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Dedication

*To my **grandparents**, may ALLAH rest their souls.*

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Acronyms and Abbreviations

ADC	**A**nalog-to-**D**igital **C**onverter
BER	**B**it **E**rror **R**ate
CP	**C**yclic **P**refix
CS	**C**ompressed **S**ensing
DAC	**D**igital-to-**A**nalog **C**onverter
FFT	**F**ast **F**ourier **T**ransform
GHz	**G**igahertz
ISAC	**I**ntegrated **S**ensing and **C**ommunication
ISI	**I**nter-**S**ymbol **I**nterference
JRC	**J**oint **R**adar and **C**ommunication
LNA	**L**ow **N**oise **A**mplifier
MHz	**M**egahertz
MIMO	**M**ultiple **I**nput, **M**ultiple **O**utput
OFDM	**O**rthogonal **F**requency-**D**ivision **M**ultiplexing
PLL	**P**hase **L**ocked **L**oop
QAM	**Q**uadrature **A**mplitude **M**odulation
RADAR	**R**adio **D**etection and **R**anging
RX	**R**eceiver
SNR	**S**ignal-to-Noise Ratio
TX	**T**ransmitter

Abstract

This thesis presents a novel, low-complexity architecture designed for 6G integrate sensing and communication (ISAC) functionalities within an OFDM-based waveform transceiver for long-to-mid-range automotive radar scenarios, the proposed architecture takes advantage of comb structure pilot arrangements to do sensing tasks threw out the entire OFDM frame ,Through simulation results, the proposed architecture demonstrates a significant reduction in computational cost, energy and complexity while maintaining efficient target detection accuracy in dynamic, multitap scenarios with changing channel conditions. Additionally, the simulation results highlight the architecture's capability to execute communication tasks with acceptable reliability, enabling information exchange between transmitters and receivers through simple implementation of error correction codes and channel estimation algorithms.

ملخص

تقدم هذه الأطروحة بنية جديدة منخفضة التعقيد مصممة لدمج وظائف الاستشعار والاتصالات ضمن جهاز إرسال واستقبال قائم على OFDMلسيناريوهات الرادار السيارات بعيدة إلى متوسطة المدى. تستفيد البنية المقترحة من ترتيب الطيارين بشكل المشط لتنفيذ مهام الاستشعار عبر الإطار الكامل لـ .OFDM من خلال نتائج المحاكاة، تُظهر البنية المقترحة انخفاضًا كبيرًا في تكلفة الحوسبة والطاقة والتعقيد مع الحفاظ على كفاءة اكتشاف الأهداف في سيناريوهات متعددة الارتدادات الديناميكية مع تغيرات في ظروف القناة. بالإضافة إلى ذلك، تسلط نتائج المحاكاة الضوء على قدرة البنية على تنفيذ مهام الاتصالات بموثوقية مقبولة، مما يمكن من تبادل المعلومات بين المرسلات والمستقبلات من خلال تنفيذ بسيط لأكواد تصحيح الأخطاء وخوارزميات تقدير القناة .

Résumé

Cette thèse présente une nouvelle architecture à faible complexité conçue pour intégrer les fonctionnalités de détection et de communication au sein d'un émetteur-récepteur basé sur une forme d'onde OFDM pour des scénarios de radar automobile à moyenne et longue portée. L'architecture proposée profite de l'agencement des pilotes en structure en peigne pour accomplir les tâches de détection tout au long de la trame OFDM. Grâce aux résultats de simulation, l'architecture proposée démontre une réduction significative du coût computationnel, de l'énergie et de la complexité tout en maintenant une précision efficace de détection des cibles dans des scénarios dynamiques à multiples trajets avec des conditions de canal changeantes. De plus, les résultats de simulation mettent en évidence la capacité de l'architecture à exécuter des tâches de communication avec une fiabilité acceptable, permettant l'échange d'informations entre émetteurs et récepteurs par la mise en œuvre simple de codes de correction d'erreurs et d'algorithmes d'estimation de canal.

General Introduction

General Introduction

In the ever-evolving dynamic landscape of mobile communication networks, each new generation brings forth critical changes that distinguish it from its predecessors. One fundamental aspect that deserves heightened attention is waveform design. As we progress through each generation, we recognize that the choice of waveform profoundly impacts system performance, efficiency, and integration with other functionalities, making it a crucial building block that sets the foundation of the generation itself.

The recent advent of 5G technologies exemplifies this trend. Notably, 5G has propelled I IoT advancements across various domains, including education, healthcare, transportation, and security. However, these strides come at the cost of complexity and energy efficiency, setting the field of technology apart from others. Looking ahead, the vision for B5G/6G networks promises to redefine sensing capabilities. Unlike previous generations, which primarily focused on faster speeds, lower latency, and broader coverage, 6G aims to integrate sensing aspects. This novel approach, known as ISAC or JRC, opens doors to broader engineering opportunities and novel inventions. Simultaneously, it presents new challenges that demand innovative solutions.

