

*DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA*

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH  
UNIVERSITY OF MOHAMED BOUDIAF - M'SILA

**FACULTY : TECHNOLOGY**

**DEPARTEMENT : ELECTRONICS**



**FIELD : SCIENCE & TECHNOLOGIE**

**SECTION : TELECOMMUNICATIONS**

**SPECIALTY : STLC**

**Thesis submitted for the award of  
the Academic Master's degree**

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**Titled**

**Performance Analysis of OTFS Modulation for  
Wireless Communication system**

**Defended before the jury composed of:**

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**Academic year : 2025 / 2026**



## Acknowledgments

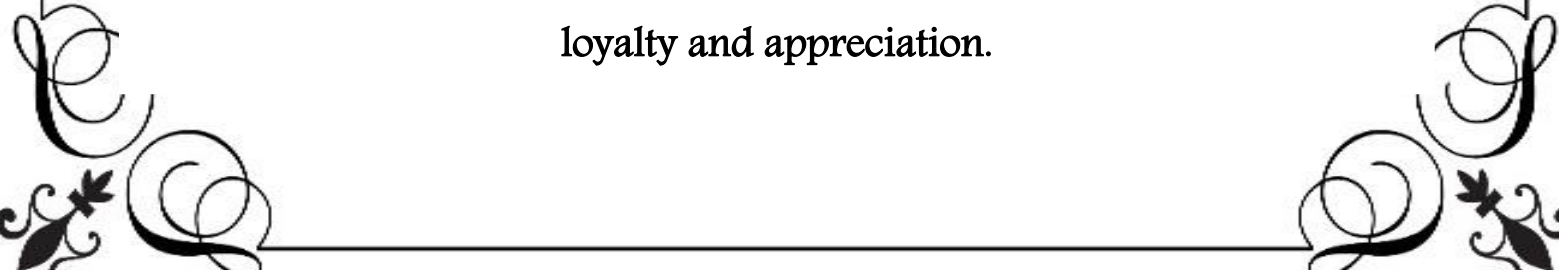
After a long journey of research and hard work, and days where fatigue intertwined with hope, and sleepless nights with ambition, we praise God Almighty for granting us the success to complete this work and helping us overcome all the difficulties we faced in achieving it.

It gives us great pleasure on this occasion to extend our deepest thanks and appreciation to our supervisor, Dr. Zerdoumi Zohra, who was the best guide and supporter. Her valuable guidance, sound advice, and immense patience had a profound impact on the completion of this thesis. He has our utmost respect and profound gratitude.

We also extend our sincere thanks to the esteemed members of the examining committee for agreeing to read and evaluate this work, and to all our honorable professors who instilled in us a love for learning and the pursuit of knowledge.

We must also express our deep gratitude to everyone who supported and accompanied us throughout this journey, whether through an encouraging word, a sincere prayer, or a gesture that lightened the burden of the path.

Finally, gratitude remains insufficient for everyone who has graced us with their kindness. To every heart that believed in us, and to every hand that reached out to help, we dedicate this humble effort as a token of loyalty and appreciation.





## Dedication

To my mother, who carried, raised, and nurtured me; may God prolong  
her life.

To my father, who dedicated his life to illuminating the paths for me;  
may God prolong his life.

To my siblings, my support, my pride, and my strength.

To everyone who lent me a helping hand, even if only with a word of  
guidance or advice, including my classmates, professors, and  
companions on my journey.

To every pure soul that dreamed of reaching serenity and purity.

Herizi Yassine





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Elkali Anwar Ameer



### Abstract:

Orthogonal Time Frequency Space (OTFS) modulation has recently emerged as a promising alternative waveform. OTFS technique operates in the delay-Doppler domain.

Our research presents a comparative study between OFDM and OTFS modulation schemes under time-varying environments. Our experiences are accomplished through MATLAB simulations, where Key performance metrics, including Bit Error Rate (BER), are analyzed over a range of Signal-to-Noise Ratio (SNR) values and Doppler frequencies through selective varying channel models to reflect practical wireless conditions. Through simulations, we show that OFDM performs well in low-mobility scenarios however; its performance deteriorates rapidly as Doppler spread increases. Although, OTFS maintains stable and significantly improved BER performance under high-mobility conditions. Thus reveals OTFS as a strong candidate for modern communication systems.

Keywords: Multicarrier Modulation; Orthogonal Frequency Division Multiplexing (OFDM); Orthogonal Time Frequency Space (OTFS), Delay-Doppler Domain, Wireless Communications.

### المخلص :

برزت تقنية التضمين Orthogonal Time Frequency Space (OTFS) مؤخرًا كإحدى الموجات الحاملة الواعدة لأنظمة الاتصالات الحديثة. تعمل تقنية OTFS في مجال التأخير-دوبلر (Delay-Doppler).

يقدم هذا البحث دراسة مقارنة بين تقنيتي التضمين OFDM و OTFS في البيئات المتغيرة زمنيًا. وقد أُجريت التجارب باستخدام محاكاة عبر برنامج MATLAB، حيث تم تحليل مؤشرات الأداء الرئيسية، وعلى رأسها معدل خطأ البتات (BER)، عبر مجموعة من قيم نسبة الإشارة إلى الضوضاء (SNR) وترددات دوبلر المختلفة، وذلك باستخدام نماذج قنوات انتقائية ومتغيرة تعكس ظروف الاتصالات اللاسلكية الواقعية.

أظهرت نتائج المحاكاة أن تقنية OFDM تحقق أداءً جيدًا في سيناريوهات الحركة المنخفضة، إلا أن أدائها يتدهور بسرعة مع زيادة انتشار دوبلر. في المقابل، تحافظ تقنية OTFS على أداء مستقر ومتفوق بشكل ملحوظ من حيث معدل خطأ البتات (BER) في ظروف الحركة العالية. وتبرز هذه النتائج تقنية OTFS كخيار قوي وواعد لأنظمة الاتصالات الحديثة.

**الكلمات المفتاحية:** التضمين متعدد الحوامل؛ التضمين بتقسيم الترددات المتعامدة (OFDM)؛ التضمين الزمني-التردد المتعامد (OTFS)؛ مجال التأخير-دوبلر؛ الاتصالات اللاسلكية.

### **Résumé:**

La modulation Orthogonal Time Frequency Space (OTFS) est récemment apparue comme une forme d'onde prometteuse pour les systèmes de communication modernes. La technique OTFS fonctionne dans le domaine délai-Doppler.

Notre recherche présente une étude comparative entre les schémas de modulation OFDM et OTFS dans des environnements à variation temporelle. Les expériences ont été réalisées à l'aide de simulations sous MATLAB, où les principaux indicateurs de performance, notamment le taux d'erreur binaire (BER), ont été analysés pour différentes valeurs du rapport signal sur bruit (SNR) et de fréquences Doppler, en utilisant plusieurs modèles de canaux afin de refléter des conditions de communication sans fil réalistes.

Les résultats des simulations montrent que l'OFDM offre de bonnes performances dans les scénarios à faible mobilité. Cependant, ses performances se dégradent rapidement lorsque l'étalement Doppler augmente. En revanche, l'OTFS maintient des performances BER stables et nettement meilleures dans les conditions de forte mobilité. Ces résultats révèlent que l'OTFS constitue un candidat très prometteur pour les systèmes de communication modernes.

**Mots-clés :** Modulation multiporteuses ; Multiplexage par répartition orthogonale de fréquences (OFDM) ; Orthogonal Time Frequency Space (OTFS) ; Domaine délai-Doppler ; Communications sans fil.

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## *List of Abbreviations*

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### *List of Abbreviations*

**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.

**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.

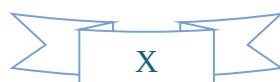
**F-OFDM:** Filtered Orthogonal Frequency Division Multiplexing.

**GFDM:** Generalized Frequency Division Multiplexing.

**Gbps:** Gigabits per second.

**GPRS:** General Packet Radio Service.

**GSM:** Global System for Mobile Communications.



## *List of Abbreviations*

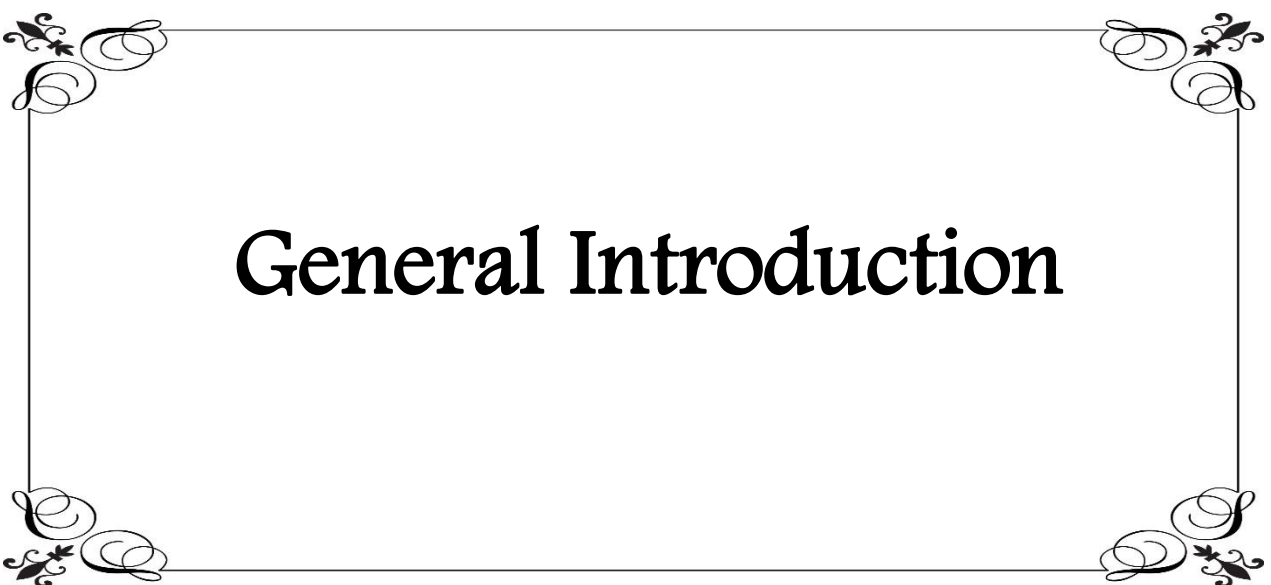
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- HSPA:** High-Speed Packet Access.
- HSPA+:** Evolved High-Speed Packet Access.
- ICI:** Inter Carrier Interference.
- IDFT:** Inverse Discrete Fourier Transform.
- IEEE:** Institute of Electrical and Electronics Engineers.
- IES/ISI:** Inter Symbol 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.

## *List of Abbreviations*

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- 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.
- ISFFT :** Inverse Symplectic Finite Fourier Transforme.
- SFFT :** Symplectic Finite Fourier Transforme.
- DD :** Delay-Doppler.
- TF :** Time-Frequency.
- TD :** Time Domain



# General Introduction

## General Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is the baseline modulation scheme used in 4G and 5G wireless systems [1]. It divides the available bandwidth into multiple orthogonal

subcarriers, allowing high data rates and efficient spectral use. Key features of OFDM include: High Spectral Efficiency: Multiple carriers are transmitted simultaneously without interference.

Resistance to Multipath Fading: Thanks to the use of cyclic prefix (CP), it reduces Inter-Symbol Interference (ISI). Simple Equalization: Operates efficiently with Fast Fourier Transform (FFT) techniques [2]. However, OFDM suffers from: High Peak-to-Average Power Ratio (PAPR): Requiring linear and power-hungry amplifiers. Sensitivity to Frequency Offset and Phase Noise. These drawbacks motivate the exploration of alternative waveforms better suited for 5G and 6G requirement [1] [2].

The rapid evolution of wireless communication systems toward high data rates and high-mobility scenarios has revealed OFDM limitation, through high Doppler spread and time-varying channels [1]. Doppler effects lead to a loss of orthogonality and causes severe degradation in system performance [2]. OTFS has recently emerged as a promising waveform, it operates in the delay-Doppler domain, thus transforms a rapidly time-varying channel into a quasi-static channel [3].

More recently, research has focused on integrating OTFS into modern wireless systems, including high-speed vehicular communications. Despite its promising performance, challenges remain in terms of receiver complexity, channel estimation, and practical waveform design [3] [4].

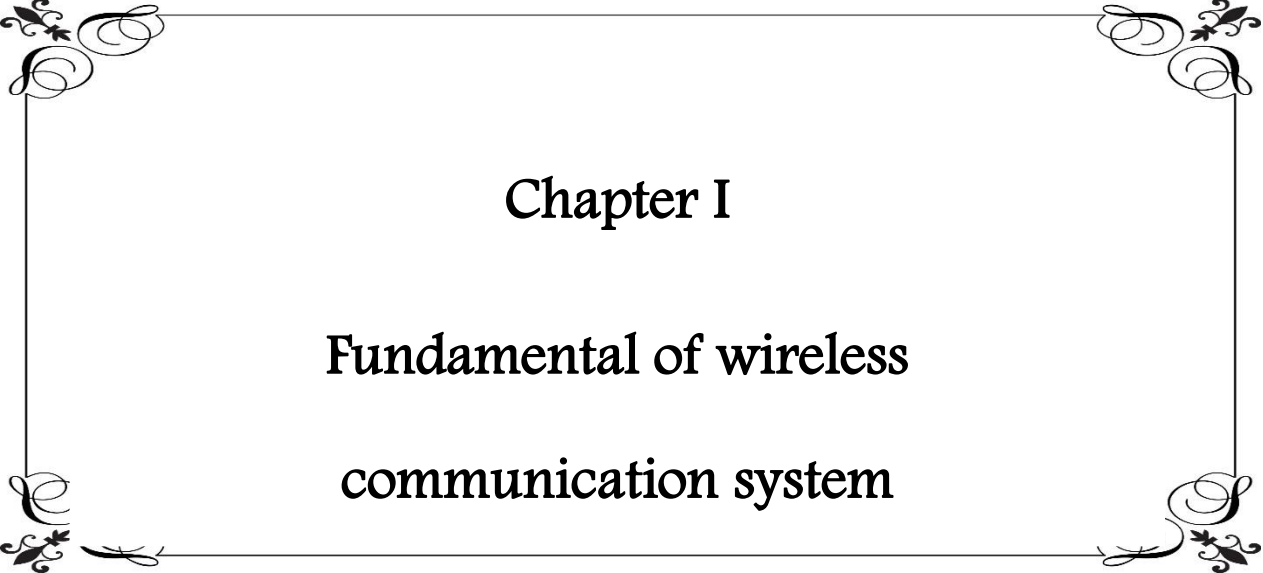
Subsequent works have demonstrated the advantages of OTFS in terms of robustness to Doppler spread, improved bit error rate (BER), and enhanced diversity gain [3,4].

In our research, we present a comprehensive comparison between OFDM and OTFS, focusing on their performance under doubly selective channels. The analysis highlights the limitations of OFDM in rapidly time-varying environments and demonstrates how OTFS overcomes these limitations through its Delay-Doppler domain processing.

## General Introduction

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- We split this thesis work into three central chapters as follows:
- **Chapter 1** describe a general overview of wireless telecommunications it provides an evolution of mobile networks from 1G to 6G.
- **Chapter 2** covers the theoretical foundations of OFDM and OTFS, conversing their principles, advantages, limitations, and applications in modern communication systems. It also gives a insight on others waveforms.
- **Chapter 3** presents a comparative assessment based on MATLAB simulations, emphasizing the performance of OFDM and OTFS across various modulation schemes and channel conditions.



# Chapter I

## Fundamental of wireless communication system

## I.1 Introduction

The history of wireless communication began with Marconi's wireless telegraph in the 19th century [5], subsequently gradually shifted towards 1G analog networks for voice transmission. The advent of digitization, offering data-based and encryption-based services, signaled the launch of 2G networks. The 3G era enabled the emergence of various data services such as internet browsing and video calls, while 4G/LTE networks, introduced in 2009, radically transformed data transmission. In terms of technology and commerce, 4G revolutionized society through the use of smartphones and advanced information technologies [6].

This chapter provide a general overview of wireless telecommunications, highlighting key challenges such as multipath propagation, Doppler effects, and different types of interference. We also trace the evolution from 1G to 6G. Finally, describe a performance measurement and evaluation metrics.

## I.2 The evolution of wireless network

Wireless networks have undergone a very significant evolution since the deployment of the first mobile network in the United States in the 1970s. In the following we present a brief history of this evolution.



**Figure 1.1:** Evolution of mobile networks from 1G to 6G

### I.2.1 Main invention of the first Generation (1G)

First generation (1G) represents the initial stage of wireless communication technologies. In 1982, the Advanced Mobile Phone System (AMPS) was launched as the first standard for this generation, Operating within a 40 MHz frequency band within the 800-900 MHz range [7].

First generation (1G) of mobile technology emerged as an alternative to zero generation (0G) technology, encompassing mobile cellular phones and various technologies such as the Mobile Telephone System (MTS), the Advanced Mobile Telephone System (AMTS), the Enhanced Mobile Telephone Service (IMTS), and Push-to-Talk (PTT) [7].

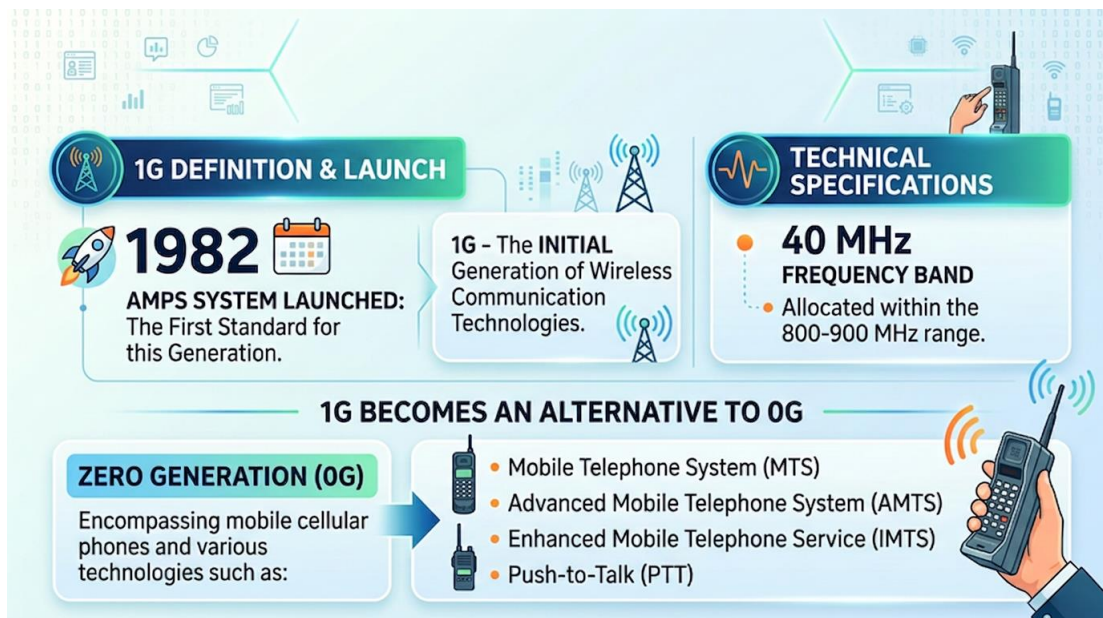


**Figure 1.2:** Main innovationn of the first Generation (1G)

### I.2.2 Key innovation of the Second Generation (2G)

The second generation was digital. Besides improved sound quality, it introduced smaller handsets and ensured a higher degree of privacy. In the early 1990s, the GSM (Global System for Mobile Communication) standard was adopted in Europe. Since then, it has become widespread almost everywhere, except in Japan, North and South America, alternative standards prevailed. In France, GSM operates on the 900 and 1800 MHz frequencies. The advent of the first second-generation networks (driven by France Télécom, under the Itinériss brand, and SFR, then Bouygues Telecom) and smaller, lighter handheld devices revolutionized access to mobile telephony and daily life. This new way of making calls gradually became

accessible to everyone. So much so that in 2004, more than 70% of the French population owned a mobile phone, according to the Telecommunications Regulatory Authority.

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

- ✓ GPRS (General Packet Radio Service): Often referred to as 2.5G, it increased data speeds up to 171.2 kbps, enabling basic internet services such as email and web browsing.
- ✓ EDGE (Enhanced Data rates for GSM Evolution): Known as 2.75G, it further enhanced data transfer rates approximately 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 [8] [9].

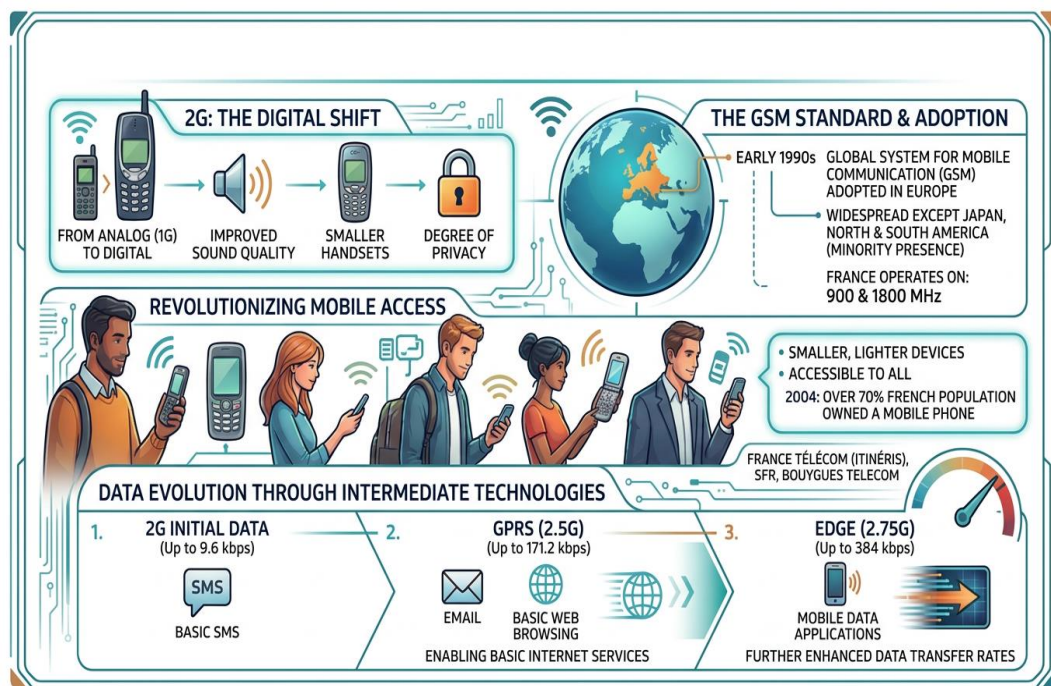


**Figure 1.3: Key innovation of the Second Generation(2G)**

### I.2.3 Basic novelty of the third Generation (3G)

In the fall of 2004, third-generation mobile telephony appeared in France. While not a revolution of the same magnitude as 2G in the 1990s, it marked a significant shift in how users interacted with their devices, high-speed wireless internet access, video calling and video messaging, and television reception on mobile phones.

