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Title:

Adaptive Co-existence of OFDM and OTFS for Multi-Mobility Scenarios in Wireless Communications

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Dedication

I dedicate this work to my beloved parents, whose unwavering support and encouragement have been my guiding light throughout this journey. To my brothers and sisters, thank you for always believing in me and standing by my side. To all my friends, your companionship and understanding have been invaluable. And to everyone I love, your inspiration and love have fueled my passion and perseverance. This achievement is as much yours as it is mine.

Abstract

The rapid evolution of technology necessitates the development of new waveforms capable of handling the increasing demands of high-mobility scenarios. Orthogonal Frequency Division Multiplexing (OFDM), although extensively used in current wireless communication systems, experiences significant performance degradation in high-mobility environments due to large Doppler shifts and Doppler spread effects. To address these challenges, a novel waveform called Orthogonal Time Frequency Space (OTFS) has been developed, offering superior performance in high-mobility scenarios by exploiting delay-Doppler diversity. However, OTFS introduces high processing complexity and does not exhibit obvious performance advantages for low-mobility users, where OFDM remains efficient and effective. Therefore, there is a critical need to develop a co-existence method that leverages the strengths of both waveforms. we proposed a method to check the user's velocity and dynamically switch between OFDM and OTFS based on user mobility. By doing so, the communication system can achieve optimal performance of Bit Error Rate (BER)versus Signal-to-Noise Ratio (SNR), maintaining robust and efficient data transmission across diverse mobility conditions.

Contents

List of Tables

List of Figures

List of Acronyms

- **3GPP:** Third Generation Partnership Project.
- **AD:** analog-to-digital
- **AI:** Artificial Intelligence.
- **AMC:** Adaptive Modulation and Coding.
- **AMPS:** Advanced Mobile Phone Service.
- **BER:** Bit Error Rate.
- **BTS:** Base stations.
- **CDMA:** code division multiple access.
- **CDPD:** Cellular Digital Packet Data.
- **CP:** Cyclic prefix.
- **DA:** digital-to-analog
- **DDD:** delay-Doppler domain
- **FD:** frequency domain
- **FDM:** Frequency Division Multiplexing.
- **FDMA:** frequency division multiple access.
- **FFT:** fast Fourier transform
- **GPRS:** General Packet Radio Service.
- **GSM:** global system for mobile communication.
- **ICI:** Inter-Carrier Interference
- **IDFT:** inverse discrete Fourier transform
- **IFFT:** inverse fast Fourier transform

- **ISFFT:** inverse symplectic fast Fourier transform
- **ISI:** inter-symbol interference.
- **ITU:** International Telecommunication Union.
- **MIMO:** multiple input multiple output.
- **MUI:** Multi User Interference
- **NMT:** Nordisk Mobile Telephony.
- **NTT:** Nippon Telegraph and Telephone.
- **OFDM:** Orthogonal Frequency Division Multiplexing.
- **P/S:** parallel to serial
- **PARP:** peak-to-average power ratio.
- **PSK:** Phase-shift keying.
- **QAM:** quadrature amplitude modulation.
- **SC-OFDM:** single carrier orthogonal frequency division multiplexing
- **SFFT:** symplectic fast Fourier transform
- **SNR:** signal-to-noise ratio.
- **S/P:** serial to parallel
- **SMS:** short message service.
- **TD:** time domain
- **TDMA:** time division multiple access.
- **VLC:** visible light communication
- **WCDMA:** Wideband Code Division Multiple Access.

General Introduction

As the first generation of communication systems (1G), the first cellular wireless network was introduced in the 1980s. Frequency division multiplexing (FDMA) was utilized to access the radio spectrum, and analog frequency modulation was applied to the voice transmissions[2].

In order to improve the advantages of cellular wireless technology (higher communication quality in disturbance), the Global System for Mobile Communications (GSM), also known as the second generation (2G), was introduced in the early 1990s. Different frequency bands were utilized in conjunction with Time-Division Multiple-Access (TDMA) for channelization[3].

The International Telecommunications Union IMT-2000 standard, which includes two variations: the Code Division Multiple Access 2000 (CDMA2000) system and the Universal Mobile Telecommunications System (UMTS) system, established the third generation (3G) systems, which mark the beginning of internet browsing. Walsh-Hadamard spreading sequences were employed by the CDMA technique as orthogonal basis functions, efficiently dispersing user information in terms of both frequency and time[2].

In the fourth generation (4G), orthogonal frequency division multiple access (OFDMA), a new multiplexing technology, was developed. Wideband communication using orthogonality as the foundation for information symbols is known as OFDM. This modulation approach has also been adopted by the fifth generation (5G). We find that the multipath high-mobility channel has broken this method[3][4].

Recently, orthogonal time frequency space (OTFS), a novel time-frequency modulation method, was proposed. Compared to OFDM, [5] offers notable benefits including high mobility wireless communication (HMWC). The delay-Doppler domain is a novel domain upon which the OTFS is based. The modulator dispersed the information symbol throughout the complete time-frequency domain needed to transmit a frame, utilizing a two-dimensional (2D) basis function[3]. The main objective of this work is to deliver suitable communication what ever the user's velocity is.

The structure of the report is:

- The first chapter is a brief introduction of cellular wireless communication technologies, mentioning their frequency band benefits and uses areas.
- The second chapter talks about the waveforms used for 4G, 5G, and 6G (OFDM and OTFS). It describes their functionalities and basics also their advantages and disadvantages.
- The third chapter (last one) is a result and discussion chapter where we compare both of the waveforms (OFDM and OTFS) in a various scenarios and find out which one is better to another. Also, test the coexistence of both last waveforms.

1 Introduction

Wireless communication refers to the transfer of information between two points without the need for any physical conductors or optical fibers. This distance between the two points can be as short as a few meters, such as in the case of garage control, or as long as the connection between two BTS stations. In the recent few years, the word Generation in the wireless communication field has adjusted the idea of framework, mobility, capacity, frequency bands, delay, etc. Each mobile Wireless Generation has some new techniques, features, and requirements that make it different from the past one. Starting with the first generation (1G) systems (1980) which started only with voice calls. The second generation (2G) (1990) was introduced into our lives with short message service (SMS). The next-generation (3G) systems afford a high data transmission rate and augmented capacity. With 3G multimedia content started to be used among people in the 2000s. The fourth generation (4G) includes 3G with fixed 24/7 internet access. there was an increase in the bandwidth and reduced cost of resources [6]. Wireless communication, which continues to headway without braking, has shifted into the fifth and sixth-generation mobile communication systems. Figure 1.1 shows the development from the first generation to the present [7].

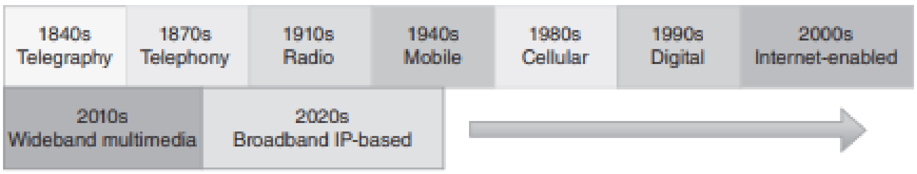

Figure 1.1: Evolution of communication system.

1.1 first generation 1G

The first generation was launched in Japan by NTT in 1979, Tokyo. During five years, the NTT has grown to cover all of Japan to become the first country to use a 1G network. This network (the first generation 1G) only supports voice calls depending on three technologies: Nordisk Mobile Telephony (NMT), Advanced Mobile Phone Service (AMPS), and Cellular Digital Packet Data (CDPD).

- NMT is the first automatic cellular phone system. It came into the field in 1981 as an answer to the heavy needs of the manual mobile phone network. Two forms exist of NMT NMT-450 (450 MHz frequency band) and NMT-900 (900 MHz frequency band). NMT-900 had more channels than NMT-450. The cell size ranges from 2-30 KM. NMT supports simultaneous receiving and transmission of voice. The main issue here is the voice was not fully encrypted [2].

• AMPS developed by Bell Labs, was introduced in America in 1983. It was the first generation to utilize independent channels for each conversation. This technology facilitates the use of a large number of phones over a geographical area. AMPS utilized the frequency division multiple access with an uplink frequency of 824-849 MHz and a downlink frequency of 869-894 with a channel limited to 30 KHz [2].

• CDPD (Cellular Digital Packet Data) utilizes a technique called RF sniffing to detect AMPS call is trying to access a frequency channel. CDPD functions as a wireless extension to the internet. It operates with A-interface, E-interface, and I-interface services. When an M-ES moves from one cell to another a Hand-off in CDPD takes place Figure 1.2.

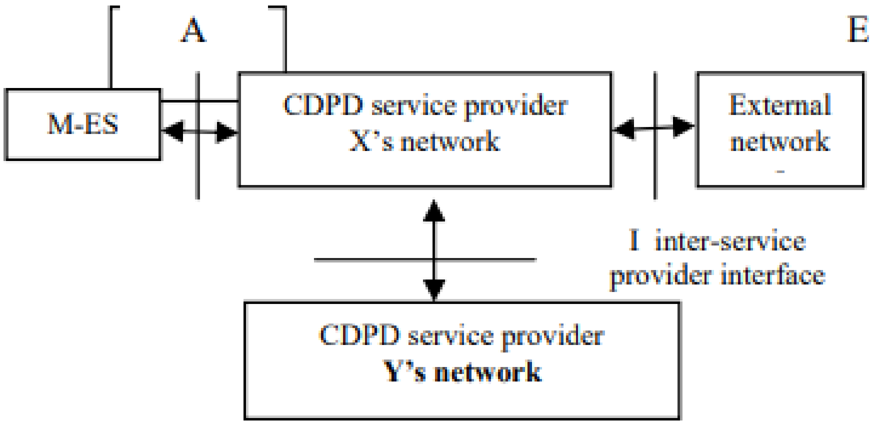

Figure 1.2: Reference architecture for CDPD.

The unique particularity of 1G is the use of cellular technology. But 1G has some falling regarding overall connection quality, with poor voice links and no security because voice calls were played back in radio towers. Table 1 will summarize the features of the 1st GENERATION [2].

Table 1.1: Features of the 1st Generation

Generation	**1G**
Starts from	1970-84
Frequency	800-900 MHz
Data capacity	2KBPS
Technology	Analog wireless
Standard	AMPS
Multiplexing	FDMA
Switching	Circuit
Service	Voice only
Main network	PSTN
Hand off	Horizontal

1.2 second generation 2G

We have mentioned the first-generation cellular networks delivered a low voice call quality. Second generation (2G) cellular network, commonly known as global system for mobile communication (GSM), has been standardized by the third-generation partnership project (3GPP) offering better signal quality and data rates. 2G systems were first introduced in the end of the 1980s and it was commercially launched on the GSM in Finland in 1991. This system is for data and voice services. The second generation (2G) operates with multiple access technology, time division multiple access (TDMA), and code division multiple access (CDMA). Figure 1.3 shows the Digital Communication system. TDMA describes the systems that first split the channel into frequency slots and then split each frequency slot into time slots. On the other hand, CDMA allows multiple users to transmit at the same time over the entire frequency range. The use of digital signals between the cell phones and the tower improves the system capacity in two manners:

1. Digital voice data can be compressed and multiplexed efficiently allowing more calls to occur in the same bandwidth.

The digital systems were constructed to reduce radio power emissions, making the cells smaller thus adjusting a greater number of cells within the same area.

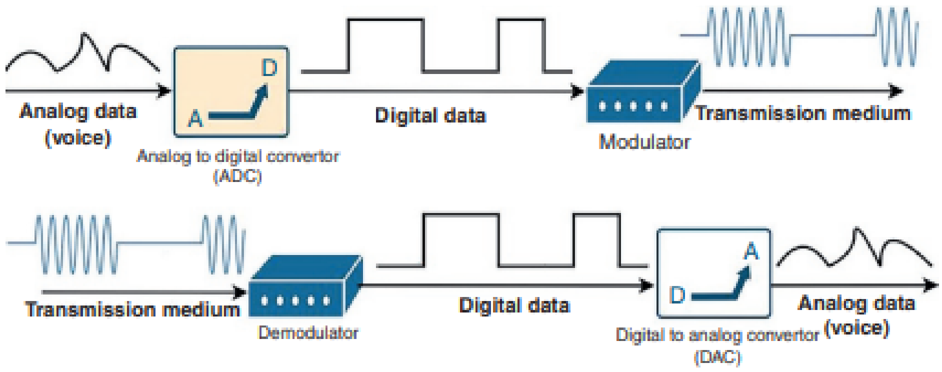

Figure 1.3: Digital Communication system.

1.2.1 2.5G (second and half generation)

It is a technology developed between 2G and 3G. General Packet Radio Service (GPRS) was the start line for 5G. GPRS is a radio technology for GSM networks that includes packet-switching protocols,shorter setup time for ISP connections, and the potential to charge by the amount of data sent. Packet switching is a method whereby the information, whether it is voice or data, is split into packets, each about a few kilobytes of data. These packets are then sent through the network and directed to different destinations based on addressing data within each packet.
Table 2 will summarize the features of the 2nd GENERATION [2].

Table 1.2: Features of the 2nd Generation

Generation	2G	2.5G
Starts from	1990	2000
Frequency	850-1900 MHz (GSM) 850-1900 MHz	825-849 MHz (CDMA)
Data capacity	10 KBPS	200 KBPS
Technology	Digital wireless	GPRS
Standard	CDMA TDMA TDMA/GSM	GSM Supported
Multiplexing	TDMA CDMA	TDMA CDMA
Switching	Circuit Packet	Packet
Service	Voice data	MMS internet
Main network	PSTN	GSM TDMA
Hand off	Horizontal	-

1.3 third generation (3G - 3.75G)

The third-generation (3G) mobile phone standard is a CDMA-based generation. It was developed by the International Mobile Telecommunication-2000 (IMT-2000). 3G depends on the Global System for Mobile Communications (GSM). This technology delivers high-speed data transmission, advanced multimedia and access, and global roaming. It revolutionized the mobile phone and handset industry by connecting phones to the internet or other IP networks for making voice and video calls, downloading and uploading data, and searching on the net. There are many 3G technologies such as WCDMA, GSM EDGE, UMTS, DECT, WiMax, and CDMA 2000. There is no difference between WCDMA and CDMA-2000 except that WCDMA is backward compatible with GSM networks, while CDMA-2000 is backward compatible with IS-95 networks. The methods used in 2G (TDMA-FDMA) are still used in 3G, like in value-added services like mobile television, GPS (Global Positioning System), and video conferencing [2]. The third generation supports the 5 major radio technologies The establishment of new mobile broadband networks resulted in the emergence of two separate families of 3G networks: 3GPP and 3GPP

The Third Generation Partnership Project (3GPP) is an international collaboration that was formed in 1998. It collaborates to create and maintain the technical specifications for 2G, 3G, 4G, LTE-Advanced, and 5G mobile networks.

The combination of HSDPA and the subsequent addition of an Enhanced Dedicated Channel (HSUPA) led to the development of the technology of High-Speed Packet Access (3.5G).

1.3.1 3.5G High-Speed Downlink Packet Access (HSDPA)

HSDPA is a packet-based data in WCDMA downlink with data transmission up to 8-10 Mbit/s (20 Mbit/s for MIMO technology) over a 5MHz bandwidth in WCDMA. Its realizations include Adaptive Modulation and Coding (AMC), Multiple-Input Multiple-Output (MIMO), Hybrid Automatic Request (HARQ), fast cell search, and advanced receiver design [2].

1.3.2 3.75G High-Speed Uplink Packet Access (HSUPA)

HSUPA is a Universal Mobile Telecommunication Standard (UMTS)/WCDMA uplink evolution technology, related to HSDPA and both are complementary to each other. HSUPA improves advanced person-to-person data applications with augmented data rates. It boosts the UMTS / WCDMA uplink to 1.4Mbps and later releases up to 5.8Mbps [2].
3G technology is capable of efficiently transmitting packet-switch data at better and improved bandwidth. 3G mobile technologies offer more advanced services to mobile users. therefore, the spectral efficiency of 3G technology is better than 2G technologies. Table 3 will summarize the features of the 3rd GENERATION [2].

Table 1.3: Features of the 3rd Generation

Generation	**3G**	**3.5G/3.75G**
Starts from	2001	2003
Frequency	1.6-5GHz	1.6-5GHz
Data capacity	384 KBPS	2 Mbps
Technology	Broadband/IP technology FDD TDD	GSM/3GPP
Standard	CDMA/WCDMA/UMTS/CDMA2000	HSDPA/HSUPA
Multiplexing	CDMA	CDMA
Switching	Circuit Packet	Packet
Service	High-speed voice/data/video	High-speed-data/video & High-speed-internet-multimedia
Main-network	Packet network	GSM TDMA
Hand off	Horizontal	Horizontal

1.4 fourth generation 4G

4G technology has been created on the merging of wired and wireless systems and has been applied to offer mobile multimedia services everywhere. The Wireless World Research Forum (WWRF) describes 4G as a network that functions on internet technology and merges it with other applications such as WI-FI and WiMax.
The term MAGIC is used to explain the 4G technology [19] Figure1.4.

The fourth generation integrates all the mobile technologies (GSM, GPRS, IMT-2000, Wi-Fi, Bluetooth). 4G delivers a downloading speed of 100 Mbps in high mobility and 1Gbps in low mobility or fixed connection. 4G is designed to accommodate the Quality of Service (QoS) requirements. It offers the same features as 3G and extra services, upgrading existing communication networks. It affords a comprehensive and secure IP-based solution where features like voice, data, and streaming multimedia are provided to the user “anytime, anywhere”. LTE (Long-term evolution) is considered 4G technology. Figure 1.5 shows licensed 4G spectrums selected by sample operators from Asia, Europe, and North America [3]. With 4.5G, created after 4G, increased download speeds have been reached with effective spectrum usage. 7-12 Mbps download speed and latency of

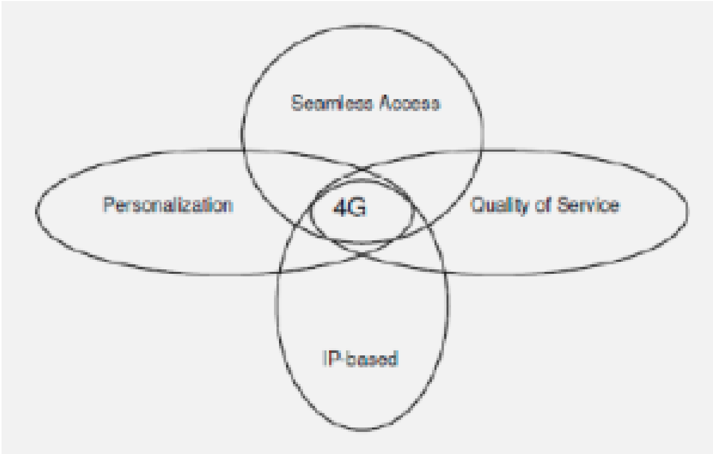

Figure 1.4: Features of 4G.

12 milliseconds (ms) in 4G have been improved to 14-21 Mbps and 5 ms, respectively, with 4.5G.

Table 4 will summarize the features of the 4th GENERATION [2].

Table 1.4: Features of the 4th Generation

Generation	**4G**
Starts from	2010
Frequency	2-8 GHz
Data capacity	200Mbps-to-1Gbps
Technology	LTE, Wi-MAX
Standard	IP-broadband LAN/WAN/PAN
Multiplexing	MC-CDMA, OFAM
Switching	Packet
Main network	Internet
Hand off	Horizontal Vertical

Figure 1.6 summarizes the evolution of the first four generations (1G - 4G) of cellular communication systems.

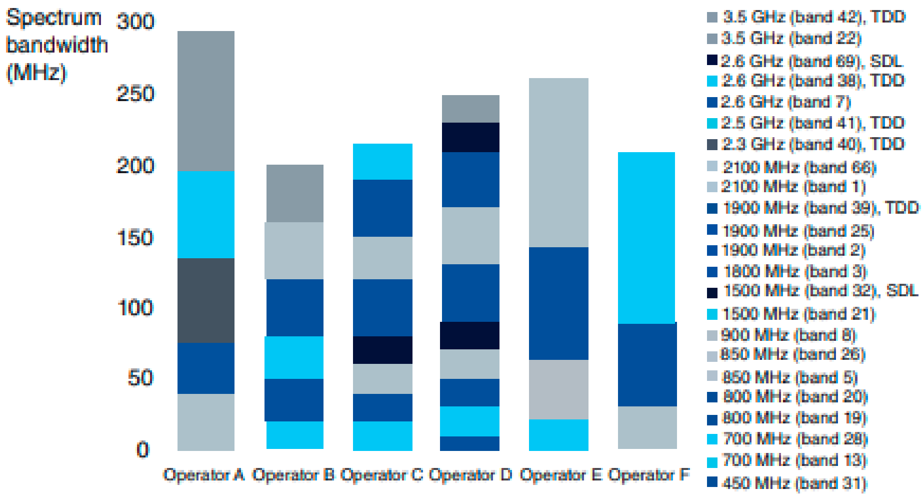

Figure 1.5: 4G Spectrum.

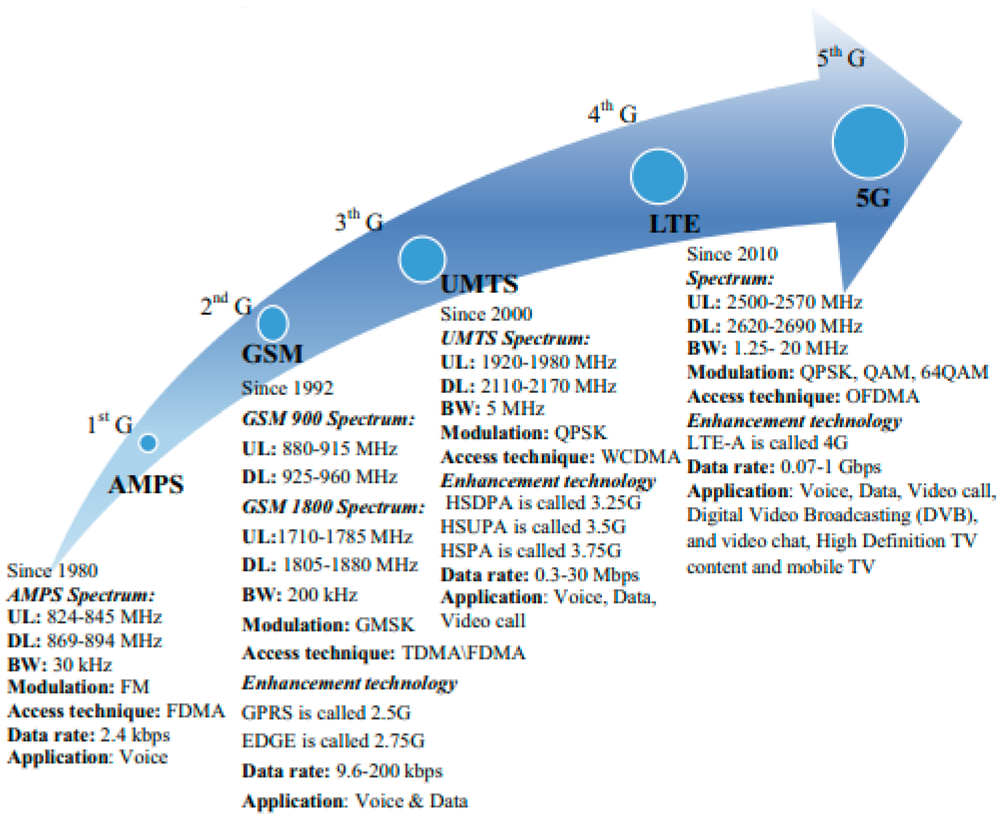

Figure 1.6: major milestones of the first four generations of cellular communication systems .