Academic and research communities worldwide are dedicating extensive efforts to shape the requirements for the 6th generation, In December 2023, the International Standardization Committee (3GPP) has officially started to set the requirements and the pre-standardization phase for the 6th generation. Focusing their endeavors combine cutting-edge technologies with innovative critical thinking all aimed at bringing the 6G vision to life, with experts in the field saying that 6G will be soon available in the year 2030.

In this study, we aim to examine the recent developments in ISAC, with a particular emphasis on waveform design and its associated prospects. Moreover, we will explore significant challenges encountered in autonomous radar systems. Our investigation will encompass an in-depth analysis of advancements in waveform design and transceiver architecture within the domain of automotive radar technology. We will highlight prevalent issues, offer corresponding resolutions, and propose a prospective solution aligned with the evolving standards of 6G technology

In chapter 1, we delve into the development of our main idea, tracing its origins from a brief historical context to the paradigm shift that led to its emergence. We then focus on the essential aspects of multicarrier modulation, specifically Orthogonal Frequency Division Multiplexing (OFDM), which serves as our desired waveform for radar applications. Additionally, we explore the theoretical foundations of radar sensing, emphasizing previous research related to oversampling challenges in wideband and automotive radar systems. Our proposed solution aims to address these issues effectively.

In Chapter 2, we implement our idea within a controlled MATLAB environment. Here, we examine the impact of multipath and fast fading channel effects on both radar sensing and communication aspects. By executing both systems within a single framework, we visualize the results in terms of target detection and information transmission.

Chapter 1
State-of-the-Art of Waveform Designs

1.1 Introduction

With each upcoming mobile communication system, we could notice a critical change in the infrastructure that operates it, the performance improvements in terms of higher speeds, more area coverage, less latency, and a higher number of users. One of the key aspects that should take special care is waveform design, which can play a crucial function in determining all the improvements aspects above.

In the case of B5G/6G systems, a new approach is been discussed that has never been proceeded before in previous generations, and that is the integration of radar/sensing capabilities in wireless mobile communication networks.

This approach holds both promises and challenges alike and in the case of waveform design and physical layer architecture, this approach holds challenges for both engineers and researchers alike, in this project, we will try to give an overview of one of the waveform designs intended for the use case of automotive radars, and then we will discuss a backward compatible novel approach that can be implemented within the frame of integrated sensing and communication.

In this Chapter we will give an overview about the paradigm shift regarding ISAC ,in terms of history, motives and approaches, additionally we will go through the problems and basics that lead to the buildup of this possible solution .

1.2 Background and Motivation

In this section, we will try to see the steps that lead towards ISAC from a theoretical concept to practice in order to build a proper back round on the subject matter.

1.2.1 Historical View of ISAC

When considering the origins of Integrated Sensing and Communication (ISAC), it emerges as a convergence of various cutting-edge technologies from the fields of communication and RADAR. These two domains share commonalities, and at their intersection, we find several key highlights: [1][2]

- mmWave systems: These high-frequency systems play a crucial role in both communication and sensing applications.
- Multiple-input Multiple-output (MIMO) technology: Multiple-Input Multiple-Output technology enhances data throughput and reliability.
- Phased array antennas: These advanced antenna arrays enable beamforming and spatial signal processing.

- Additional advancements: Notably, improvements in ADC's and signal processing algorithms contribute to the overall development of ISAC.

Table 1.1 : historical development of sensing in wireless communication [1]

Year	Event
1944	The first practical phased-array radar, FuMG 41/42 Mammut, is built by the Germany company GEMA.
1963	The world's first ISAC signaling scheme is proposed in, in which the communication bits are modulated on the radar pulse interval.
1994	The first patent on MIMO communication system is granted.
1996	The Advanced Multifunction RF Concept (AMRFC) Program is initiated by the Office of Naval Research (ONR) of the US.
2003	The first ISAC scheme that exploits chirp signals is proposed.
2004	The concept of the collocated MIMO radar is proposed in by the MIT Lincoln Lab.
2005	The HAD structure is introduced into MIMO communication.
2010	T. L. Marzetta's seminal work on massive MIMO communication is published.
2010	The concept of the phased-MIMO radar is proposed, with a similar RF front-end structure to the HAD communication system.
2011	The OFDM based ISAC signaling scheme is proposed.
2013	NYU WIRELESS's landmark paper on mmWave mobile communication is published.
2013	DARPA launches the project "Shared Spectrum Access for Radar and Communications (SS-PARC)", which aims at releasing part of the radar spectrum for use of commercial communication.
2014	The HAD technique is applied to the mmWave massive MIMO communication system.
2017	The concept of the perceptive mobile network is proposed.
2020	The first theoretical analysis of the asymptotic performance of the massive MIMO radar is presented.
2021	The definition and scope of ISAC are formally given in and this paper.