After much delay, the deployment of third-generation telephony in Europe finally began. The UMTS/W-CDMA standard was chosen for the continent by the 3GPP (Third Generation Partnership Project), an association of major telecommunications organizations. For each mobile operator wishing to participate, this required the purchase of a license issued by the state and the deployment of infrastructure alongside the existing GSM/GPRS network. This represented a capital investment of several billion euros.

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 enabled to access rich multimedia services on mobile devices with considerably improved speed and performance [8] [9].



**Figure 1.4:** Basic novelty of the third Generation (3G)

#### I.2.4 Principal novelty of the fourth Generation (4G)

LTE (4G) technology relies exclusively on packet switching (IP). Unlike 3G, which uses circuit switching for voice, LTE transmits calls solely via Voice over IP (VoIP). Using frequency bands up to 20 MHz, it achieves a theoretical throughput of 300 Mbps, while "true

4G" can reach speeds of up to 1 Gbps. This performance, combined with low latency, is made possible by OFDMA, which optimizes frequencies without interference, and by multi-antenna technology (MIMO), which multiplies the communication channels to boost speed and range. [8]

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 [8] [9].

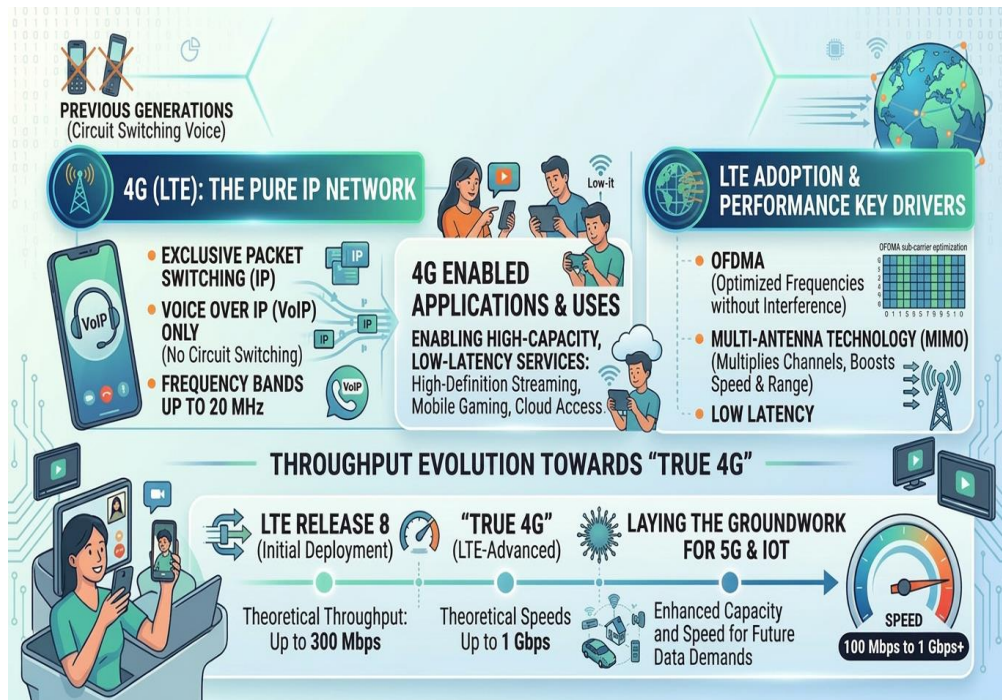


**Figure 1.5:** Principal novelty of the fourth Generation (4G)

### 1.2.5 The revolution of the fifth Generation (5G) Mobile Network

Fifth generation (5G) is the first generation of mobile communications designed for uses other than voice and data. Its commercial launch is planned for 2020. 5G promises speeds up to ten times faster than fourth generation (4G), particularly for ultra-high-speed broadband (eMBB) applications, and sub-millisecond latency ten times better than 4G for mission-critical applications (uRLLC) and a greater number of connected devices for the Internet of Things (mMTC). 5G will have a wider spectrum for its deployment: it will be able to reuse spectrum already allocated to mobile communications, especially the lower bands around 1 GHz, to ensure good coverage. New frequency bands will also be allocated to it, notably in the millimeter wave bands, used for the first time for consumer services, thus increasing capacity.

5G will use OFDMA technology like 4G, but with much greater flexibility in time and frequency allocation to meet the highly diverse needs of users [8].

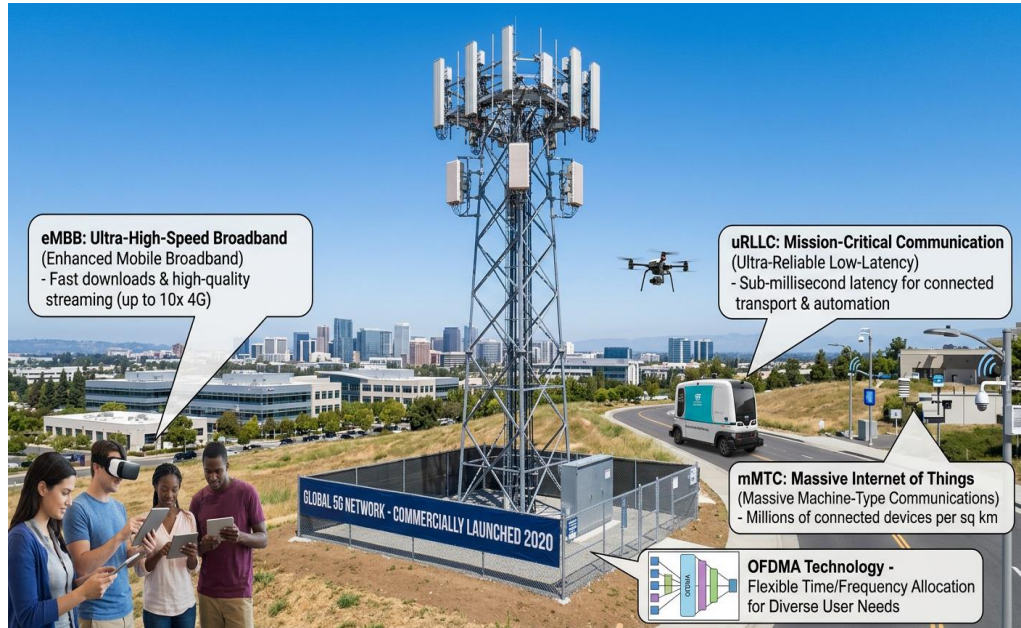


**Figure 1.6:** The revolution of the fifth Generation (5G)

### I.2.6 The future 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.

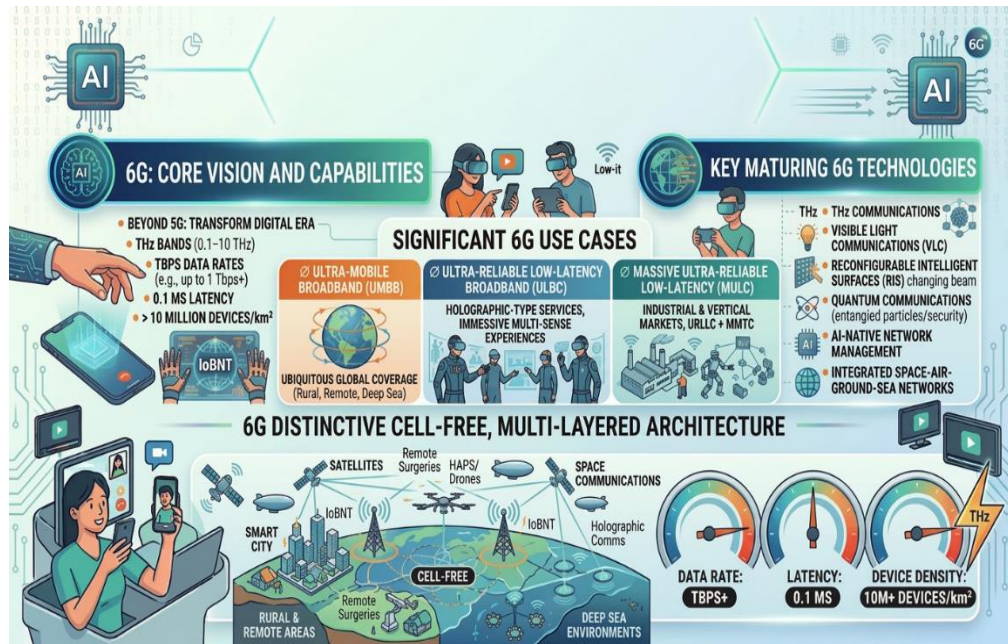


**Figure 1.7:** The abilities of the Sixth Generation (6G)

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.

#### **I.2.6.1 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.

#### **I.2.6.2 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

### **I.2.6.3 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 [8] [10].

**I.2.6.4 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.

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 [10] [11].

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.

The following table summarizes the key performance metrics and technological advancements introduced in each wireless generation:

**Table 1.1:** Comparison of Key Characteristics of 1G to 6G Wireless Networks

| 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 (mm Wave) | 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 |

### **I.3 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 [12].

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.

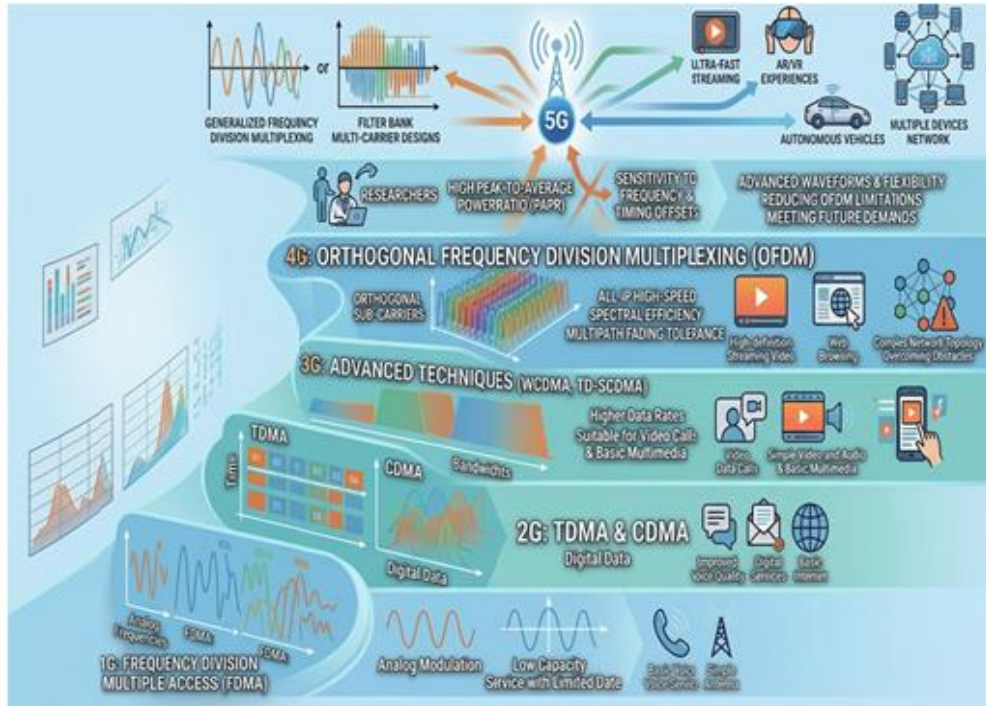


**Figure 1.8:** Evolution of mobile communications waveforms

### I.3.1 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 [12].

#### **I.4 Multicarrier modulation**

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 [12]. This led to the development of improved alternatives waveforms multi-Carrier which will be detailed in chapter II.

#### **I.5 Channel impairments**

The transmitted signal is subject to many phenomena, during its passage through the different parts of a communication system, most of which often have degrading effects on the quality of the signal. These effects may be internal to the system or external, emanating from the propagation medium. They generate distortions of a linear or non-linear nature and the addition of unwanted signals that result in errors in the received messages, leading to loss of information. In what follows, we find certain disruptive effects often encountered in communication systems.

### I.5.1 Multipath Propagation

Channel propagation includes multiple paths due to obstacles surrounding the transmitter and receiver (Figure 1.9). In such cases, multiple replicas of the transmitted signal arrive at the receiver through numerous paths, each experiencing distinct levels of attenuation, phase shift, and delays caused by differences in path lengths.

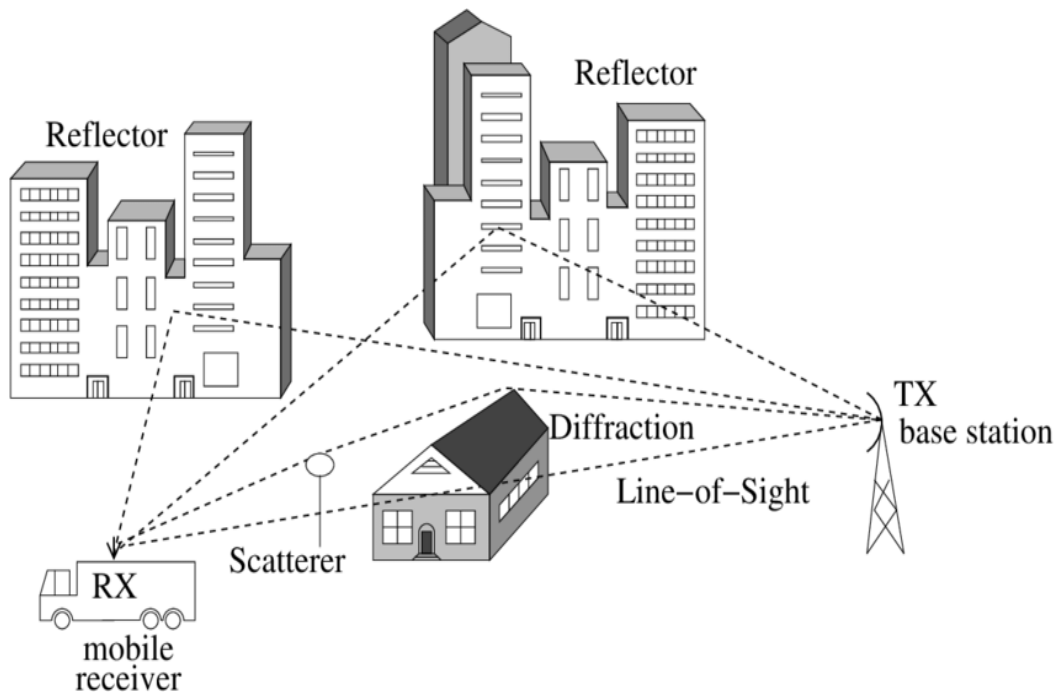


**Figure 1.9:** Multipath propagation

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

Common causes of multipath propagation include:

- Reflection from surfaces (e.g., walls, water, metal objects)
- Refraction through atmospheric layers.
- Scattering by small objects or rough surfaces
- Diffraction around obstacles.

In multipath propagation, two propagation circumstances are commonly distinguished. The first is referred to as NLOS (None Line of Sight) where there is no direct visibility

between the transmitter and the receiver. In this case, the probability density of the fading amplitude of the total received signal follows Rayleigh's law (Figure 1.10)

The second situation will occur when there is a predominant direct path called LOS (Line of Sight) and therefore the fading amplitude is characterized by the Rice distribution (Figure 1.10).

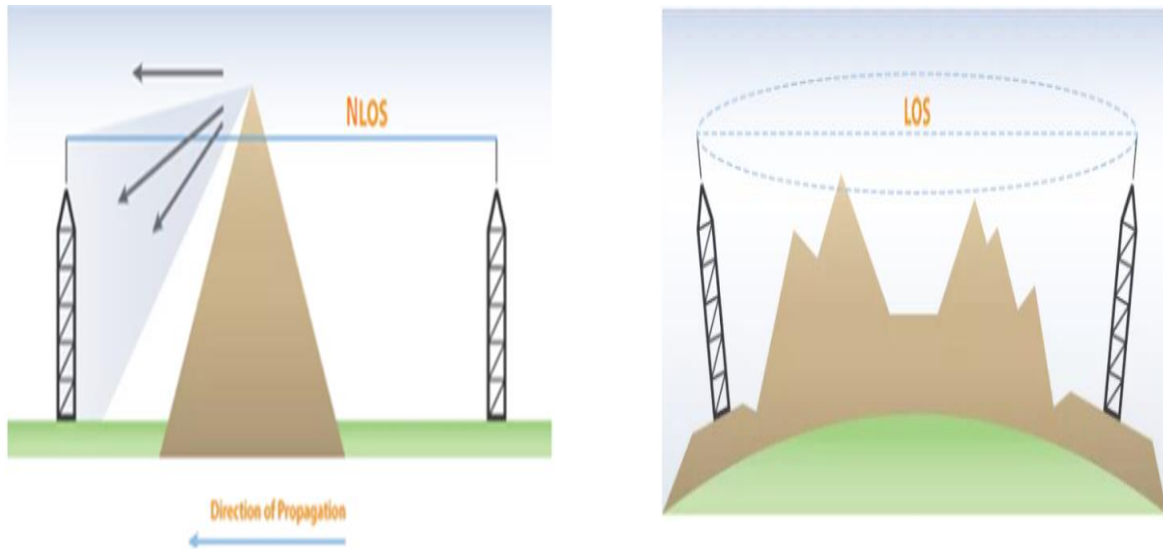


**Figure 1.10:** Multipath propagation: No line of sight (NLOS (Rayleigh channel)); Existence of a line of sight (LOS (Rice channel))

Numerous phenomena are generated, such as reflection, diffraction, and scattering on obstacles, depending on the nature of the objects encountered during the multipath propagation.

#### I.5.1.1 Effects of multipath propagation:

- **Inter symbol Interference (ISI):** In this situation, the transmitted signal can take two or more paths to reach the receiver: a direct path and a reflected path. Since the propagation times are different, the receiver observes the superposition of two shifted versions of the transmitted signal. When these combine, they cause constructive or destructive interference. Delayed signal copies can overlap with subsequent symbols, making it difficult for the receiver to correctly interpret the data. This is particularly problematic at high data rates and in environments with significant delay spread
- **Fading:** Rapid fluctuations in signal strength, known as small-scale fading, occur due to the vector sum of the multipath components. This can cause deep fades (signal drops) or occasional signal amplification.

- **Shadowing:** Obstacles may block the direct path, causing additional attenuation and signal variability.

### 1.5.2 Doppler shift and mobility

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

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

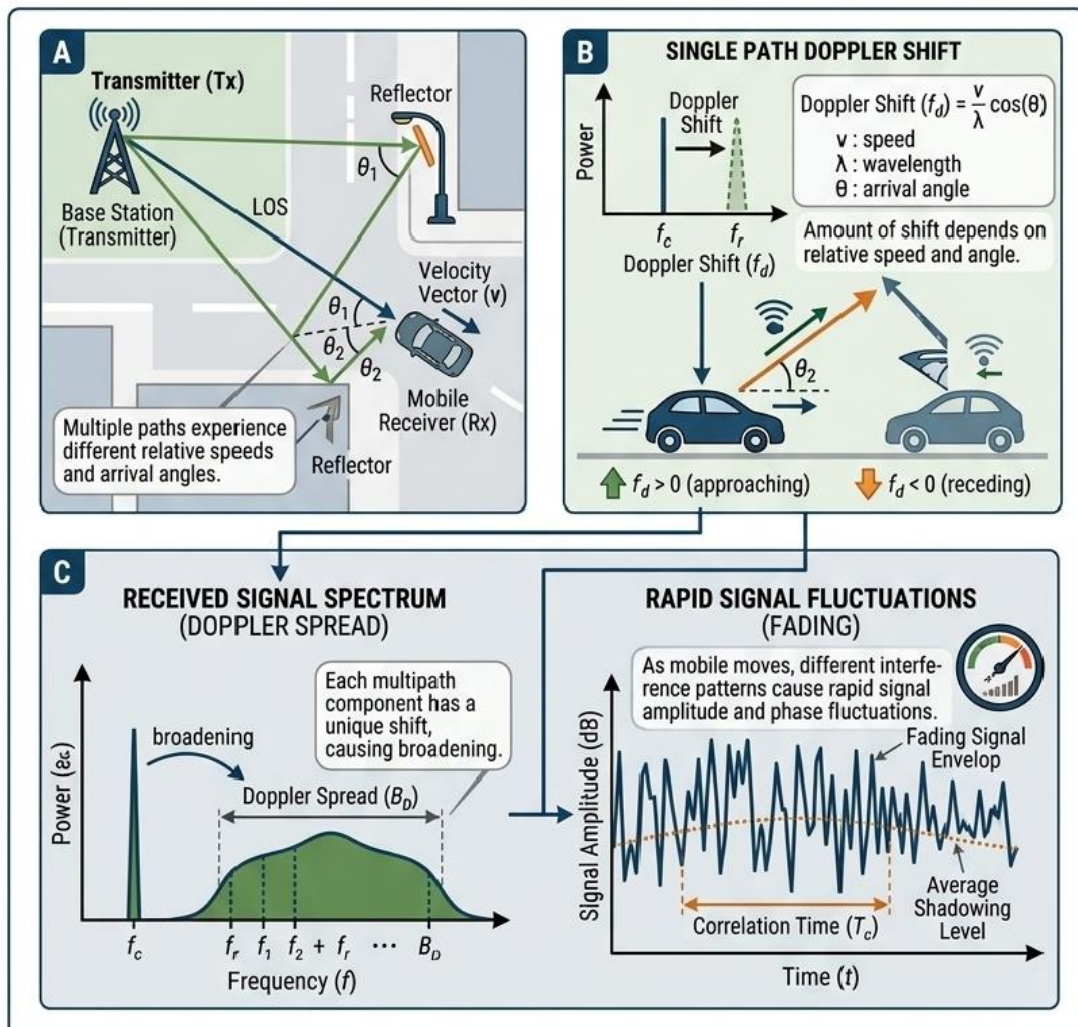


**Figure 1.11:** Effect of doppler shift

**Commentary:** This figure represents the effect of doppler shift in mobile environment:

A. Multipath Propagation Scenario

- ✓ LOS (Line of Sight): The direct signal between the transmitter and the receiver.
- ✓ Reflectors: Signals bounce off objects like buildings or lampposts before reaching the car.
- ✓ Consequence: The receiver receives multiple copies of the same signal, each arriving at a different angle ( $\theta$ ) and with a different delay.