1.5 fifth generation 5G

Mobile communication has been one of the most productive technological innovations in the present day. However, the continuous increase in mobile data traffic based on high-quality video streams, and online gaming have been the main driving force toward 5G. Since the end of 2014, 5G mobile wireless networks have received notable attention from both academia and industry. The key challenge was to reach the different goals mentioned in Fig 1.7. As a result, the 5G mobile network has supported a set of new technologies to augment the volume of traffic. Figure 1.8 describes the technologies for supporting the increase in the volume of traffic [4].

This is the explanation of the, 5G flower, 5G key business indicators put forward by Chinese Mobile and accepted by the ITU [8] Figure 1.9.

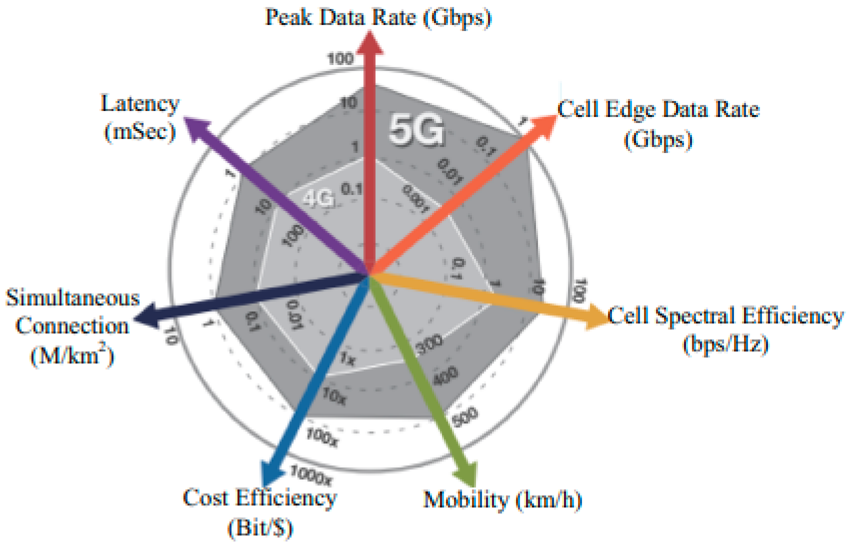

Figure 1.7: key performance indicator for evolution to 5G.

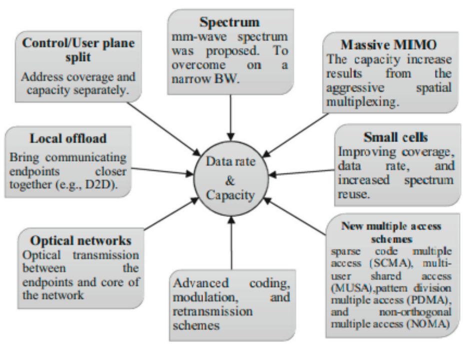

Figure 1.8: 5G considerations to provide high capacity .

1.5.1 Petals (six performance indicators of 5G):

1. 100×(0.1 – 1Gbps) user speed compared to 4G Much higher connection density (1 million/Km2) 3. Reduced interface latency (one-fifth of 4G-1 ms) 4. 4× accelerated

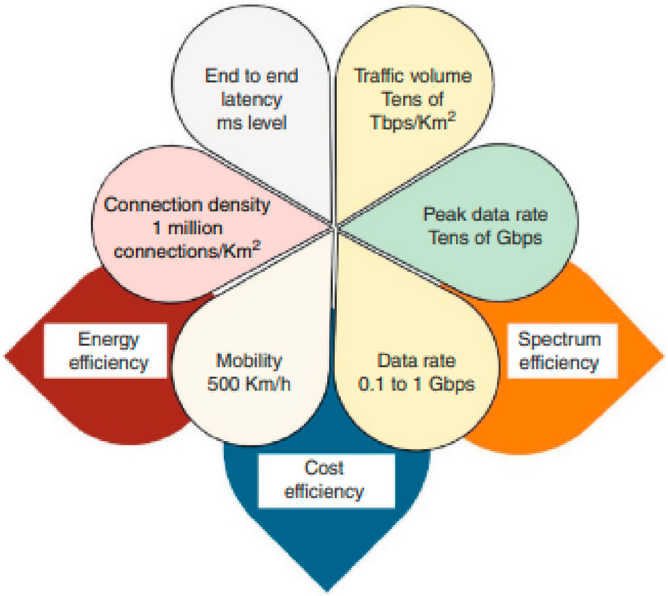

Figure 1.9: 5G flower.

mobility of 4G (500+ Km/h) 5. About 20 times the peak rate of 4G (10-20 Gbps) 6. High flow density (10-100 Tbps/Km2)

1.5.2 Green leaves (three separate productivity indicators):

1. Energy efficiency Cost efficiency 3. Spectrum efficiency

The International Telecommunication Union (ITU) has introduced different standards for mobile communication technologies. International Mobile Telecommunication-2000 (IMT-2000) is the standard for 3G, IMT-Advanced is for 4G, and IMT 2020 is for 5G. The ITU Radio Communication Sector (ITUR) has outlined three basic usage scenarios in its M.2083 document for 5G and beyond systems: Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communication (mMTC), and Ultra-reliable and Low-Latency Communications (uRLLC). These scenarios are well described in Figure 1.10 [3].

- Enhanced Mobile Broadband (eMBB): Dealing with a substantial surge in data rates, supporting hotspot scenarios with dense user populations and large traffic demands, and offering high mobility options without interruption.
- Massive Machine-Type Communication (mMTC): linking numerous devices to IoT that require minimal power consumption and low data rates.
- Ultra-reliable and Low-Latency Communications (uRLLC): Establishes infrastructure for security and mission-critical applications Figure 1.11.

Various communication ecosystems will be established in our world using 5G, which will provide a backbone for smart cities/buildings, autonomous vehicles, and virtual/augmented reality, where devices are designed to meet the mentioned needs and criteria are interconnected Figure 1.12 [23]. Table 5 will summarize the features of the 5th GENERATION [2].

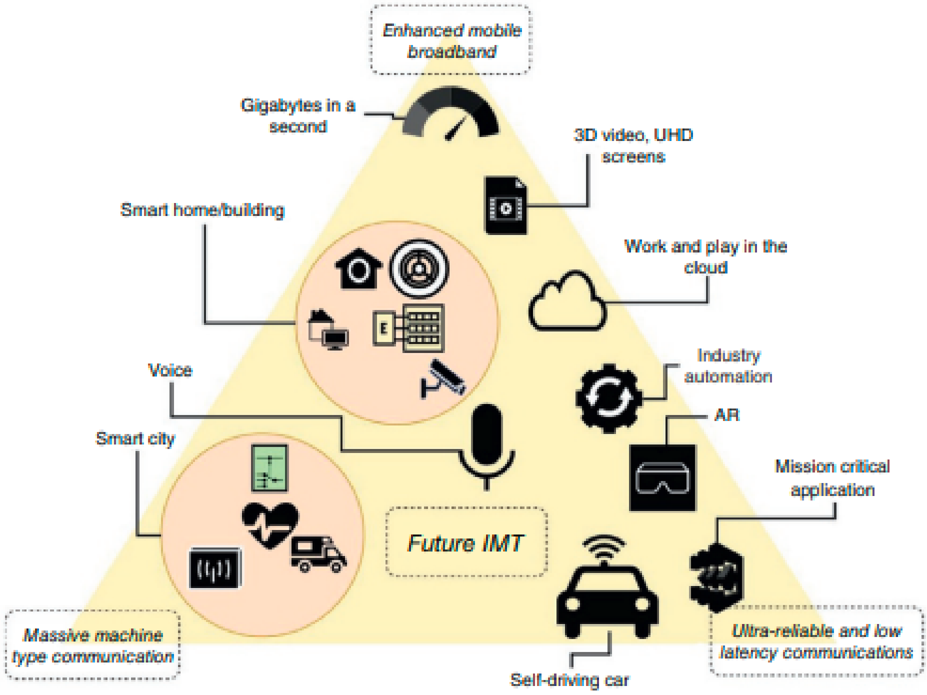

Figure 1.10: IMT-2020 use cases.

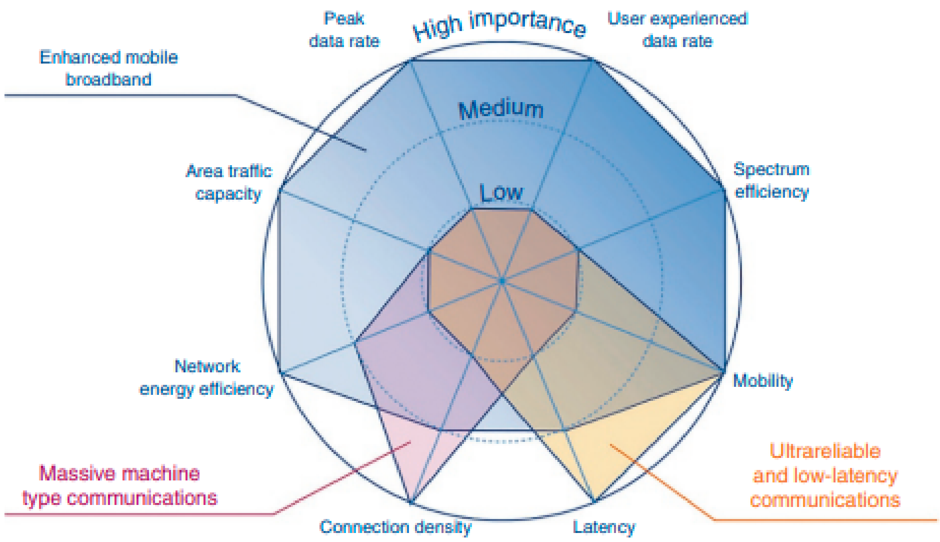

Figure 1.11: 5G network capacity [1] .

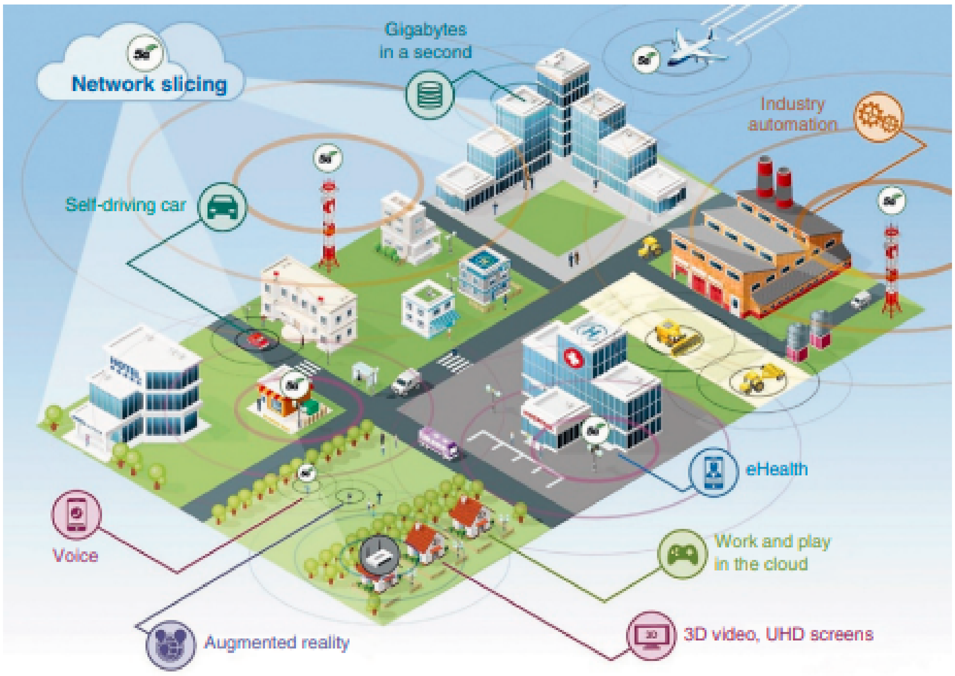

Figure 1.12: 5G ecosystem .

Table 1.5: Features of the 5th Generation

Generation	**5G**
Starts from	2015
Data capacity	Higher than 1Gbps
Technology	IPv6
Standard	IP-broadband LAN/WAN/PAN/WWW
Multiplexing	CDMA
Switching	All Packet
Service	Dynamic Information access, wearable devices with AI capabilities
Main network	Internet
Hand off	Horizontal Vertical

1.6 sixth generation 6G

The sixth-generation technology uses a combination of radio and fiber optics technology. 6G will integrate 5G wireless mobile system and satellite network and global coverage. Telecommunication satellite is used for internet, voice, data, and video broadcasting; the earth imaging satellite networks are for the extraction of weather and environmental information, and the Navigational Satellite Network for Global Positioning System (GPS). It is assumed that 6G will make the speed of 1GB. The journey from 1G to 6G is in Figure 1.13 and the technical standards are shown in Table 6 [3].

1.6.1 6G vision

6G technology is expected to play a crucial role in bringing the blueprint to life. It will enable seamless connectivity, ensuring comprehensive wireless coverage and the integration of all functions such as sensing, communication, computing, caching, control,

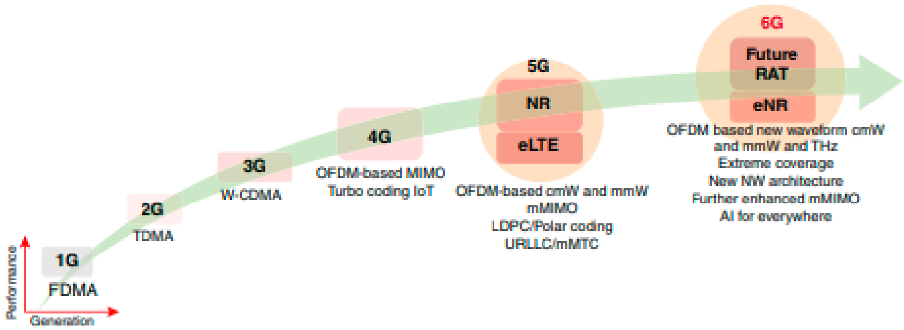

Figure 1.13: Evolution to 6g .

Table 1.6: Comparison of Parameters between 5G and 6G

Parameters	**5G**	**6G**
Downlink	20 Gbps	> 1 Tbps
Uplink	10 Gbps	1 Tbps
Traffic capacity	10 Mbps/m^2	1-10 Gbps/m^2
Latency	1 ms	10-100 μs
Reliability	Up to 99.999%	Up to 99.99999%
Mobility	Up to 500 Km/h	Up to 1000 Km/h
Connectivity density	10^6 devices/Km^2	10^7 devices/Km^2
Security and privacy	Medium	Very high

positioning, radar, navigation, and imaging. This will support a wide range of vertical applications. 6G will be an autonomous ecosystem that possesses human-like intelligence and consciousness. It will evolve to serve both human and machine-centric systems. 6G will also offer multiple ways to communicate and interact with smart terminals, including through fingers, voice, eyes, and brainwaves (or neural signals).

1.6.2 Fundamental enabling technologies of 6G

Based on the past evolution of mobile networks, 6G networks are mostly based on 5G architecture inheriting the benefits achieved in 5G.some technologies of 5G will improved in 6G, and new technologies will be added. A few expected vital technologies for 6G are discussed below. Figure 1.14 will illustrate the envision 6G network.

Artificial Intelligence

Intelegence is the essential characteristic of 6G autonomous networks. Therefore, the most introduced technology for 6G is AI. There was no involvement of AI in 4G wireless networks and limited support of AI in 5G communication systems. However, 6G will be fully supported by AI for automatization. AI will enable the transformation from cognitive radio to intelligent radio. The introduction of AI in communication systems will facilitate and enhance the transport of real-time data. AI augments efficiency and reduces the processing delay of the communication steps. AI can be used in time-consuming tasks such as handover and network selection quickly, and it will play a crutial role in M2M,machine-to-human, human-to-machine. AI will support 6G sensing use case and helps in data processing for information extraction.

Terahertz communications

Spectral efficiency can be enhanced by increasing the bandwidth. It can be done by applying massive multiple-input multiple-output (MIMO) technologies, and by widening the bandwidths. The fifth generation (5G) introduces the mmWave frequencies for higher data rates and allows new applications. However, 6G will push the limits of the frequency band to THz to meet even higher demands and new applications. THz waves (submillimeter radiation), usually refer to the frequency band between 0.1 THz and 10 THz with the equivalent wavelengths of 0.03 mm- 0.3 mm range. The 6G cellular communication will be increased by adding the THz and (275 GHz–3THz) to the mmWave band (30–300 GHz). The band under the range of 275 GHz–3 THz has not yet been assigned for any purpose worldwide; therefore, this band has the capacity to accomplish the required high data rates. THz communication will improve the 6G potentials by supporting wireless cognition, sensing, imaging, communication, and positioning.

Optical wireless technology

OWC technologies are projected for 6G communication in addition to RF-based communication for all possible devices to access networks. OWC technologies have been used since the fourth generation (4G) communication systems. Thus, it is aimed to meet the requirements of 6G communication systems. OWC technologies, such as light fidelity, visible light communication (VLC), optical camera communication, and FSO communication based on the optical band, are already well-known technologies These communication technologies will be extensively used in several applications such as V2X communication, indoor mobile robot positioning, VR, and underwater OWC. LiDAR, which is also based on the optical band, is a likely technology for very high-resolution 3D mapping in 6G communications. OWC confidently will enhance the support of uMUB, uHSLLC, mMTC, and uHDD services in 6G communication systems.

Massive MIMO and intelligent reflecting surfaces

The massive MIMO technology will play an essential role in the 6G system supporting uHSLLC, mMTC, and uHDD services. The application of the MIMO technique is one way to improve spectral efficiency. The development of the MIMO technique will lead to the improvement of the spectral efficiency. the massive MIMO will be integral to both 5G and 6G systems due to the need for better spectral and energy efficiency, higher data rates, and higher frequencies. We expect to shift from traditional massive MIMO (5G) toward IRS in 6G wireless systems to provide large surfaces for wireless communication. This technology will be considered as a great solution to maximize the data rate and to minimize the transmit power in upcoming 6G networks

Big data analytics

Big data analytics is a complex process for analyzing a variety of large data sets or big data. This process uncovers information, such as hidden patterns, unknown correlations, and customer inclinations, to ensure comprehensive data managementt. Big data is collected from a wide variety of sources, such as videos, social networks, images, and sensors. This technology is widely used for handling a large amount of data in 6G systems. The prospects of leveraging an enormous amount of data, big data analytics, and deep learning tools are anticipated to advance 6G networks through automation and self-optimization.

Figure 1.14: Illustration of the envisioned 6G network, including deployment scenarios/environments, selected use cases, and requirements.[24]

1.6.3 6G requirements

The key performance of 6G wireless networks can be evaluated using indicators like spectrum and energy efficiency, peak data rate, user-experienced data rate, area traffic capacity(or space traffic capacity), connectivity density, latency, and mobility. The technical objectives include achieving the following[9]:

- A peak data rate of at least 1 Tb/s , which is 100 times that of 5G. For some special scenarios, such as THz wireless backhaul and fronthaul (x-haul) , the peak data rate is expected to reach up to 10 Tb/s.
- A user-experienced data rate of 1 Gb/s, which is 10 times that of 5G. It is also expected to provide a user-experienced data rate of up to 10 Gb/s for some scenarios, such as indoor hotspots.
- An over-the-air latency of 10–100 µs and high mobility 1,000 km/h. This will provide acceptable QoE for such scenarios as hyper-HSR and airline systems.
- Ten times the connectivity density of 5G. This will reach up to 10 devices/k 7 2 m and area traffic capacity of up to 1 / Gb/s m2 for scenarios such as hotspots.
- An energy efficiency of 10–100 times and spectrum efficiency of 5–10 times those of 5G. To satisfy typical scenarios and applications for the 2030 intelligent information society, 6G will provide superior network capabilities. The network features of human-oriented 4G, IoE-oriented 5G, and the future interaction of everything-oriented 6G. Next, we discuss design considerations for 6G, as shown in Figure 1.15.

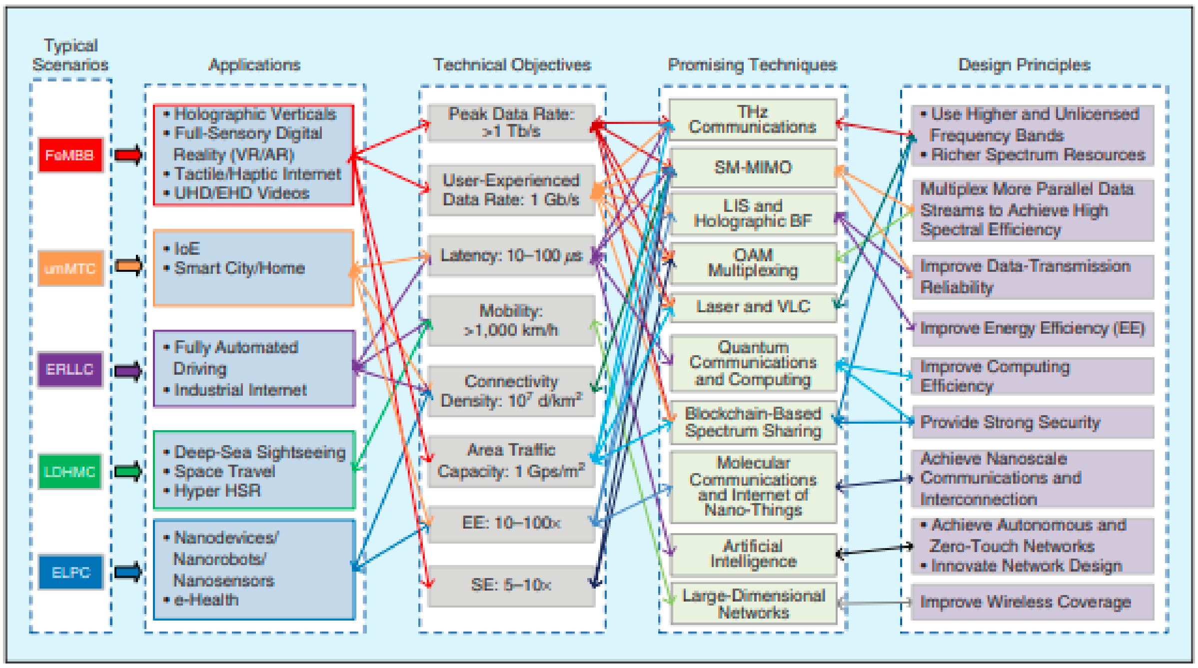

Figure 1.15: Design considerations for 6G networks. SE: spectrum efficiency.