1.2.2 Paradigm Shift in Wireless Network Design (ISAC)

In a broader context, the goal of sensing involves collecting data from noisy channel observations using specialized signals and methodologies. Conversely, communication aims to transmit data from point A to point B through a channel. The essence of ISAC lies in cooperatively harmonizing these two operations, leveraging the strengths of each while maintaining their functionalities. [1][2]

The paradigm shift resembles a spectrum rather than a polarity. At one extreme, we have sensing, and at the other, communication, and in the middle comes joint radar communication (JRC), let us explore the three main design paradigms: [1][2]

- Sensing-Centric Design:

In this approach, sensing takes precedence, with communication playing a secondary role. While this ensures optimal sensing performance, it often comes at the expense of lower data rates. Such designs often involve reconfiguring existing radar signals (e.g., chirp) to achieve data transmission. [1][2]

- Communication-Centric Design:

Here, the primary focus is on data transmission, while sensing serves as a complementary feature. This approach emphasizes efficient communication while still accommodating sensing needs. [1][2]

- Joint Design or Co-Design:

Striking a balance between sensing and communication, joint designs seek to optimize both aspects simultaneously, without compromising performances in both fields making a considerable tradeoff between sensing accuracy and communication quality. [1][2]

1.2.3 Reasons for ISAC Emergence

To establish the theoretical foundation that underpins the integration of both sensing and communication (S&C), it is essential to delineate the similarities and objectives of the two systems. This alignment is crucial to comprehending the rationale behind the paradigm shift towards their convergence. [3]

Table 1.2 : Reasons for ISAC Emergence [3]

Reason	Description
Shared Hardware Modules	Both sensing/radar systems and communication systems can benefit from shared hardware components.
Radio-Frequency (RF) Front Ends	These modules handle signal reception and transmission, leading to cost savings, reduced device size, and optimized energy consumption.
Analog-Digital (A/D) Converters	Critical components digitizing analog signals, facilitating seamless integration between the two domains.
Phased Array Antennas	Consisting of multiple antenna elements, used in both mmWave communication systems and MIMO radar systems. Supports multiuser communication and high spatial resolution sensing.
Signal Processing Modules	Basic signal processing modules shared between sensing/radar and communication systems, contributing to technology convergence.
Operation Frequencies	Both radar and communication systems operate at high frequencies, reaching the mmWave band.
Sparse Channel Characteristics	The mmWave communication channel is sparse and dominated by LoS, similar to radar channels.
Improved Spectral and Energy Efficiencies	ISAC improves spectral and energy efficiencies by merging sensing and communication into a single system, reducing hardware and signaling costs.
Falls within the 6G vision	Offers improvements over 5G technologies and introduces new opportunities for applications.

1.3 Applications and Use Cases

Each generation of cellular networks begins with identifying possible applications, use cases, and requirements, The same can be said about 6G.

The 3GPP showcased in its 19th release December 2023 a series of use cases depicting a whopping 32 different detailed use cases that illustrate the scale and reach of the 6th generation vision of applications with the emergence of ISAC in terms of versatility in various fields (autonomous vehicles, medical fields, security, ...).

The Table 1.2 presents all of the mentioned use cases along with their key performance indicators (KPIs):

Table 1.3 : Case Studies and Key Performance Indicators [1]