#### B. Doppler shift on a single path

- ✓ Doppler shift formula:  $f_d = \frac{v}{\lambda} \cos \theta$ , where  $v$  is the velocity,  $\lambda$  the wavelength, and  $\theta$  the angle of arrival.
- ✓ Direction of motion: If the car is approaching ( $f_d > 0$ ), the frequency increases. If the car is moving away ( $f_d < 0$ ), the frequency decreases.

#### C. Signal Spectrum and Rapid Fluctuations

- ✓ Doppler Spread: Because each multipath component arrives at a different angle, they undergo different Doppler shifts. This causes a spectral "broadening" of the original signal ( $f_c$ ) over a range of frequencies ( $B_D$ ).
- ✓ Fading: Due to interference between these multiple paths, the amplitude of the received signal fluctuates chaotically and rapidly over time.
- ✓ Correlation Time ( $T_c$ ): This is the duration for which the signal remains stable before changing drastically.
- ✓ Signal Envelope: The blue line shows sudden drops in power (fading dips), while the orange dotted line represents the average level (shadowing).

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

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

## **I.6 Interference types in digital communication**

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

### **I.6.1 Inter-Symbol Interference (ISI)**

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

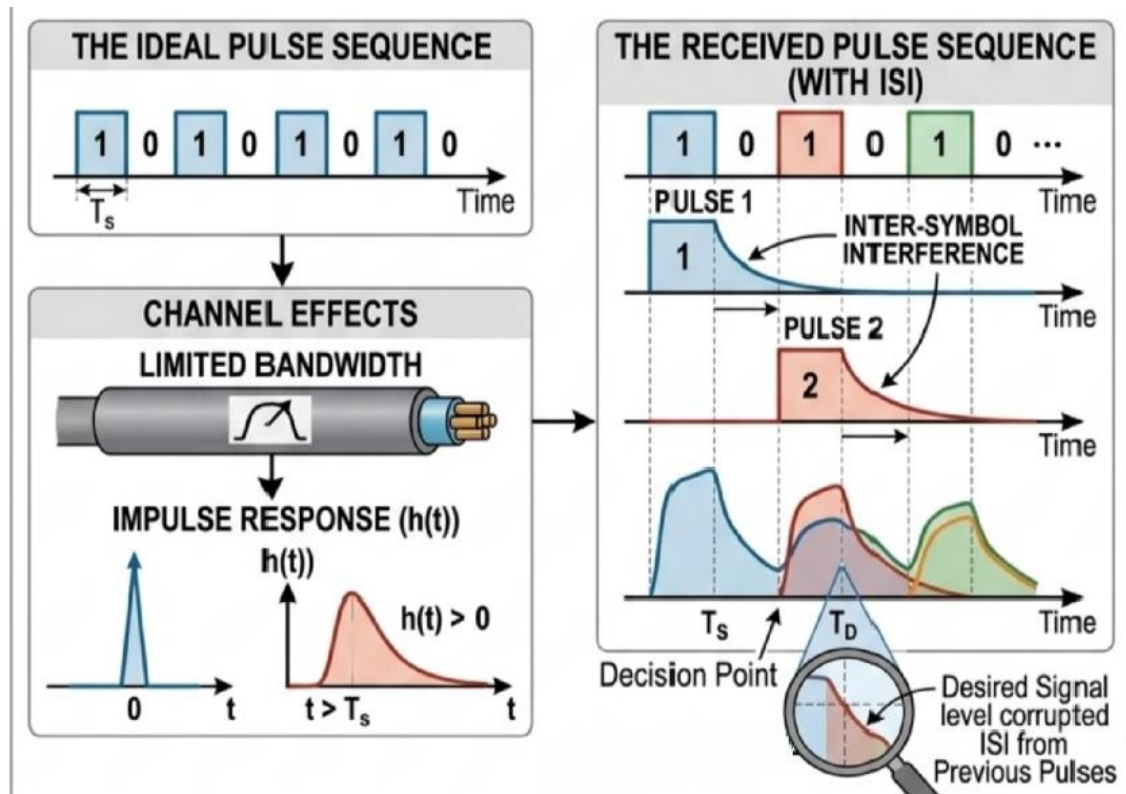


Figure 1.12: Effect of Inter-Symbol Interference (ISI)

### I.6.2 Inter-Carrier interference (ICI)

ICI is primarily associated with multicarrier systems like Orthogonal Frequency Division Multiplexing (OFDM). It occurs when subcarriers, which are supposed to be orthogonal, lose this property often due to Doppler shifts, frequency offsets, or insufficient cyclic prefix length in OFDM systems. The loss of orthogonality causes energy from one subcarrier to spill into others, resulting in interference and degraded performance. ICI can be mitigated by careful synchronization, frequency offset correction, and appropriate design of the cyclic prefix.

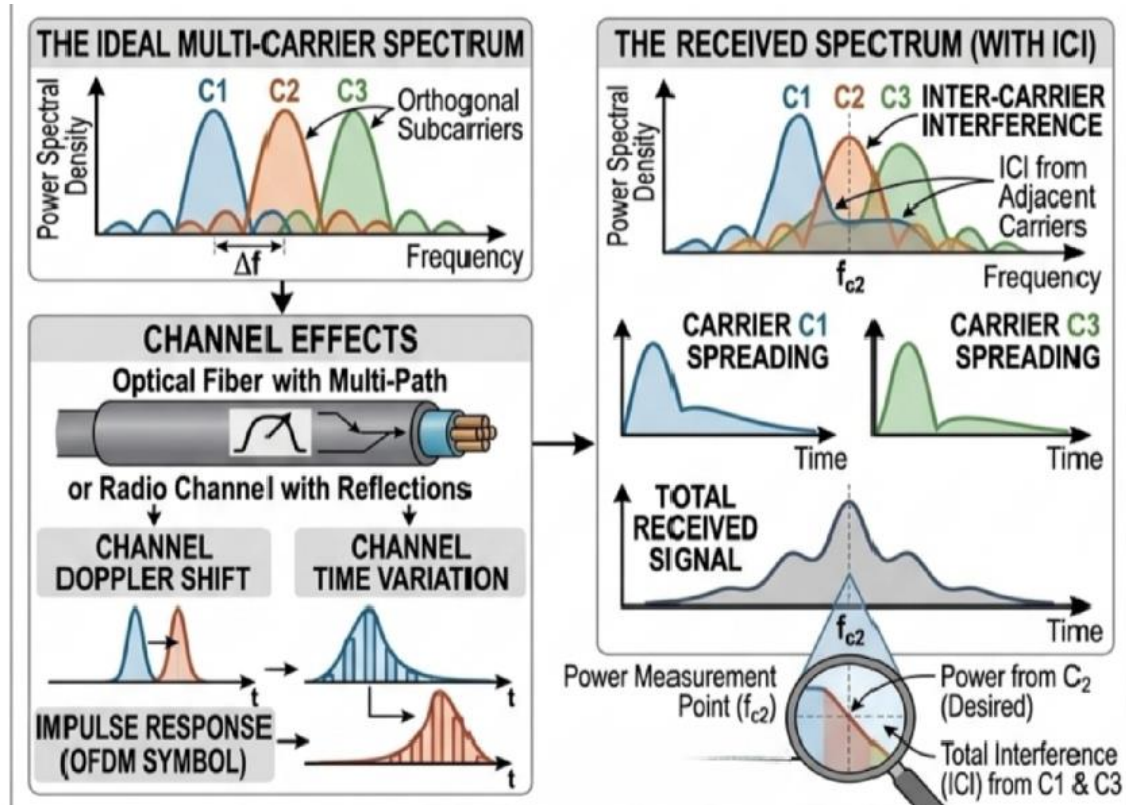


**Figure 1.13:** Effect of Inter-Carrier interference (ICI)

### I.6.3 Co-channel interference (CCI)

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

### I.6.4 Adjacent channel interference (ACI)

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

## I.7 Performance Measurement and Evaluation Metrics

### I.7.1 Peak-to-Average Power Ratio (PAPR)

The peak power-to-average power ratio (PAPR) represents the ratio between the maximum instantaneous power and the average power of the transmitted signal. In multicarrier transmission systems such as OFDM, the PAPR determines the sharpness of the signal peaks, which can affect the efficiency of power amplifiers.

The peak power/average power ratio (PAPR) is expressed in decibels (dB) and is calculated as follows:

$$PAPR = P_{peak} / P_{avg} = \frac{\max(|x(t)|^2)}{\frac{1}{T} \int_0^T |x(t)|^2 dt} \quad (1-1)$$

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

$$PAPR_{dB} = 10 * \log_{10} (P_{peak} / P_{avg}) = 10 * \log_{10} \left( \frac{\max(|x(t)|^2)}{\frac{1}{T} \int_0^T |x(t)|^2 dt} \right) \quad (1-2)$$

High PAPR values indicate significant power fluctuations, which can lead to reduced power amplifier efficiency. Therefore, reducing PAPR is crucial for improving power amplifier efficiency in wireless communication systems [13].

### I.7.2 Complementary Cumulative Distribution Function (CCDF)

To evaluate the statistical behavior of a systems peak power-to-average power ratio (PAPR), the complementary cumulative distribution function (CCDF) is commonly used. The CCDF determines the probability that the PAPR of a transmitted signal will exceed a predefined threshold. It accurately quantifies the frequency at which PAPR peaks occur within a given signal, thus providing a valuable tool for designers to assess the suitability of different modulation systems and waveforms under various operating conditions. Generally, a waveform with a low CCDF for a given PAPR threshold is considered more energy-efficient and better suited to practical applications in wireless communication systems.

### I.7.3 Bit Error Rate (BER)

The bit error rate (BER) is a key indicator used to evaluate the performance of digital communication systems. It determines the frequency of errors in the data stream transmitted through a communication channel.

The bit error rate (BER) is defined as the ratio between the number of bit errors and the total number of bits transmitted:

$$\text{BER} = \frac{\text{Number of Bit Errors}}{\text{Total Number of Bits Transmitted}} \quad (1 - 3)$$

A low bit error rate (BER) indicates a more reliable communication system. Factors such as noise, interference, and signal distortion can increase the bit error rate, thus affecting the overall performance of the system [13].

### I.7.4 Symbol Error Rate (SER)

The symbol error rate (SER) measures the probability that a symbol will be misinterpreted in a digital communication system. Unlike the bit error rate (BER), which measures errors bit by bit, the SER considers the entire symbol, which may be composed of multiple bits depending on the modulation system. The symbol error rate (SER) is defined as follow:

$$\text{SER} = \frac{\text{Number of Symbol Errors}}{\text{Total Number of Transmitted Symbols}} \quad (1 - 4)$$

The use of a higher-order modulation system, despite the increased data transfer rate, can lead to a higher symbol error rate (SER) due to the proximity of the symbol points, making them more susceptible to distortion and other influencing factors [13].

### I.7.5 Out-of-Band Emissions

Out-of-band (OOB) emissions refer to the spectral components of a transmitted signal that lie outside its nominal frequency range. These emissions are unintentional and can cause interference with neighboring channels or systems.

In multicarrier modulation systems such as OFDM, out-of-band (OOB) emissions are primarily caused by abrupt transitions between symbols, resulting in spectral leakage.

Therefore, controlling out-of-band emissions is essential to ensure spectral efficiency and minimize interference with adjacent frequency bands.

Regulatory bodies, such as the European Conference of Postal and Telecommunications Administrations (CEPT), set specific limits on out-of-band emissions to ensure the coexistence of multiple services in the radio spectrum [13].

## **I.8 Conclusion**

In this chapter we provide a general overview of wireless telecommunications, highlighting key challenges such as multipath propagation, Doppler effects, and different types of interference. We also trace the evolution from 1G to 6G, showing the different innovation of one generation relatively to the precedent. The necessity and advantages of multicarrier modulation were emphasized, particularly for improving spectral efficiency, managing interference, and combating channel fading. We finely, give an insight on the important performance metrics such as constellation diagrams, spectral efficiency, BER, FER, and PAPR. These metrics are introduced to evaluate the efficiency and reliability of the modulation techniques and assessing their feasibility in practical deployments in wireless system.



## Chapter II

# Candidate Waveforms for Wireless Communication Systems



## II.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 [8], 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.

Although orthogonal frequency division multiplexing (OFDM) remains the basis, advanced and novel multicarrier modulation methods, are being investigated in wireless communication. The main waveforms are Filter-Bank Multi-Carrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universally Filtered Multi-Carrier (UFMC), and Orthogonal Time Frequency Space (OTFS). These waveforms are being explored to meet specific requirements of wireless communication systems. Within this chapter we give an overview of the various multicarrier modulation methods, especially OFDM and OTFS. We present also other contender waveforms that are suggested for new wireless communication systems.

## II.2 Orthogonal Frequency Division Multiplexing OFDM

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 [14].

### II.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 Local Area Network (LANs) and personal communication systems. The earliest multicarrier modulation systems date back to the 1950s, particularly in military High Frequency (HF) systems [15].

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 [16].

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 [17].

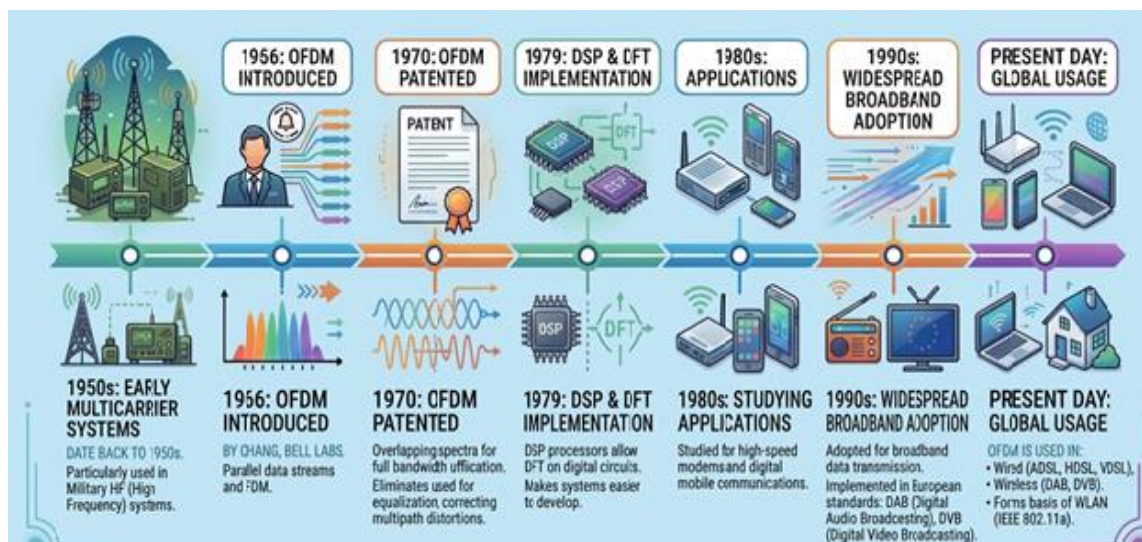


**Figure 2.1:** Evolution of OFDM modulation

## II.2.2 Orthogonality propriety

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 performance [18].

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

$$\int_a^b f(t) \cdot g(t) dt = 0 \quad (2-1)$$

We can speak about two types of orthogonality: temporal orthogonality and Frequency Orthogonality.

- **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  $f_k = \frac{k}{T_s}$ , 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:

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

Thus, two subcarriers  $s_i(t)$  and  $s_j(t)$  of respective frequencies  $f_i$  and  $f_j$ , defined by expression (2-2), are orthogonal over the interval  $[0, T_s]$ , as they satisfy equation (2-1). [18]

- **Frequency Orthogonality**

One can also perceive the notion of orthogonality of the OFDM signal in the frequency domain. Indeed, if each subcarrier  $s_k(t)$  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),

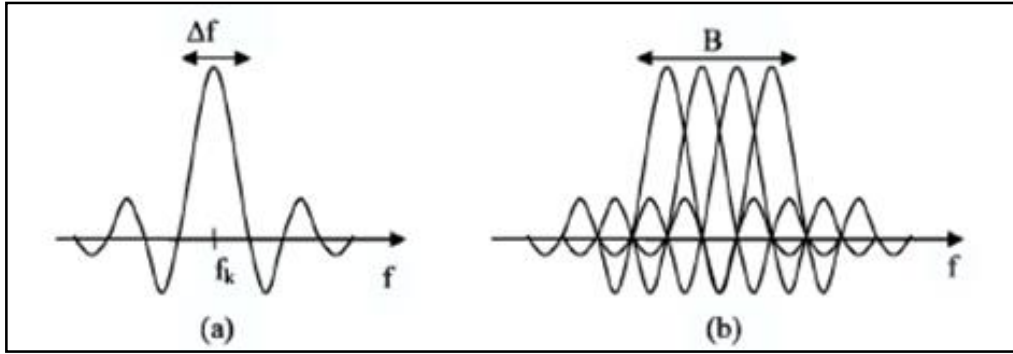


**Figure 2.2:** (a): Spectrum of a subcarrier (b): Spectrum of an OFDM signal

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

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 [18].

### II.2.3 OFDM transmission system

The general diagram of an OFDM transmission system is designed on two parts a transmission part and a reception part, as shown in figure (2.3).

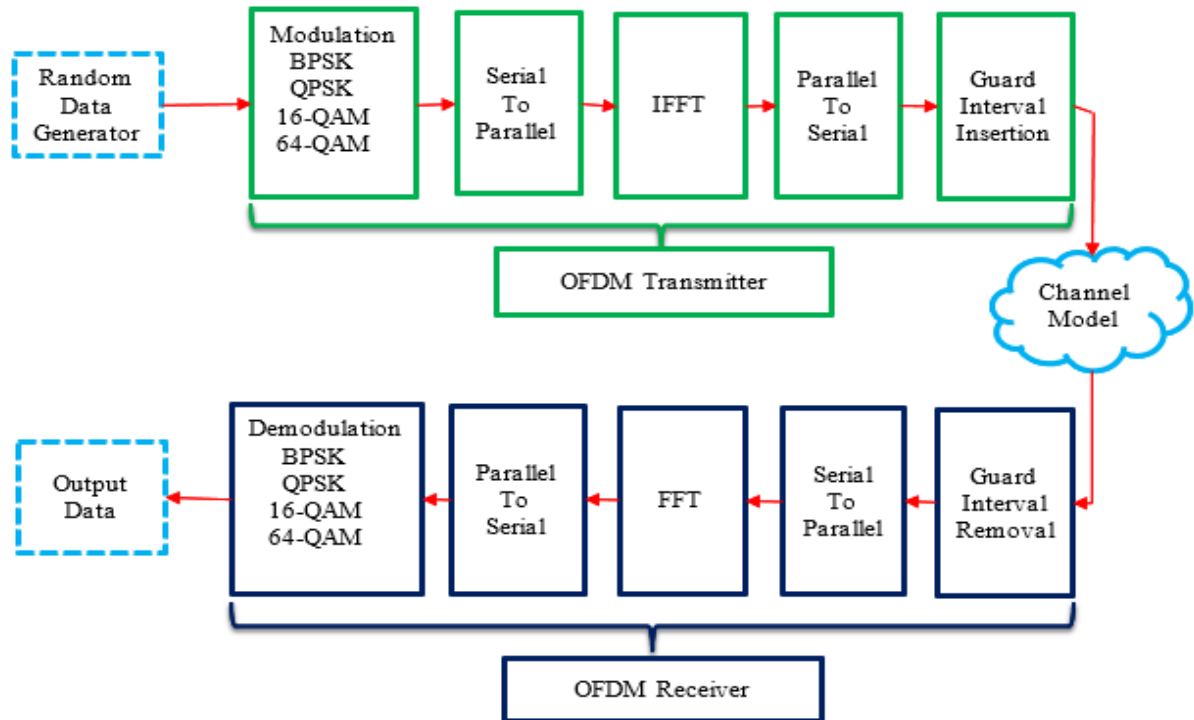


**Figure 2.3:** Block diagram of an OFDM transmission system

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  $\Delta f = 1/T_s$ .

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

The pilots (Estimation Pilots) 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 [19].

After the IFFT function, a cyclic prefix (CP) 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.

The 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 are Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) methods [14], [12], [19].

### II.2.3.1 OFDM Modulation

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  $C_1, C_2, \dots, C_{N-1}$  constitutes the OFDM symbol.

The  $N$  symbols are transmitted in parallel and modulate the  $N$  subcarriers:  $f_0, f_1, \dots, f_{N-1}$ . The subcarriers are separated by  $\Delta f = 1/T_s$ , Or  $f_k = f_0 + K \cdot \Delta f$  with  $K=0, 1 \dots N-1$ , to guarantee orthogonality between adjacent subcarriers [17].

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

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

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

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

Where is the duration:  $T_s$  of the OFDM symbol:

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

By discretizing this signal and digitizing it at baseband at instant  $t = n T_s$ , we obtain an output  $S_n$  in the form:

$$S[n] = \sum_{k=0}^{N-1} C_k e^{j2\pi \frac{kn}{N}} \quad (2-6)$$

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 [14].

