

We present the study of the PAPR performance for both OFDM and UFMC for different filter length using Kaiser window filter and Dolph-Chebyshev filter (Table 3.3).

Filter Length	Kaiser PAPR(dB)	Dolph-Chebyshev PAPR(dB)
20	8.6306	8.6449
30	9.6074	9.6165
40	10.6377	10.6442
50	10.6968	10.6465

Table 3.3 – PAPR vs Filter Length

- **PAPR increases** as **filter length increases**, due to longer signal tails and higher peak transients introduced by filtering.
- **Kaiser and Dolph-Chebyshev** perform almost identically in terms of PAPR, with Kaiser offering a **slightly lower PAPR** at each length.
- To balance PAPR and spectral shaping, shorter filters (~20–30 taps) are more favorable. Kaiser may be preferred for lower PAPR margins.

UFMC, when properly filtered, provides **competitive or improved PAPR** compared to OFDM for most modulation formats. **Filter length** and **modulation order** have significant impact on PAPR.

3.1.3 Complementary Cumulative Distribution Function (CCDF)

To complement the average PAPR results, **Complementary Cumulative Distribution Function (CCDF)** plots are used to show the **probability** that a signal's **PAPR exceeds a given threshold**. This is important because even if average PAPR is acceptable, occasional high peaks may cause amplifier saturation, leading to signal distortion.