Application	Case	Key Performance Indicators							mmWave
		Max. Range (m)	Max. Velocity (m/s)	Range Resolution	Doppler Resolution	Temporal Resolution	Angular Resolution	Data Rate Per User (Avg./Peak)	
Sensing as a Service	• Drone Monitoring and Management.	500	40	◉	◉	/	○	Low	/
	• Localization and Tracking in Cellular Network	300	10	◉	●	/	⊙	Low/Very High	/
	• Human Authorization and Identification.	300	5	◉	●	/	⊙	Low/Very High	/
	• Human Counting	200	5	◉	●	●	⊙	Low/Very High	/
	• Area Imaging	200	/	⊙	●	●	⊙	Low/Very High	✓
	• Mobile Crowd Sensing	300	5	◉	●	/	⊙	Low/Very High	/
	• Channel Knowledge Map Construction	300	5	◉	●	/	⊙	Low/Very High	/
	• Passive Sensing Network	300	30	◉	/	/	●	Low/Very High	/
Smart Home and In-Cabin Sensing	• Human Puzzle detection	20	2	◉	⊙	⊙	⊙	High	/
	• Human proximity detection	20	4	◉	⊙	●	⊙	High	/
	• Fall detection	10	3	◉	⊙	◉	⊙	High	/
	• Sleep monitoring	1	2	◉	⊙	●	◉	High	/
	• Daily activity Recognition	10	4	◉	⊙	●	◉	High	/
	• Breathing / Heart rate estimation	1	2	◉	⊙	⊙	◉	High	/
	• Intruder detection	20	5	◉	⊙	◉	◉	High	/
	• Location-away Control	20	3	◉	⊙	/	◉	High	/
	• Sensing Aided Wireless charging	5	4	◉	⊙	◉	○	High	✓
	• Passenger monitoring	2	/	○	⊙	○	⊙	High	✓
	• Driver attention monitoring	1	/	○	○	○	○	High	✓
Vehicle to Everything (V2X)	• Raw data Exchange and high perception location	300	30	●	/	/	⊙	High	/
	• Secure Hand - Free Access	300	/	◉	●	/	⊙	Low/Very High	/
	• Vehicle platooning	100	30	⊙	◉	/	○	High	/
	• Simultaneous localization and mapping	300	30	◉	●	/	⊙	Low/Very High	/
	• Extended sensor	300	30	◉	●	/	○	Low	/
Smart Manufacturing and Industrial IoT	• Employee Localization And Authorization	1000	5	●	◉	/	◉	Low/Very High	/
	• Manufacture Defect Analysis	20	/	●	/	⊙	◉	High	✓
	• Automatic Guided Vehicle	500	5	◉	◉	/	⊙	Low	✓
	• Predictive Maintenance	100	/	●	/	◉	◉	Low/Very High	✓
Remote Sensing and Geoscience	• Downs Swarm SAR Imagine	1000	40	◉	/	/	⊙	Low	✓
	• Satellite Imaging and Broadcasting	10000	/	●	/	/	/	Low	✓
Environmental Monitoring	• Weather Production	500	/	◉	/	/	/	Low/Very High	✓
	• Pollution Monitoring	200	/	⊙	/	/	/	Low/Very High	✓
	• Rain Monitoring	200	/	◉	/	/	/	Low/Very High	✓
	• Insect Monitoring	200	/	◉	/	/	/	Low/Very High	✓
Human Computer Interaction (HCI)	• Gesture Recognition	1	20	○	●	●	/	Low/Very High	✓
	• Keystroke Recognition	1	20	○	●	●	/	Low/Very High	✓
	• Head Activity Recognition	>2	20	○	◉	◉	/	Low/Very High	✓
	• Arm Activity Recognition	>2	10	○	◉	◉	/	Low/Very High	/

Where:

- In order to indicate requirement of Range/Doppler/Temporal/Angular resolutions. We artificially categorize these KPI values into four levels, e.g.,: ○ : Very Low; ⊙:Low ; ◉: High ; ●: Very High .
- The symbol "/" represents that there are few requirements on this scenario.

1.4 Motive Behind Using OFDM

Due to its ability for backwards compatibility feature in terms of 6G physical layer approach, and the fact that it already serves a communication function so well, on top of it can be utilized to do sensing and radar by manipulating the parameters of pilot waves. Taking the communication centric approach in terms of ISAC has its own perks that, especially when using OFDM waveform. Additionally, it has gained a well-received amount of attention threw out the years, making it well developed waveform, and finally, the most known attributes of OFDM are the following: [4][5]

- **High Spectral Efficiency**: remarkable spectral efficiency, leading to very high achievable data rates, very well utilization of spectral resources.
- **Resilience to Multipath Fading and Inter Symbol Interference (ISI)**: OFDM copes well with channel impairments caused by multipath propagation and inter-symbol interference.
- **Simplified Channel Equalization**: due to its generalized frequency structure in the frequency domain, and the use pilot waves for channel estimation and equalization.
- **Flexibility**: OFDM is adaptable to varying conditions by adjusting different parameters such as subcarrier spacing, cyclic prefix duration, pilot wave allocation, the use different FFT/DFT conditions and different windowing parameters can all shape the signal in terms of physical layer towards adaptable and flexible signals depending on the used scenario.
- **Backwards compatibility** : the ability to ensures that newer technology can seamlessly interact with older legacy versions without the need to change the hardware.