1.7 Wireless channel

1.7.1 Free-space propagation

A radio transmission system allows transforming an electrical signal emitted e(t) into an electrical signal received s(t) via electromagnetic waves. The propagation channel is the medium that transforms electromagnetic waves during their propagation. At this stage, it is important to differentiate between the propagation channel, which only takes into account interactions of the emitted signal with the traversed environment, and the transmission channel, which additionally includes effects induced by the transmitting and receiving antennas, as shown in Figure 1.16.

Generally, the propagation environment influences the electromagnetic wave emitted. In free space, the transmission system is characterized by the absence of obstacles. The power density W in free space is expressed as a function of the distance between the transmitter and the receiver d, the gain of the transmitting antenna Gt, and the power of the transmitted signal Pe.

$\mathrm{P}_d = \mathrm{Pe} \cdot Gt\frac{}{4\pi d^2(1.1)}$

The power of the signal available at the terminals of a receiving antenna Pr is related to the power density W by the following relationship:

$$P_r = \frac{W\lambda^2 G_r}{4\pi} \tag{1.2}$$

Where Gr represents the gain of the receiving antenna and **lambda** represents the wavelength at the operating frequency. We can calculate the signal attenuation in free space using the two previous formulas as follows:

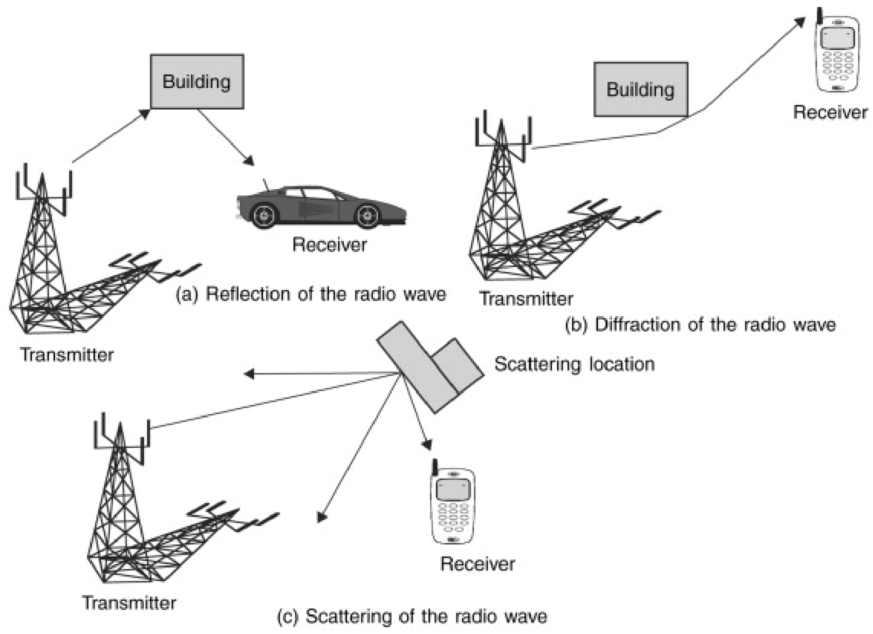

Figure 1.16: Radio channel propagation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{c}{2\pi f d} \right)^2 \tag{1.3}$$

Where c is the light speed.It should be noted that the above formula is only valid when the receiving antenna is considered in the far-field of the transmitting antenna. This condition is met when the distance d between the antennas is greater than the Fraunhofer distance (d_f), which is related to the largest dimension (D) of the transmitting antenna:

$$d_f = \frac{2D^2}{\lambda} \tag{1.4}$$

Where D is the dimension of the transmitting antenna. The free-space attenuation is given by the following relationship:

$$PL = 10 \log_{10} \left(\frac{P_t}{P_r} \right) = -10 \log_{10} \left(G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \right) \tag{1.5}$$

1.7.2 Radio channel model

In wireless communication systems, the information travels via electromagnetic waves through a propagation channel. The main phenomena that effect the wave traveling by the propagation channel are reflection, refraction, scattering, and diffraction as in Fig 1.17. these phenomena depend on the wavelength of the transmitted wave.

Fading

the phenomenon where the strength or quality of a received signal fluctuates over time and space due to various factors in the transmission medium. These fluctuations can result in signal attenuation, distortion, or even complete loss of signal, impacting the reliability

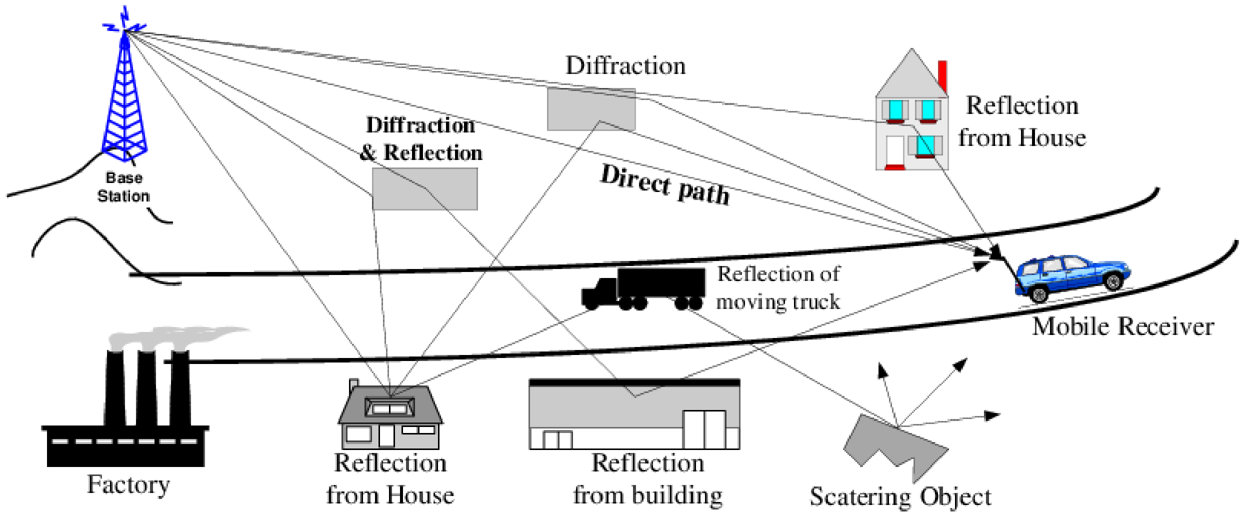

Figure 1.17: reflection, refraction, scattering, and diffraction

and performance of the communication system. Fading can occur in both terrestrial and satellite communication systems. Fading is the result of different phenomena that are :

doppler shift: It occurs when the transmitter of a signal is moving in relation to the receiver. When a mobile is moving at a constant velocity v, the equation of Doppler frequency is given by:

$$f_d = \left(\frac{v f_c}{c}\right) \cos\theta \tag{1.6}$$

Reflections: occur when the EMWs impinge (or collide) on an object which has a very large dimension as compared to the wavelength. The big surfaces (large objects) like the earth, hills, buildings, walls, etc. form reflecting surfaces.

Diffractions: occur when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities, for example, edges.

Scattering: occurs when the medium has objects that are smaller or comparable to the wavelength. Again small and large are always concerning the wavelength. Small objects, such as trees, uneven walls (rough surfaces), cars and other irregularities in the channel will cause scattering.

Fading can occur in both terrestrial and satellite communication systems and is classified into two main types:
Small-Scale Fading:

- Small-scale fading occurs due to multipath propagation, where multiple versions of the transmitted signal arrive at the receiver after bouncing off various objects or reflecting off surfaces in the environment.
- Multipath propagation causes constructive and destructive interference between the signal components, resulting in rapid variations in signal amplitude, phase, and

frequency.

- Small-scale fading effects include Rayleigh fading, Rician fading, and Nakagami fading, which are characterized by different statistical distributions of signal strength variations.

Large-Scale Fading:

- Large-scale fading, also known as path loss, refers to the gradual decrease in signal strength as the distance between the transmitter and receiver increases.
- Large-scale fading is primarily influenced by factors such as distance, obstacles, terrain, and atmospheric conditions, leading to signal attenuation over long propagation paths.
- Path loss models, such as the Friis transmission equation and the Hata model, are used to estimate the attenuation of the signal based on the distance between the transmitter and receiver and other environmental parameters.

Figure 1.18 illustrates the difference between large and small-scale fading. Small-scale fading movements are rapid fluctuation while large Small fading movements are much slower average change in signal strength.

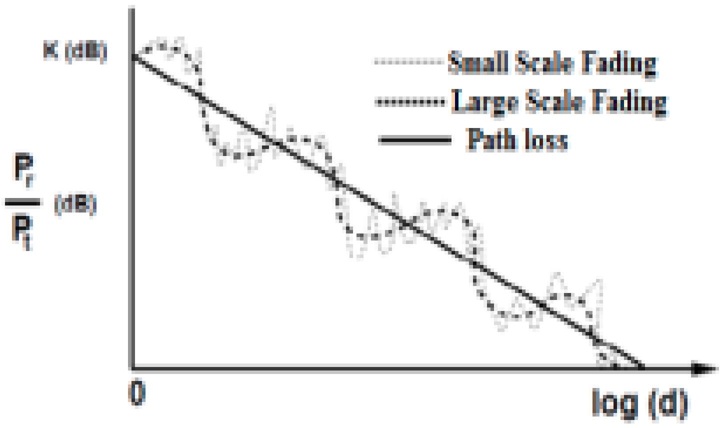

Figure 1.18: Large Scale Fading versus Small Scale Fading.

1.8 mm Waves (millimeter waves)

The term mmWave typically refers to the 10-100 GHz band of the electromagnetic spectrum. Modern day communication systems primarily utilize the 0-6 GHz band. It is true that some ultra wideband and especially high frequency applications currently exist, but nothing compares to what is coming for mmWave technology. This nascent technology, which lies at the other end of the spectrum, is foreign to many electrical engineers and nonexistent in most electrical engineering curriculums. mmWave systems differ from their lower frequency counterparts in many ways. The primary enabling factor for these systems is the employment of high directivity RF apparatus such as horns, high gain arrays, and parabolic reflectors. These antennas are highly directive with very narrow beamwidths. This is a distinct difference from omni antennas or even lower gain array antennas that are commonplace at lower frequencies. The massive path loss at mmWaves makes omni-directional transmissions impractical for nearly all applications. Instead, the high free space loss is overcome by employing highly directional links with gains upwards of 30 dB. This achieves high SNR and link robustness, albeit at the cost of beam tracking complexity. Imagine a world of almost invisible waves, waves which will change the way we live. The promise of unseen waves has long fascinated science fiction enthusiasts, but with the current technological revolution and the advent of steerable antennas for wireless systems, it is now possible to take this vision out of the realm of fiction. The recent Federal Communications Commission's (FCC) allocation of 7 GHz of spectrum around 60 GHz has opened up an enormous amount of bandwidth for unlicensed use. This allocation is fostering an explosion in research and development into all things related to millimeter wave (mmWave) frequency electronics. This wide swath of unlicensed spectrum poses an attractive prospect for RF engineers because previous bands for wireless communications have become increasingly crowded and the demand for greater and greater bandwidth is insatiable. Development of 60 GHz wireless systems and the push to exploit the available 60-90 GHz and 70/80 GHz bands have given birth to a whole new class of wireless systems that are primarily implemented above 30 GHz.

1.9 Massive MIMO

Massive MIMO is the upcoming key technology in wireless communication and can potentially increase spectrum efficiency by orders of magnitude over the current 4G systems. It is postulated to be the most important upcoming wireless physical layer technology for next-generation cellular systems. Phase array processing has been a key technology option being researched for 5G cellular; however, more recently, phase array processing has been shown to only perform optimally when a very large number of antennas are used at the base station. Currently, cellular systems have up to 4 antennas at the base station, or 2 such radios for a dual-polarized antenna case. Therefore, this new realization is suitably named Massive MIMO. It can be shown through asymptotic information-theoretic analysis that the spectral efficiency scales linearly with the minimum number of antennas at the base station on the order of log N, where N is the number of transmit antennas, irrespective of the propagation environment. On the other hand, a single-user MIMO system scales with the log det function of the channel matrix, where M is the number of transmit antennas and K is the number of users, with the same complexity order for the capacity per user when the transmit antennas are set equal to the receive antennas. A simple example to justify this is a single-user MIMO system compared to a single-antenna system, whereby it is well known that the capacity scales at order M, compared to the single-antenna case. This ideal, so-called very large or asymptotic MIMO system has sparked much interest recently as it is seen as the pathway forward to extreme high spectral efficiency in next-generation systems and is only suitable for cellular systems or local area wireless networks complying with regulations on radiated power limits from base stations, such as Wi-Fi. The concept of asymptotic MIMO transmission does apply to point-to-point topology MIMO links; however, the extreme case of dimension is unnecessary just for personal communications, and the capacity increase does not justify the additional hardware expenses required for the large cases.

1.10 Chapter Recap

In this chapter, we embarked on a journey through the evolution of wireless communication, tracing its path from the pioneering days of 1G to the cutting-edge advancements of 6G. We witnessed the remarkable progression of cellular communication technologies, each generation building upon the foundations laid by its predecessors to deliver faster, more reliable, and more versatile wireless connectivity.

The transition from 1G analog systems to 2G digital networks marked a pivotal moment, introducing digital voice transmission and paving the way for the mobile data revolution. With 3G, we saw the dawn of mobile internet access, enabling users to browse the web and access multimedia content on their handheld devices. The advent of 4G LTE brought about unprecedented data speeds and low-latency connections, empowering applications like video streaming, online gaming, and real-time communication.

As we look ahead to the future, the promise of 5G and 6G technologies looms large on the horizon. 5G promises ultra-fast data rates, ultra-low latency, and massive device connectivity, unlocking the potential for transformative applications like autonomous vehicles, remote surgery, and smart cities. Meanwhile, 6G aims to push the boundaries even further, envisioning terabit-per-second speeds, ubiquitous connectivity, and seamless integration with emerging technologies like artificial intelligence and the Internet of Things (IoT).

The next chapter in our exploration delves into the underlying modulation techniques that have played a crucial role in shaping the wireless landscape: Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) modulation. We will unravel the principles behind these modulation schemes, examining their strengths, weaknesses, and applications across various wireless communication systems.

2 5G & 6G Waveforms

2.1 Orthogonal Frequency Division Multiplexing (OFDM)

In single-carrier wireless communication, to avoid Inter-Symbol Interference (ISI) the symbol period must be much greater than the delay time. This leads to low data rates and communication efficiency. In multi-carrier systems, such as FDM, the available bandwidth is divided into sub-bands for multiple carriers for parallel transmission. The closer the carriers are to each other in the spectrum, the higher data rates are achieved. However, this leads to Inter-Carrier Interference (ICI) a second wireless communication issue.

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier wireless communication scheme that solves both of the previous problems. OFDM offers an alternative to single-carrier modulation techniques such as FDMA, TDMA, and CDMA.

OFDM is a multiplexing technique widely used in various technologies including digital radio, digital television, wired data transmission, wireless LAN, cellular data, and other proprietary systems. it combines a large number of sub-carriers to composite a high data rate communication system. The term 'Orthogonal' gives the carriers a valid reason to be closely spaced, even overlapped, and that is a key to avoid ICI. A reduced data rate for each carrier results in extended symbol duration, significantly reducing the impact of inter-symbol interference. Figure 2.1 shows an example of an OFDM signal.

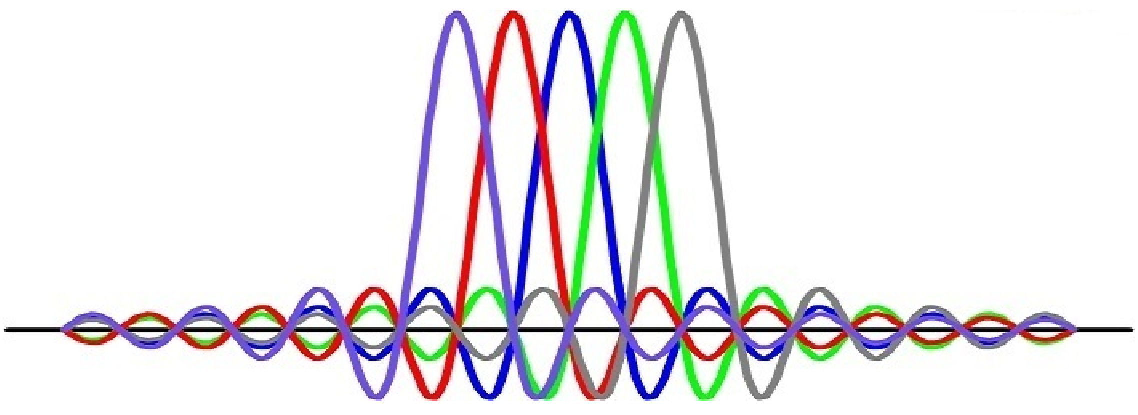

Figure 2.1: OFDM frequency signal

2.1.1 OFDM basics

In digital communications, the information symbols are expressed in the form of bits, the term "Symbol" is a collection of bits. OFDM data are generated by taking information symbols in the spectral space by various modulation techniques; QAM, PSK, Q-PSK, M-PSQ, etc. After that, the spectral space symbols are converted to the time domain via DFT or FFT. Usually, we use the Fast Fourier transform due to its cost-effectiveness implement. Once all data symbols are in the time domain (TD), all carriers transmit in parallel to fully occupy the available frequency bandwidth. To ensure synchronization between the transmitted signal and the receiver, OFDM symbols are usually organized into frames, which are then modulated sequentially, allowing the receiver to accurately process the received data. long symbol period is effective for inter-symbol interference (ISI) reduction, but could not eliminate it. In order to nearly eliminate the ISI phenomena, the Cyclic prefix (CP) is introduced and added to every symbol period. Figure 2.2 shows the effect of ISI[10] where the green symbol is the 1st transmitted symbol.

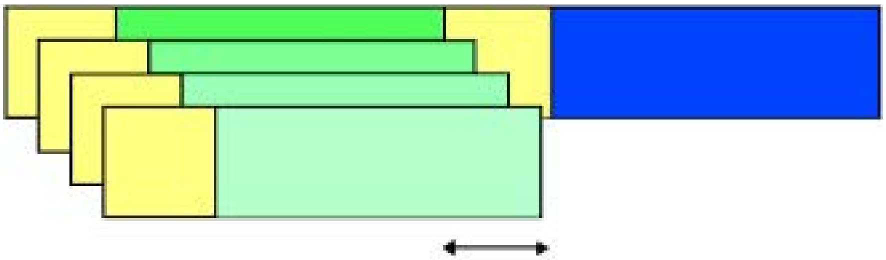

Figure 2.2: ISI phenomena

InterSymbol interference

ISI is a type of distortion that can occur in OFDM systems, where the transmitted symbols interfere with each other due to the multipath propagation of the signal. This happens because the signal takes multiple paths to reach the receiver, and these paths have different delays, resulting in the received symbols overlapping and interfering with each other.The presence of ISI can degrade the performance of the OFDM system, as it can introduce errors in the received data. To mitigate the effects of ISI, OFDM systems typically employ a Cyclic Prefix (CP) or Guard Interval (GI) between consecutive OFDM symbols.

Cyclic prefix (CP)

Infinite length of OFDM symbols is not practical, but it is possible to the symbol to appear periodic. The periodicity is achieved by substituting the guard interval with a parameter called the cyclic (extension) prefix (CP) of a length Lp. The cyclic prefix is adding an exact copy of a fraction, typically 25%, of the cycle; taken from the end and added to the front. Figure 2.3 illustrates the extension of the cyclic prefix

Since the CP contains redundant information, it is excluded on the receiver side. Figure 2.4 illustrates the symbols jointly in the time and frequency domains.

- **CP advantages:**
  - Efficient against multi-path propagation and ISI.
  - Simple signal processing at the receiver.
  - Helps for channel estimation and equalization.
- **CP disadvantages:**
  - reduce data capacity.

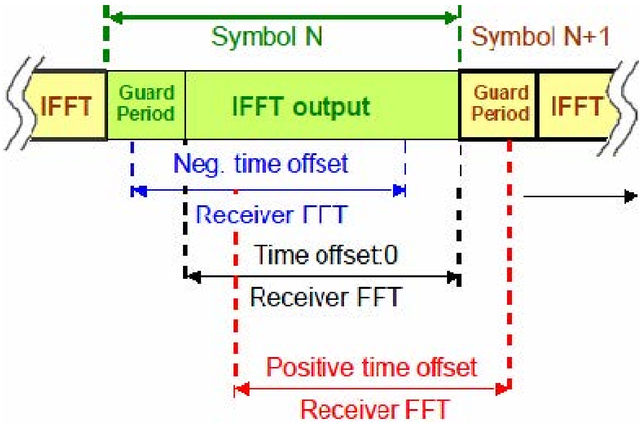

Figure 2.3: Cyclic prefix (CP)

- increase the peak-to-average power ratio (PARP) of the OFDM systems.