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 [17].

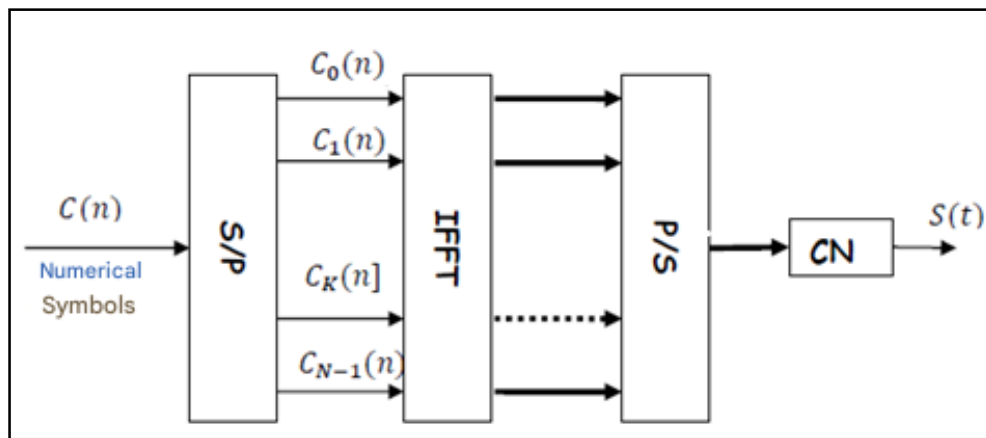


**Figure 2.4:** Principle of an OFDM modulator

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

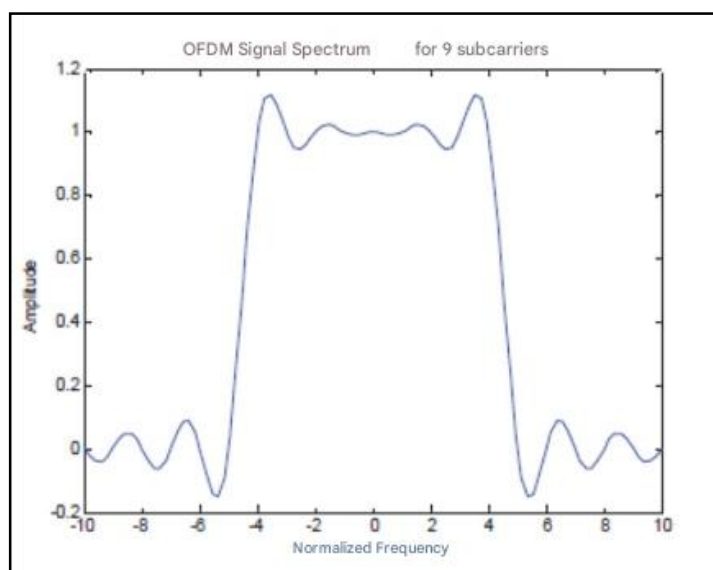


**Figure 2.5:** Spectrum of the sum of OFDM subcarriers

### II.2.3.2 OFDM Demodulation

The received discretized signal takes the following form:

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

$H_k(t)$  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) [14], [20], [17]. The diagram for an OFDM demodulator is depicted in figure 2.6 [21] [12].

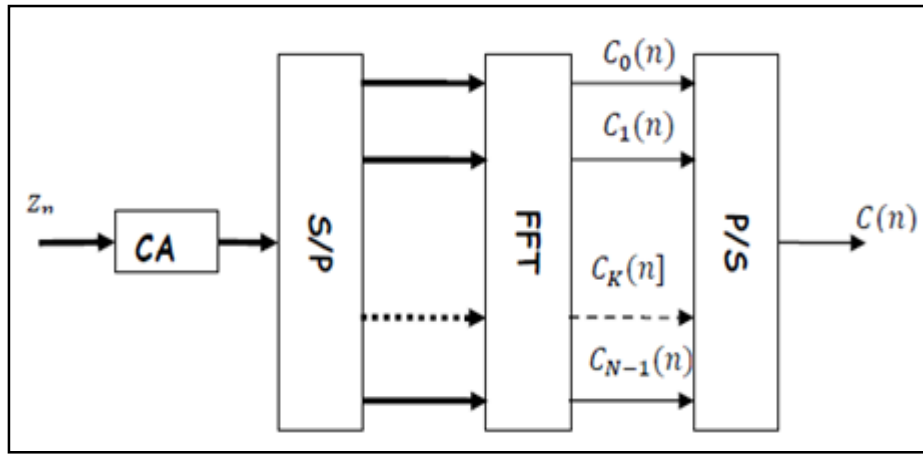


**Figure 2.6:** Block diagram of an OFDM demodulation

### II.2.4 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.

#### II.2.4.1 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 [22].

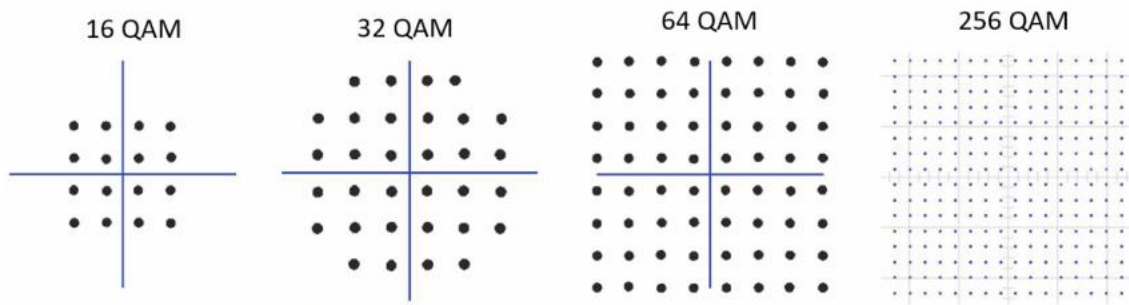


**Figure 2.7:** Constellation diagram of (16-32-64-256) QAM modulation

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

**Table 2-1:** Illustration of the gain provided by QAM modulation

| N | Modulation<br>Ordre (M) | Modulation<br>Scheme | Bit Rate | Spectral<br>Efficiency |
|---|-------------------------|----------------------|----------|------------------------|
| 1 | 2                       | BPSK                 | D        | $\eta$                 |
| 2 | 4                       | QPSK                 | 2D       | $2\eta$                |
| 4 | 16                      | 16-QAM               | 4D       | $4\eta$                |
| 6 | 64                      | 64-QAM               | 6D       | $6\eta$                |
| 8 | 256                     | 256-QAM              | 8D       | $8\eta$                |

Where D is the data rate and  $\eta$  is the spectral efficiency.

### II.2.5 Variants OFDM Technique

- ✓ **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.

### II.2.6 Applications of the OFDM technique

OFDM is a dominant technology; it is used in the European Digital Broadcasting (DAB) project, Digital Terrestrial Broadcasting (DVB), and in high-speed wireless local area networks (ETSI's HiperLAN2) or the 802.11a and 802.11g standards. OFDM is ideal for mobile communications and appears essential for future communication standards [23].

- ✓ **ETSI HiperLAN II Standard**

HiperLAN2 is a European standard developed by the European Telecommunications Standards Institute (ETSI), with the support of the HiperLAN2 Global Forum (H2GF), founded in 1999 by Bosch, Dell, Ericsson, Nokia, Telia, and Texas Instruments. HiperLAN2 uses a frequency band from 5.15 to 5.25 GHz, divided into nine 200 MHz carriers (with a 20 MHz gap between carriers). This second version offers data rates of up to 54 Mbps and uses the OFDM (Orthogonal Frequency Division Multiplexing) protocol, just like the 802.11a standard.

✓ **IEEE 802.11a (Wi-Fi 5)**

The IEEE 802.11a standard originated from studies conducted within the HiperLAN standardization framework by the European Telecommunications Standards Institute (ETSI). An extension of the IEEE 802.11 standard, it improves transmission speeds, offering data rates between 6 and 54 Mbps. This standard operates in the UNII (National Unlicensed Information Infrastructure) frequency band (5 GHz), the use of which does not require a license.

✓ **IEEE 802.11g**

The 802.11a standard offers a relatively high data transfer rate, but its range is shorter and its use in open spaces is often limited. To overcome these problems, the IEEE (Institute of Electrical and Electronics Engineers) developed the new 802.11g standard, which offers the same data transfer rate as Wi-Fi 5 while remaining compatible with Wi-Fi 2 (operating on the 2.4 GHz frequency band). This standard also aims to replace Wi-Fi 2 on the 2.4 GHz frequency band, but with a higher data transfer rate, up to 54 Mbps, and uses OFDM modulation technology.

✓ **Digital Audio Broadcasting (DAB)**

Digital Audio Broadcasting (DAB) is a standard for transmitting digital radio signals. Used in Europe and worldwide, it was the first standard to utilize OFDM modulation technology. It aims to guarantee signal reception even under the most challenging propagation conditions (such as in-vehicle reception in densely populated urban areas and resistance to Doppler effects). Broadcast modes are defined by different frequency bands for signal transmission (VHF, 1.5 GHz, and 2.3 GHz).

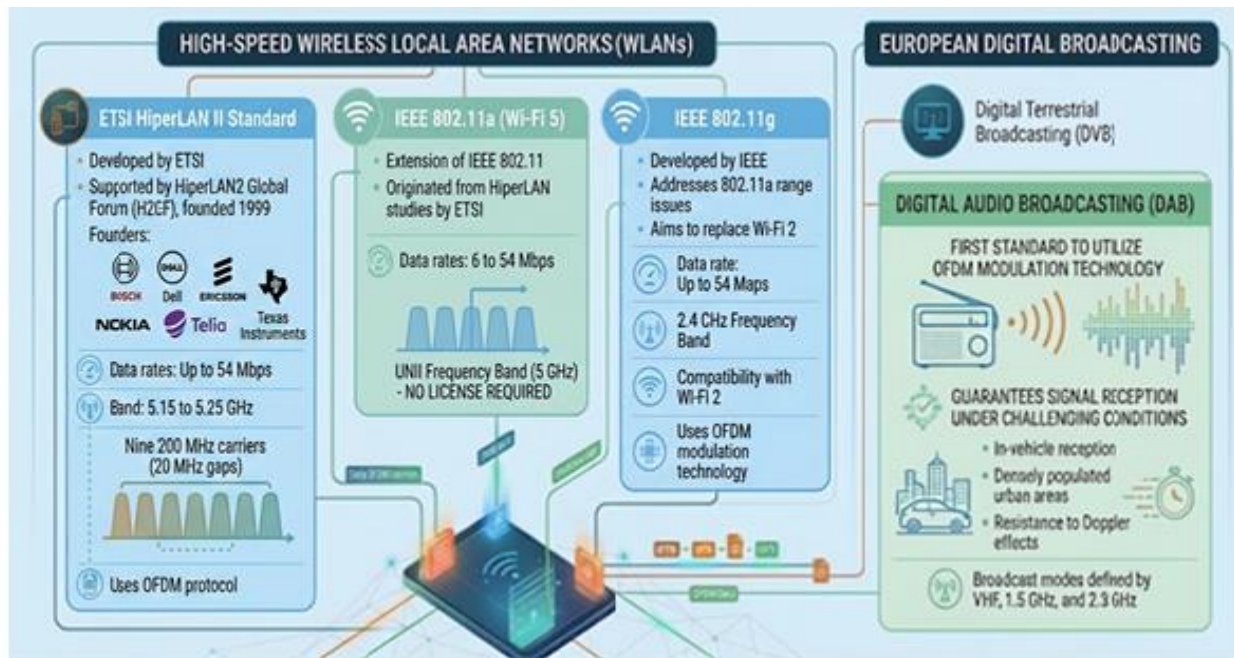


*Figure 2.8: Application of the OFDM technique*

## II.2.7 Advantages and Disadvantages of OFDM

### Advantages

- ✓ The longer the symbol duration, the more resistant the signal becomes to multipath effects.
- ✓ Guard intervals help reduce inter-symbol interference caused by multipath.
- ✓ High spectral efficiency is achieved through the near-orthogonality of the subcarriers, allowing for very tight frequency spacing between them without interference.
- ✓ Reception is characterized by its simplicity, requiring only the application of the FFT transform at the (UE) level.
- ✓ Furthermore, the system requires no intracellular interference cancellation mechanisms or the use of an equalizer.

### Disadvantages

- **Peak-to-average power ratio (PAPR)**

A high PAPR reduces the efficiency of power amplifiers and causes spectrum broadening, interference between adjacent channels, and an increase in BER due to intermodulation and constellation distortion.

- **Frequency shift sensitivity :**

Frequency shift leads to a loss of orthogonality between subcarriers, generating intercarrier interference (ICI) and significantly degrading network performance.

### II.3 Orthogonal Time Frequency Space (OTFS)

The OTFS modulation is a two-dimensional technique, which modulates the information in a Delay Doppler domain and then transforms the signals into Time Frequency domains. This modulation scheme is designed to overcome challenges posed by time-varying channels, such as those encountered in high-mobility scenarios [3] [4].

#### II.3.1 OTFS Transmission system

The diagram depicted in figure 2.9 represents the architecture of an Orthogonal Time Frequency Space (OTFS) transmission system. Unlike a classic OFDM system, which operates in the time frequency (TF) domains, an OTFS system places information codes in the Delay Doppler (DD) domain to improve its robustness [3] [4].

In this section, we present the relationship between the transmitted and received signals of the OTFS modulator in both the time domain and the Delay Doppler domain. As mentioned earlier, the OTFS modulator places the complex symbols to be transmitted on to a Delay Doppler network, which are then converted into a time-domain signal using the Inverse Symplectic Finite Fourier Transform (ISFFT). This will be discussed in more detail in the next subsection.

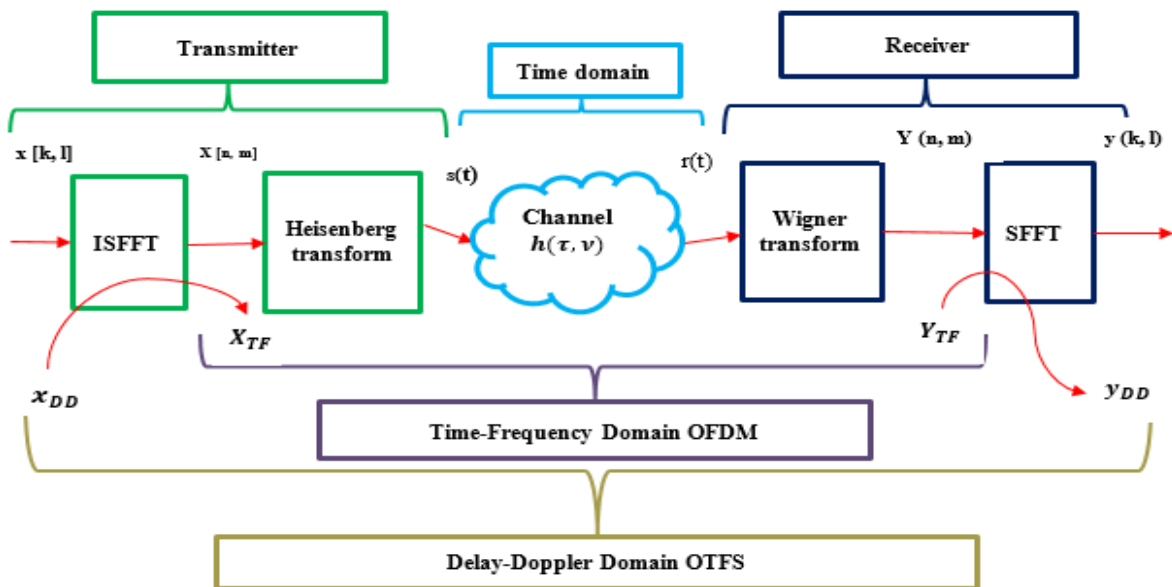


**Figure 2.9:** Blok diagram of OTFS modulation and demodulation

### II.3.2 OTFS modulation

At the transmitter the modulation process is performed by different operations, that we introduce in follows.

#### II.3.2.1 Inverse Symplectic Finite Fourier Transform (ISFFT)

L'OTFS map the symbols placed on a Delay-Doppler (DD) domain into symbols placed on a time-frequency domain using the Inverse Symplectic Finite Fourier Transform, the specific steps of the procedure are explained far ahead.

The DD domain is split in to an  $M \times N$  grid as flowing [3] [4]:

$$\left( \frac{K}{NT}, \frac{l}{M\Delta f} \right) \quad K = 0, \dots, N-1; \quad l = 0, \dots, M-1 \quad (2-8)$$

Where  $1/\Delta Mf$  and  $1/NT$  stand for the quantization spacing of the Delay and Doppler frequency axis.  $N$  and  $M$  denote the total number of time intervals and frequency sub-channels respectively.

In the OTFS modulation, a block of information bits is first mapped to  $N \times M$  grid on the DD plane as:

$$X_{DD} = [X_0 \ X_1 \ \dots \ X_{N-1}] \quad (2-9)$$

$$\begin{bmatrix} x(0,0) & x(0,1) \dots & x(0,N-1) \\ x(1,0) & x(1,1) \dots & x(1,N-1) \\ \vdots & \vdots & \vdots \\ x(M-1,0) & x(M-1,1) \dots & x(M-1,N-1) \end{bmatrix} \quad (2-10)$$

Therefor the ISFFT transform converts the symbols  $x[k, l]$  ; placed on a Doppler delay grid  $x_{DD}$  into symbols  $X[n, m]$  in the time-frequency (TF) domain (Figure 2.10).

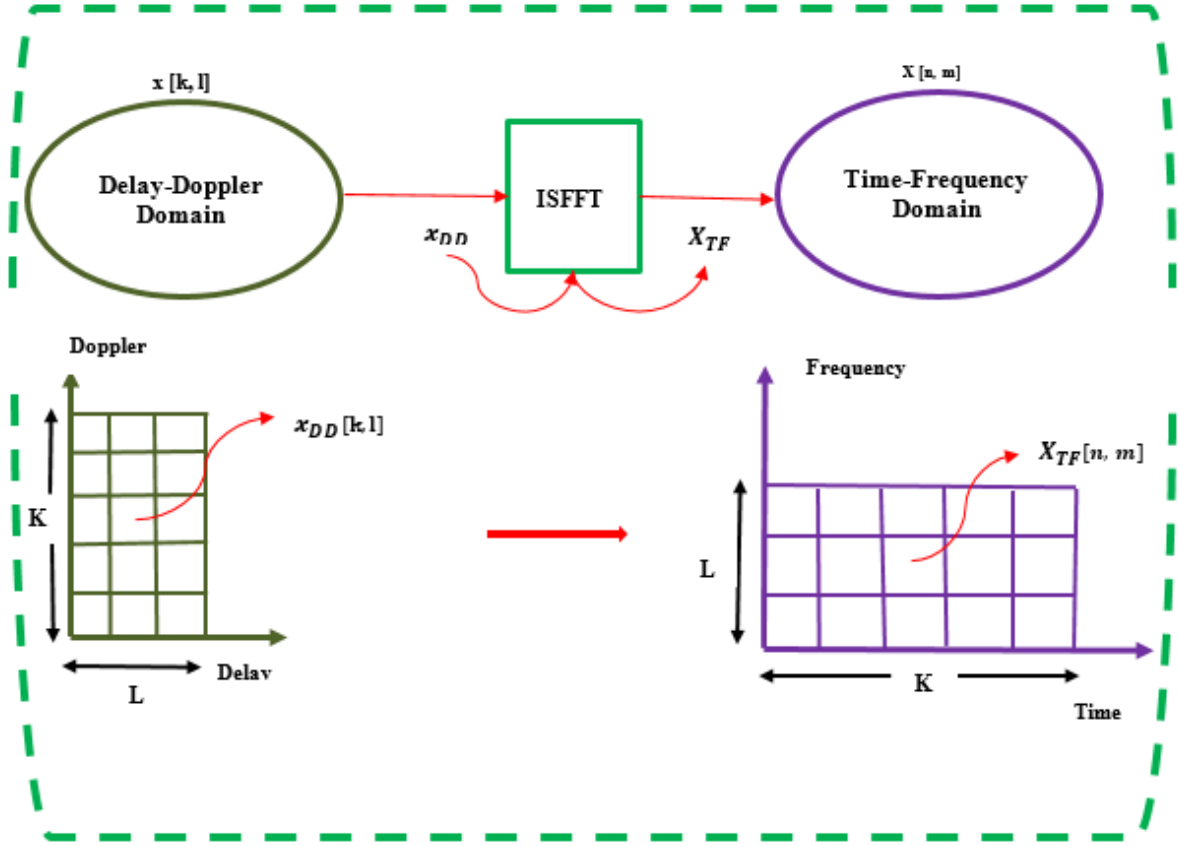


**Figure 2.10: ISFFT Operator**

The ISFFT transform performs a two D transform as flows:

$$X[n, m] = \frac{1}{\sqrt{MN}} \sum_{K=0}^{N-1} \sum_{l=0}^{M-1} x(K, l) e^{j2\pi (\frac{nk}{N} - \frac{ml}{M})} \quad (2 - 11)$$

### II.3.2.2 Heisenberg transform

The Heisenberg transform is considered as a crucial step in the OTFS transmission system, occurring immediately after the transposition of symbols  $x[k, l]$  into the frequency-time domain  $X[n, m]$ . The Heisenberg transform acts as a modulator, its principal role is to convert the two-dimensional digital data network into an analog signal in the time domain  $s(t)$  (Figure 2.11). Then the signal engendered become ready to be transmitted over the wireless channel.