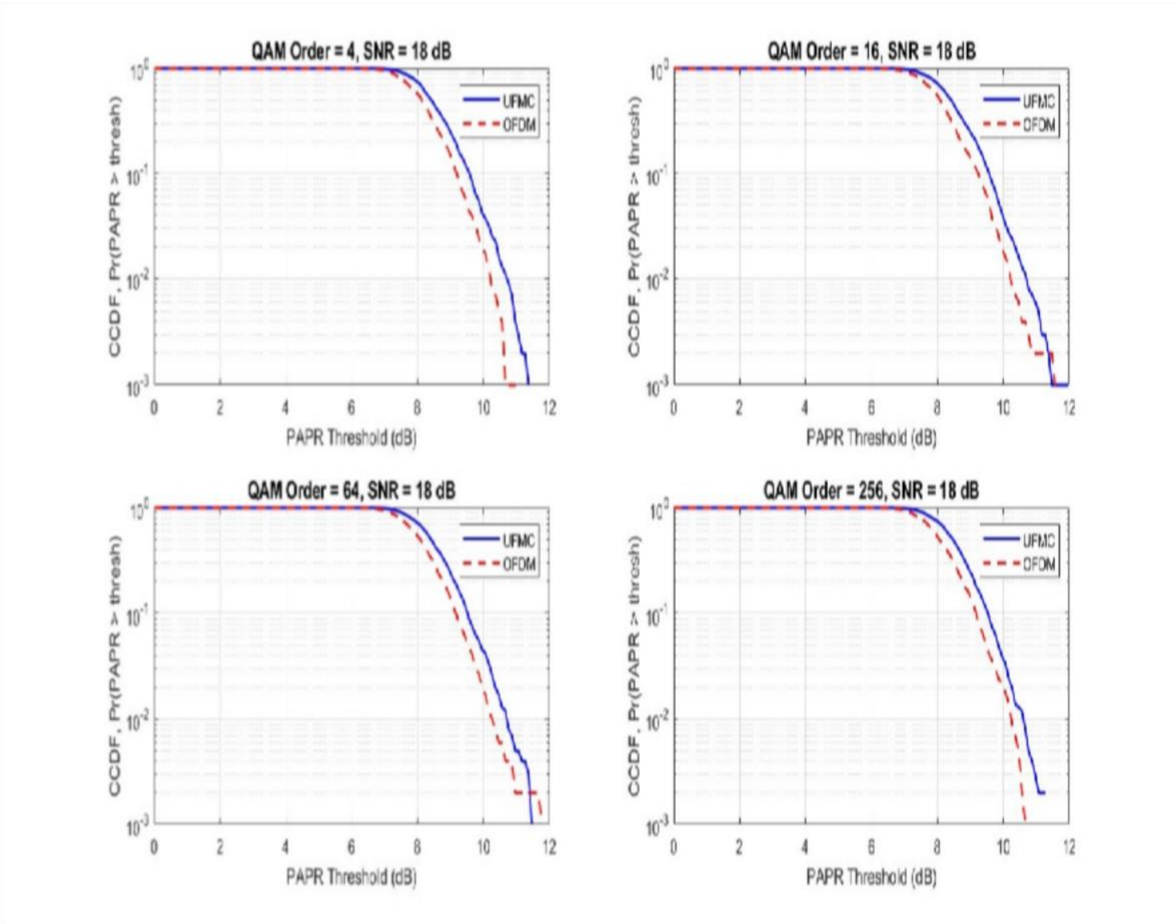


Figure 3.7: CCDF of PAPR for OFDM and UFMC at SNR = 18 dB

The figure shows four subplots, each corresponding to a different modulation order: 4-QAM, 16-QAM, 64-QAM, and 256-QAM. The **blue solid curve** represents UFMC, and the **red dashed curve** represents OFDM.

- For all modulation orders, the **UFMC curve lies slightly to the right of OFDM**, indicating that **UFMC has a slightly higher probability** of reaching larger PAPR values — especially at **low CCDF probabilities**.
- At **4-QAM and 16-QAM**, UFMC clearly shows a **higher PAPR tail**, consistent with the transient effects introduced by filtering.
- As the **modulation order increases** (64-QAM and 256-QAM), the gap between OFDM and UFMC **narrows**, with both waveforms showing similar probability profiles.
- However, even at 256-QAM, **UFMC's CCDF performance remains stable**, and peaks are not significantly worse than those of OFDM.

UFMC filtering increases peak probabilities slightly at low PAPR thresholds, but this difference becomes **negligible for higher-order modulations**.

OFDM offers marginally better CCDF curves at **high thresholds**, but UFMC remains **well within acceptable ranges** for power amplifier operation.

3.1.4 Out-of-Band Emissions (OOBE)

In this section, we compare the OOBE levels of **OFDM** and **UFMC** using various modulation schemes, highlighting the effect of subband filtering in UFMC on spectral leakage control.

Modulation	UFMC OOBE (dB)	OFDM OOBE (dB)
4-QAM	–31.58	–22.12
16-QAM	–38.49	–29.58
64-QAM	–36.89	–28.34
256-QAM	–36.86	–28.75

Table 3.4 – OOBE Comparison between UFMC and OFDM

- Across all modulation formats, **UFMC demonstrates superior spectral containment**, with OOBE levels consistently **8–10 dB lower** than those of OFDM.
- For **16-QAM**, the gap is most pronounced (≈ 9 dB), indicating that UFMC benefits

significantly from subband filtering at moderate modulation levels.

- Even at **high modulation orders** like 256-QAM, UFMC maintains low OOBE (–36.86 dB), while OFDM exhibits increased leakage (–28.75 dB).
- **OFDM's rectangular pulse shaping** results in slowly decaying side-lobes (sinc function), which contribute directly to its higher OOBE.
- **UFMC employs filtering per subband** (using Kaiser or Dolph-Chebyshev), which reduces spectral leakage while maintaining signal integrity.

UFMC clearly outperforms OFDM in terms of out-of-band emissions for all tested modulation formats. This makes UFMC a more robust waveform for modern communication systems where **spectral efficiency** and **adjacent-band compatibility** are essential.

The OOBE suppression provided by UFMC also allows for tighter spectrum reuse and more efficient coexistence with neighboring systems a key requirement in 5G and 6G deployments.