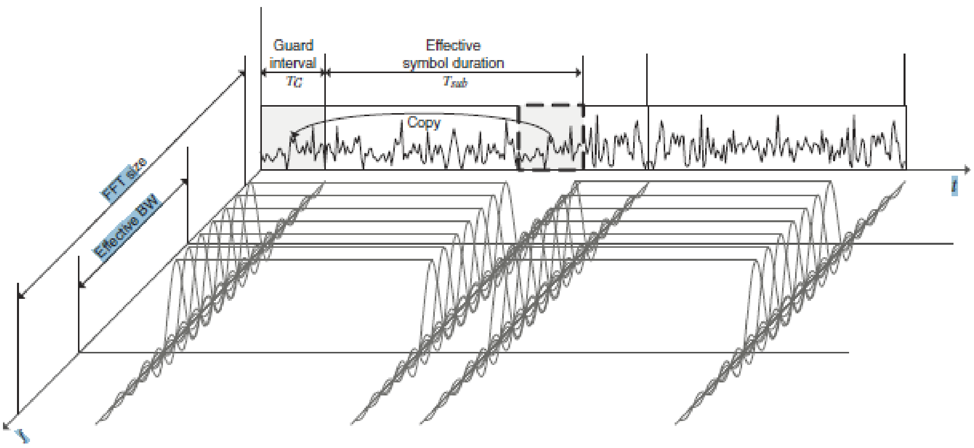

Figure 2.4: TFD description of OFDM symbols with CP

Orthogonality

Mathematically, two signals are considered orthogonal if their inner product or integral over a specific time interval is equal to zero. The inner product of two cosine signals and y(t) over the time interval T is defined as:

$$\int_0^T \cos(2\pi n f_0 t)\cos(2\pi m f_0 t)\,dt = 0 \quad (n \neq m) \tag{2.1}$$

Where OFDM maintains orthogonality between the carriers. The parameters n and m are two unequal integers; f_0 is the fundamental frequency; T is the period over which the integration is taken. In OFDM, T_s is one symbol period, and f_0 is set to $f_0 = 1/T_s$ for optimal effectiveness. Figure 2.5 shows how the orthogonality occurs.

OFDM Carriers number

The number of carriers in the OFDM system is limited by the IFFT size and the availability of spectral bandwidth. The relationship below illustrates how the IFFT

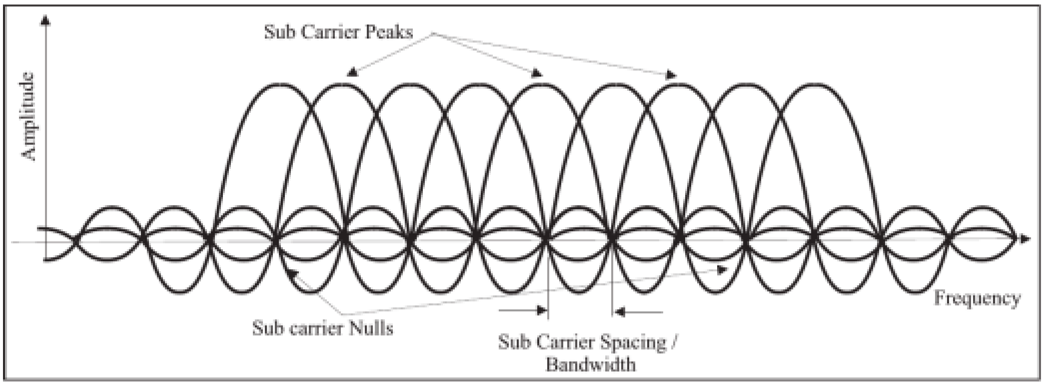

Figure 2.5: OFDM subcarriers orthogonality

affects the number of carriers.

$$\text{Number of carriers} \leq \left(\frac{\text{ifft - size}}{2} - 2 \right) \tag{2.2}$$

Increased complexity and cost in an OFDM system typically correspond to larger IFFT sizes. Consequently, a larger number of carriers can be employed, leading to higher data transmission rates.

The selection of M-PSK modulation impacts both the data rate and Bit Error Rate (BER). Opting for a higher order of PSK results in larger symbol sizes, reducing the number of symbols needed for transmission and thus achieving a higher data rate. However, this choice also leads to a higher BER because the phase range of 0-360 degrees is divided into more sub-regions, requiring smaller sub-region sizes. Consequently, received phases have a higher likelihood of being incorrectly decoded. Despite OFDM signals having a high peak-to-average ratio, they demonstrate relatively high tolerance of peak power clipping resulting from transmission limitations[10].

2.1.2 OFDM system model

In an $M \times N$ OFDM setup, with M representing subcarriers and N for time slots, the OFDM signal spans a bandwidth $B = M \times \Delta f$ and lasts for a frame duration of $T_f = NT = NM \times T_s$, where $f = 1/T$ is the subcarrier spacing, and $T = MT_s$ is the duration of an OFDM symbol. The sampling interval is $T_s = 1/f_s$, where f_s is the sampling frequency.

A static multipath channel is considered, where $\tau_{\max}$ is the maximum delay spread and $l_{\max} < M$ is the maximum channel delay tap. Typically, OFDM adopts a CP of sufficient length $L_{\text{CP}} \geq l_{\max}$ for reliable communications. We choose $L_{\text{CP}} = l_{\max}$.

The discretized time-frequency domain with sampling points at multiples of $\Delta f = 1/T$ spaced by T can be represented as an $M \times N$ array of points as shown in Figure 2.6.

$$\Lambda = (m\Delta f, nT), m = 0, \ldots, M-1, n = 0, \ldots, N-1 \tag{2.3}$$

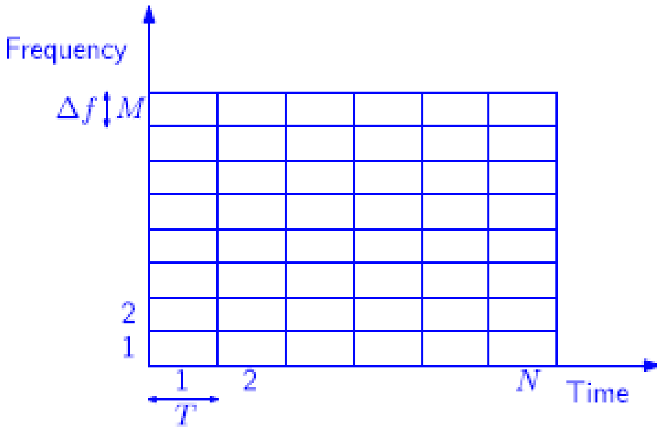

Figure 2.6: Time Frequency OFDM grid

Specifically:

- M represents the number of rows in the matrix X, where each row corresponds to a different time instance or OFDM symbol.

- N represents the number of columns in the matrix X, where each column contains N OFDM symbols.

Let X be the information matrix in the time-frequency plane, with elements $X[m, n]$, $m = 0, \ldots, M-1$, $n = 0, \ldots, N-1$. The multicarrier modulation transmitted OFDM signal can be expressed as:

$$s(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X[m, n] g_{tx}(t - nT) e^{j2\pi m\Delta f(t-nT)} \tag{2.4}$$

- g_{tx}(t) $for\ 0 \leq t < T$ denotes the pulse shaping waveform used to shape the continuous-time transmitted signal.

Choice of the OFDM Modulation

The general modulation schemes of the OFDM sub-carriers are quadrature amplitude modulation (QAM) or phase shift keying (PSK), in conjunction with both coherent and non-coherent detection. Differential coded star-QAM (DSQAM) can also be used.
In Figure 2.7 the simulated BER versus SNR curves for OFDM System Performance over AWGN Channels usig binary phase shift keying (BPSK), differential BPSK (DBPSK), quaternary phase shift keying (QPSK), differential QPSK (DQPSK), and coherent 16-quadrature amplitude modulation (16-QAM) are shown, together with the theoretical BER curves of serial modems[11]. The lines show how well coherently detected modulation techniques in a serial modem work theoretically over AWGN channels. Figure 27 shows that, in AWGN channels, the experimental BER performance of the OFDM modem agrees quite well with the theoretical BER curves of conventional serial modems.

OFDM transceiver

In the multi-carrier OFDM system, the frequency spectrum of subcarriers overlaps with minimal frequency spacing, and orthogonality is achieved among the different subcarriers.

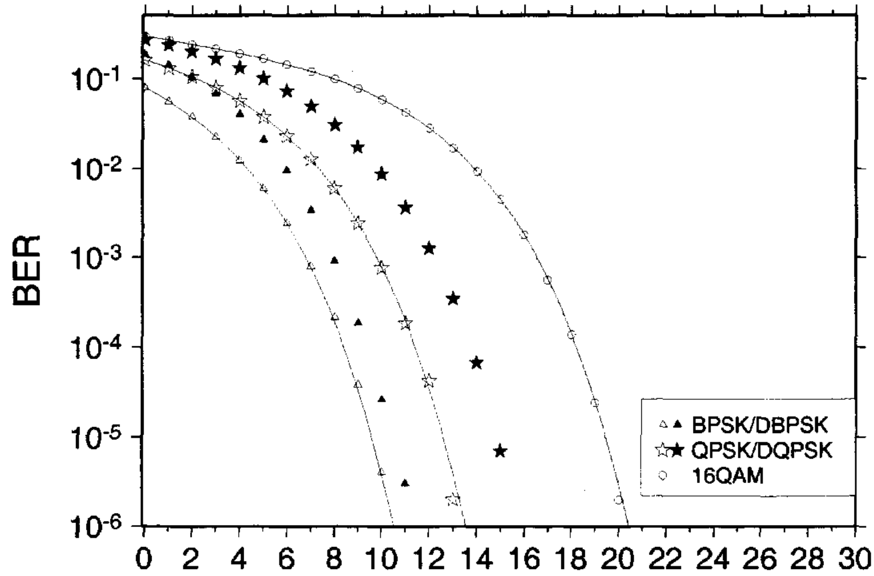

Figure 2.7: BER versus SNR curves for the OFDM modem in AWGN channel using BPSK, DBPSK, QPSK, DQPSK, and 16-QAM.

In Figure 28, the input flow is divided into parallel data flows using a serial-to-parallel converter (S/P), which is then passed through an Inverse Fast Fourier Transform (IFFT) block to produce a temporal sequence of flows. Consequently, by adding a cyclic prefix (CP), the temporal sequences of OFDM symbols are extended. The CP is a copy of the last part of the symbol added at the beginning of the sequence and must exceed the propagation delay to reduce Inter-Symbol Interference (ISI) caused by multipath signals. The resulting digital signal is transformed into an analog form and transmitted over the channel. On the receiver side, the signal is reconstructed in digital form. The Fast Fourier Transform (FFT) is applied to the received flows after cyclic prefix removal. Finally, the parallel flows are combined into a single flow.

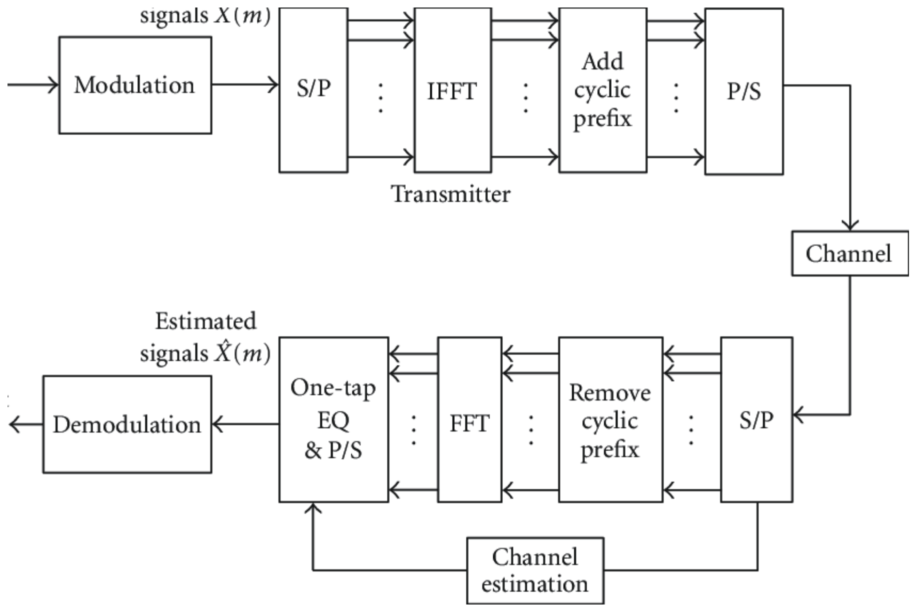

Figure 2.8: OFDM tranceiver

OFDM transmitter and receiver grid demonstration

Figure 2.9 and Figure 2.10 [12] demonstrate the transmitter and receiver blocks, with $N \times M$ information symbols. The QAM modulation alphabet $A = a_1, ..., a_Q$ of size Q. The arrangement of the modulated OFDM symbols is in the time-frequency plane (M subcarriers and N time slots); making an information symbol matrix $\mathbf{X} \in C^{M \times N}$, holding N OFDM symbols [13].
A static multipath channel is considered, where $\tau_{\max}$ is the maximum delay spread, $l_{\max} < M$ is the maximum channel delay tap, and one OFDM symbol (N = 1), we denote a column x as follows :

$$x = \left[x[0], \quad \ldots, \quad x[M-1]\right]^T \in C^{M \times 1} \tag{2.5}$$

with element

$$x[m] \in A, \text{ for } m = 0, \ldots, M-1.$$

$F_M^\dagger$ (M-pint inverse fast Fourier transform (IFFT)) is applied to x resulting in the OFDM symbol vector $\tilde{x}$.

$$\tilde{x} = \left[\tilde{x}[0], \quad \ldots, \quad \tilde{x}[M-1]\right]^T = F_M^\dagger x \in C^{M \times 1} \tag{2.6}$$

- Where $F_M^\dagger$ is the conjugate transpose (also known as the Hermitian transpose) of the Discrete Fourier Transform (DFT) matrix F_M

A pulse-shaping waveform g_{tx} is applied to the time domain OFDM symbol vector $\tilde{\mathbf{X}}$ to improve the system's robustness against the time and frequency distortions, yield to the time domain matrix $G_{tx}\tilde{X}$.

Where G_{tx} is the diagonal matrix containing the samples of g_{tx} as its entries :

$$\mathbf{G}_{tx}\mathbf{G}_{tx}\mathbf{G}_{tx}\mathbf{G}_{tx} = \mathbf{diag}\left(g_{tx}(0), g_{tx}\left(\frac{T}{M}\right), \ldots, g_{tx}\left(\frac{(M-1)T}{M}\right)\right) \in C^{M \times M}(2.7)$$

After the parallel-to-serial conversion, each column of $\tilde{X}$ is the OFDM symbol vector, given by

$$\tilde{x} = s = \left[s[0], \quad \ldots, \quad s[M-1]\right]^T \in C^{M \times 1} \tag{2.8}$$

A CP of length $L_{CP} = l_{\max}$, denoted by

$$s_{CP} = \left[s[M - l_{\max}], \quad \ldots, \quad s[M-1]\right]^T,$$

is prepended to each s to obtain $\tilde{s} = \left[s_{CP}^T, \quad s^T\right]$.

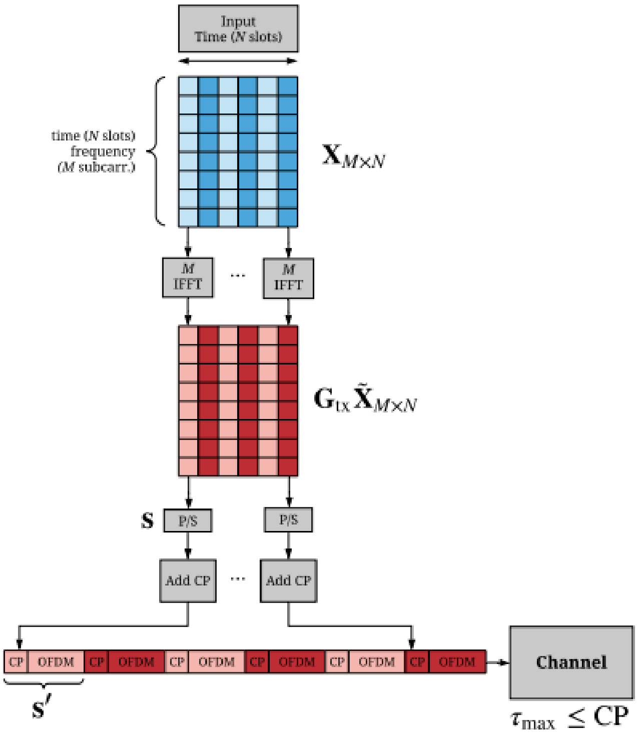

Figure 2.9: OFDM transmitter

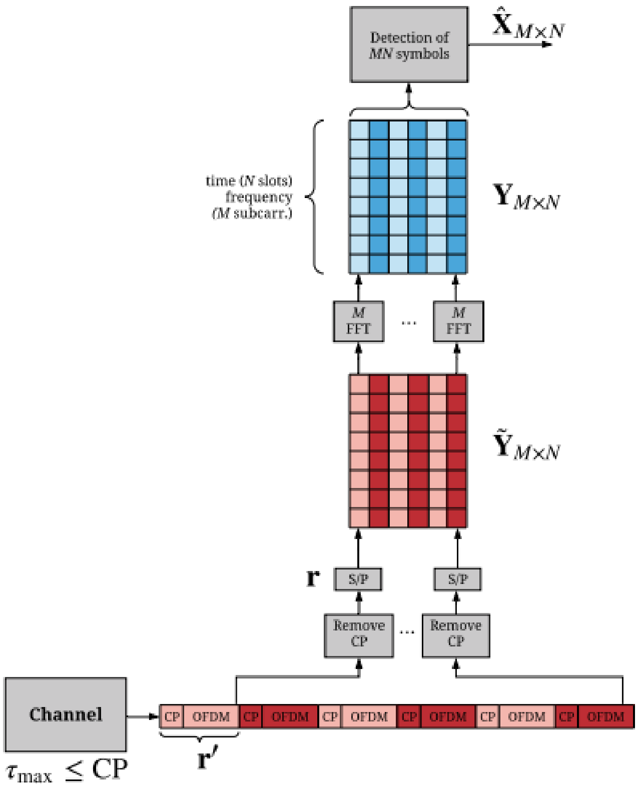

Figure 2.10: OFDM receiver

After digital-to-analog conversion and frequency up-conversion, the bandpass signal is transmitted over a static multipath channel. The received signal on the other side passes through the opposite steps of the transmitter. The CP is removed first then it passes through a series-to-parallel convertor, and the time domain received OFDM symbols transformed into the frequency domain via FFT conversion. The OFDM symbol is extracted[14].

2.1.3 The advantages and disadvantages of Orthogonal Frequency Division Multiplexing (OFDM)

Advantages[15]

- **Simple Equalization:** OFDM bypasses the need for a long equalizer as in single-carrier systems and requires a computational load of only 1 division operation per subcarrier as the equalization part.

- **Hardware Implementation:** In an OFDM system, modulation at the transmiter side is performed through an inverse Fast Fourier Transform (iFFT) block, and the demodulation at the receiver side is done through a Fast Fourier Transform (FFT) block, both of which are hardware optimized leading to simpler implementations.

- **Intercell Interference:** Orthogonality among the subcarriers not only helps in preventing Inter-Symbol Interference (ISI) from multiple copies of the same signal but also helps in avoiding interference among transmissions from neighboring cells.

- **Flexibility:** This is perhaps the biggest advantage offered by OFDM. Having a sliced spectrum allows the designer to control different parts of the spectrum in an adaptive manner. For example, a higher-order modulation can be sent for good subcarriers and a lower-order modulation for bad subcarriers.

Disadvantages[16]

- **Sensitivity to Phase Noise and Frequency Offset:** OFDM is sensitive to phase noise and frequency offset which can break the orthogonality between the subcarriers, leading to Inter-Carrier Interference (ICI).

- **Complexity of Implementation:** The implementation of OFDM involves complex operations such as FFT and IFFT, which can increase the complexity of the system.

- **Synchronization Issues:** OFDM requires accurate synchronization between the transmitter and receiver. Any slight offset can result in a loss of orthogonality between the subcarriers, leading to ICI.

- **High mobility communication system:** OFDM's performance degrades in high-mobility scenarios due to Doppler spread, rapid channel variations, and inefficient cyclic prefix. OTFS, a delay-Doppler domain modulation scheme, addresses these issues by being inherently resilient to Doppler effects, enabling more accurate channel estimation, and requiring a shorter cyclic prefix. The advantages of OTFS make it a promising solution for high-mobility communication applications.

2.2 Orthogonal Time Frequency Space (OTFS)

Due to the advance of the appearance of high-speed trains, unmanned aerial vehicles(UAVs), and self-driving cars, the 5G interface and associated waveform have to obey the different requirements and high-mobility wireless channel. In Orthogonal Frequency Division Multiplexing (OFDM), the channel estimation is no longer effective because of the Doppler shifts and multipath reflections. Therefore, these issues motivate the research academia to examine a new waveform that can handle the desired performance requirement in the new 6G usage scenarios. Orthogonal Time Frequency Space (OTFS) modulation, is a new modulation scheme where each transmitted symbols experiences a near-constant channel gain [5] even at high Doppler, large antenna arrays, or at high frequencies. The OTFS modulation establishes a new coordinate system to reveal the geometry of the wireless channel. OTFS multiplexes each information symbol over a two-dimensional (2D) orthogonal basis function that spans the entire time and frequency resources.

OTFS is a generalization of CDMA, TDMA, and OFDM; in every trade of one of these waveforms to another, there will be a trade of one good property to another, therefore we want to combine them not to lose good properties, as a result, OTFS came to combine all the properties of these waveforms in a single one. OTFS can be implemented as a pre-and post-processing block to filtered OFDM systems, thus enabling architectural compatibility with LTE [5][13].
OTFS is a sequence of pulses evenly spaced in time, and each of the pulses is multiplied by a complex phase and the phase is rotating in the iQ (in-phase and quadrature) plane according to a specific frequency. So it is a tone modulated over a pulse train (locally it looks like a pulse and behaves like one, globally it looks like a tone and behaves like one). it is a spread spectrum. OTFS is invariant under the operations of time delay and Doppler shift (if you shift it in time or frequency or apply Fourier transform to it; it preserves its shape). If we transmit this wave through a channel full of reflectors you receive the same wave (does not be affected by Doppler shift. Figures 2.11 illustrate the OTFS example.