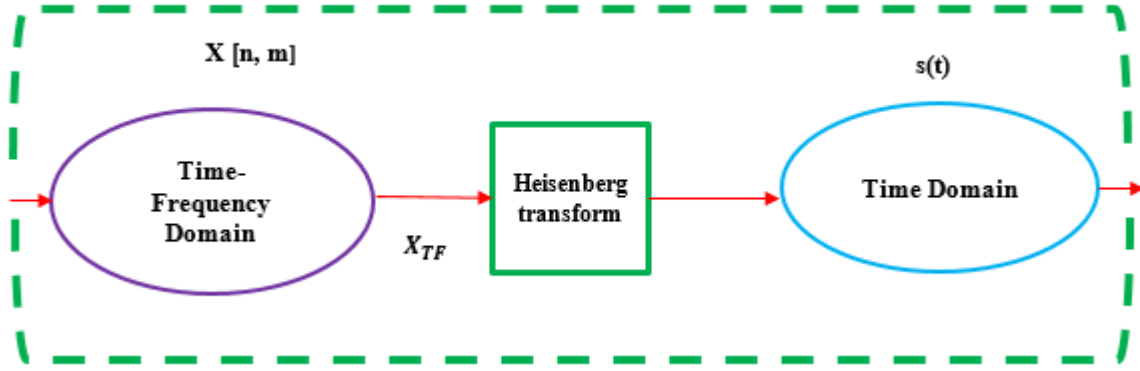


**Figure 2.11:** Heisenberg transform

The Heisenberg transform converts the transformed symbols  $X[n, m]$  to a time-domain signal as follow [3] [4]:

$$s(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X(n, m) g_{tx}(t - nT) e^{j2\pi m\Delta f(t - nT)} \quad (2 - 12)$$

Where  $g_{tx}$  denote the transmitted pulse.

### II.3.3 The transmission channel

The signal  $s(t)$  is transmitted over a time-varying channel with complex baseband channel impulse response  $h(\tau, \nu)$ , which characterizes the channel response to an impulse with delay  $\tau$  and Doppler  $\nu$ , figure 2.12. The received signal  $r(t)$  is given by the following equation [3] [4]:

$$r(t) = \iint h(\tau, \nu) s(t - \tau) e^{j2\pi\nu(t - \tau)} d\nu d\tau \quad (2 - 13)$$

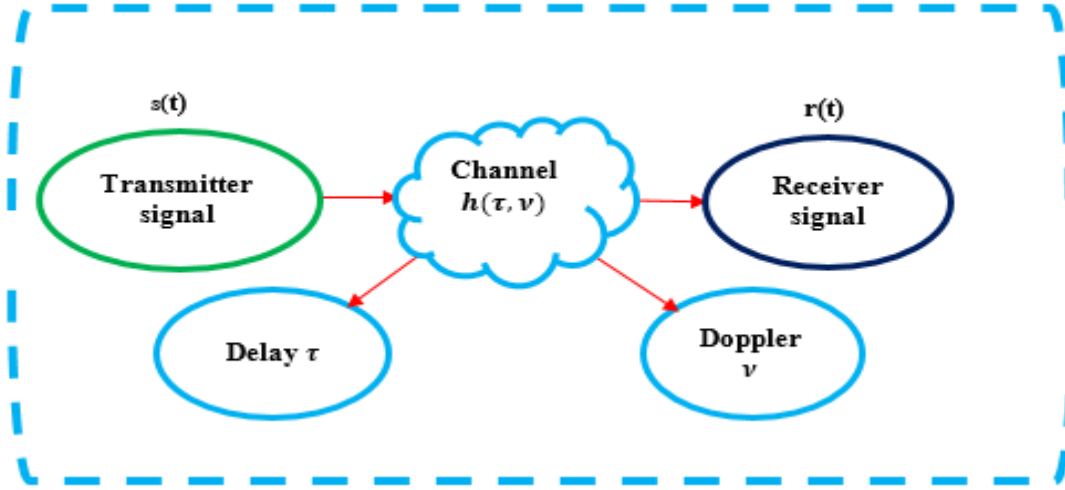


**Figure 2.12:** Channel model

The sparse representation of the channel  $\mathbf{h}(\tau, \nu)$  is given as [3] [4]:

$$\mathbf{h}(\tau, \nu) = \sum_{i=1}^P \mathbf{h}_i \delta(\tau - \tau_i) \delta(\nu - \nu_i) \quad (2-14)$$

Where:

$P$  : The number of propagation paths.

$\mathbf{h}_i$  : The path gain.

$\tau_i$  : Delay.

$\nu_i$  : Doppler shift.

### II.3.4 OTFS demodulation

At the receiver the demodulation process is performed by different operations, that we present in follows

#### . II.3.4.1 Wigner transform

The Wigner transform is considered as the inverse process of the Heisenberg transformation. Wigner transform performs as a demodulator, projecting the received signal into the available time-frequency domain (Figure 2.13).

The principal role of Wigner transform is to convert the two-dimensional digital data network into an analog signal in the time domain  $\mathbf{s}(t)$  (Figure 2.13).

Wigner transform receives as input the signal  $\mathbf{r}(t)$  in time domain and performs a conversion into time-frequency domain to obtain  $\mathbf{Y}(\mathbf{n}, \mathbf{m})$  as follow [3] [4]:

$$\mathbf{Y}(t, f) = A_{g_{rx,r}}(t, f) \triangleq \int \mathbf{g} *_{rx}(t' - t) \mathbf{r}(t') e^{-j2\pi f(t' - t)} dt' \quad (2 - 15)$$

The matched filter output is obtained by sampling  $\mathbf{Y}(t, f)$  as [3] [4]:

$$\mathbf{Y}[\mathbf{n}, \mathbf{m}] = \mathbf{Y}[t, f]|_{t=nT, f=m\Delta f} \quad (2 - 16)$$

for  $n = 0, \dots, N - 1$  and  $m = 0, \dots, M - 1$

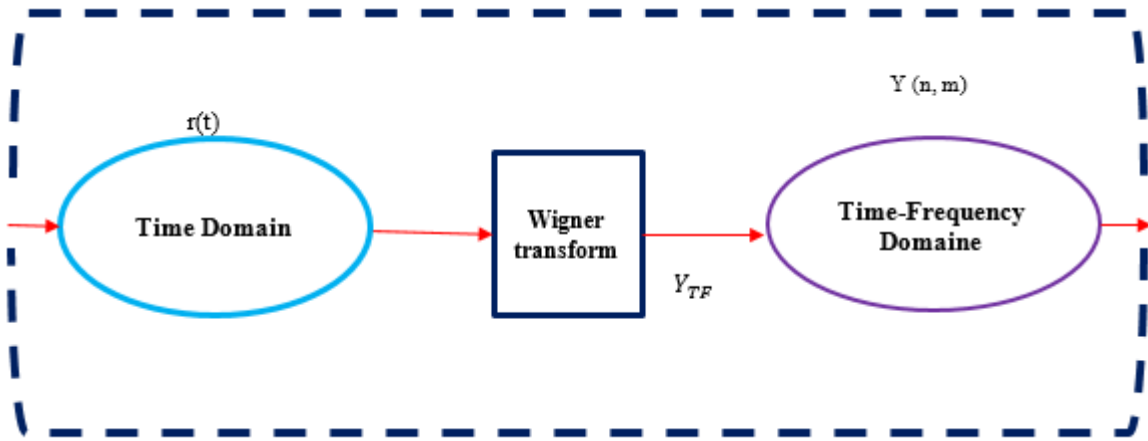


**Figure 1.13:** Wigner transform

#### II.3.4.2 Symplectic Finite Fourier Transform (SFFT)

The Symplectic Finite Fourier Transform is considered as a dual of the Inverse Symplectic Finite Fourier Transform. The SFFT ensure that  $\mathbf{Y}(\mathbf{n}, \mathbf{m})$  symbols are converted from time-frequency domain to the Delay Doppler domain  $\mathbf{y}(\mathbf{k}, \mathbf{l})$  using SFFT, which is the inverse process of ISFFT (Figure 2.14).

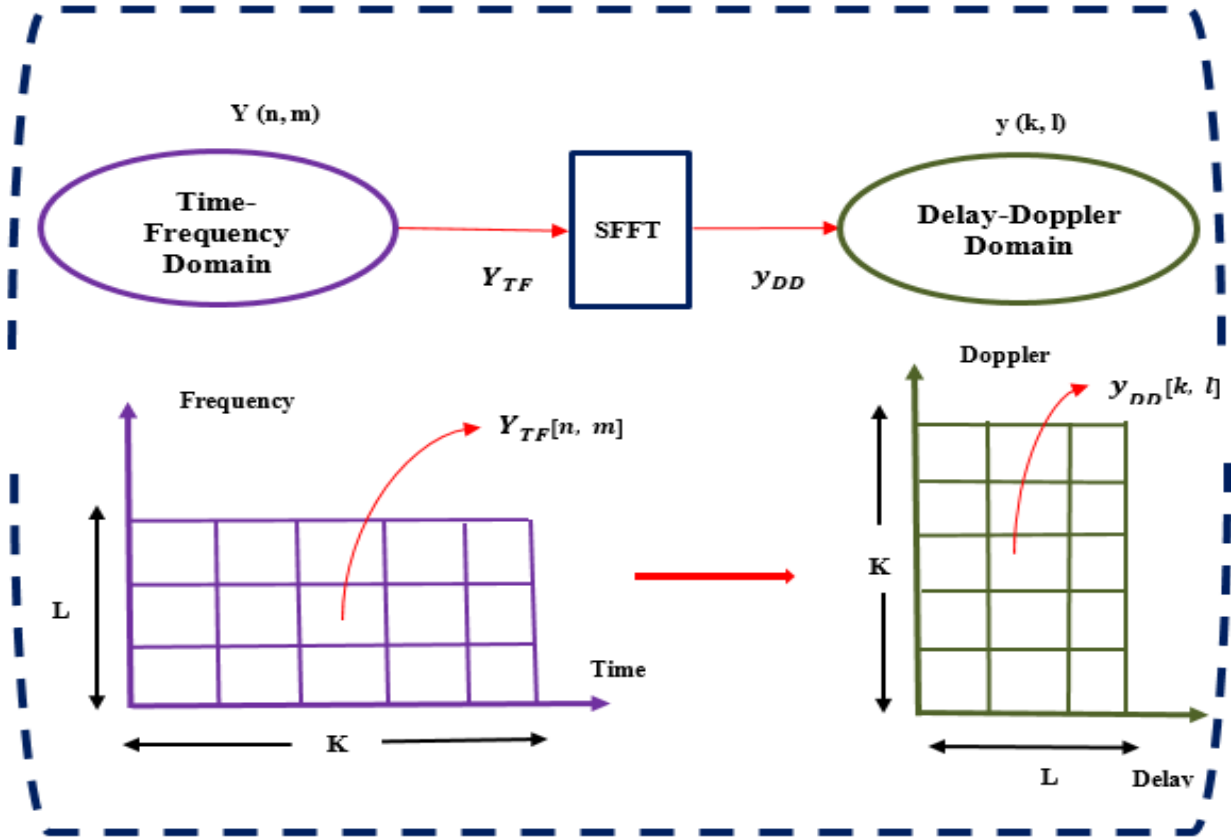


Figure 2.14: SFFT Operator

Similarly to the ISFFT transform, SFFT performs a two D transform as flows [3] [4]:

$$y[k, l] = \frac{1}{\sqrt{MN}} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} Y(n, m) e^{-j2\pi(\frac{nk}{N} - \frac{ml}{M})} \quad (2-17)$$

## II.4 Other Candidate Waveforms

We give above an insight on Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) multicarrier waveforms. Other modulation waveforms are similarly studied by the scientific community and investigated in wireless communication as alternatives to OFDM.

The principal waveforms are Filter-Bank Multi-Carrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universally Filtered Multi-Carrier (UFMC). We provide an overview of these various multicarrier modulation methods.

### II.4.1 Universal-Filtered-Multi-Carrier (UFMC)

Universal filtered multicarrier modulation (UFMC) is a new multicarrier modulation technique that incorporates sub band filters and aims to replace orthogonal frequency division modulation (OFDM). The goal of UFMC is to eliminate the strict synchronization limitations of OFDM [22].

As mentioned earlier, OFDM technology suffers from two major problems: the peak power-to-average power ratio (PAPR) and synchronization. Out-of-band (OOB) radiation from this waveform also results in significant losses. Therefore, researchers are striving to find new waveforms to replace OFDM technology in future mobile radio communication systems [12].

UFMC is a technology initially proposed by Alcatel-Lucent & Bell Laboratories [24], and is also referred to as UF-OFDM in the literature.

UFMC technology combines ZP-OFDM (a traditional CP-OFDM technique where the cyclic prefix is replaced by a zero-filling (ZP)) and filtered OFDM. Each OFDM code is filtered at the output of a discrete inverse Fourier transform (IDFT), and the zero-filling (ZP) attenuates the filter's transient response. In the absence of multipath, UFMC preserves the orthogonality of the subcarriers. However, this orthogonality is no longer maintained as the channel's temporal amplitude increases, and the protection against the effects of multipath at the receiver is then only partial.

At the receiver, multi-user interference due to time and frequency asynchrony is first reduced by applying a window to the received UFMC block symbols. It should be noted that this treatment results in a loss of subcarrier orthogonality, even in the case of an ideal channel. Finally, a Fast Fourier Transform (FFT) with an amplitude twice that of the Inverse Fast Fourier Transform (IFFT) used during transmission is applied to the received OFDM block symbols, and only the subcarrier indices are retained. [22]

It is important to note that the receiver's complexity can be reduced by collecting additional samples of equal length to the zero period and using an interference combination method to perform circular convolution. In this case, the required fast Fourier transform amplitude is identical to that of the inverse Fourier transform used during transmission.

### II.4.1.1 Principle of UFMC

The received UFMC block symbols are given as follows:

$$x(l) = \frac{1}{M} \sum_{k=0}^{M-1} X(j, k) e^{2\pi j \frac{(k+\Theta_j)}{K} l} \quad (2-18)$$

With  $l = 0, \dots, K-1$  and  $\Theta_j = (j-1) \cdot M$ . Each sub-band sequence  $x(l)$  passes through a finite impulse response filter  $f_j(l)$  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:

$$f_j(l) = f(l) e^{2\pi j \frac{(\Theta_j + M - 1)}{K} l} \quad (2-19)$$

The prototype filter  $f(l)$  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:

$$y(l) = x_j(l) * f_j(l) = \sum_{l'=0}^{K-1} x_j(l') f_j(l-l') \quad (2-20)$$

with  $*$  denoting discrete-time convolution and index  $l = 0, \dots, (K + L - 2)$ .

The different sub-band signals  $y(l)$  are then added, resulting in:

$$y(l) = \sum_{j=1}^B y_j(l) \quad (2-21)$$

Finally, the discrete-time baseband signal  $y(l)$  is converted into an analog signal for transmission by analog shaping and Radio Frequency (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:

$$r_j(l) = r(l) * f_j^*(-l) = \sum_{l'=0}^{K+L-2} r(l') f_j^*(l' - l) \quad (2 - 22)$$

Where only the samples with index  $l = 0, \dots, K - 1$  are retained. For each sub-band, the signal  $r_j(l)$  is mapped into the frequency domain by applying an FFT despreading operation. [22]

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

$$R_j(k) = \sum_{l=0}^{M-1} r_j(l) e^{-2\pi j \frac{l(k+\Theta_j)}{K}} \quad (2 - 23)$$

Where  $r_j(l)$  The received time-domain complex signal samples belonging to the  $j$ -th sub-band.

With  $k=0, \dots, M - 1$ .

#### II.4.1.2 Advantages and Disadvantages of UPMC Modulation

##### Advantages

- ✓ UPMC exhibits better spectral efficiency than OFDM because, unlike OFDM, it does not add a periodic prefix.
- ✓ The absence of bit repetition allows for very efficient use of the allocated frequency spectrum.
- ✓ UPMC has fewer sidelobes than OFDM, which reduces interference on adjacent subcarriers.
- ✓ The peak power-to-average power ratio (PAPR) is lower in UPMC than in OFDM because the OFDM signal is composed of a large number of independently modulated subcarriers, which can result in a high PAPR when they are combined in phase. In UPMC, the total bandwidth is divided into sub bands. Since the probability of combining a large number of subcarriers in phase is lower in UPMC, the peak power is reduced.

##### Disadvantages

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

## II.4.2 Filter Bank Multicarrier

Filter bank multicarrier modulation (FBMC) is a multicarrier modulation technique that uses a filter bank to achieve better spectral confinement than orthogonal frequency division modulation (OFDM). An alternative to circular orthogonal frequency division modulation (CP-OFDM), it avoids the use of a periodic prefix, thus allowing for increased spectral efficiency. In FBMC, each subcarrier is modulated using a modular filter, and the data codes are modulated and transmitted with a time shift between the phase and quadratic components (the real and imaginary parts of QAM modulation), hence the name OQAM (orthogonal frequency division modulation with phase shift).

### II.4.2.1 FBMC operating principle

The FBMC system operates using a series of digital filters that divide the bandwidth into several sub-bands, each corresponding to a subcarrier. These subcarriers are modulated using QAM codes. A set of synthetic filters is used at the transmitter to optimize each subcarrier and prevent inter-code (ISI) and inter-carrier (ICI) interference. At the receiver, a set of analytical filters is used to decode the received signal and extract the transmitted codes.

The code is modified by applying a time and frequency shift, allowing the separation of subcarriers without requiring shielding or a periodic prefix. This approach ensures excellent spectral confinement.

### II.4.2.2 Advantages and disadvantages of FBMC

#### Advantages of FBMC

- ✓ Improved spectral efficiency due to the absence of a periodic prefix.
- ✓ Excellent spectrum control, reducing out-of-band emissions.
- ✓ No synchronization required between users.
- ✓ Better resistance to frequency dispersion, suitable for asynchronous communication systems.

#### Disadvantages of FBMC

- ✓ Increased implementation complexity, particularly for the receiver.
- ✓ More complex equalization process.
- ✓ More difficult integration with MIMO systems.
- ✓ Longer response time due to the filter length.

### II.4.3 Generalized Frequency Division Multiplexing

Generalized frequency-division modulation (GFDM) is a multicarrier modulation technique designed to be more flexible than orthogonal frequency-division modulation (OFDM). This technique is based on block transmission, where each subcarrier is filtered by a conventional filter. In GFDM, the data to be transmitted is divided into several blocks, each composed of multiple subcodes distributed across multiple subcarriers.

Each GFDM block is generated by applying filtering to each subcarrier, using circular convolution with a conventional filter. The system employs a time-frequency grid where each time interval corresponds to a subcode and each frequency interval to a subcarrier. Thus, GFDM modulation allows for more precise control of both time and frequency positioning.

#### II.4.3.1 Characteristics of GFDM

Generalized Frequency Division Modulation (GFDM) is a flexible multicarrier signal modulation system characterized by its block architecture. Each block consists of several sub symbols transmitted over multiple subcarriers. Unlike conventional Orthogonal Frequency Division Modulation (OFDM), GFDM uses circular pulse shaping, allowing individual filtering of each subcarrier using a modular filter. This approach generates a non-orthogonal waveform, a source of intercarrier interference (ICI) that necessitates more complex receivers for efficient signal detection. Furthermore, GFDM uses a single periodic prefix for the entire block, thus improving spectral efficiency by reducing redundancy. The inherent flexibility in filter design and block configuration within the modulation system makes it adaptable to diverse transmission requirements, making it a prime candidate for next-generation wireless communication systems

### II.4.3.2 Advantages and disadvantages of GFDM

#### Advantages of GFDM

- ✓ High flexibility in filter and parameter selection.
- ✓ Good spectral confinement (low out-of-band emissions).
- ✓ Improved adaptation to segmented spectrum.
- ✓ Faster response time than OFDM technology.

#### Disadvantages of GFDM

- ✓ Non-orthogonal modulation, which complicates receiver design.
- ✓ Increased signal equalization complexity.
- ✓ Residual interference between subcarriers (intercarrier interference).

## II.5 Conclusion

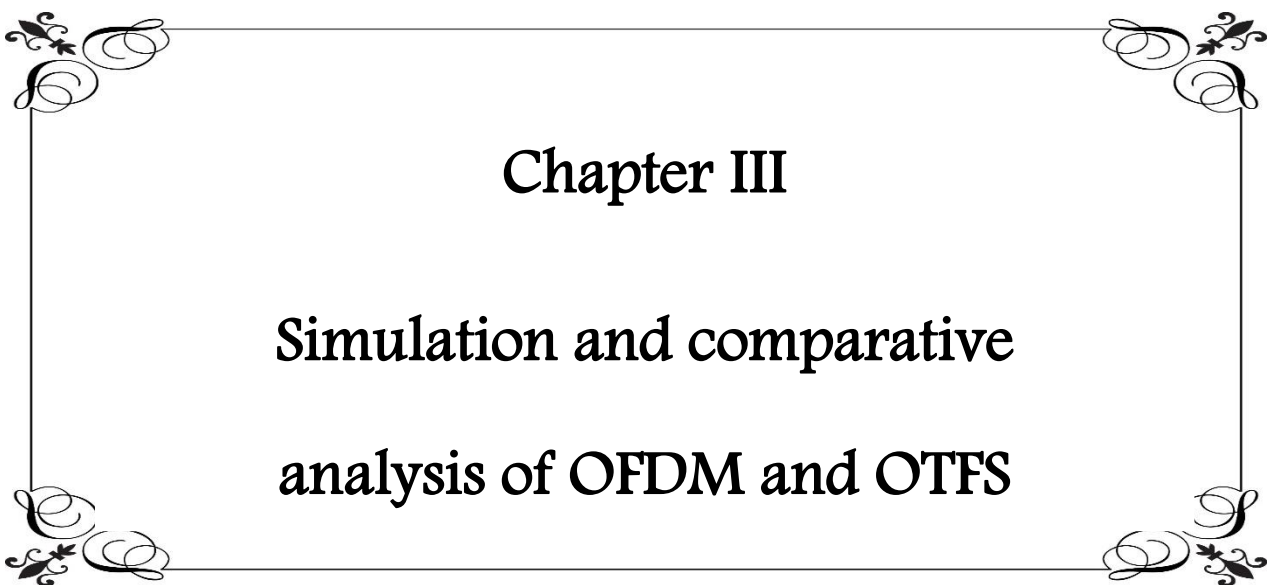
In this chapter we explored in detail the fundamental principles, architectures and performance aspects of multicarrier modulation schemes. We began by revisiting the historical development and theoretical foundations of Orthogonal Frequency Division Multiplexing (OFDM), analyzing its strengths such as spectral efficiency and robustness against multipath fading.