1.5 Principal of OFDM

In order to properly set the ground for OFDM sensing, a general overview of the basic characteristics that set apart this multicarrier modulation from other types must be briefly mentioned. [4]

1.5.1 Transceiver architecture

Every modulation scheme has a unique a transceiver architecture that helps shape the waveform in its domain, the Figure 1.2 shows the conventional OFDM transceiver architecture. [4]

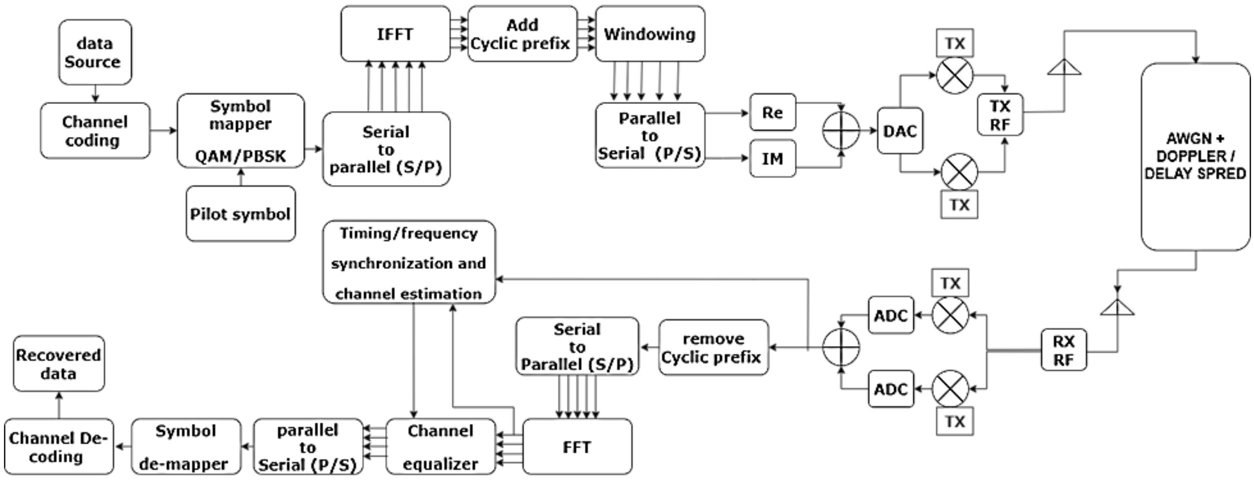

Figure 1.1 : Block diagram of transmitter and receiver in an OFDM system

We will briefly indicate the purpose of each block in Table 1.3. that depicts the standard OFDM communication transceiver architecture.

Table 1.4 : Description of each block [4]

Block	Purpose
Symbol mapper/de-mapper	Converts data bits into symbols for transmission and vice versa.
(S/P) & (P/S)	Converts between serial and parallel data streams.
Pilot symbols	Allocates pilot symbols within communication symbols for channel estimation.
IFFT/FFT	Converts symbols between frequency and time domains, this is the main block of OFDM based transceivers .
CP addition and removal	Adds a cyclic prefix for guard interval and removes it upon reception to mitigate inter-symbol-interference.
Windowing	Shapes the signal to concentrate energy efficiently and reduce sidelobes.
ADC/DAC	Converts signals between analog and digital states.
RF Tx/Rx	Transmits and receives electromagnetic waves via antennas for wireless communication.
Time/frequency synchronization	Ensures aligned clocks between transmitter and receiver and compensates for frequency offsets for proper signal reception.
Channel estimation	Estimates channel response between transmitter and receiver for coherent detection and interference mitigation.
Channel equalization	Compensates for channel-induced distortion in received signals to improve signal quality.

1.5.2 Orthogonality

Orthogonal frequency division multiplexing (OFDM) is a type of frequency modulation and multicarrier transmission scheme. It divides the available bandwidth into overlapped orthogonal subcarrier signals using both the (IDFT/DFT) and the Nyquist criterion [4]. In a mathematical sense, the orthogonality of OFDM comes at the cost of the integral of the products of the subcarriers at their fundamental period equals to zero[4]:

$$\frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi f_k t}\, e^{-j2\pi f_k t} dt = \frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi\left(\frac{k}{T_{sym}}\right)t}\, e^{-j2\pi\left(\frac{i}{T_{sym}}\right)t} dt \tag{1.1}$$

$$\frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi\left(\frac{k-i}{T_{sym}}\right)t}\, dt = \begin{cases} 1, \forall\ integer\ k = i \\ 0, otherwise \end{cases} \tag{1.2}$$

$Where\ e^{j2\pi fkt}$, $\{\ 0 < t < Tsym\}; k = \{0, \dots . N-1\}$ represents the subcarriers at different frequencies ,T_{sym}: is the fundamental period of a symbol ,f_k is the subcarrier frequency of a k index subcarrier ,k and I are indexes of adjacent subcarriers and $f_k = \frac{k}{T_{sym}}$

Orthogonality is critical to achieve high spectral efficiency. The Nyquist criterion guarantees an ISI-free communication even with a short symbol period T for high-rate transmission in a single-carrier transmission system: [4]

$$\sum_{i=-\infty}^{\infty} G\left(f - \left(\frac{i}{T}\right)\right) = T \tag{1.3}$$

Where G(f) is the Fourier transform of g(t) , T is the period of the symbol period , i is the index operator of the i-th subcarrier.