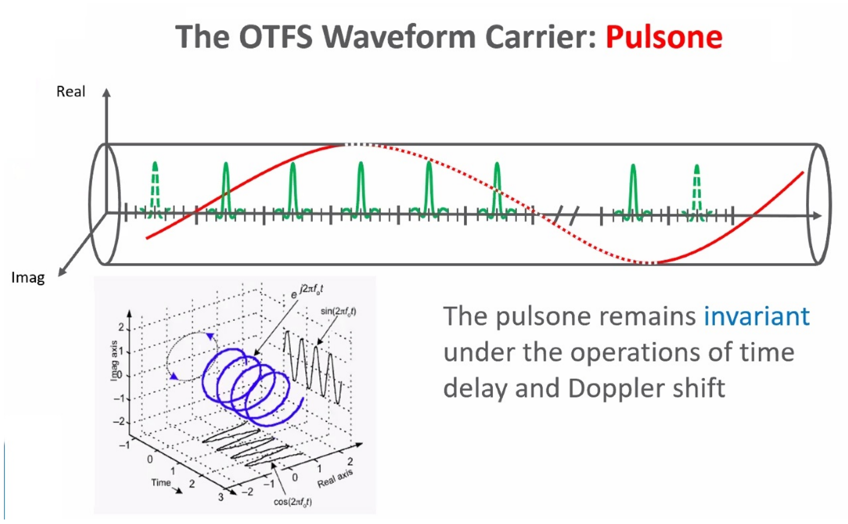

Figure 2.11: OTFS waveform representation

2.2.1 Delay-Doppler channel

The received signal travels through a channel response h(τ; ν) characterized with Delay (τ) and Doppler (ν). Therefore, the received signal due to a random input s(t) transmitted through this channel is given by :

$$r(t) = \int\int h(\tau, \nu)s(t-\tau)e^{j2\pi\nu(t-\tau)}\, d\nu\, d\tau. \tag{2.9}$$

Due to the small number of channel reflectors with associated Dopplers, there are few channel estimation parameters in the Delay-Doppler domain compared to the time-frequency domain.

Note that (14) can be represented as a linear operator $\prod_h(.)$, that operates on the input s(t) to produce the output r(t):

$$\prod h(s) : \prod s(t) \rightarrow \quad r(t) \tag{2.10}$$

the representation of the relationship h(τ; ν) in (14) as an operator $\prod_h$ parameterized by a function and operating on a function s(t) as defined in (15) is called the **Heisenberg** transform.

The OTFS signals bounce off reflectors and arrive at the other part, this results in echos placed both on delay and Doppler, every echo with a specific phase. As shown in Figure 2.12.

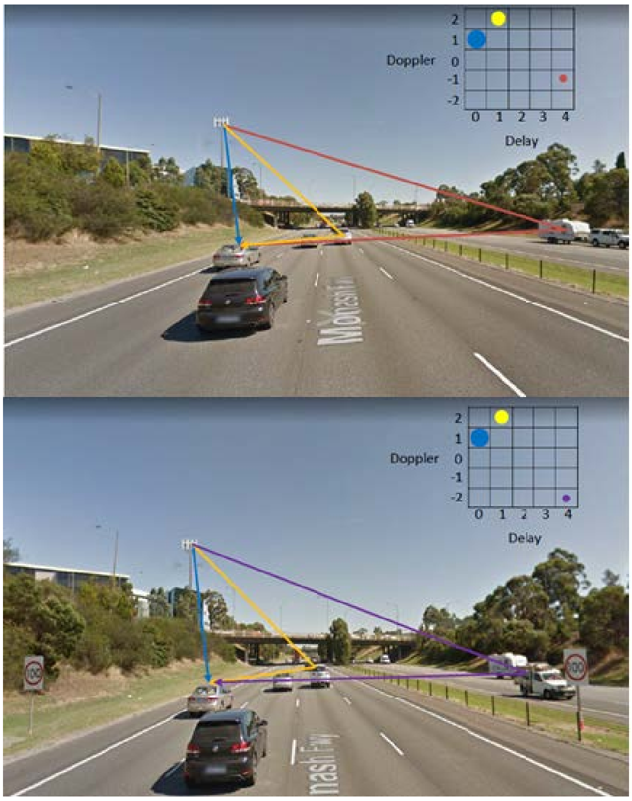

Figure 2.12: OTFS channel representation

As we see in this figure each reflector corresponds to one of these beams along with the transmitted signal with corresponding delay and Doppler which helps to know the reflector range and velocity respectively, this representation eases the channel estimation process. OTFS is designed so that its information symbols experience minimal cross-interference as well as full diversity in the delay-Doppler domain through appropriate design of the modulation lattice and pulse shape design in that domain.

OTFS System model

Let an OTFS system operate on a P-path high-mobility channel with bandwidth B, maximum delay spread τ_{max}, and maximum Doppler shift ν_{max}. the OTFS signal is sampled at the discrete-time domain $f_s = \mathrm{B} = 1/T_s$; T_s is the sampling interval.
The OTFS frame is composed of NM samples, which are organized into N blocks (time slots), and each block contains M samples. Therefore, the OTFS frame duration is $T_f = NMT_s = NT$, with $T = MT_s$ denoting the duration of each block.

The time-frequency signal plane is discretized into a grid Λ by sampling the time and frequency axes at intervals T (seconds), and Δf (Hz).

$$\Lambda = \{(nT, m\Delta f) \,|\, n = 0, \dots, N-1,\, m = 0, \dots, M-1\} \tag{2.11}$$

A packet burst with a total duration of NT seconds and a total bandwidth $M\Delta f$ Hz in which The time-frequency modulated symbols X[n, m], n = 0, . . . , N - 1, m = 0, . . . , M - 1 are transmitted within.

The transmit and receive parts are denoted as g_{tx} and g_{rx} respectively, whose inner product is orthogonal concerning translations by time T and frequency Δf. Let $A_{grx,gtx}(t, f)$ denote the cross-ambiguity function between $g_{tx}(t)$ and $g_{rx}(t)$, i.e.,

$$A_{grx,gtx}(t, f) = \int g^*_{rx}(t' - t) g_{tx}(t') e^{-j2\pi f(t'-t)} dt'. \tag{2.12}$$

The delay-Doppler signal plane is discretized into a grid :

$$\Gamma = \left\{ \left(\frac{k}{M\Delta f}, \frac{l}{NT} \right) \middle| \, k = 0, \dots, N-1,\, l = 0, \dots, M-1 \right\} \tag{2.13}$$

The delay-Doppler grid Γ is the dual representation of the time-frequency grid Λ.

- $1/M\Delta f$ and $1/NT$ represent the quantization steps of the delay and Doppler frequency, respectively Figure 33 illustrates the OTFS system model (transceiver).

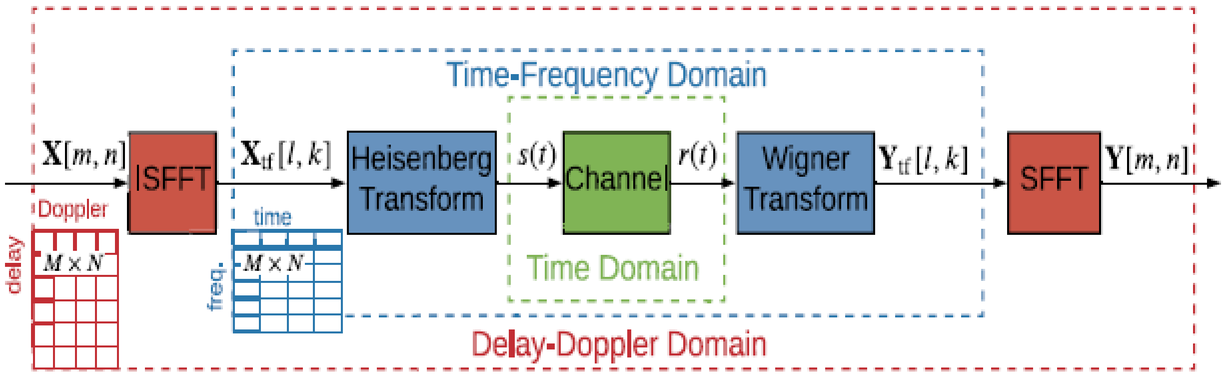

Figure 2.13: OTFS tranceiver

OTFS modulation

The NM information symbols, taken from a modulation alphabet $A = \{a_1, \dots, a_Q\}$ of size Q, are placed in the delay-Doppler domain matrix $X \in C^{M\times N}$ with entries $X[m, n]$, for $m = 0, \dots, M-1$ and $n = 0, \dots, N-1$.

The transmitter first maps the delay-Doppler information symbol on the time-frequency grid Λ via inverse symplectic fast Fourier transform (ISFFT). The time-frequency symbols then are :

$$X_{tf}[l, k] = \frac{1}{MN} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X[m, n] e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)} \tag{2.14}$$

For $l = 0, \ldots, M-1$, $k = 0, \ldots, N-1$, The ISFFT corresponds to a 2D transformation which takes an M-point DFT of the columns of $\mathbf{X}$ and an N-point inverse DFT (IDFT) of the rows of $\mathbf{X}$ which is explained in Figure 2.14.

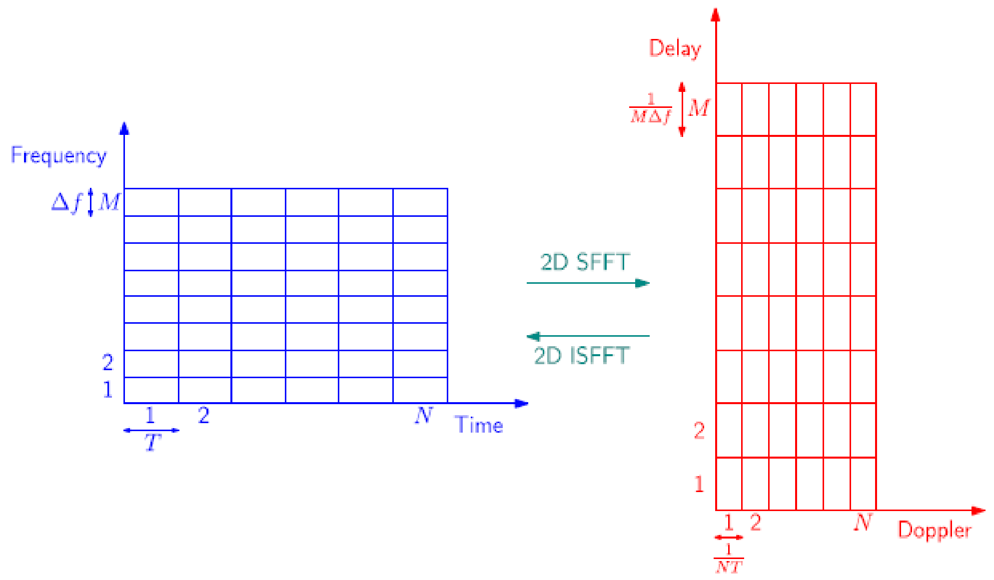

Figure 2.14: 2D transformation using ISFFT

Next, the Heisenberg transform a modulator a time-frequency transform the time-frequency samples $X_{tf}[l, k]$ into a continuous transmitted signal $s(t)$ using a transmit signal g_{tx} as follows :

$$s(t) = \sum_{l=0}^{M-1} \sum_{k=0}^{N-1} X_{tf}[l, k] g_{tx}(t - kT) e^{j2\pi l \Delta f (t-kT)} \tag{2.15}$$

Where the Heisenberg transform depends on N, M, g_{tx}.

Wireless transmission and reception

The signal $s(t)$ is transmitted through a time-varying channel with a Delay and Doppler channel response h(τ; ν), where τ and ν denoted the delay and Doppler respectively. Discarding the noise the received signal $r(t)$ is :

$$r(t) = \iint h(\tau, \nu) s(t - \tau) e^{j2\pi\nu(t-\tau)} \, d\tau \, d\nu \tag{2.16}$$

Equation (21) represents the continuous Heisenberg transform parameterized by $s(t)$. For every point τ, ν, the value $h(\tau, \nu)$ represents the reflectivity of a cluster of reflectors sharing these specific delay and Doppler parameter values[17].
The sparse representation of the channel $h(\tau, \nu)$ is given as:

$$h(\tau, \nu) = \sum_{i=1}^{P} h_i \delta(\tau - \tau_i) \delta(\nu - \nu_i) \tag{2.17}$$

Where P is the number of paths, $\delta(\cdot)$ signifies the Dirac delta function. the parameters h_i, τ_i, and ν_i stand for the path gain, delay, and Doppler shift (or frequency) corresponding to the i-th path, respectively. We denote the delay and the Doppler of a corresponding path as follows:

$$l_{\tau_i} = \frac{\tau_i}{M\Delta f}, \quad \nu_i = \frac{k\nu_i + \kappa\nu_i}{NT} \tag{2.18}$$

The delay tap and Doppler tap integers $l_{\tau i}$ and $k_{\nu i}$, respectively, correspond to the (continuous) delay τ_i and the Doppler frequency ν_i, and with positive integer κ_{ν_i} where $\left(-\frac{1}{2}\right) < \kappa_{\nu_i} \leq \left(\frac{1}{2}\right), and \kappa_{\nu_i}$ is the fractional Doppler which represents the fractional shift from the nearest Doppler tap $k_{\nu i}$.

OTFS demodulation

As shown in Figure 33, the received signal $r(t)$ passes through a matched filter computing the cross ambiguity function $\mathrm{A}_{grx,r}(f,t) as:$

$$Y(f,t) = A_{grx,r}(f,t) = \int_{-\infty}^{\infty} r(t')g^*_{rx}(t'-\tau)e^{-j2\pi f(t'-\tau)}\,dt' \tag{2.19}$$

And then sampling Y(f, t) on the grid points Λ forms the time-frequency domain received samples matrix $\mathrm{Y}_{tf} \in C^{M\times N} with entries:$

$$Y_{tf}[l,k] = Y(f,t)\Big|_{f=l\Delta f,\, t=kT} \tag{2.20}$$

Joining (24) and (25) are the Weigner transform the inverse of the Heisenberg transform, it takes the received signal $r(t)$ from the time domain and spreads it to the frequency domain as $Y_{tf}[l,k]$ samples.
The symplectic fast Fourier transform (SFFT) is applied then to the time-frequency samples in order to map them in the delay Doppler domain. the delay-Doppler domain samples are :

$$Y[m,n] = \frac{1}{\sqrt{NM}} \sum_{k=0}^{N-1}\sum_{l=0}^{M-1} Y_{tf}[l,k]e^{-j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)} \tag{2.21}$$

which, after receiving the samples matrix $Y \in C^{M\times N}$, creates the delay-Doppler domain. The SFFT is equivalent to a 2D transformation that requires an N-point DFT of Y's rows and an M-point IDFT of Y's columns.

The Zak transform

In a summary of the OTFS system, the information symbols are first mapped in the delay-Doppler domain then an ISFFT is applied to transform them to the time-frequency domain. The time-frequency domain symbols is transmitted through the channel as a continuous-time signal by the Heisenberg transform. The opposite steps are happened on the receiver side.

The transmitter can be realized using an inverse discrete Zak transform as shown in Figure 2.15 and a digital-to-analog (DA) converter to form the transmitted signal $s(t)$. The receiver side applies an analog-to-digital (AD) converter on the received signal $r(t)$ followed by a discrete Zak transform[13][5].

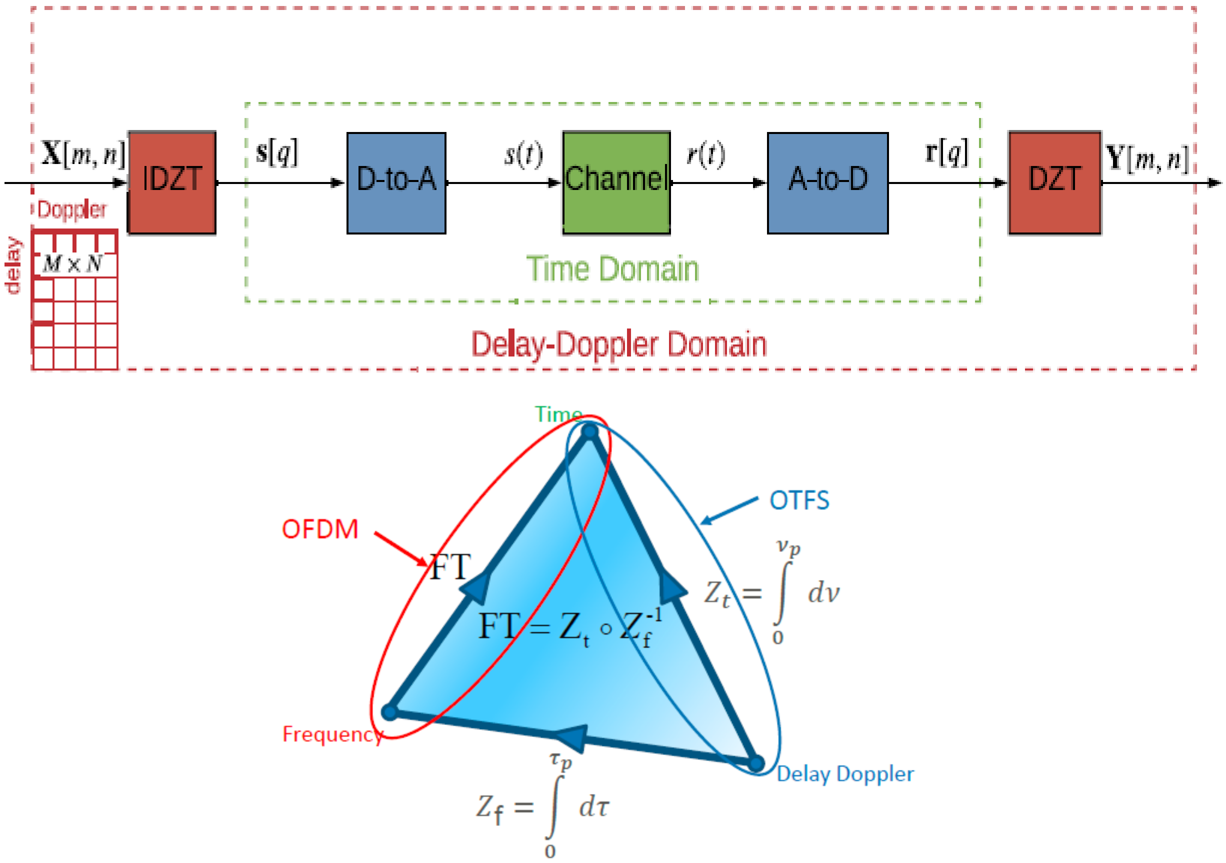

Figure 2.15: OTFS transceiver using the discrete Zak transform

2.2.2 the advantages and disadvantages of Orthogonal Time Frequency Space (OTFS)

Advantages

- In contrast to OFDM, OTFS has a distinct lattice structure with symbols positioned in the delay-Doppler plane. Better performance in high-mobility conditions is made possible by this.

- In wireless channels, OTFS offers enhanced robustness against delay and Doppler effects.

- In high-mobility circumstances, OTFS can achieve better performance and higher spectrum efficiency than OFDM.

disadvantages

- When compared to OFDM, the performance of OTFS can deteriorate in low-mobility situations.

- Since OTFS has not yet gained the same level of traction as OFDM, the standards and device ecosystem are not as developed.

2.3 Co-existence of OFDM and OTFS

In high-mobility settings, OFDM suffers from severe performance deterioration due to huge Doppler shifts that disrupt the orthogonality of its subcarriers. Serious inter-carrier interference (ICI) and decreased communication dependability result from this. OTFS, on the other hand, has been suggested as a solution to these problems by utilizing delay-Doppler diversity [18][5], which makes it suited for high-speed communication and resistant to Doppler effects. At the same time, OTFS performance degrades at low mobility scenarios because the channel is relatively static with limited time-frequency diversity[19].

This researcher's main goal is to look into the coexistence of OFDM and OTFS waveforms in multi-mobility situations in Figure 2.16. In order to strike a compromise between complexity and performance, one of the solutions is to create a downlink transmission system [20] that can dynamically switch between OTFS and OFDM depending on the user's mobility.

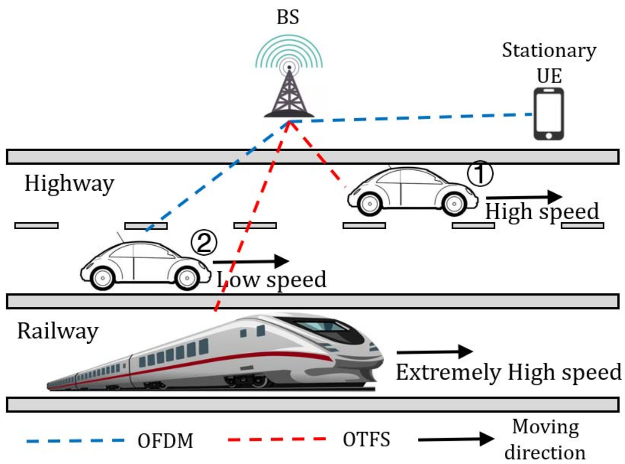

Figure 2.16: Multi mobility scenarios

Recently, two multiplexing schemes—Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM)—to facilitate this co-existence[21]. Where:

- **Time Division Multiplexing (TDM):** Allocates different time slots to OTFS and OFDM users, allowing each to occupy all available subcarriers during their respective slots.

- **Frequency Division Multiplexing (FDM):** Allocates different subcarrier sets to OTFS and OFDM users, allowing both to operate simultaneously but on different frequency resources.

In this system, OTFS is treated as precoded OFDM. OTFS symbols are mapped to the delay-Doppler domain and then transformed to the time-frequency domain using ISFFT. These symbols are then multiplexed with OFDM symbols in the time-frequency grid. The system employs Heisenberg transformation for multi-carrier modulation before transmission Figure 2.17.

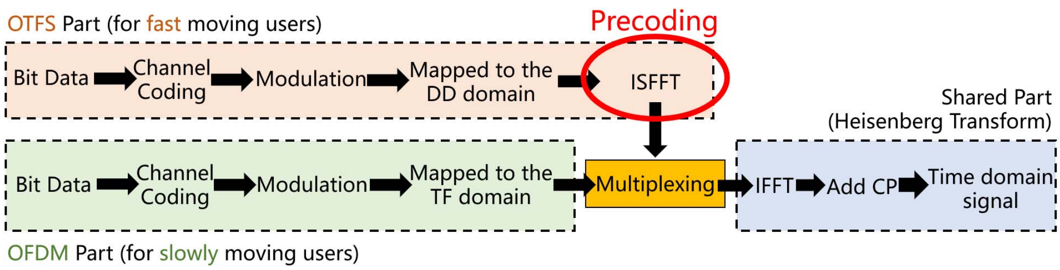

Figure 2.17: Downlink OFDM-OTFS system

In the co-existence system, the interference is divided into internal ICI within the user's subcarriers and multi-user interference (MUI) from other users' subcarriers. Guard bands are introduced in the FDM scheme to mitigate MUI by placing null subcarriers between the OTFS and OFDM symbols. The FDM and TDM schemes are shown in Figure 2.18.