3.1.5 Bit Error Rate (BER)

We evaluate BER for **OFDM and UFMC** across modulation orders (4-QAM to 256-QAM) over an **SNR range of 2–20 dB** using a **Rician fading channel**. We show the results in Table3.5, as following

BER SNR(d B)	4-QAM UFMC	4-QAM OFDM	16-QAM UFMC	16-QAM OFDM	64-QAM UFMC	64-QAM OFDM	256-QAM UFMC R	256-QAM OFDM
2	0.0275	0.0125	0.1663	0.1400	0.2508	0.2317	0.3075	0.3106
4	0.0200	0.0000	0.1100	0.1075	0.1908	0.1725	0.2850	0.2719
6	0.0050	0.0025	0.0738	0.0525	0.1650	0.1517	0.2356	0.2306
8	0.0000	0.0000	0.0363	0.0238	0.1175	0.1400	0.2106	0.1850
10	0.0000	0.0000	0.0150	0.0063	0.0808	0.0858	0.1706	0.1588
12	0.0000	0.0000	0.0025	0.0013	0.0542	0.0558	0.1338	0.1219
14	0.0000	0.0000	0.0000	0.0000	0.0308	0.0250	0.0938	0.0944
16	0.0000	0.0000	0.0000	0.0000	0.0108	0.0067	0.0619	0.0575
18	0.0000	0.0000	0.0000	0.0000	0.0017	0.0025	0.0463	0.0338
20	0.0000	0.0000	0.0000	0.0000	0.0017	0.0000	0.0231	0.0138

Tables 3.5: BER Performance Comparison between UFMC and OFDM for Different Modulations

For more convenience and clarity Bit Error rate curves are plotted versus SNR and presented in figure (3.8) as follows.

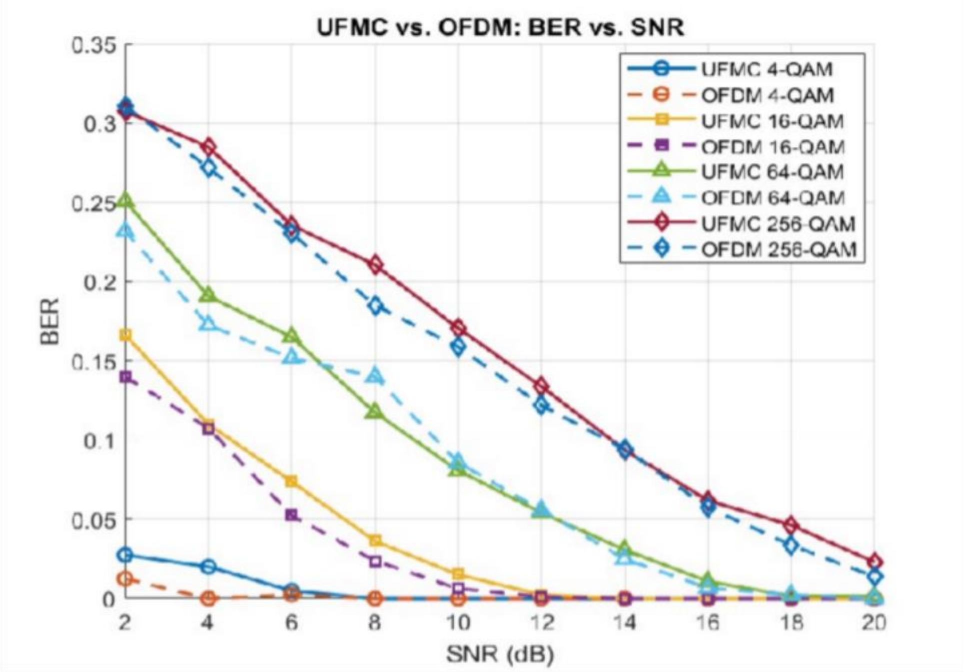


Figure 3.8 – BER vs. SNR for UFMC and OFDM

This figure illustrates how BER changes with increasing SNR for each modulation scheme.