1.6 Cyclic prefix/suffix /zero padding

It acts as guard interval that adds additional protection against ISI and multipath channels effects in terms of the addition of multiple signal delays. It is a time domain operation that simplifies the estimation process by turning the interaction between the transmitted signal and the channel from linear convolution to circular convolution in the time domain, which itself can be regarded as normal multiplication operation in the frequency domain. This addition of guard intervals can take two forms. [4]

1.6.1 Zero padding

Zero padding (ZP) pads the guard interval with zeros and OFDM symbol containing ZP has Power Spectral Density with the smaller in band ripple and the larger out-of-band power allowing more power to be used for transmission with the same power resources. This technique is used to increase the length of the OFDM symbol, thereby increasing the frequency resolution in the frequency domain. [4]

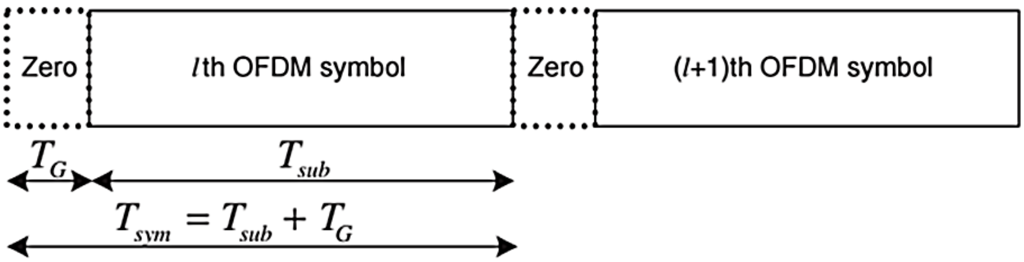

Figure 1.2 : OFDM symbols with ZP

1.6.2 Cyclic Extension

Cyclic extension of the OFDM symbol (for some continuity) with CP (cyclic prefix) or CS (cyclic suffix), it is used to prevent the interference between upstream and downstream, and is also used as the guard interval for frequency hopping or RF convergence. In addition, it typically used in scenarios where the channel exhibits time-selective fading, such as in wireless channels with significant delay spread, helps in mitigating ISI caused by time dispersion in the channel.

The idea is to copy the first or last samples of a symbol duration T_g and extend it to one of the ends of the symbol itself as an additional time duration to the original subcarrier duration T_{sub} , given the result: [4]

$$T_{sym} = T_{sub} + T_g \tag{1.4}$$

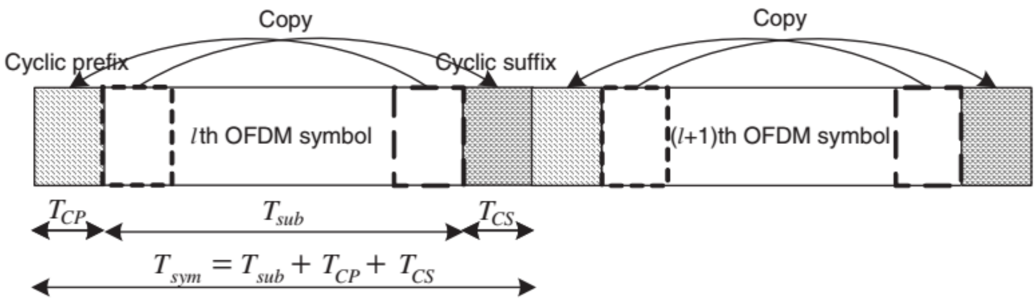

Figure 1.3 : OFDM symbol with both CP and CS

1.7 **Pilot Signal**

In wireless communication systems, the deployment of pilot signals is indispensable for a myriad of sensing and estimation tasks. Pilot signals facilitate crucial functions such as frequency synchronization, phase noise compensation, channel tracking, interpolation, channel estimation, and equalization. By providing known reference points, pilot symbols enable the receiver to accurately estimate and characterize the communication channel, adapting to dynamic channel conditions and mitigating the impacts of various impairments. This adaptability enhances the system's performance and robustness, ensuring reliable data transmission even in the presence of noise and interference. Additionally, pilots play a vital role in maintaining orthogonality between subcarriers in OFDM systems, which is essential for minimizing inter-carrier interference and maximizing spectral efficiency. [4]