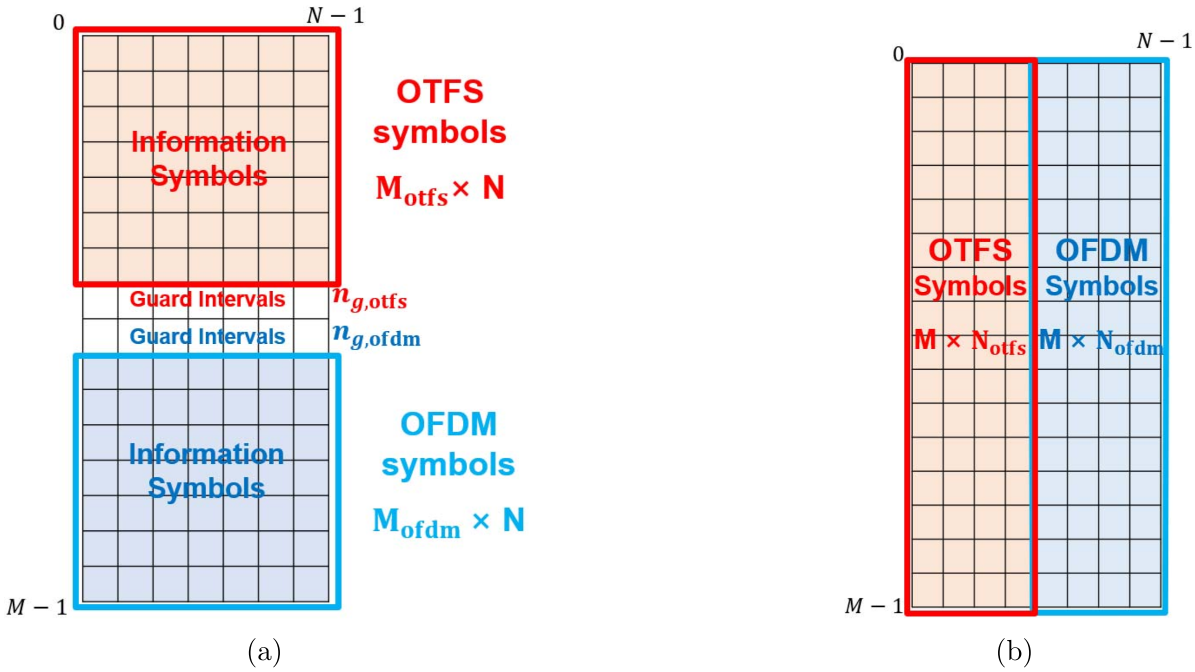

Figure 2.18: OTFS-OFDM co-existence schemes: (a) FDM scheme; (b)TDM scheme

Frequency Division Multiplexing (FDM):

1. **OTFS Symbols (Motfs x N):** Located in the upper portion of the grid, these symbols represent the data transmitted using the OTFS modulation scheme. This section is highlighted in red.

2. **OFDM Symbols (Mofdm x N):** Located in the lower portion of the grid, these symbols represent the data transmitted using the OFDM modulation scheme. This section is highlighted in blue.

The white area between the OTFS and OFDM symbol blocks represents the guard intervals. These intervals are crucial for minimizing interference between the two types of modulation schemes.

ng,otfs: The guard interval associated with the OTFS symbols.

ng,ofdm: The guard interval associated with the OFDM symbols

Time Division Multiplexing (TDM):

1. **OTFS Symbols (M x Notfs):**

   Location: The OTFS symbols are positioned on the left side of the grid, spanning a specific number of time slots (0 to Notfs-1). This section is highlighted in red.
   Purpose: OTFS modulation is designed to handle high mobility scenarios by exploiting delay-Doppler diversity, which provides robustness against Doppler shifts and multipath effects.
   Notfs: Denotes the number of time slots allocated to OTFS symbols.

2. **OFDM Symbols (M x Nofdm):**

   Location: The OFDM symbols are positioned on the right side of the grid, spanning the remaining time slots (Notfs to N-1). This section is highlighted in blue.
   Purpose: OFDM is suitable for low mobility scenarios where the channel conditions are relatively stable. It offers high spectral efficiency and simplicity.
   Nofdm: Denotes the number of time slots allocated to OFDM symbols.

2.4 Chapter Recap

This chapter explores OFDM and OTFS modulation techniques. OFDM divides high-speed data into parallel low-speed streams, mitigating multipath and fading. It is a cornerstone of modern wireless, used in Wi-Fi, LTE, and 5G. OTFS jointly modulates signals in time and frequency, making it resilient to time-varying channel effects like delay and Doppler shifts. OTFS offers advantages for high-mobility and severe multipath scenarios compared to OFDM. The chapter delves into the principles behind OFDM and OTFS. In the next chapter, a simulation-based comparison will evaluate their performance on metrics like spectral efficiency and error rates. The focus will shift from theory to practice, comparing OFDM and OTFS in realistic scenarios. The co-existence of Orthogonal Time Frequency Space (OTFS) and Orthogonal Frequency Division Multiplexing (OFDM) waveforms in multi-mobility scenarios presents a promising approach to enhance the performance of wireless communication systems. Table 7 nsummarizes the main difference between OFDM and OTFS.

Aspect	**OFDM**	**OTFS**
Full Name	Orthogonal Frequency Division Multiplexing	Orthogonal Time Frequency Space
Domain	Time-Frequency Domain	Delay-Doppler Domain
Modulation Technique	Modulates data over multiple orthogonal subcarriers	Modulates data over orthogonal basis functions in delay-Doppler domain
Implementation	Uses FFT/IFFT blocks, cyclic prefix for guard interval	Uses Zak transform, SFFT/ISFFT for mapping between domains
Equalization	Simple equalization due to orthogonal subcarriers	Complex equalization but more robust to Doppler shifts and delay spreads
Interference Handling	Handles inter-symbol interference with cyclic prefix	Handles both inter-symbol and inter-carrier interference due to its robustness
Performance in High Mobility	Performance degrades due to Doppler spread and rapid channel variations	Maintains performance due to robustness against Doppler effects
Bit Error Rate (BER)	Lower BER at low mobility, higher BER at high mobility	Higher BER at low mobility, lower BER at high mobility
Computational Complexity	Lower due to efficient FFT/IFFT operations	Higher due to additional processing for domain transformation
Hardware Implementation	Well-established, simpler due to optimized FFT/IFFT	Emerging, more complex due to advanced processing requirements
Flexibility and Adaptability	Flexible with adaptive modulation schemes	Highly adaptable to varying channel conditions, particularly high mobility
Applications	Widely used in Wi-Fi, LTE, 5G, digital radio, and TV	Promising for future 6G networks, high-speed trains, UAVs, and autonomous vehicles

Table 2.1: Comparison of OFDM and OTFS

3 RESULTS & DISCUSSION

3.1 Introduction

By examining the most recent waveforms for the newest 4G, 5G, and 6G technologies. Thanks to MATLAB software, we can now simulate both OFDM and OTFS and have a better understanding of them. We will compare the behavior of each waveform in various environments and see how these waveforms look. Furthermore, we combine the two waveforms in one system to study the coexistence of OTFS and OFDM, that give us the chance to gather the advantages of each technique and improve the performance of the system. In this chapter the study will be the tracking of the behaving of both waveforms based on two parameters :

- Bit error rate(BER)
- Signal to noise ratio (SNR).

3.2 Simulation parameters

3.2.1 Bit error rate (BER)

The variable we will count on to compare both of the waveforms is called the Bit Error Rate (BER).
The rate at which data bits are incorrectly received or transferred within a communication system is measured by the Bit Error Rate (BER), a crucial performance indicator in wireless communication. It is the proportion of bits received incorrectly to bits sent across a communication channel as a whole. Stated differently, it represents the likelihood that a bit sent across a channel would be misinterpreted. It is a matrix that can be used to describe how well a communication system is doing. Bit Error Rate (BER) is defined as the rate at which errors occur in a transmission system. In simple form,

$$\text{BER} = \frac{\text{number of bits in error}}{\text{total number of bits sent}} \tag{3.1}$$

the BER expression is given as:

$$\text{BER} = \int_0^\infty P_b(E|r)P(r)\,dr \tag{3.2}$$

where,

$$P_b(E|r) = \text{the conditional error probability}$$
$$P(r) = \text{the pdf of the SNR}$$

3.2.2 Signal to noise ratio (SNR)

Another parameter is the dimensionless ratio of the signal power to the noise power contained in a recording. When it comes to measurement quality, the Signal to Noise Ratio SNR is what matters most. A high signal-to-noise ratio SNR ensures crisp captures with few noise-induced distortions and aberrations. The more advanced your SNR indicates how well the signal contrasts, how well your information bits seem, and how well you can see the outcomes you want. The SNR can be calculated as follows:

$$\text{SNR} = \frac{\text{Power of the Signal}}{\text{Power of the Noise}} \tag{3.3}$$

3.3 Simulation of the Orthogonal Frequency Division Multiplexing (OFDM) waveform

In this part, we are going to see the simulation and the application of the steps discussed in the second chapter about OFDM.
First, we need to follow the system described in Figure 2.8 Parameters used for simulation are in Table 7, and the result of each block can be shown in the following:

Table 3.1: Simulation Parameters for OFDM

Parameter	**Value**
Data Source	Random
Number of Subcarriers (N)	512
SNR (dB)	-10:4:20
Slots per Frame	20
Symbols per Slot	7
Symbols per Slot (Pilot)	2
Symbols per Slot (Data)	5
Channel Type	AWGN

The first step of every signal transmission is generating data to be transmitted, the result is shown below in Figure 3.1. These random data are being modulated using 16 QAM along with pilot symbols which are being modulated using QPSK. The modulated symbols are converted from serial to parallel. This conversion process is necessary because OFDM transmits data over multiple parallel subcarriers rather than a single carrier. After S/P conversion the information data pass through an inverse fast Fourier transform to be converted from the frequency domain to the time domain for transmission. The output signal of the FFT is then modified by adding a CP, last 36 bits of the symbol are added to the beginning. as illustrated in Figure 3.2. The data then through an upsampler to increase the sampling rate and then converted to an analog signal to be transmitted and propagated in an AWGN channel as shown in Figure 3.3:

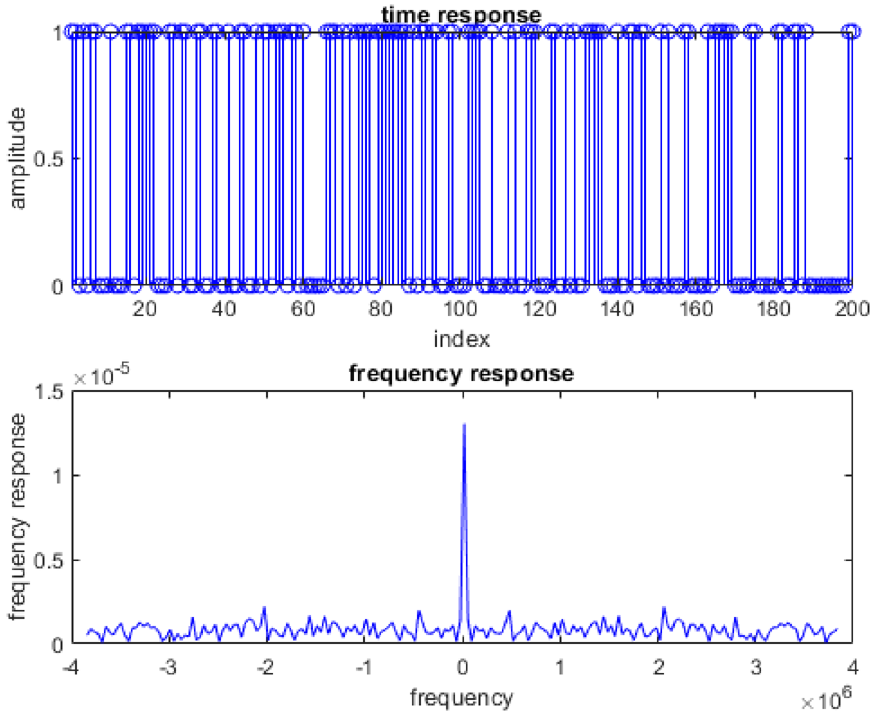

Figure 3.1: Time and Frequency domains of data generating

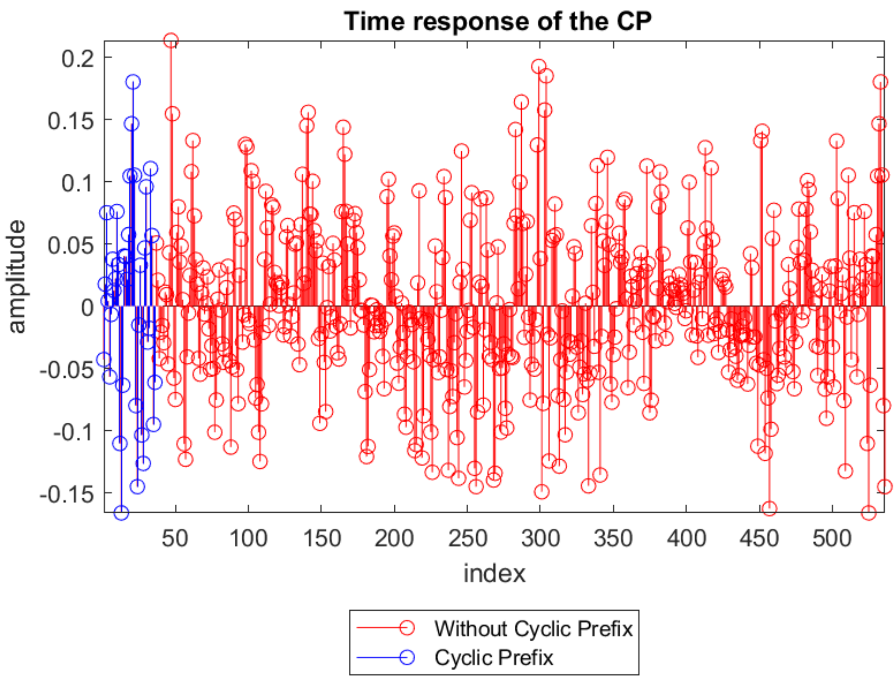

Figure 3.2: output of cyclic prefix

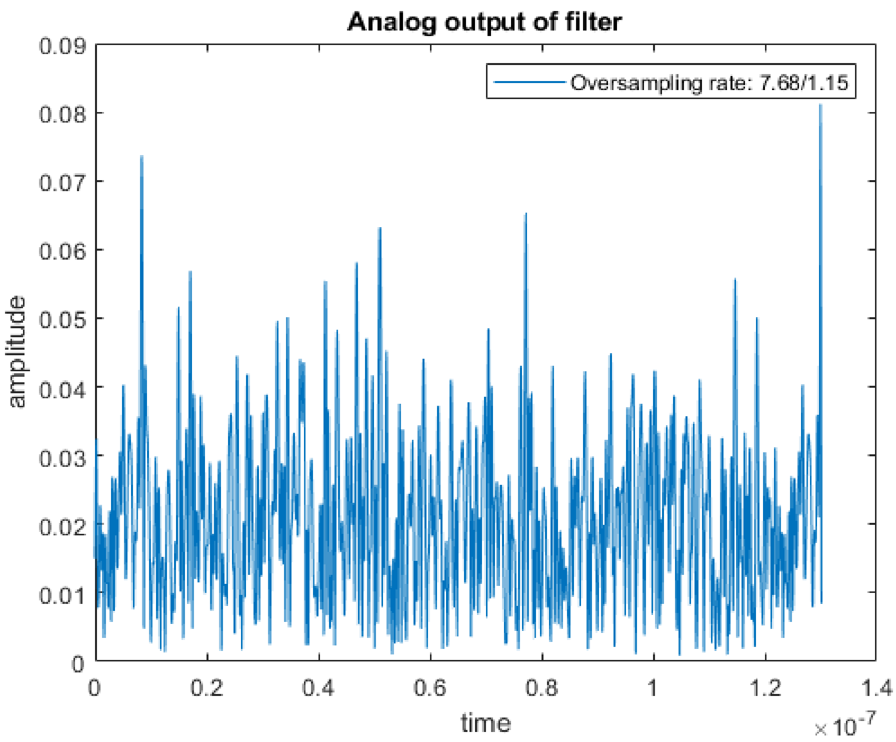

Figure 3.3: transmitted signal

Finally, the BER analysis versus SNR of the transmitted OFDM signal shows a very good result according to the theoretical one. From Figure 3.4, we remark that increasing SNR leads to decreasing the probability of error.

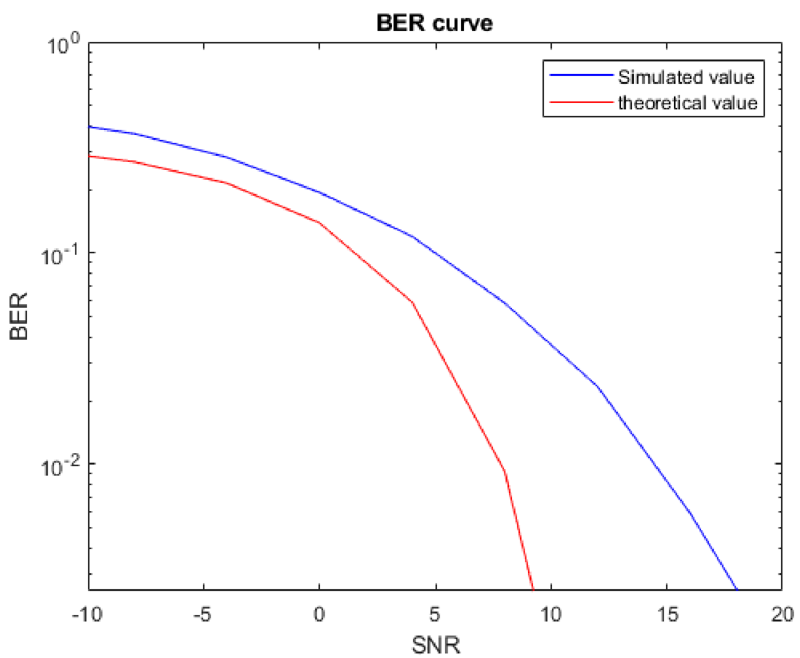

Figure 3.4: BER vs SNR

For the coming sections, there will be a change in OFDM parameters to study the behaviour of the waveform and how it can be affected. **parameters used**

Table 3.2: Parameters of the OFDM-based Communication System

Parameter	Value
Physical Layer Parameters	
number of Subcarriers Per Block	12
number of Symbols Per Block	14
$f_{\text{SubcarrierSpacing}}$	15 kHz
number of FFT	256
lenghth of Cyclic Prefix	12/15/17
Modulation and Coding Parameters	
modOrder	4, 16, 64, 256
$n_{\text{TxAntennas}}$	1
$n_{\text{RxAntennas}}$	1
Fading Channel Parameters	
$\text{velocity}_{\text{Km/h}}$	50/120/500
$\text{delaySpread}_{\text{ns}}$	300
f_{Center}	0.8 GHz
channelModel	EVA

3.3.1 Rx velocity effect

Figure 3.5 shows the BER performance of an OFDM system using 16 QAM modulation under different vehicle speeds, specifically 120 km/h, 500 km/h, and 50 km/h.

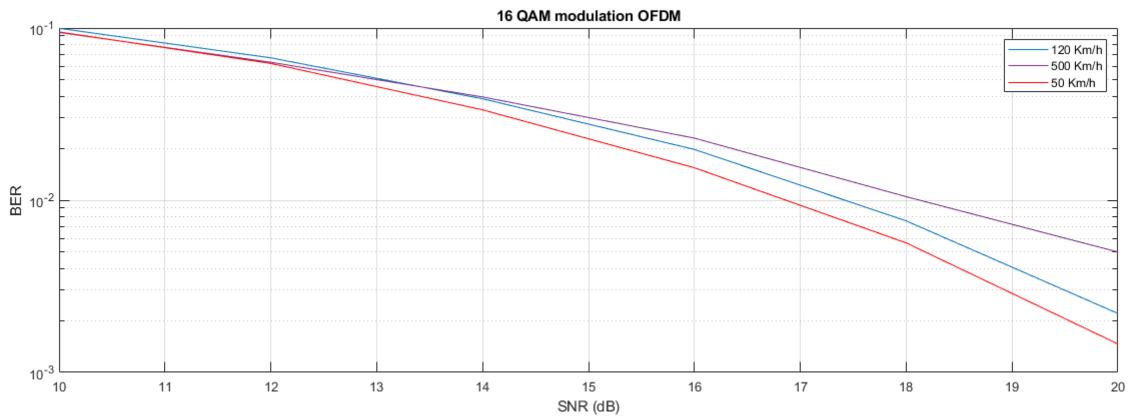

Figure 3.5: receiver Velocity effect

The key observations regarding how velocity affects the OFDM system are: As the vehicle speed increases, the BER performance of the OFDM system degrades. This can be seen by the BER curves shifting upwards as the speed increases from 50 km/h to 120 km/h and then to 500 km/h. At lower SNR (Signal-to-Noise Ratio) values (below 12 dB), the BER curves for different speeds start to converge, indicating that the system performance is primarily limited by the noise rather than the Doppler effects caused by the higher speeds.

3.3.2 Cyclic prefix effect

Figure 3.6 illustrates how changing the cyclic prefix (CP) length affects an OFDM system's bit error rate (BER) performance. Samples with CP lengths of 12, 15, and 17 are displayed.

For all three CP lengths, the BER falls as predicted as the SNR (signal-to-noise ratio) rises. This is because higher SNR denotes reduced noise and better signal quality, which reduces bit mistakes. Additionally, a longer CP length leads to a lower BER for a given SNR. According to the plot, the BER is lowest for a CP of 17 samples, followed by 15 samples, and lastly 12 samples. A longer CP can better manage multipath propagation effects and intersymbol interference (ISI) in the channel, explaining this behavior. The receiver performs better because it can distinguish between the required signal and the delayed reflections more clearly due to the longer guard interval that the CP provides.