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 Orthogonal Time Frequency Space (OTFS).

We also presented the transceiver architecture for OTFS-based systems, which represent new candidate waveforms, along with a detailed explanation of the various components of this architecture, their roles, and their transformation (ISFFT, Heisenberg, Wigner, SFFT) and mathematical relationships.

The chapter concluded with an overview of other candidate waveforms, including Filter Bank Multicarrier (FBMC), Universal-Filtered-Multi-Carrier (UFMC) and Generalized Frequency Division Multiplexing (GFDM), outlining their principles of operation, unique characteristics, and comparative advantages and disadvantages.

The next chapter will implement simulations to evaluate and compare the performance of some of these waveforms under various channel conditions using MATLAB



## **Chapter III**

### **Simulation and comparative analysis of OFDM and OTFS**

### III.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 waveform for the development of multicarrier modulation schemes, the Orthogonal Time Frequency Space (OTFS) technique presents as an alternative to the traditional Orthogonal Frequency Division Multiplexing (OFDM), which suffers from high out-of-band emissions and high sensitivity to synchronization errors.

In this chapter we present a simulation-based comparison of Orthogonal Time Frequency Space (OTFS) and conventional Orthogonal Frequency Division Multiplexing (OFDM) in MATLAB Environment. Through simulation we evaluate the performance of an OTFS and OFDM system in terms of constellation diagram for various modulation type and order.

We evaluate also the Bit Error Rate (BER) as a function of the SNR (signal-to-noise ratio). The Peak-to-Average Power Ratio (PAPR) and its corresponding Complementary Cumulative Distribution Function (CCDF) will be analyzed for different system parameters. Examining their evolution in delay Doppler domain and speed variation for different modulations. The findings are crucial for guiding waveform design and optimization in future wireless networks.

### III .2 Simulation parameters

In order to fairly compare the performance of OFDM and OTFS, we use a consistent set of simulation parameters across all MATLAB scenarios. These parameters govern the behavior of waveform generation, modulation, and performance metrics such as BER, PAPR, and CCDF.

**Table 3.1:** Simulation Parameters

| Parameter                  | Value / Description    |
|----------------------------|------------------------|
| Carrier frequency          | 4 GHz                  |
| Number of subcarriers (M)  | 64                     |
| Number of OTFS symbols (N) | 30                     |
| Subcarrier spacing         | 15 KHz                 |
| Speed (Km/h)               | 50, 120, 200, 300, 500 |
| Modulation Schemes         | 4-QAM, 16-QAM, 64-QAM  |

### III.3 Performances study of OFDM and OTFS

The objective of this section is to study the performance of OTFS and OFDM systems

#### III.3.1 Constellation comparison for OFDM and OTFS

A constellation diagram is a two-dimensional graphical representation in the complex plane of the different symbols emitted by a digital modulation system. It is a fundamental diagnostic tool in signal processing that allows for the analysis of transmission quality and observation of how data is mapped onto the carrier wave.

The main utility of the constellation diagram lies in its ability to visualize the degradation suffered by the signal as it passes through the propagation channel.

In evaluating the performance of advanced modulations and communication systems operating under very high mobility conditions (such as at 500 km/h), the diagram allows for instant visualization of the severity of rapid fading, the impact of the Doppler effect, or for illustrating the robustness of techniques such as OTFS against inter-symbol interference (ISI) compared to a classic modulation such as OFDM.

Figures (3.1) - (3.3) show the constellation diagram for OFDM and OTFS across modulation orders 4-QAM, 16-QAM and 64-QAM over an SNR of 25dB.

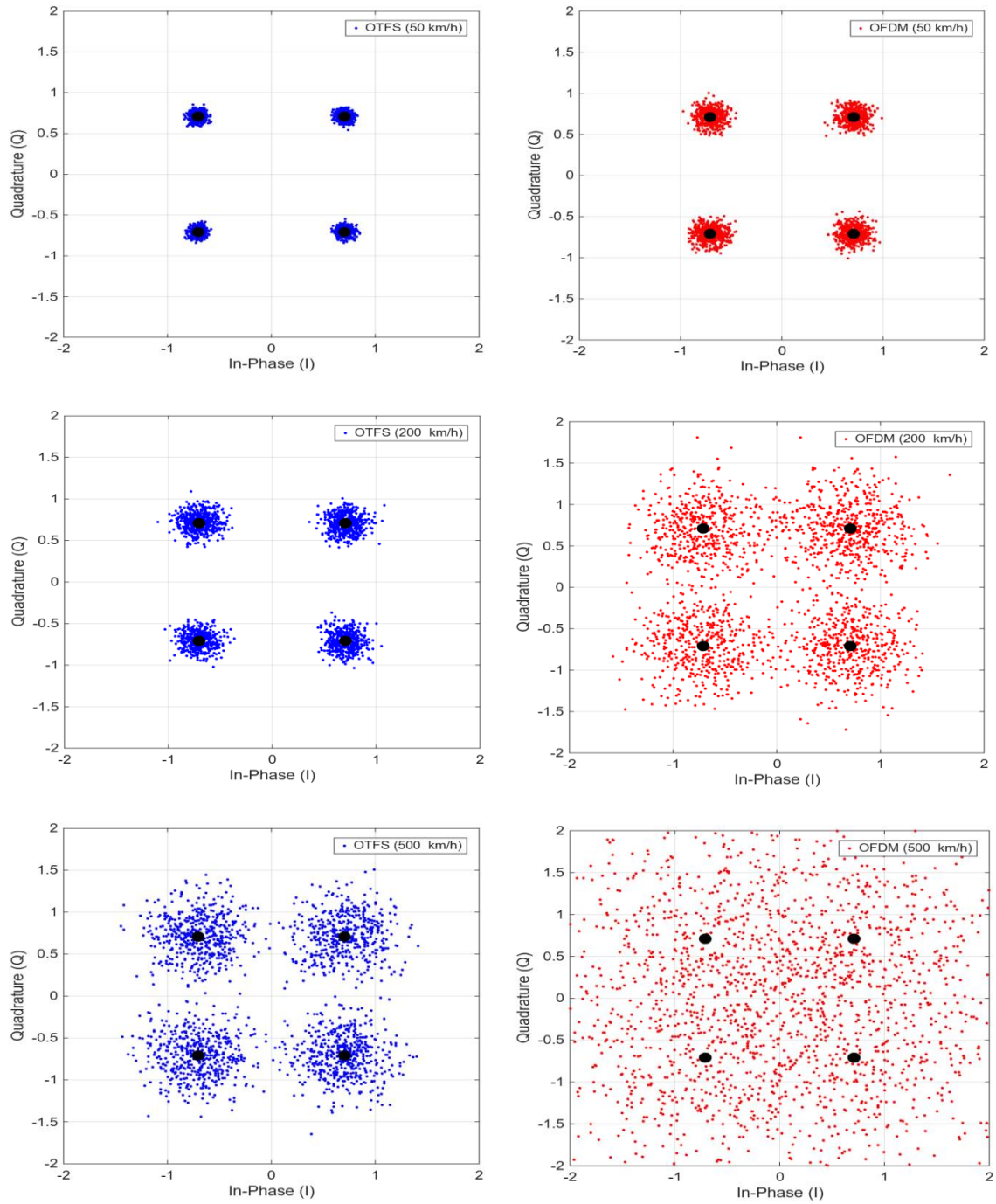


**Figure 3.1:** Constellation of OFDM and OTFS in diverse mobility, 4QAM SNR=25dB

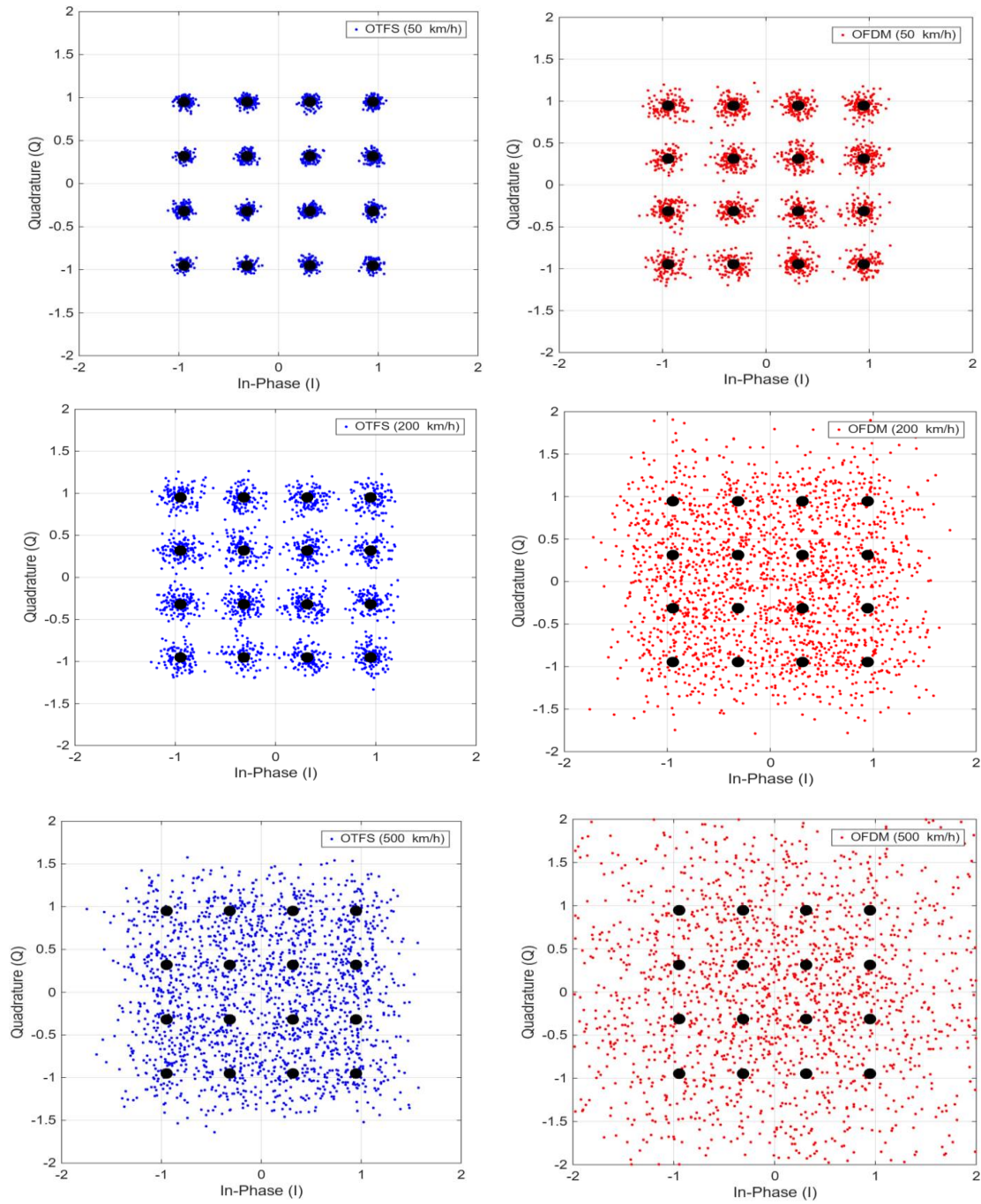


**Figure 3.2:** Constellation of OFDM and OTFS in diverse mobility, 16QAM SNR=25dB

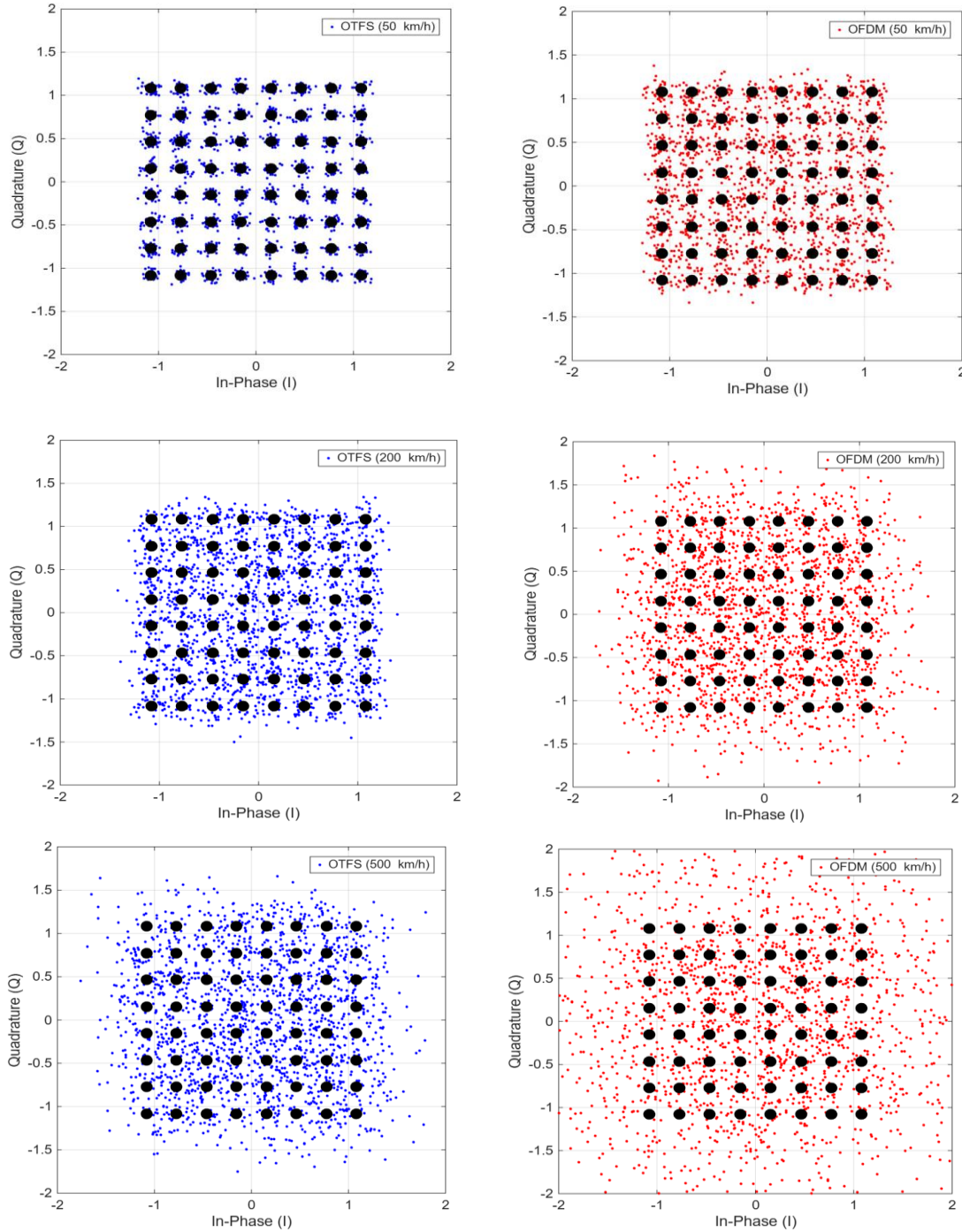


**Figure 3.3:** Constellation of OFDM and OTFS in diverse mobility, 64QAM SNR=25dB

Figure 3.1, Figure 3.2 and Figure 3.3 represent the constellation diagram for OFDM and OTFS across 4-QAM, 16QAM and 64QAM respectively. We compare these constellations in diverse mobility scenarios: in low mobility revealed by 50 Km/h and in high mobility materialized by 200 Km/h and 500, for a typical SNR value of 25 dB, we can perceive that:

**At 50 km/h (Low Mobility):** The OFDM (red) and OTFS (blue) point clouds are very dense and well-centered on their theoretical coordinates. The Doppler shift is too small to disrupt orthogonality. This is why, at this speed, both techniques exhibit the same performance.

**At 200 km/h:** The divergence becomes apparent spatially in 16 and 64 modulation order. The OFDM symbols (red) expand in a circular fashion, indicating that the interferences (Inter Symbol Interference (ISI) and inter-carrier interference (ICI)) effects become strong. On the OTFS side (blue), the clusters spread out slightly but remain perfectly separated and confined, ensuring reliable detection.

**At 500 km/h (High Mobility):** This is the critical case, the interferences become stronger, the OFDM constellation transforms into a completely dispersed point cloud that fills the entire complex plane and this effect increases with modulation order. The ISI and ICI are so strong that it's almost impossible to distinguish the different phase states of the 4QAM 16QAM and 64QAM. Conversely, OTFS maintains distinct clusters thanks to its robustness in the Delay-Doppler domain, allowing the receiver to correctly decode the bits.

In the same manner figures (3.4) - (3.6) show the constellation diagram for OFDM and OTFS across modulation orders 4-QAM, 16-QAM and 64-QAM over a noisy environment with a weak SNR value of 10dB.