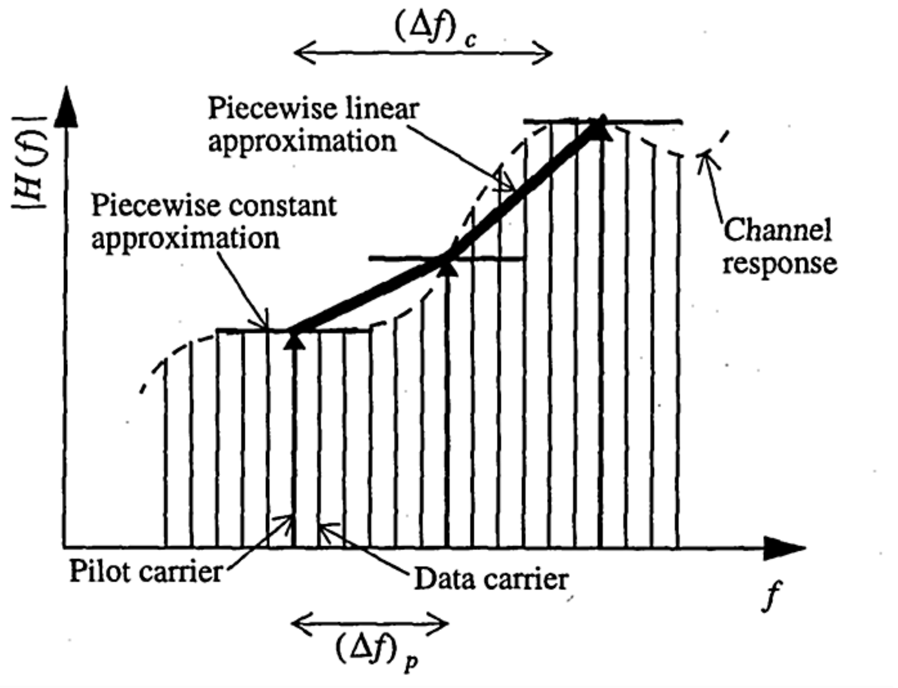

Figure 1.4 : Pilot Spacing of OFDM carriers in the Channel [14]

In this work, pilots play the role of the waveform function that allows for environment radar sensing by utilizing proper analog and digital signal processing to extract the environment information from the received pilots.

Pilots are organized and structured in different formations that serve different purpose depending on the requirement and use case.

1.7.1 Block type

This arrangement best suits frequency selective and fast fading channels, and has a direct correlation between it and frequency resource allocation given best range resolution results. However, it introduces too much overhead when used in fast-fading channels, where frequent updates are needed to track the rapidly changing conditions.

In terms of dynamic scenario, this is the best suited combination for automotive radar scenarios. It requires:

$$S_t \leq \frac{1}{f_{doppler}} \tag{1.5}$$

- St: the period of pilot symbols in time.
- f doppler: Doppler spreading.

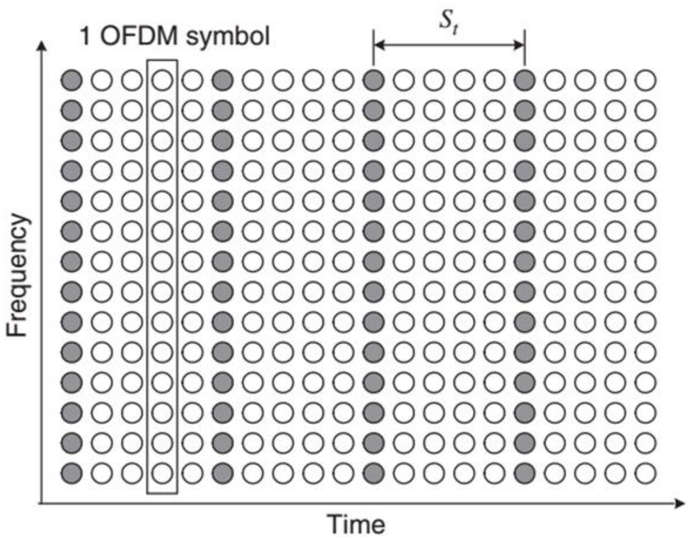

Figure 1.5 : Block-type pilot arrangement

This arrangement simplifies implementation because entire OFDM symbols are dedicated to pilots, allowing for straightforward and accurate channel estimation. This arrangement is particularly effective in slow-fading channels where the channel state remains relatively constant over several OFDM symbols. It provides robust channel estimates without the need for complex interpolation techniques.