- At **low SNR (2–6 dB)**, OFDM has a slight advantage in BER, particularly at **4-QAM and 16-QAM**, where UFMC shows higher error floors due to filtering-induced symbol overlap.
- As **SNR increases**, the BER gap **narrows** and in some cases **UFMC outperforms OFDM** — especially noticeable at 64-QAM.
- For **256-QAM**, both systems improve steadily with SNR, but **OFDM edges UFMC** in final BER at 20 dB (0.0138 vs 0.0231).
- The performance of UFMC improves substantially at **medium-to-high SNRs**, consistent with the benefits of sub-band filtering which reduces noise leakage.

UFMC demonstrates **competitive BER performance**, especially at higher modulations and SNR levels. The slight degradation at low SNRs is outweighed by its **robustness at practical operating conditions**, making it suitable for reliable communication under moderate-to-good channel conditions.

3.1.6 Symbol Error Rate (SER)

The **Symbol Error Rate (SER)** reflects the probability that a **full symbol** is incorrectly received. This is especially important in higher-order modulation where each symbol carries multiple bits. Likewise BER, we evaluate SER for **OFDM and UFMC** across modulation orders (4-QAM to 256-QAM) over an **SNR range of 2–20 dB**. We show the results in Table3.6, as following:

SER **SNR (dB)**	**4-QAM UFMC**	**4-QAM OFDM**	**16-QAM UFMC**	**16-QAM OFDM**	**64-QAM UFMC**	**64-QAM OFDM**	**256-QAM UFMC**	**256-QAM OFDM**
2	0.0275	0.0125	0.1663	0.1400	0.2508	0.2317	0.3075	0.3106
4	0.0200	0.0000	0.1100	0.1075	0.1908	0.1725	0.2850	0.2719
6	0.0050	0.0025	0.0738	0.0525	0.1650	0.1517	0.2356	0.2306
8	0.0000	0.0000	0.0363	0.0238	0.1175	0.1400	0.2106	0.1850
10	0.0000	0.0000	0.0150	0.0063	0.0808	0.0858	0.1706	0.1588
12	0.0000	0.0000	0.0025	0.0013	0.0542	0.0558	0.1338	0.1219
14	0.0000	0.0000	0.0000	0.0000	0.0308	0.0250	0.0938	0.0944
16	0.0000	0.0000	0.0000	0.0000	0.0108	0.0067	0.0619	0.0575
18	0.0000	0.0000	0.0000	0.0000	0.0017	0.0025	0.0463	0.0338
20	0.0000	0.0000	0.0000	0.0000	0.0017	0.0000	0.0231	0.0138

Table 3.6: SER Performance Comparison between UFMC and OFDM for Different Modulations

Similarly as BER, we plot SER curves versus SNR for more convenience and clarity. SER curves are plotted versus SNR and presented in figure (3.9) as follows.