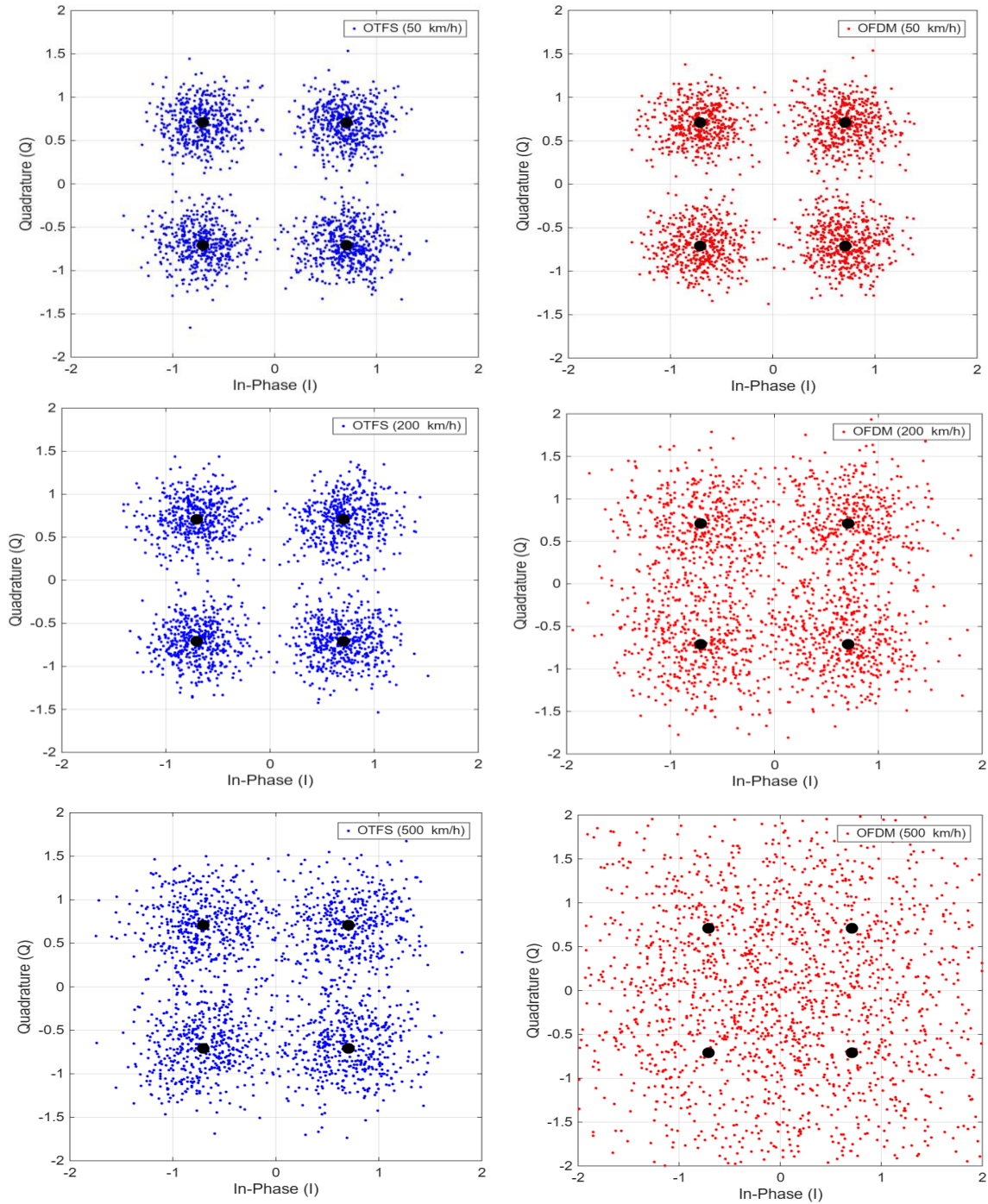


**Figure 3.4:** Constellation of OFDM and OTFS in diverse mobility, 4QAM SNR=10dB

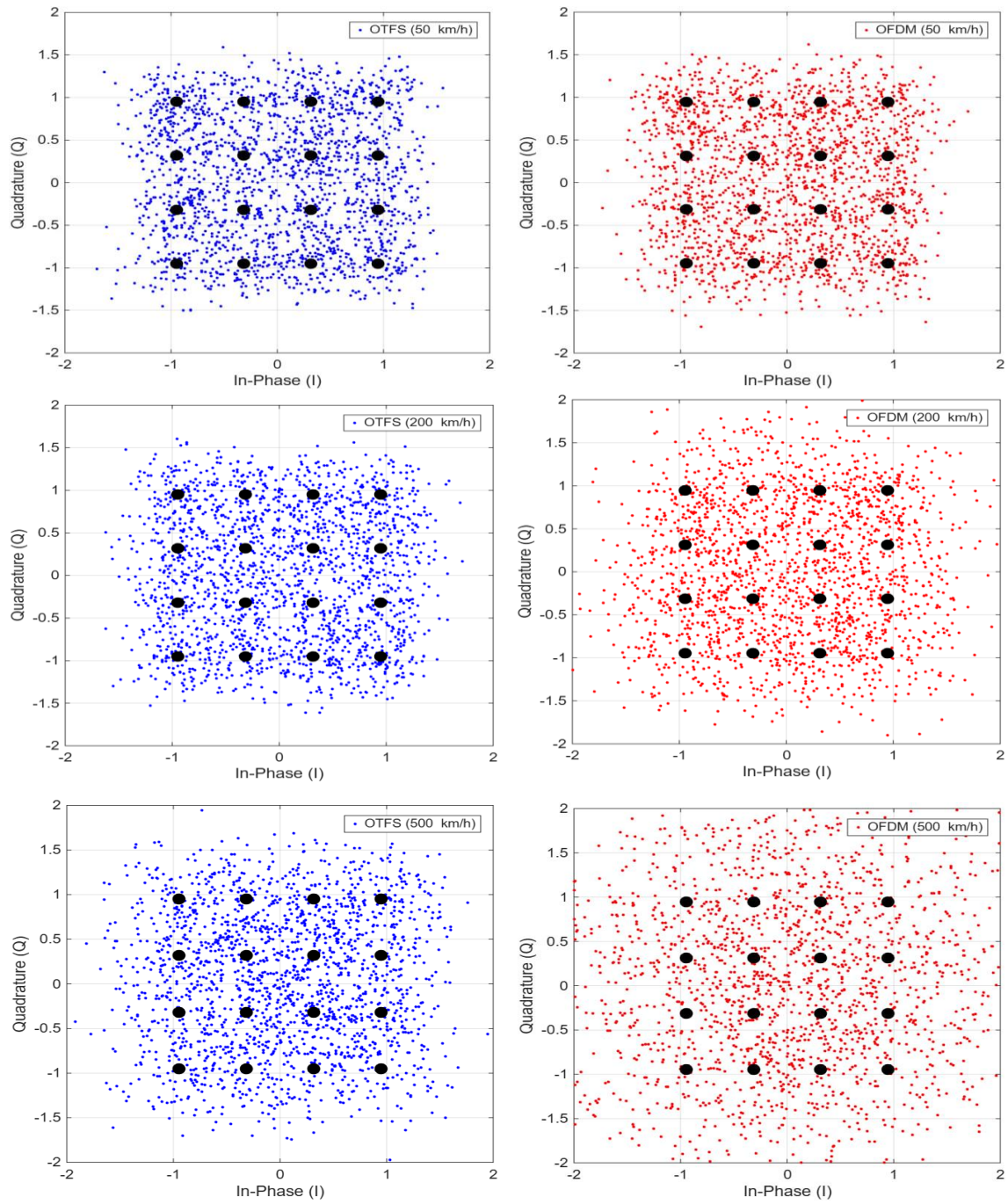


**Figure 3.5:** Constellation of OFDM and OTFS in diverse mobility, 16QAM SNR=10dB

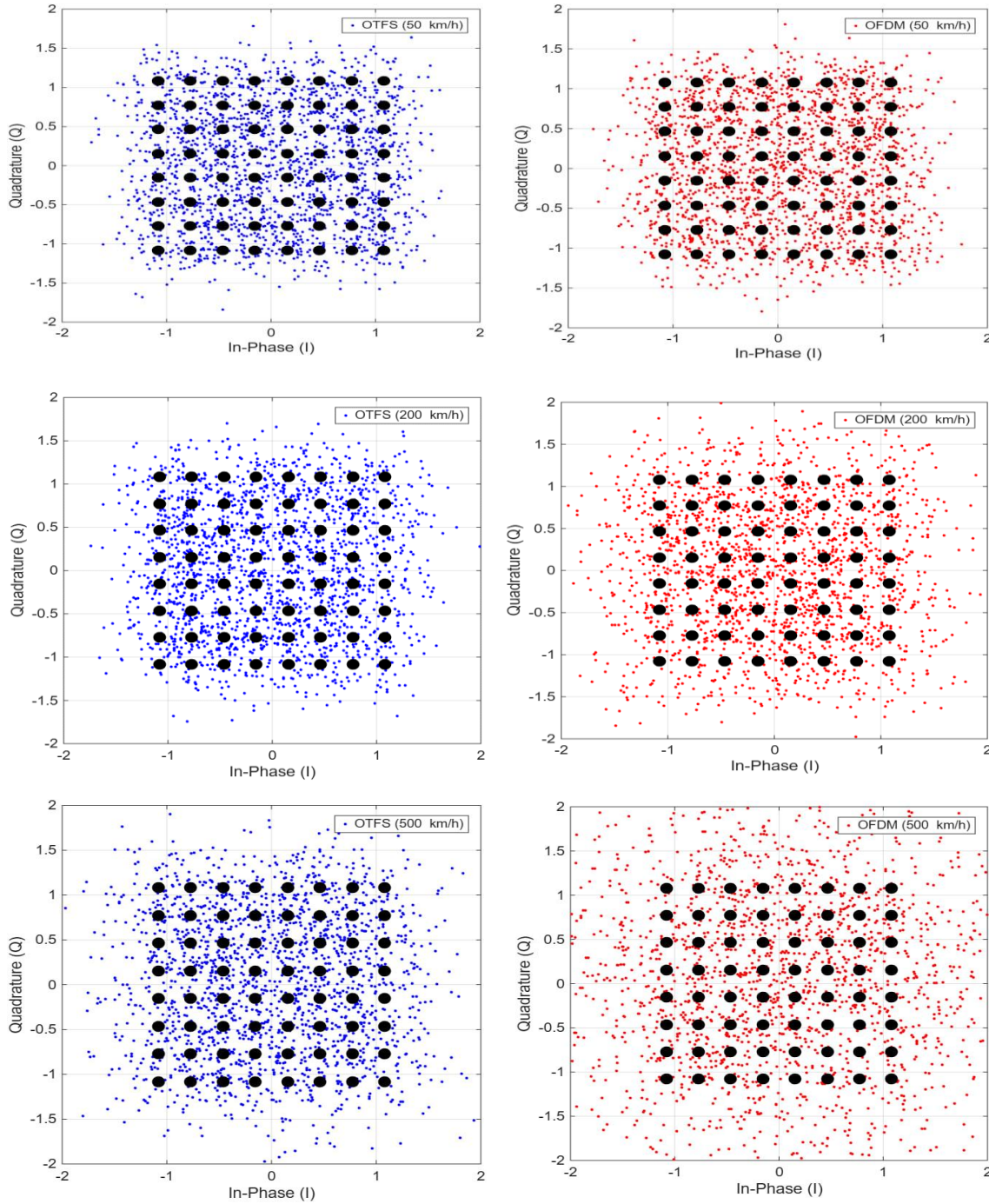


**Figure 3.6:** Constellation of OFDM and OTFS in diverse mobility, 64QAM SNR=10dB

Figure 3.4, Figure 3.5 and Figure 3.6 represent the constellation diagram for OFDM and OTFS across 4-QAM, 16QAM and 64QAM respectively. We compare these constellations in diverse mobility scenarios: in low mobility revealed by 50 Km/h and in high mobility materialized by 200 Km/h and 500, in noisy environment with a weak value of 10 dB. we can notice that:

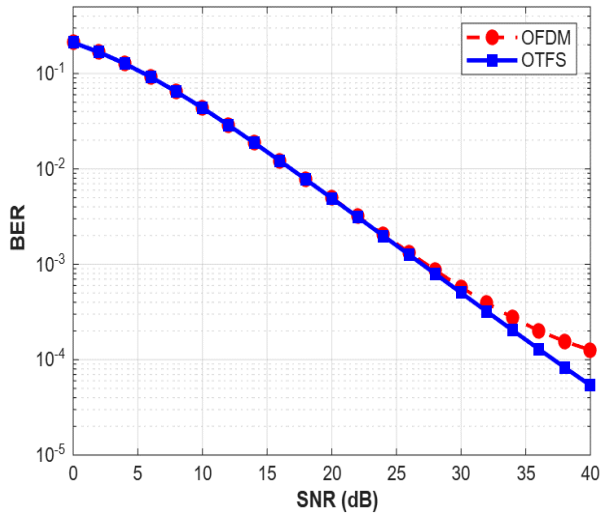
**At 50 km/h (Low Mobility):** We observe that the OTFS constellation points form dense, well-centered clusters around ideal 4-QAM sites; however, the Doppler effect remains marginal for both techniques on 16-QAM and 64-QAM. Furthermore, the decrease in signal-to-noise ratio from SNR = 25 dB in the figures (3.4) - (3.6) to SNR = 10 dB affects both techniques.

**At 200 to 500 Km/h:** The combination of a low signal-to-noise ratio (SNR) and high mobility is highly disruptive. OFDM Thermal noise contrast rapidly overwhelms the already distorted signal boundaries caused by carrier interference (ICI). The severe modulation dispersion observed at high speeds is exacerbated, leading to point overlap across the resolution boundaries even at low speeds. This, in turn, significantly increases the bit-rate error minimum (BER), as background noise completely obscures structurally weak subcarriers, making accurate decoding impossible.

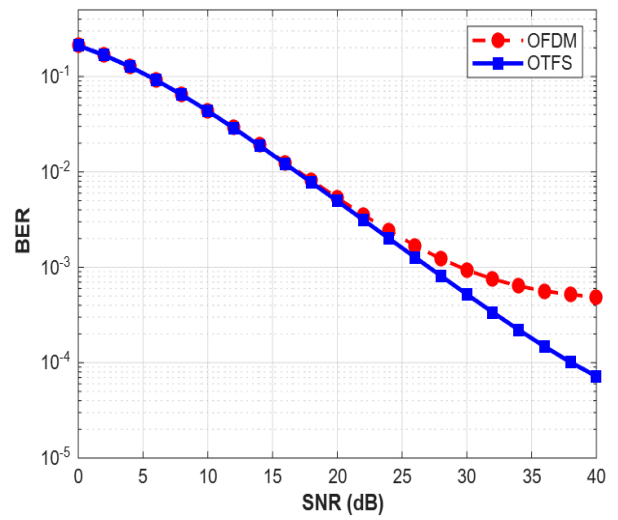
OTFS also exhibits degradation, but more smoothly, under low signal-to-noise ratio (SNR) conditions. While noise contrast inevitably leads to cluster expansion, the inherent two-dimensional diversity gain achieved by distributing each data token across the entire delay-Doppler network allows the receiver to effectively average the noise power across the monitoring frame. Thus, as clusters expand, their centers remain stable in their optimal geometric positions. This power diffusion feature preserves the four-way separation capability and maintains a reliable decision area for much longer than OFDM technology under the same extreme noise and mobility constraints.

### III.3.2 Bit Error Rate (BER) performance in various, mobility

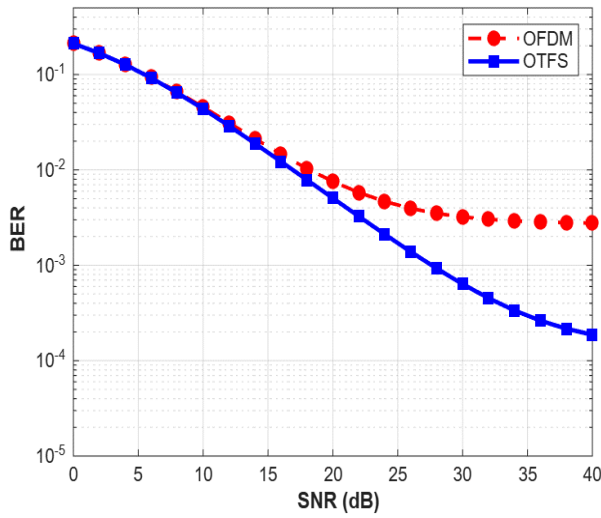
We evaluate BER for OFDM and OTFS across modulation orders (4-QAM, 16-QAM and 64-QAM) over an SNR range of 0–40 dB.



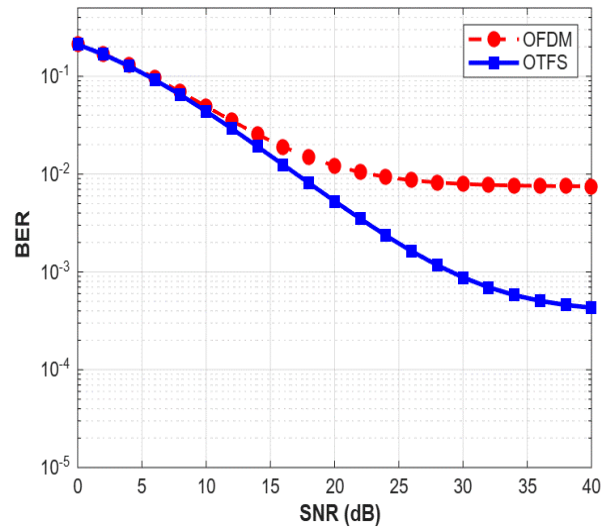
a) 50 Km/h



b) 120 Km/h

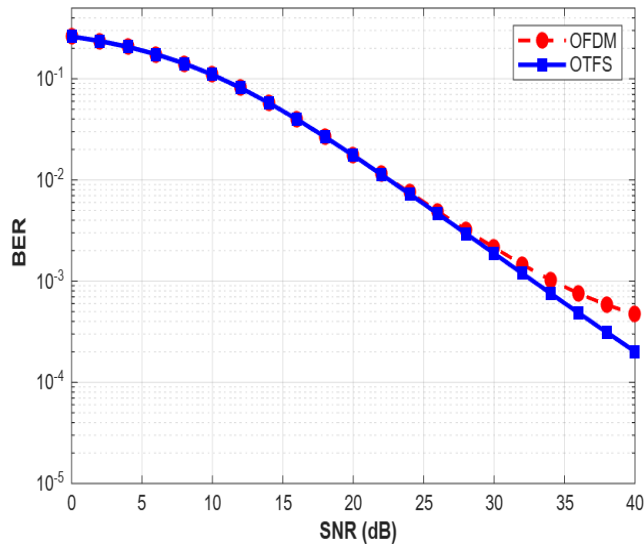


c) 300 Km/h

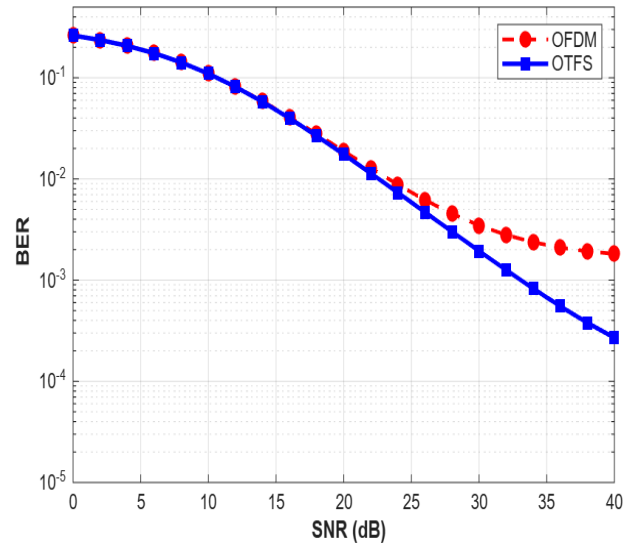


d) 500 Km/h

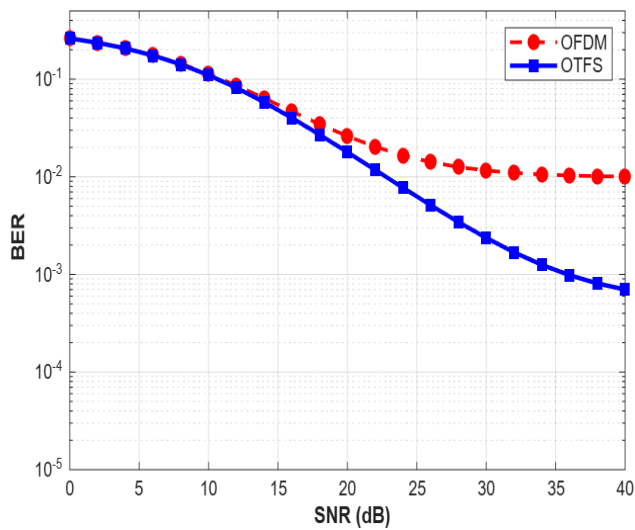
**Figure 3.7:** Bit Error Rate (BER) of OFDM and OTFS in diverse mobility, 4QAM



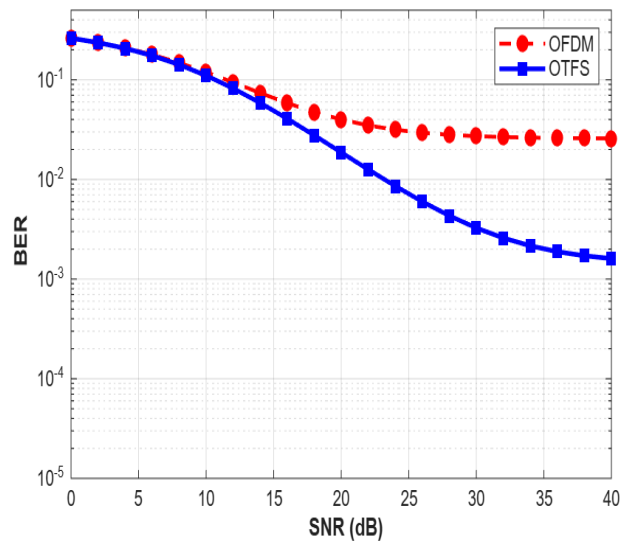
a) 50 Km/h



b) 120 Km/h



c) 300 Km/h



d) 500 Km/h

**Figure 3.8:** Bit Error Rate (BER) of OFDM and OTFS in diverse mobility, 16 QAM

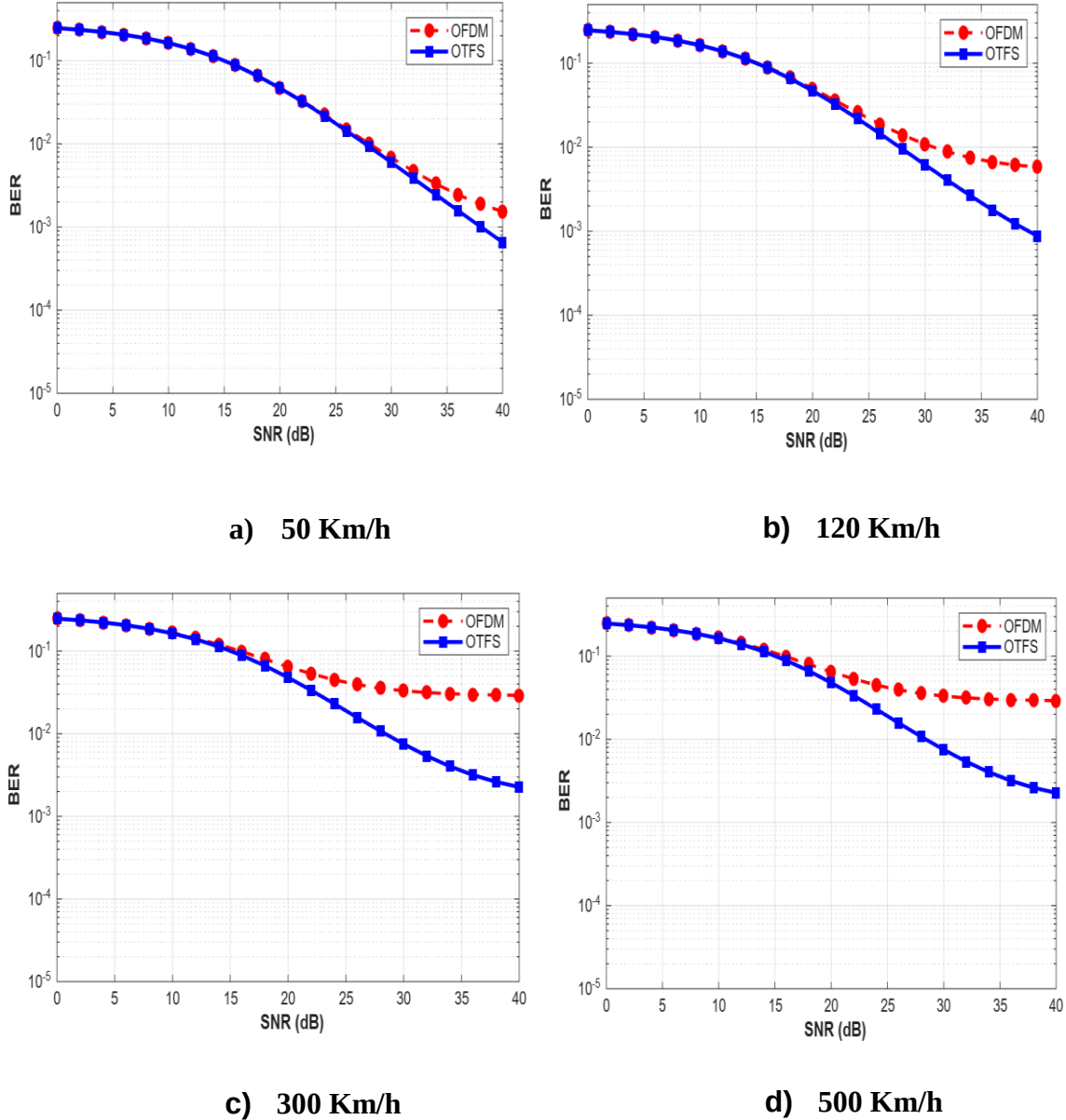


**Figure 3.9:** Bit Error Rate (BER) of OFDM and OTFS in diverse mobility, 64QAM

This Figures (3.7), (3.8), and (3.9) illustrate the performance in terms of bit error rate (BER) as a function of signal-to-noise ratio (SNR) for OFDM and OTFS modulation systems. Performance was evaluated under different high-speed driving conditions (50 km/h, 120 km/h, 300 km/h, and 500 km/h) for three different modulation orders: 4-QAM, 16-QAM, and 64-QAM respectively.

- ✓ **At low mobility (50 Km/h):** lower speeds, both modulation system exhibits closely matched BER performance. The Doppler spread is relatively small, allowing

conventional OFDM to maintain orthogonal subcarriers without experiencing severe Inter-Carrier Interference (ICI).