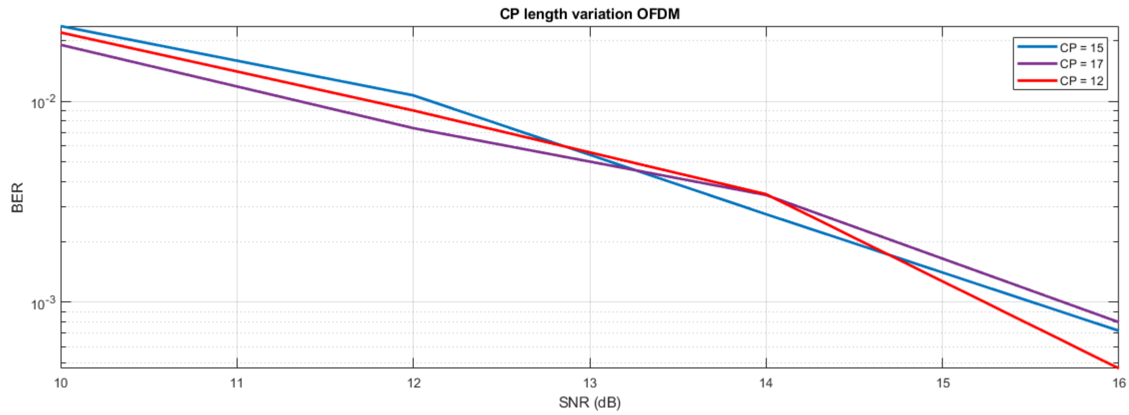

Figure 3.6: BER vs SNR Cyclic prefix effect analysis

3.3.3 Modulation technique effect

The BER (Bit Error Rate) performance of an OFDM system under various vehicle speeds and modulation methods (16 QAM and 4 QAM) is displayed in Figure 3.7.

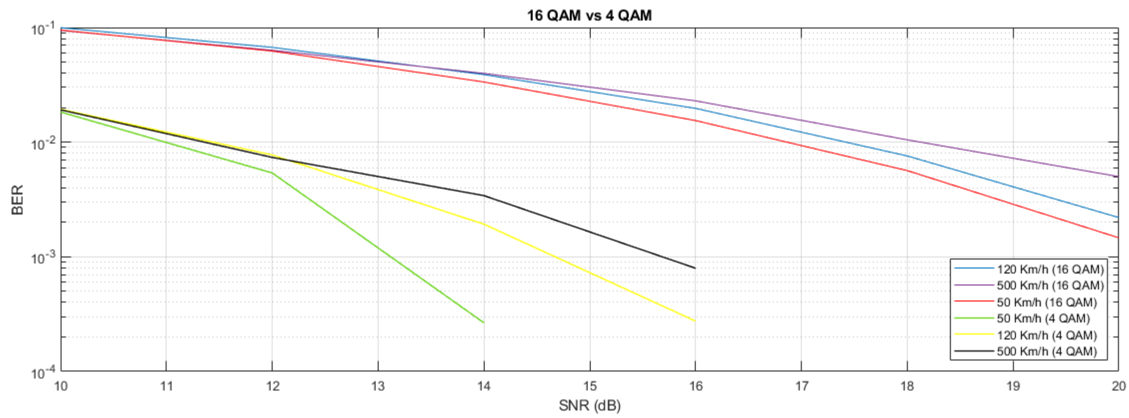

Figure 3.7: BER vs SNR OFDM moduation effect analysis

From these figures, we observe that Over the entire SNR (signal-to-noise ratio) spectrum, 4 QAM modulation consistently performs better than 16 QAM modulation. This is because the lower-order 4 QAM modulation technique is more resilient to noise and channel impairments compared to the higher-order 16 QAM. For both 16 QAM and 4 QAM, the BER performance deteriorates with increasing vehicle speed. This is due to faster speeds enhancing the Doppler effect, which increases frequency offsets and channel fluctuations, leading to more bit errors.

In summary, the OFDM system's performance is heavily influenced by the choice of cyclic prefix length and modulation scheme, as well as the vehicle speed. Increasing the cyclic prefix length improves BER, but reduces spectral efficiency. Lower-order modulation like 4 QAM outperforms higher-order 16 QAM, especially at high vehicle speeds, due to better resilience to Doppler effects. However, 4QAM sacrifices the data rate compared to 16QAM. As vehicle speed increases, the Doppler shift degrades OFDM performance by introducing frequency offsets and rapid channel variations. Careful system design and adaptation are required to balance the tradeoffs and maintain reliable OFDM communications in high-mobility scenarios.

3.4 Simulation of the Orthogonal Time Frequency Space Multiplexing (OTFS) waveform

To simulate the OTFS and prove the shape and the efficiency of this waveform in a multipath channel for channel estimation we have to follow the OTFS system blocks in Figure 2.13. A set of parameters is used in our simulation in Table 8 followed by resultant Figures.

Table 3.3: Simulation Parameters for OTFS

Parameter	**Value**
Span of delay axis (T)	$50\mu s$
Span of Doppler axis (Δf)	20 kHz
Number of Doppler cells (M)	128
Number of Delay cells (N)	128
Number of Channel Paths (P)	6
Channel Coefficients	Random
Channel Delay Shifts	Random (1 to M)
Channel Doppler Shifts	Random (1 to N)

- **Data generation:** The OTFS frame is composed of NM samples, which are organized into N blocks (time slots), and each block contain M samples. Therefore, the OTFS frame duration is Tf =NMTs = NT, with T = MTs denotes the duration of each block. the result is shown in Figure 3.8.

  In high-mobility settings, the Delay-Doppler domain offers a more effective and intuitive channel representation. Compared to the time-frequency domain employed by OFDM, it more easily captures the effect of multipath propagation and Doppler shifts. This is especially useful in situations where there is a lot of relative motion, like aerial or vehicle communication systems.

- **ISFFT:** the random delay Doppler data is spread over the time-frequency domain by the inverse symplectic finite Fourier transform (ISFFT) as illustrated in Figure 3.9.

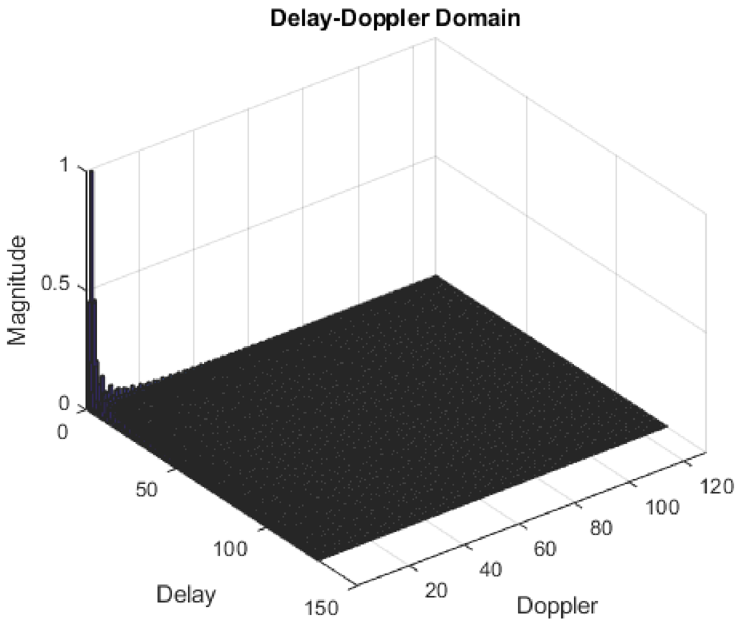

Figure 3.8: transmitted symbols in DDD

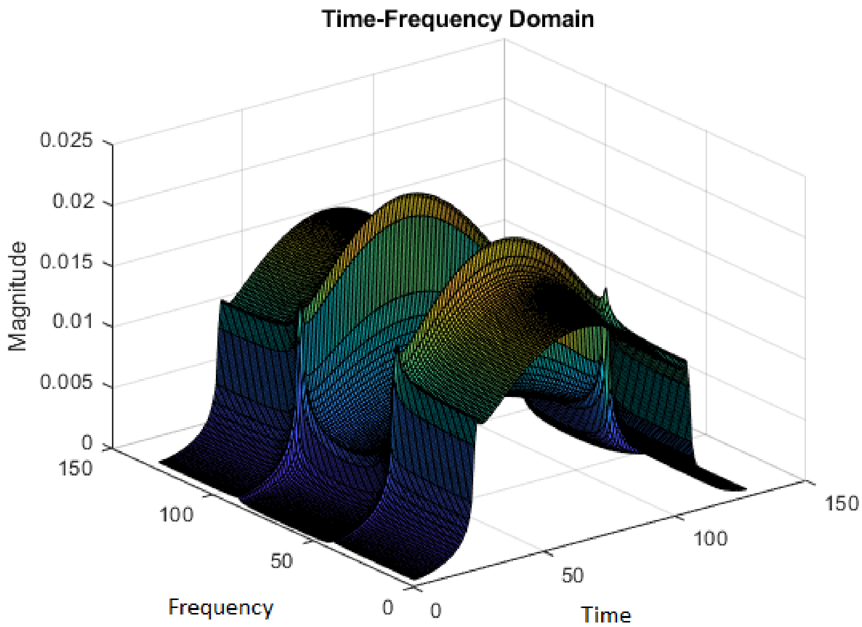

Figure 3.9: TF data spread

The Delay-Doppler domain often exhibits sparse characteristics, where a few dominant paths represent the majority of the channel's effect. The ISFFT leverages this sparsity to efficiently map data, making it robust against multipath fading and Doppler shifts.

- **Heisenberg transform:** The role of the Heisenberg transform is to convert these TF data in Figure 3.9 to a time-domain signal to be transmitted through a multipath channel. The transmitted signal is in Figure 3.10.

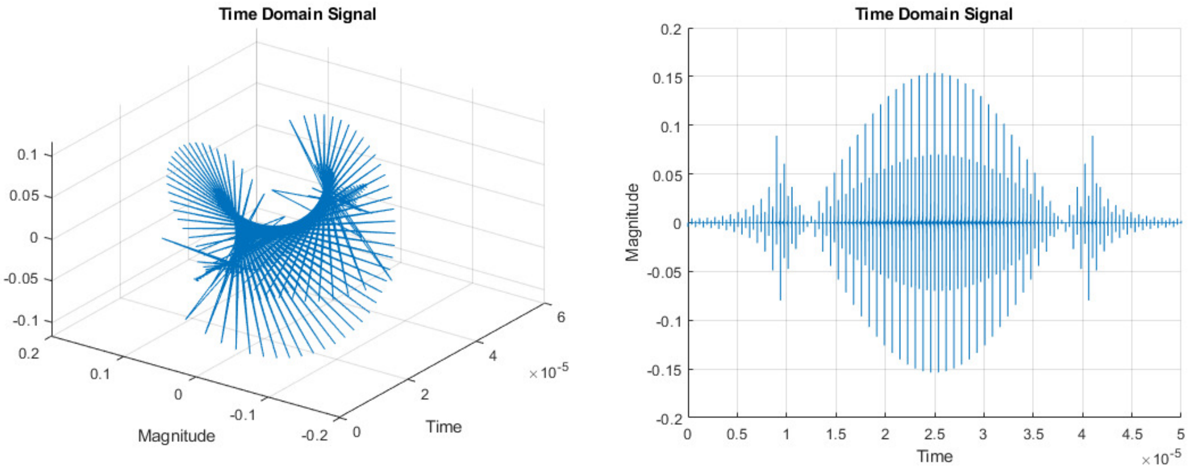

Figure 3.10: Transmitted pulsone

- **Channel:** As we can see in Figure 3.10, the transmitted signal is in the shape of a pulsone That will be bounced off reflectors and arrive at the other part. The received time-domain signal is shown in Figure 3.11.

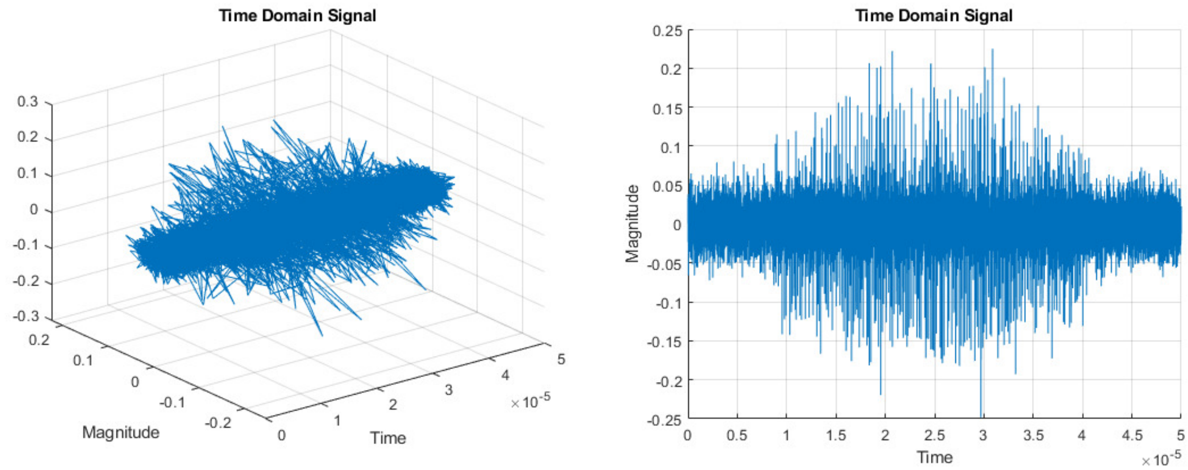

Figure 3.11: Received time domain signal

- **Wigner transform:** This block is the inverse of the Heisenberg transform, where the received time-domain signal is spread over the TFD. A better view to understand this is in Figure 3.12.

- **SFFT:** In order to make the received signal easy to read and to extract channel information, we need to convert it back to the delay Doppler domain using SFFT. Figure 3.13 illustrates the received signal in the delay Doppler domain.

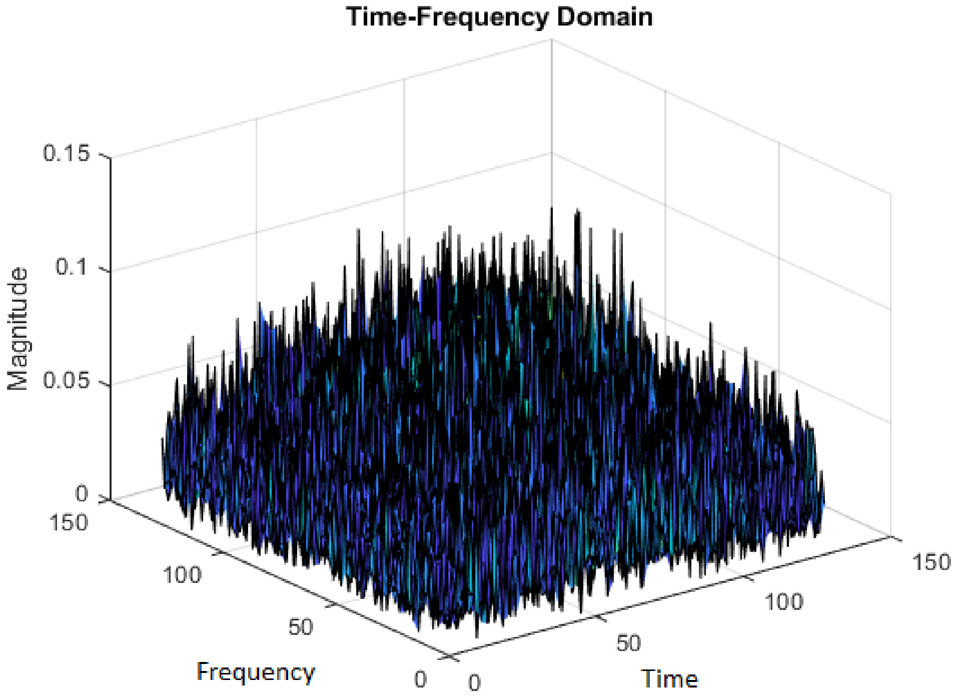

Figure 3.12: TF received signal

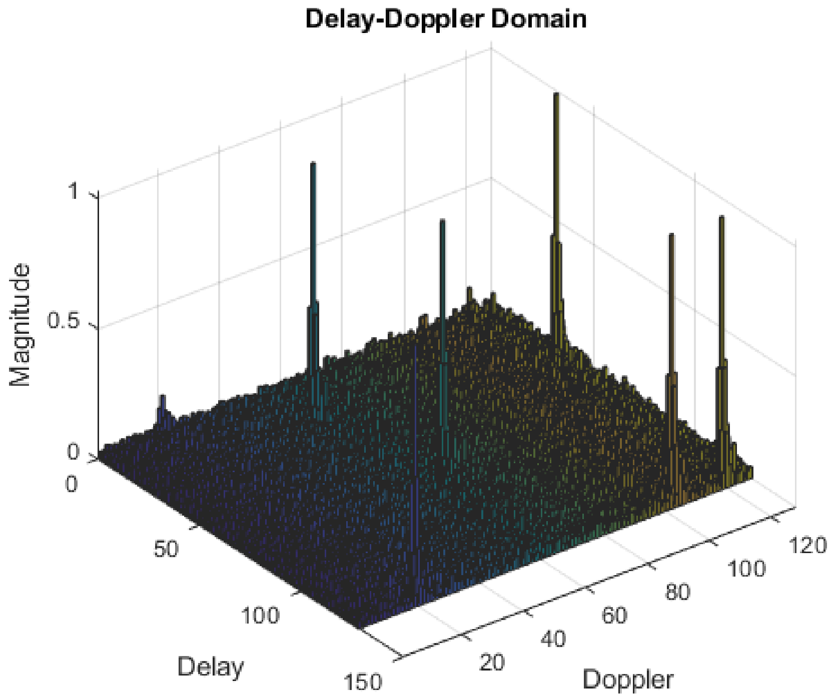

Figure 3.13: Delay Doppler domain received signal

Channel equalization is a crucial process in communication systems, especially in scenarios where the channel introduces distortion or interference to the transmitted signal. We use equalization is to mitigate the effects of the channel and recover the original transmitted symbols as accurately as possible. The DDD signal after equalization is shown in Figure 3.14.

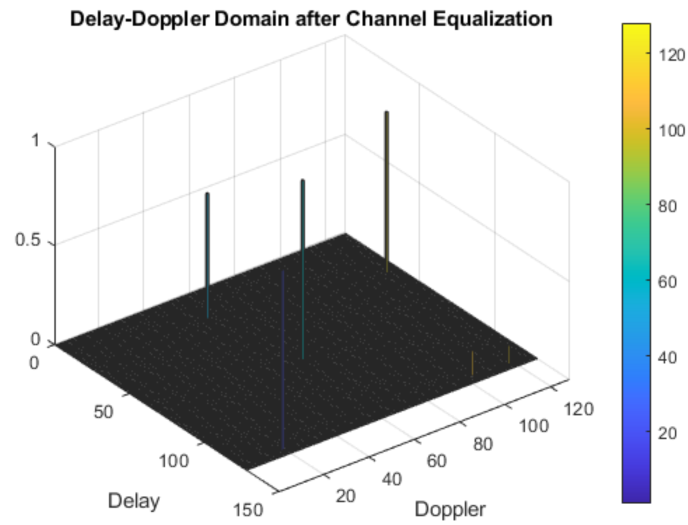

Figure 3.14: Equalized signal

3.4.1 OTFS in multi-mobility scenarios

Figure 3.15 illustrates the Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) for an Orthogonal Time Frequency Space (OTFS) modulation system under different vehicle speeds: 50 Km/h (blue line), 120 Km/h (red line), and 500 Km/h (purple line). Here's a detailed discussion of how velocity affects the OTFS system:

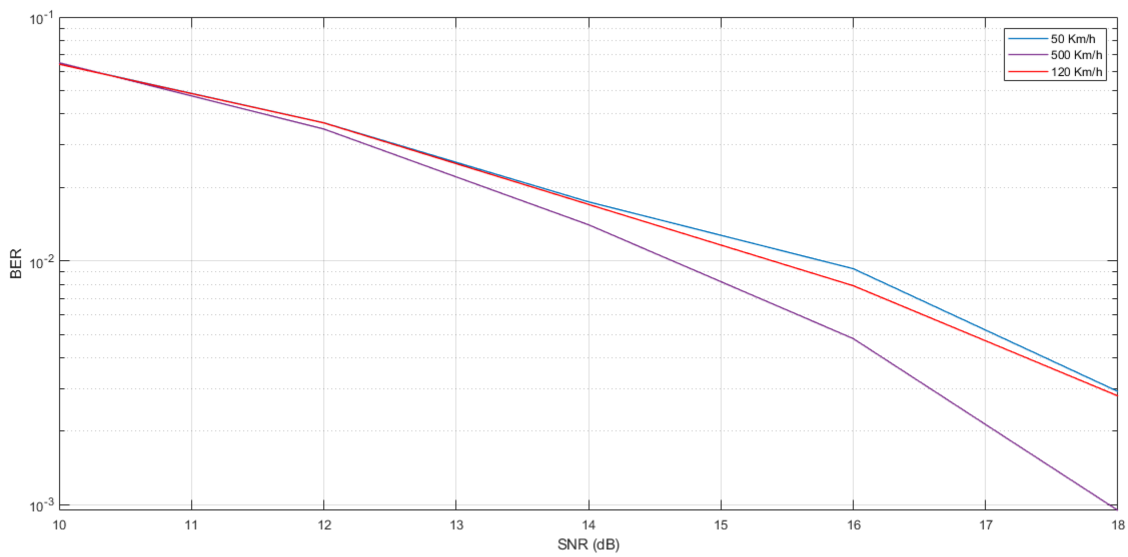

Figure 3.15: BER vs SNR OTFS performance in multi-mobility scenarios

At low speeds, the Doppler effect is minimal, resulting in relatively stable channel conditions. The OTFS system can effectively handle such conditions, leading to lower

BER. The BER is the lowest among the three velocities, demonstrating that OTFS performs well under stable conditions. At moderate speeds, the Doppler shift is more pronounced, introducing some variability in the channel. The OTFS system is still able to cope with these variations fairly well. The BER is slightly lower than at 50 Km/h but remains relatively low, indicating that OTFS can handle moderate mobility scenarios effectively. At high speeds, the Doppler effect is significant, causing rapid changes in the channel conditions. The channel becomes highly time-varying, which poses higher Doppler shifts for the OTFS system. The BER is the lowest among the three velocities, particularly noticeable at lower SNR values. This indicates that while on high mobility scenarios, OTFS is the best performing waveform.

3.5 Comparision of OFDM and OTFS for mobility scenarios

3.5.1 OTFS vs OFDM BER at 10 km/h

In Figure 3.16, at a low velocity of 10 km/h, we observe that the Bit Error Rate (BER) performance of OFDM is slightly better than that of OTFS across the range of Signal-to-Noise Ratios (SNRs). The green curve (OFDM) consistently shows lower BER values compared to the red curve (OTFS), indicating that OFDM performs better in low-mobility scenarios.