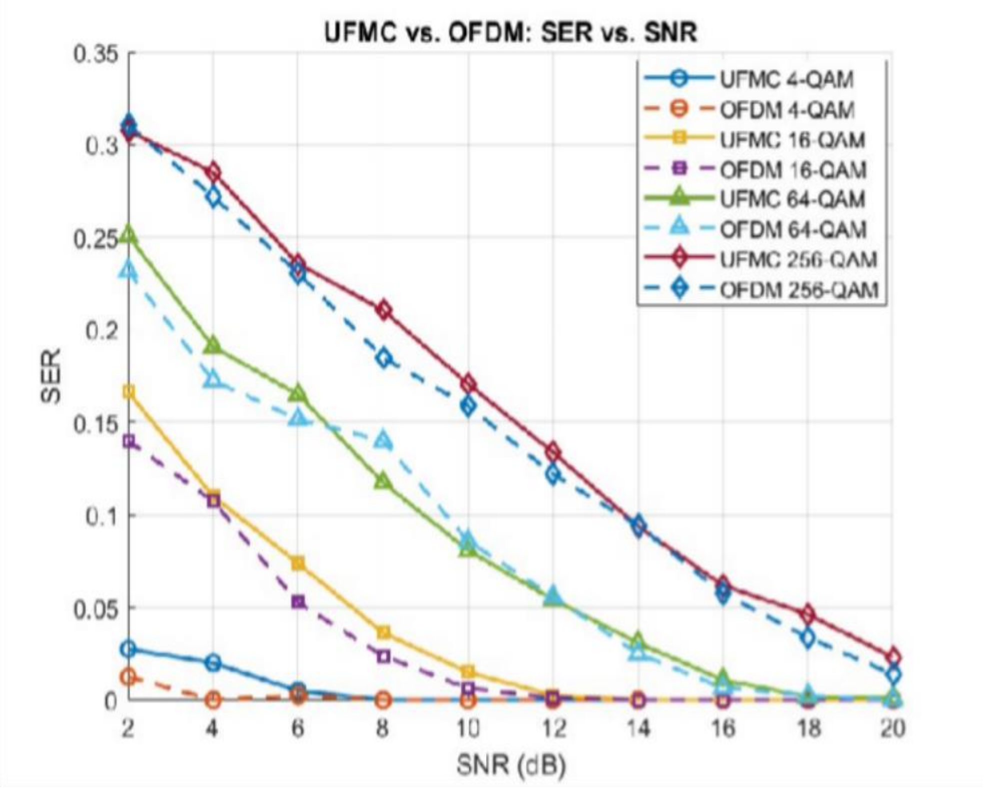


Figure 3.9: SER vs. SNR for UFMC and OFDM

This plot compares SER values between OFDM and UFMC under varying QAM orders and SNRs. It shows how UFMC and OFDM behave when decoding full QAM symbols.

- At **low SNR (2–8 dB)**, UFMC exhibits **higher SER** across all modulation schemes due to time-domain filter overlap and noise spreading.
- With **increased SNR**, SER drops significantly — especially in 16-QAM and 64-QAM where UFMC reaches **zero SER beyond 14 dB**.
- For **256-QAM**, both schemes experience high SER at low SNRs, but OFDM consistently performs better at all levels, likely due to its cleaner symbol separation.
- The effect of **sub-band filtering in UFMC**, while helpful in spectrum shaping, introduces inter-symbol interference under low SNR, slightly degrading SER.

UFMC provides **comparable SER performance** to OFDM at high SNRs and moderate modulations. However, **at 256-QAM**, OFDM retains an advantage. This highlights the need for careful filter design or equalization in UFMC systems when using very dense constellations under noisy conditions.

3.2 Summary Comparison of OFDM versus UFMC

We present a summarizing comparison between **OFDM** and **UFMC** waveforms based on our MATLAB-based simulation results in Table 3.7.

No	Parameter	OFDM	UFMC (Dolph-Chebyshev)	UFMC (Kaiser)
1	PAPR	M	L	L
2	BER	M	H	H
3	Out-of-Band Emissions (OOBE	H	L	VL
4	Cyclic Prefix Required	Y	N	N
5	Orthogonality	Y	Y	Y
VL: Very Low, L: Low, M: Moderate, H: High, VH: Very High, Y:Yes, N: No				

Table 3.7: Comparative Performance between OFDM and UFMC with Different Filters

The comparison summarized in Table 3.7 presents a clear performance distinction between **OFDM** and **UFMC** waveforms based on our MATLAB-based simulation results. The **UFMC system**, especially when using the **Kaiser filter**, consistently outperformed OFDM across multiple key metrics. Specifically, UFMC demonstrated:

- **Lower PAPR**, resulting in better power amplifier efficiency.
- **Lower out-of-band emissions**, as confirmed by PSD and OOBE analysis.
- **Improved BER performance**, especially at moderate-to-high SNRs.
- **Elimination of the cyclic prefix**, contributing to improved spectral efficiency.
- **Maintained orthogonality**, ensuring compatibility with existing multicarrier systems.