- ✓ **At high mobility (120, 300 and 500 Km/h):** As the speed scales up to 300 km/h to 500 km/h, the performance of OFDM degrades drastically, manifesting as an early error floor at level 0.02190 in SNR=15 dB. This degradation occurs because high Doppler shifts destroy the orthogonality between OFDM subcarriers, leading to severe ICI. In stark contrast, OTFS maintains a continuously decreasing BER curve even at extreme velocities at level 0.00043 in SNR=40 dB. By multiplexing information symbols in the Delay-Doppler (DD) domain rather than the Time-Frequency (TF) domain, OTFS transforms a time-varying fading channel into a time-invariant, localized channel. Consequently, it effectively exploits the full time-frequency diversity of the wireless channel.

Each time we increase the modulation order as show in figure 3.8 and 3.9, the bit error rate (BER) increases for both modulation systems (OFDM, OTFS).

We can summarize the study of the BER performance for both OFDM and OTFS for different modulations and diverse mobility as follows (Table 3.2 ;3.3; 3.4):

**Table 3.2:** BER performance comparison between OFDM and OTFS for different speed, 4QAM

| SNR (dB) | BER OFDM (50 km/h) | BER OTFS (50 km/h) | BER OFDM (500 km/h) | BER OTFS (500 km/h) |
|----------|--------------------|--------------------|---------------------|---------------------|
| 5        | 0.1087             | 0.1086             | 0.1122              | 0.1088              |
| 10       | 0.04362            | 0.04350            | 0.04925             | 0.04385             |
| 15       | 0.01516            | 0.01510            | 0.02190             | 0.01544             |
| 20       | 0.00500            | 0.00492            | 0.01216             | 0.00529             |
| 25       | 0.00164            | 0.00157            | 0.00895             | 0.00195             |
| 30       | 0.00057            | 0.00050            | 0.00792             | 0.00087             |
| 35       | 0.00023            | 0.00016            | 0.00760             | 0.00053             |
| 40       | 0.00012            | 0.00005            | 0.00749             | 0.00043             |

**Table 3.3:** BER performance comparison between OFDM and OTFS for different speed, 16QAM

| SNR (dB) | BER OFDM (50 km/h) | BER OTFS (50 km/h) | BER OFDM (500 km/h) | BER OTFS (500 km/h) |
|----------|--------------------|--------------------|---------------------|---------------------|
| 5        | 0.1912             | 0.1911             | 0.1944              | 0.1913              |
| 10       | 0.1099             | 0.1098             | 0.1193              | 0.1103              |
| 15       | 0.04832            | 0.04814            | 0.06556             | 0.04907             |
| 20       | 0.01769            | 0.01746            | 0.03991             | 0.01868             |
| 25       | 0.00606            | 0.00580            | 0.03037             | 0.00714             |
| 30       | 0.00214            | 0.00187            | 0.027               | 0.0032              |
| 35       | 0.00087            | 0.00060            | 0.026               | 0.0020              |
| 40       | 0.00047            | 0.00020            | 0.025               | 0.0016              |

**Table 3.4:** BER performance comparison between OFDM and OTFS for different speed, 64QAM

| SNR (dB) | BER OFDM (50 km/h) | BER OTFS (50 km/h) | BER OFDM (500 km/h) | BER OTFS (500 km/h) |
|----------|--------------------|--------------------|---------------------|---------------------|
| 5        | 0.2145             | 0.2144             | 0.2161              | 0.2145              |
| 10       | 0.1638             | 0.1637             | 0.1709              | 0.1641              |
| 15       | 0.1007             | 0.1005             | 0.1223              | 0.1018              |
| 20       | 0.04745            | 0.04693            | 0.08846             | 0.04961             |
| 25       | 0.01840            | 0.01766            | 0.07261             | 0.02142             |
| 30       | 0.006812           | 0.005982           | 0.06678             | 0.01022             |
| 35       | 0.002828           | 0.001963           | 0.06484             | 0.006388            |
| 40       | 0.001533           | 0.0006569          | 0.06421             | 0.005141            |

### III.3.3 Complementary Cumulative Distribution Function (CCDF)

We evaluate the Complementary Cumulative Distribution Function (CCDF) of the Peak-to-Average Power Ratio (PAPR) for both OFDM and OTFS modulation schemes. The performance is analyzed across three distinct modulation orders: 4-QAM, 16-QAM, and 64-QAM.

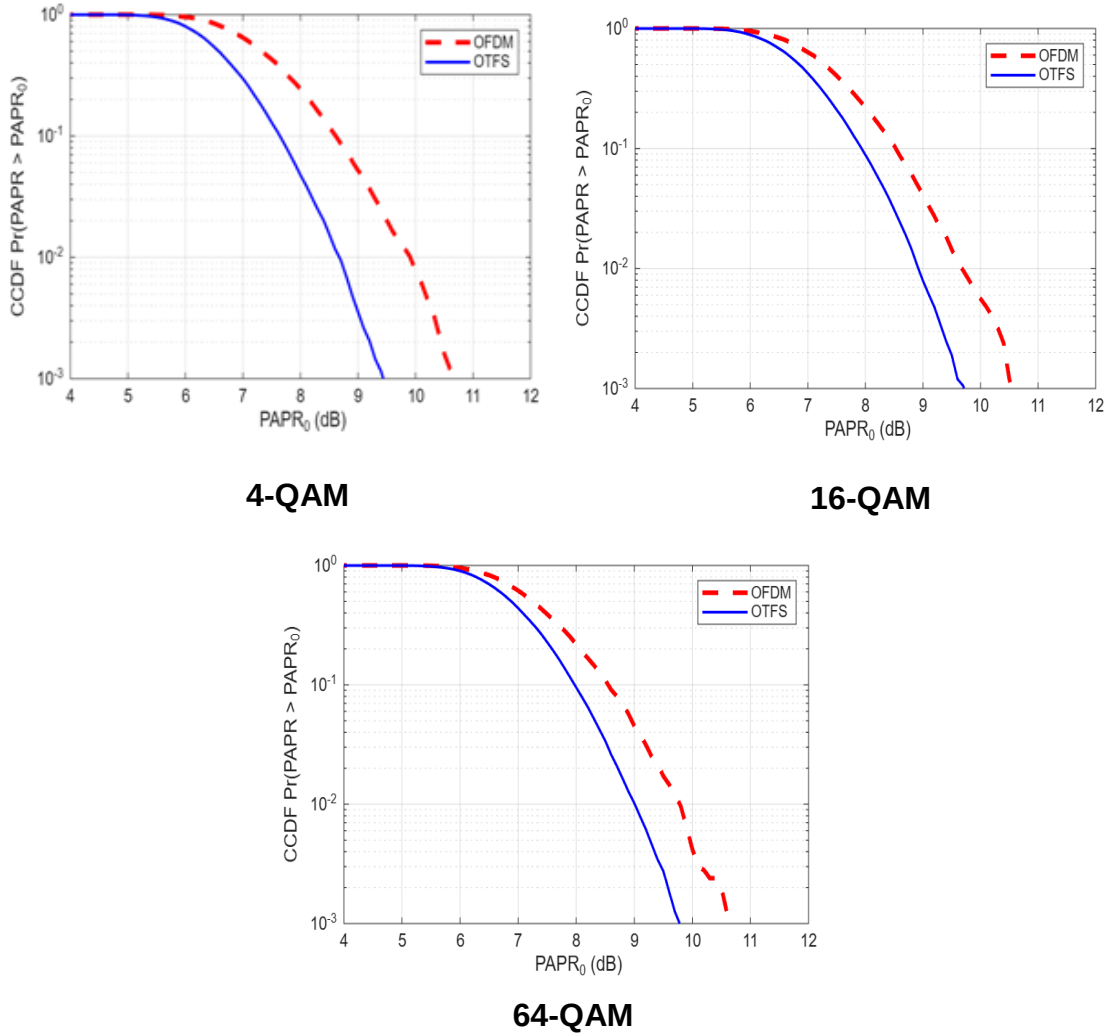


**Figure 3.10:** CCDF of PAPR for OFDM and OTFS

The figure (3.10) shows three subplots, each corresponding to a different modulation order: 4-QAM, 16-QAM and 64-QAM, the blue solid curve represents OTFS, and the red dashed curve represents OFDM.

- ✓ For all modulation orders, the OTFS curve lies slightly to the left of OFDM, indicating that OTFS has a slightly low probability of reaching larger PAPR values especially at low CCDF probabilities.
- ✓ For any given probability, the OTFS curve lies to the left of the OFDM curve. For example, at CCDF level of  $10^{-2}$ , the PAPR required by OTFS is approximately 1 dB to 1.2 dB lower than that required by OFDM.

- ✓ With the change in modulation order from 4-QAM to 16-QAM and 64-QAM, the overall appearance of the CCDF curves remains remarkably stable and the relative performance gain of OTFS compared to OFDM is strictly maintained.

Unlike OFDM, which concentrates energy on isolated subcarriers, OTFS distributes the energy of each symbol over the entire two-dimensional network, thus avoiding critical power spikes.

### III.3.4 Peak-to-Average Power Ratio (PAPR)

We evaluate the Peak-to-Average Power Ratio (PAPR) values obtained for OFDM and OTFS modulation schemes across three distinct modulation orders: 4-QAM, 16-QAM, and 64-QAM. Unlike the CCDF statistical curves, this bar chart directly illustrates the concrete peak power values (in dB) evaluated under identical system parameters.

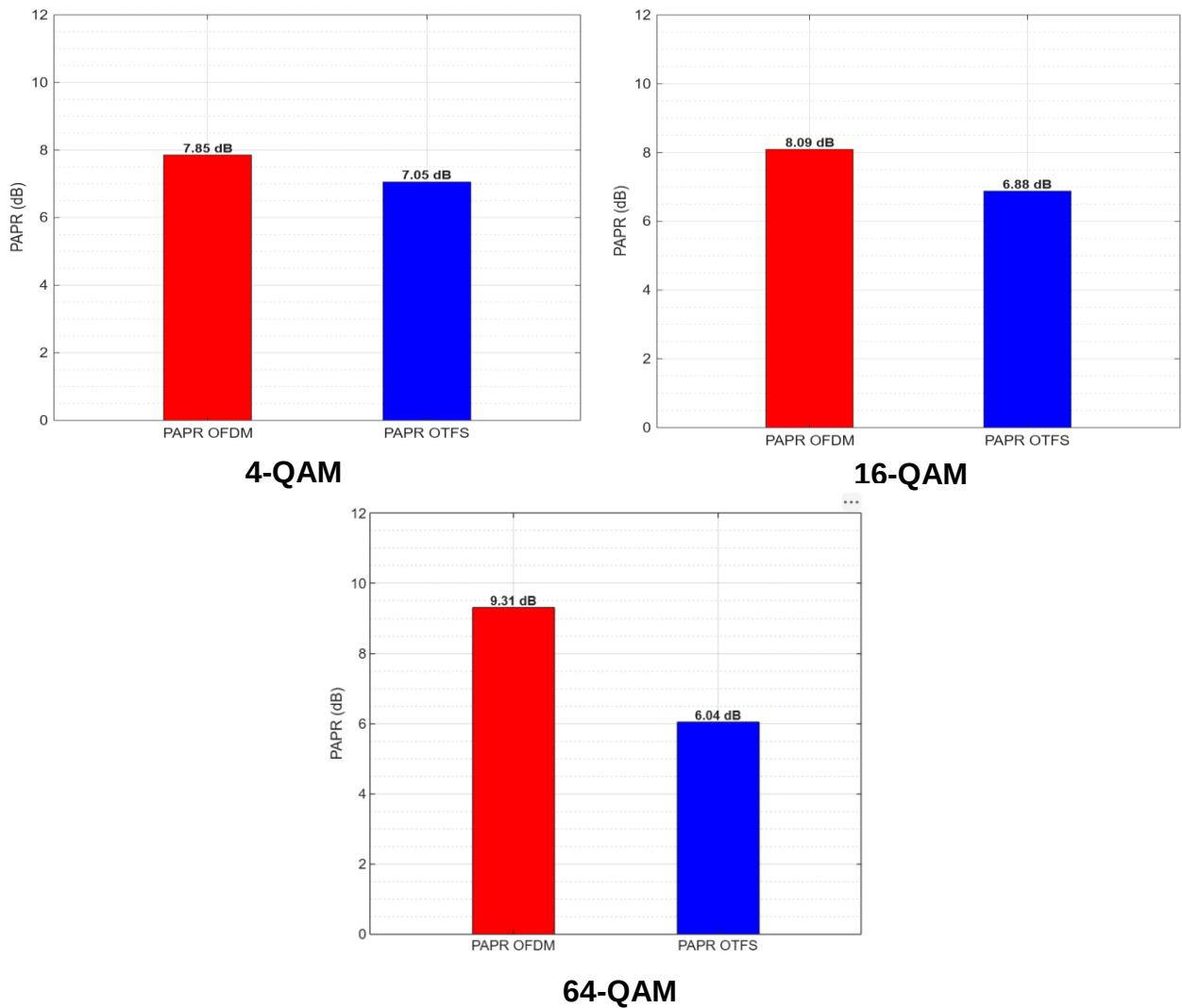


**Figure 3.11:** PAPR Comparison between OFDM and OTFS

The figure (3.11) illustrated the PAPR comparison between OFDM and OTFS where:

- ✓ **For 4-QAM:** The PAPR drops from 7.85 dB for OFDM to 7.05 dB for OTFS, yielding a clear gain of 0.80 dB.
- ✓ **For 16-QAM:** OFDM exhibits a PAPR of 8.09 dB, whereas OTFS restricts the peak envelope to 6.88 dB. This represents an enhanced reduction gain of 1.21 dB.
- ✓ **For 64-QAM:** In the high-order constellation scenario, the performance gap becomes even more pronounced. OFDM reaches a significant peak power value of 9.31 dB, while OTFS maintains a much lower profile at 6.04 dB.

OTFS generally shows more stable and lower PAPR for higher-order modulations, in contrast to OFDM shows higher PAPR.

We can summarize the study of the PAPR performance for both OFDM and OTFS for different modulations as follows (Table 3.5):

**Table 3.5: PAPR Comparison OFDM ; OTFS**

| <b>Modulation</b> | <b>OFDM-<br/>PAPR (dB)</b> | <b>OTFS- PAPR<br/>(dB)</b> |
|-------------------|----------------------------|----------------------------|
| <b>4-QAM</b>      | <b>7.85</b>                | <b>7.05</b>                |
| <b>16-QAM</b>     | <b>8.09</b>                | <b>6.88</b>                |
| <b>64-QAM</b>     | <b>9.31</b>                | <b>6.04</b>                |

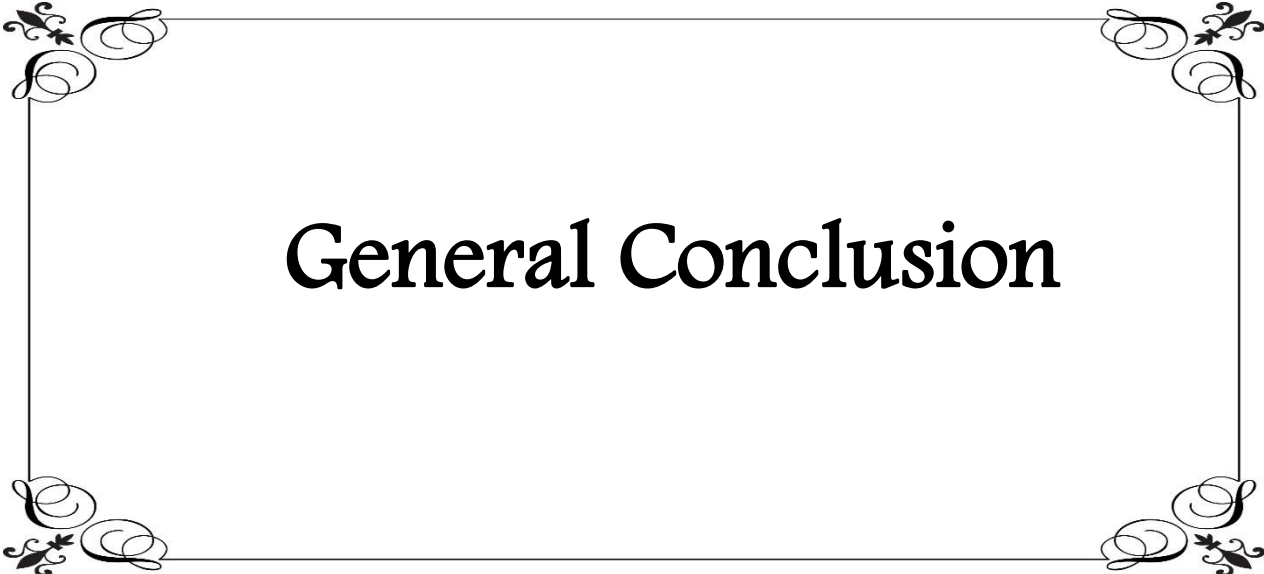
### III.4 Conclusion

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

Based on our results, we observe that OTFS especially in high mobility scenarios, significantly outperforms OFDM in terms of performance accuracy for the constellation behavior, BER and *PAPR* reduction.

The main innovation of OTFS is the use of the domain Delay-Doppler which allows for better channel stability, better Doppler resistance, a lower BER at high speed, and better performance for 5G/6G communications.

Although OFDM technology still has advantages in its simplicity and compatibility with legacy infrastructure, its high PAPR and terms of performance accuracy and bit error rate reduction especially in high-mobility scenarios pose a challenge for modern wireless communication environments. Therefore, OTFS technology is a powerful alternative that addresses most of the key shortcomings of OFDM and supports its use in next-generation wireless communication systems.



# General Conclusion

### **General Conclusion**

The rapid evolution of mobile communication technologies has generated a growing need for more efficient, flexible, and robust waveform solutions to meet the increasing demands of modern wireless systems. With the transition from 5G to the ambitious concepts of 6G, waveform design has become crucial for enabling high data transfer rates, extremely low latency, and broadband connectivity.

This research focused on the study, analysis, and comparison of multi-carrier modulation techniques, from the theoretical foundations of wireless telecommunications to emerging technologies that are candidates for next-generation networks (5G/6G). First, we laid the groundwork for our study by exploring the evolution of mobile generations (from 1G to 6G) and the inherent challenges of the radio-mobile propagation channel, such as multipath propagation, the Doppler effect, and interference. This step enabled us to define the crucial performance metrics (BER, PAPR, and constellation diagrams) necessary for the rigorous evaluation of any communication system. Subsequently, an in-depth analysis of transmitter/receiver architectures highlighted the strengths and limitations of OFDM (Orthogonal Frequency Division Multiplexing), a cornerstone of current networks, as well as other advanced waveforms (FBMC, UFMC, GFDM). Faced with the limitations of OFDM in high-mobility environments, we introduced and detailed OTFS (Orthogonal Time Frequency Space) modulation, deconstructing its architecture based on mathematical transformations in the Delay-Doppler domain (ISFFT, Heisenberg/Wigner transformations, SFFT). Finally, in-depth numerical simulations performed using MATLAB allowed us to directly compare the performance of OFDM and OTFS. The results obtained lead to the following key conclusions:

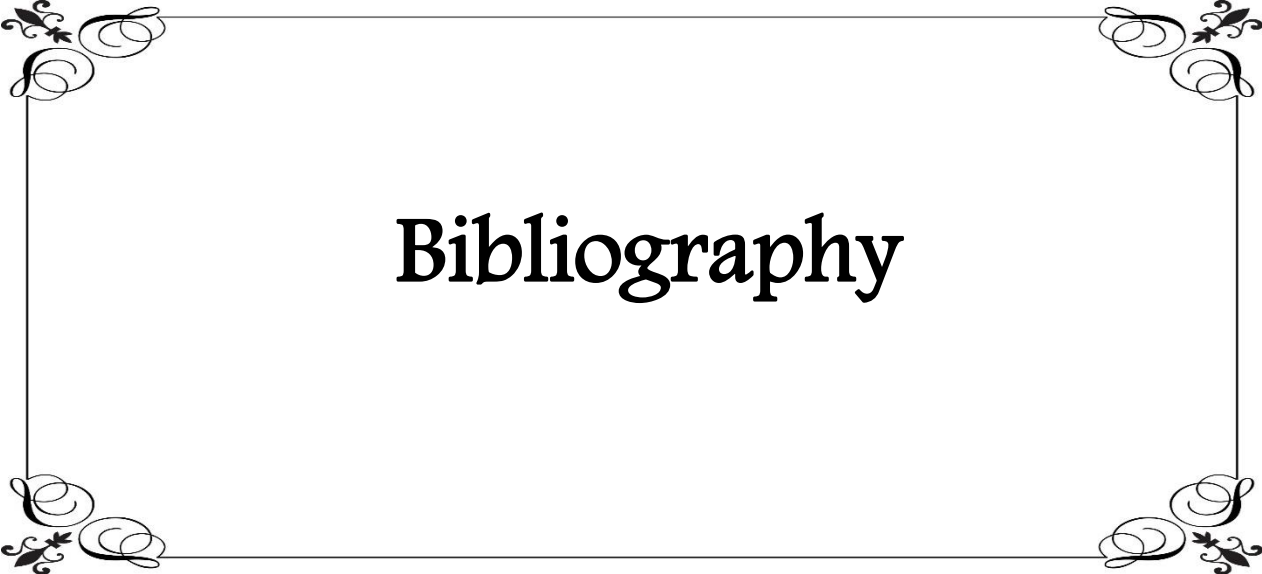
**Superiority of OTFS in high mobility:** Thanks to its unique formulation in the Delay-Doppler domain, OTFS offers excellent resistance to the Doppler effect and increased channel stability. It clearly surpasses OFDM in terms of accuracy and reduction of the bit error rate (BER) at high speed.

**Persistent challenges of OFDM:** Although OFDM remains advantageous for its algorithmic simplicity and compatibility with existing infrastructures, its sensitivity to Doppler shifts and its high crest factor (PAPR) limit its effectiveness in future mobile scenarios.

## ***General Conclusion***

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Going forward, this work could be extended combining OTFS with Massive MIMO Systems. 6G networks will rely heavily on multiple antenna technologies. A logical next step in this study would be to extend the numerical simulations to evaluate the performance of OTFS coupled with Massive MIMO architectures. The objective would be to analyze how the combined use of the spatial domain (MIMO) and the Delay-Doppler domain (OTFS) can maximize spectral efficiency while managing interference.



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