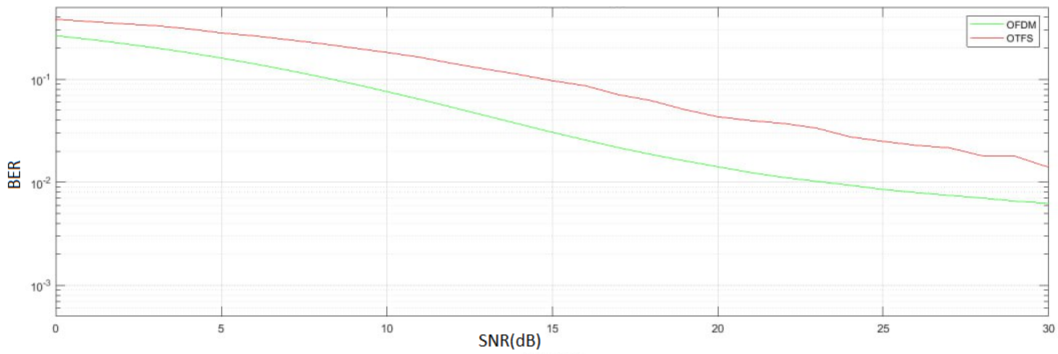

Figure 3.16: BER versus SNR with speed of 10 km/h

At low velocities (10 km/h), the Doppler effect is minimal, meaning that the time variation of the channel is relatively slow. OFDM is well-suited for such static or near-static environments because its primary challenge—inter-symbol interference (ISI)—is not significant. OFDM can effectively handle multipath fading with its use of cyclic prefixes and subcarriers, which explains its slightly better performance compared to OTFS in low mobility scenarios.

3.5.2 OTFS vs OFDM BER at 30 km/h

The BER performance of OFDM and OTFS become more similar at a modest speed of 30 km/h which is shown in Figure 3.17. Particularly at higher SNR values, there is a close alignment between the two curves. In terms of BER, OFDM is still marginally superior, though. This suggests that the performance difference between OFDM and OTFS narrows with moderate mobility.

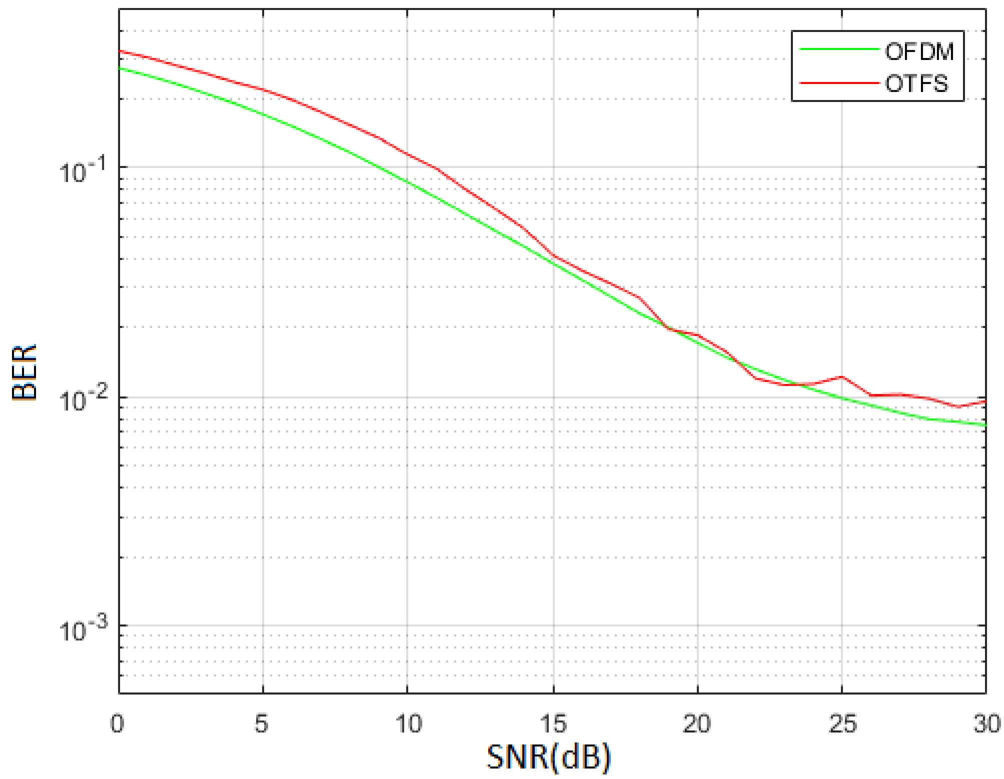

Figure 3.17: BER versus SNR with speed of 30 km/h

At moderate velocities (30 km/h), there is a moderate Doppler shift, but it is still within the tolerance of OFDM. Both OFDM and OTFS can handle this level of mobility reasonably well, which is why their performance is quite similar. OFDM's performance begins to slightly degrade due to increased Doppler effects, but the impact is not yet severe enough to give OTFS a significant advantage. OTFS, designed to exploit the full diversity of the time-frequency domain, starts to show its robustness in handling these moderate Doppler shifts.

3.5.3 OTFS vs OFDM BER at 120 km/h

In Figure 3.18, representing a higher velocity of 120 km/h, OTFS starts to show its strengths. The red curve (OTFS) outperforms the green curve (OFDM) across most of the SNR range. The BER for OTFS is significantly lower than that for OFDM, demonstrating OTFS's better handling of high mobility and Doppler shifts.

At higher velocities (120 km/h), the Doppler effect becomes more pronounced, causing rapid changes in the channel. OFDM's performance degrades because it struggles to cope with the fast-changing channel conditions, leading to increased inter-carrier interference (ICI). OTFS, on the other hand, transforms the time-varying channel into a quasi-static one in the delay-Doppler domain. This transformation allows OTFS to maintain a more consistent signal quality by leveraging the diversity in both time and frequency domains, resulting in better BER performance.

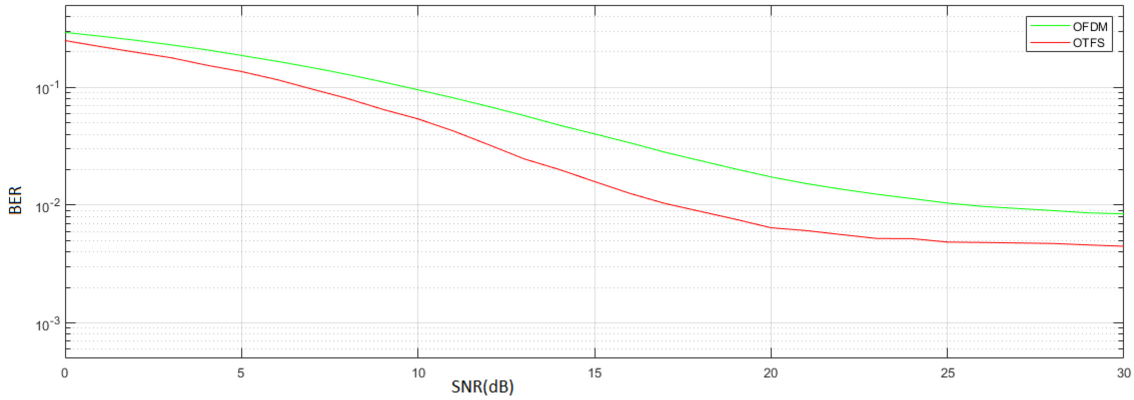

Figure 3.18: BER versus SNR with speed of 120 km/h

3.5.4 OTFS vs OFDM BER at 500 km/h

There is a noticeable performance difference when traveling at 500 km/h. When SNR values are higher, OTFS (red curve) exhibits a significantly lower BER than OFDM (green curve) in Figure 3.19. This significant gain demonstrates that OTFS may retain lower error rates in extremely high-mobility situations, a critical capability for applications like airborne communication and high-speed trains.

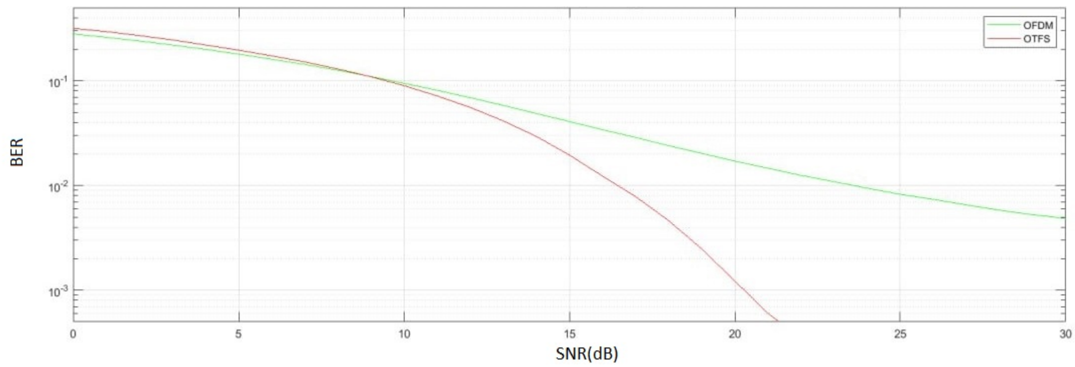

Figure 3.19: BER versus SNR with speed of 500 km/h

The Doppler shift is particularly strong at very high velocities (500 km/h), leading to severe channel fluctuations. The high Doppler shift strongly affects OFDM, resulting in considerable ICI and a sharp rise in BER. Since its delay-Doppler domain representation can handle the strong Doppler shifts and significant time variations, OTFS performs exceptionally well in this situation. In such high-mobility settings, the ability of OTFS to maintain a consistent complex channel gain for all symbols is especially helpful, leading to a much lower BER compared to OFDM.

3.6 Discussion of BER Analysis for OFDM and OTFS Co-existence

By previous simulations, our goal was to determine what waveform is suitable for a certain mobility scenario. This system dynamically selects the appropriate waveform (OFDM or OTFS) based on user velocity. The threshold for switching is set at 40 km/h.

The figures show the Bit Error Rate (BER) analysis for different user velocities: 20 km/h, 40 km/h, and 500 km/h. Let's discuss the results for each scenario.

Table 3.4: Parameters of the OFDM-based Communication System

Parameter	**Value**
Physical Layer Parameters	
Velocity threshold Km/h	40
number of Subcarriers Per Block	12
number of Symbols Per Block	14
$f_{\text{SubcarrierSpacing}}$	15 kHz
number of FFT	256
length of Cyclic Prefix	17
Modulation and Coding Parameters	
modOrder	16
$n_{\text{TxAntennas}}$	1
$n_{\text{RxAntennas}}$	1
Fading Channel Parameters	
$\text{velocity}_{\text{km/h}}$	20/40/500
$\text{delaySpread}_{\text{ns}}$	300
f_{Center}	0.8 GHz
channelModel	EVA

Low Mobility User at 20 km/h

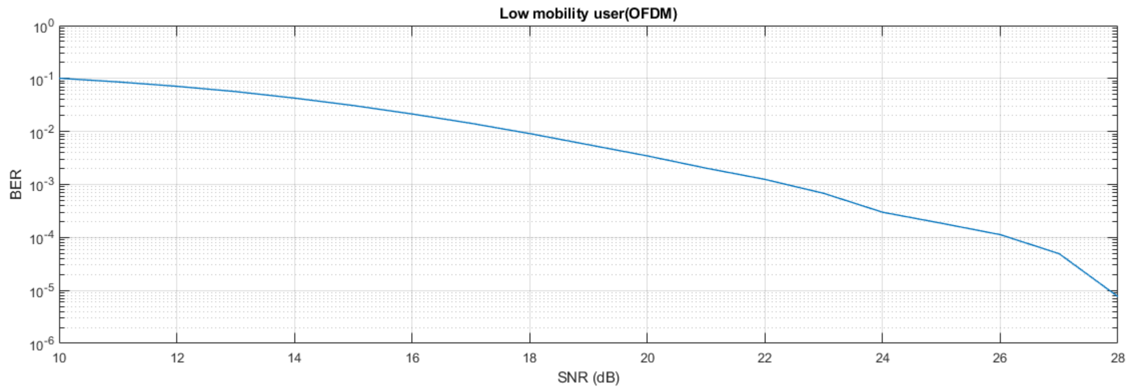

Figure 3.20: BER vs SNR for Low Mobility User at 20 km/h (OFDM)

Waveform Chosen: OFDM

Reason: The user velocity (20 km/h) is below the threshold of 40 km/h, making OFDM the preferred choice.

BER Performance: The BER decreases as the Signal-to-Noise Ratio (SNR) increases, which is typical for OFDM in low mobility scenarios. The performance curve shows that OFDM maintains a low BER at higher SNR values, confirming its suitability for low mobility users. The BER starts from about 10^{-1} and drops below 10^{-5} as the SNR reaches around 28 dB, indicating robust performance in stable channel conditions.

User at Threshold Velocity of 40 km/h

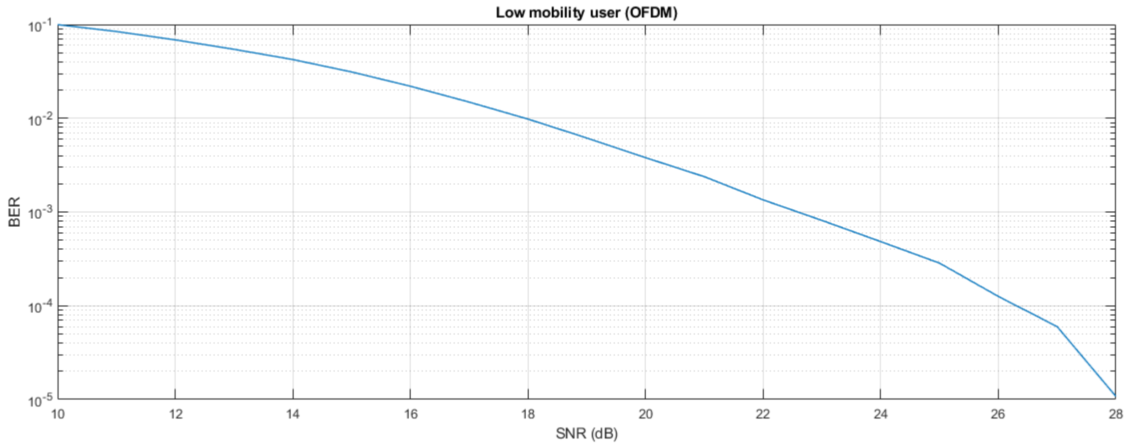

Figure 3.21: BER vs SNR for User at Threshold Velocity of 40 km/h (OFDM)

Waveform Chosen: OFDM

Reason: The user velocity is exactly at the threshold of 40 km/h. The system still chooses OFDM as it is efficient for this borderline low mobility scenario.

BER Performance: Similar to the 20 km/h case, the BER decreases as the SNR increases. The BER curve shows that OFDM can handle up to this threshold velocity effectively, with the BER dropping below 10^{-5} at around 28 dB SNR. This indicates that OFDM can still provide reliable performance at the upper limit of the low mobility range.

High Mobility User at 500 km/h

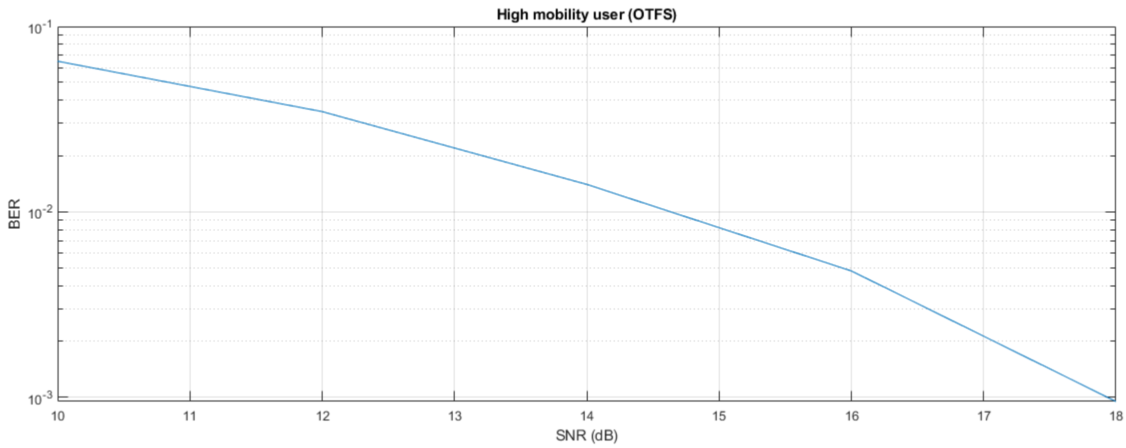

Figure 3.22: BER vs SNR for High Mobility User at 500 km/h (OTFS)

Waveform Chosen: OTFS

Reason: The user velocity (500 km/h) is well above the threshold of 40 km/h, making OTFS the preferred choice to handle high mobility conditions.

BER Performance: The BER decreases with increasing SNR, but the starting BER at lower SNRs is higher compared to the OFDM cases. The BER drops from about 10^{-1} to around 10^{-3} as the SNR increases to approximately 18 dB, showing OTFS's robustness in high mobility scenarios. Although the BER does not drop as low as in the OFDM cases at similar SNRs, OTFS effectively manages the high Doppler shifts and multipath effects at high velocities.

Conclusion

- **Low Mobility (20 km/h and 40 km/h)**: OFDM is chosen and shows excellent performance with BER reducing significantly at higher SNR values, demonstrating its suitability for stable channel conditions with low Doppler effects.
- **High Mobility (500 km/h)**: OTFS is chosen and shows a higher initial BER at lower SNRs but effectively reduces BER as SNR increases, highlighting its ability to handle severe Doppler shifts and multipath effects in high mobility environments.
- **Dynamic Switching**: The system's dynamic switching based on the velocity threshold of 40 km/h ensures that each user experiences optimal performance tailored to their mobility scenario, leveraging the strengths of both OFDM and OTFS waveforms.

Recent studies on the coexistence of OFDM and OTFS waveforms highlight their complementary benefits. [22] proposed a hybrid system switching between OFDM and OTFS based on real-time channel conditions, showing enhanced system performance. [23] highlighted OTFS's superior performance in high-Doppler scenarios compared to OFDM. [24] introduced a novel hybrid design with a switching algorithm to optimize performance. [25] presented an adaptive algorithm for real-time waveform selection, improving reliability. [26] proposed a coexistence strategy integrating both waveforms for enhanced flexibility and performance. Recent 2023 studies further support these findings, exploring the input-output relationship for OTFS alongside OFDM, a hybrid approach in massive MIMO systems, and multi-mobility scenario analysis demonstrating optimized performance using OTFS as a precoded OFDM[21][27].

Our approach is to compare the user's velocity to a threshold we set, in this analysis is 40 Km/h, and then select the suitable waveform for it either OFDM or OTFS for downlink transmission.

Aspect	Summary
Introduction	This chapter examines and compares OFDM and OTFS waveforms using MATLAB simulations, focusing on Bit Error Rate (BER) and Signal to Noise Ratio (SNR) in various environments, and their coexistence to enhance system performance.
Simulation Parameters	Key parameters include BER and SNR. BER is the rate at which errors occur in a transmission system, while SNR measures the ratio of signal power to noise power.
OFDM Simulation	The OFDM waveform simulation involves data generation, modulation (16 QAM and QPSK), serial to parallel conversion, IFFT, addition of cyclic prefix, upsampling, and transmission through an AWGN channel. BER analysis shows a decrease in BER with increasing SNR.
OTFS Simulation	The OTFS simulation involves generating data in the delay-Doppler domain, ISFFT, Heisenberg transform, channel transmission, Wigner transform, and SFFT. Results show OTFS efficiency in multipath channels and robustness against Doppler shifts.
Comparison in Mobility Scenarios	OFDM and OTFS are compared in different mobility scenarios (10 km/h, 30 km/h, 120 km/h, and 500 km/h). OTFS shows better performance in high mobility scenarios due to its resilience to Doppler effects and multipath fading.
Discussion of BER Analysis	The BER analysis for OFDM and OTFS coexistence indicates that OTFS performs better in high mobility scenarios, while OFDM is more suitable for low mobility scenarios.

Table 3.5: Summary of Results and Discussion Chapter

General Conclusion

This report has explored the evolution and advancements in wireless communication technologies. Through an extensive review of generational transitions from 1G to 6G, it is evident that each generation has contributed significantly to the enhancement of wireless communication capabilities, including improved data rates, reduced latency, and enhanced connectivity. .

OFDM, with its unique ability to divide a high-speed data stream into multiple parallel lower-speed streams, has become the backbone of modern wireless systems. We explore the principles behind OFDM, understanding how it mitigates the effects of multipath interference and frequency-selective fading to deliver robust and efficient data transmission. From its applications in Wi-Fi and LTE to its role in emerging standards like 5G NR, OFDM continues to shape the future of wireless connectivity.

OTFS, on the other hand, represents a paradigm shift in modulation techniques, offering a novel approach to combatting the challenges posed by time-varying channels. By jointly modulating signals in the time and frequency domains, OTFS achieves remarkable resilience to delay spread and Doppler shifts, making it ideal for scenarios with high mobility and severe multipath propagation. We delve into the intricacies of OTFS, uncovering its unique advantages and exploring its potential applications in next-generation wireless networks.

The simulation results demonstrated that OTFS outperforms OFDM in scenarios involving high mobility, with superior bit error rate (BER) performance across various speeds. This indicates that OTFS is better suited for future communication systems where high-speed mobility and reliable connectivity are paramount. The comparative analysis provided valuable insights into the modulation techniques' behavior under different conditions, reinforcing the potential of OTFS as a key enabler for next-generation wireless networks.

The co-existence of OFDM and OTFS, guided by user velocity, offers a robust solution for modern wireless communication systems. By leveraging the strengths of both modulation schemes, it is possible to achieve optimal performance in a wide range of mobility scenarios. This dynamic approach ensures that users experience reliable and efficient communication, whether stationary or in motion.

Future aspects

Integration and Co-existence of OTFS with OFDM:

The future of wireless communication will likely see a harmonious integration of OTFS and OFDM. By dynamically selecting the appropriate modulation scheme based on user velocity and environmental conditions, network performance can be optimized. This adaptive strategy ensures that users, whether stationary or in motion, experience the highest levels of reliability and efficiency. The co-existence of OTFS and OFDM leverages the strengths of both technologies, offering a comprehensive solution to the diverse needs of modern wireless systems.

The integration of OTFS and OFDM in a cohesive framework allows users to experience seamless communication regardless of their mobility state. As users move from one environment to another, the system can automatically switch between modulation schemes without interruption. This seamless transition is crucial for applications such as autonomous driving, where vehicles must maintain reliable communication with infrastructure and other vehicles while moving at high speeds.

The co-existence strategy is particularly relevant as we move towards 6G networks, which aim to provide ubiquitous connectivity with high data rates, low latency, and enhanced reliability. The flexibility to use both OTFS and OFDM enables 6G networks to cater to a wide array of use cases, from ultra-reliable low-latency communications (URLLC) to enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC). The ability to dynamically adapt to user conditions and environmental factors is essential for meeting the diverse requirements of these applications.

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