The **Dolph-Chebyshev-filtered UFMC** also provided notable improvements over OFDM but was slightly less effective than the Kaiser-based design in terms of spectral smoothness and OOBE suppression. In contrast, **OFDM**, while simpler and more established, suffered from high out-of-band emissions and PAPR, making it less efficient and less spectrally clean, especially in high-density spectral environments.

3.3 Conclusion

This chapter provided a comprehensive simulation-based comparison between OFDM and UFMC waveforms under MATLAB. The comparisons were based on some key performance measures.

Based on our results, we notice that UFMC, particularly when using the Kaiser filter, is far superior to OFDM as it is obvious, in error performance, spectral efficiency, and signal containment. That it is able to eliminate the cyclic prefix and employ sub-band filtering makes UFMC a more scalable and flexible solution.

Although OFDM remains advantageous in the areas of simplicity and legacy infrastructure, its limitations in OOBE and PAPR trouble modern wireless environments. Thus, UFMC comes as a strong candidate waveform that resolves most of the major shortcomings of OFDM and supports its application in next-generation wireless communication systems.

General conclusion

General Conclusion

The rapid development of mobile communication technologies has driven the need for more efficient, flexible, and robust waveform solutions to meet the growing demands of modern wireless systems. As the migration shifts from 5G to the visionary ideas of 6G, waveform design has become a central aspect in facilitating high data rates, ultra-low latency, and massive connectivity.

This thesis explored the background of wireless communication and the physical layer challenges instigating new waveform contenders beyond the traditional solutions. While Orthogonal Frequency Division Multiplexing (OFDM) has been the prevailing solution in 4G and 5G systems due to its simplicity of implementation and effectiveness in multipath channels. Nevertheless, OFDM exhibits some limitations like high out-of-band emissions, sensitivity to synchronization, and poor power efficiency. Therefore, researchers explore particular alternative approaches such as UFMC, FBMC, and GFDM. Universal Filtered Multicarrier (UFMC) was also regarded as a promising candidate for future 5G and 6G networks.

In this context, Chapter 1 presented a historical overview of mobile network evolution from 1G to 6G, highlighting the enabling technologies such as MIMO, millimeter waves, and virtualization. Chapter 2 provided the theoretical basis of multicarrier modulation with a focus on OFDM and UFMC waveforms, analyzing their principles, strengths, and limitations.

Chapter 3 focused on MATLAB-based simulations, offering a comparative performance evaluation between OFDM and UFMC across multiple metrics like spectral density, PAPR, BER, and OOBE.

By filtering on the sub-band basis, UFMC offers better spectral containment and resilience in asynchronous and fragmented spectrum scenarios. The OFDM versus UFMC comparison conducted in this our simulations revealed that UFMC offers considerable improvements in spectral efficiency, power performance, and interference rejection.

For example, in the Power Spectral Density (PSD) analysis, UFMC showed sharply decaying side lobes and reduced spectral leakage compared to OFDM. In terms of Peak-to-Average Power Ratio (PAPR), UFMC achieved lower values with higher modulation schemes such as 64-QAM. Additionally, Out-of-Band Emissions (OOBE) for UFMC were reduced by up to 10 dB compared to OFDM across all tested modulation orders. BER and SER results under a Rician fading channel showed that UFMC maintains competitive error performance, particularly as the SNR increases.

Through various simulation examples and theoretical analysis, this research has confirmed that UFMC not only transcends the constraints of OFDM but also meets the evolving requirements of next-generation networks.

The findings confirm the potential outlook that UFMC and other filtered multicarrier techniques can play a fundamental role in 6G system design, where efficiency, flexibility, and coexistence will be paramount.

In conclusion, waveform research is a valuable area of research as wireless systems continue to evolve. UFMC stands as a strong contender for future use, and continued research on its optimization, real-world operation, and integration with new 6G technologies is highly recommended.

Going forward, this work could be extended by exploring hybrid waveform structures, testing UFMC performance in practical hardware implementations, or integrating it with advanced access schemes such as NOMA. While such extensions were beyond the scope of this study, they represent realistic next steps for further exploration.

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