On the downside, block pilots provide intermittent channel updates since they do not appear in every OFDM symbol. This can be problematic in fast-fading environments where more frequent channel updates are necessary. Furthermore, dedicating whole symbols to pilots reduces the number of symbols available for data transmission, which leads to a decrease in overall throughput, add to that the need for good synchronization between the ends of the systems for proper use of this arrangement.

1.7.2 Comb type

This arrangement allocates the pilots in the time domain and keeps track of fast-fading channels, but not for frequency-selective channels, the pilot symbols must be placed as frequently as coherent bandwidth is and satisfies the following:

$$S_f \leq \frac{1}{\sigma_{max}} \tag{1.6}$$

- S_f: subcarrier frequency.
- σ_{max}: maximum delay spread.

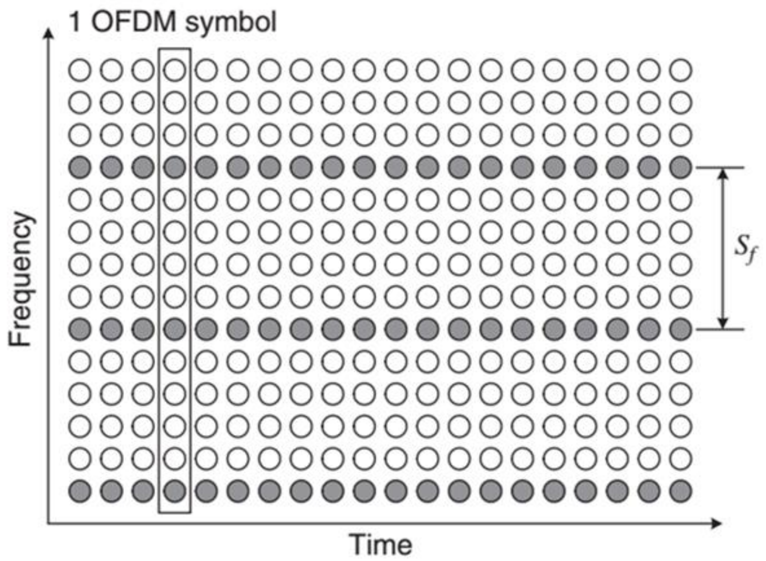

Figure 1.6 : Comb-type pilot arrangement

This type of arrangement provides excellent frequency domain coverage because pilots are distributed across all OFDM symbols. This is particularly advantageous in fast-fading environments where the channel conditions change rapidly. The frequent presence of pilots allows for continuous channel state updates, ensuring that the receiver can adapt quickly to these changes and maintain reliable communication.

But the arrangement reduces the overall data rate as it dedicates a portion of the subcarriers in every OFDM symbol to pilots instead of data. This reduction in data-carrying subcarriers can be significant. Additionally, the process of interpolating the channel estimates for the data subcarriers can be complex and computationally intensive, especially in channels with significant variations.

1.7.3 Lattice type

This arrangement scatters pilots both in time and frequency allowing it to track the time-varying and frequency-selective channel characteristics. The pilot symbol arrangement must satisfy both equations (3) and (4).

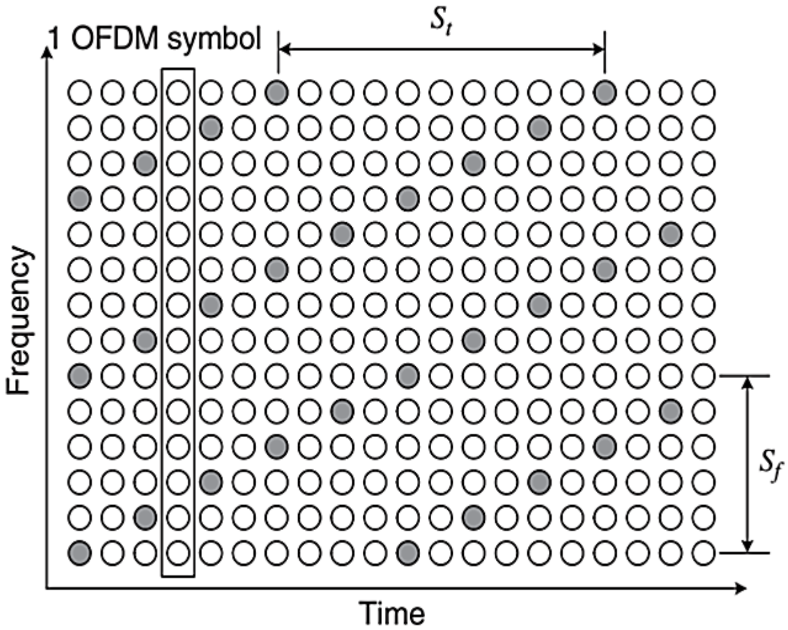

Figure 1.7 : Lattice-type pilot arrangement

This pilot arrangement offers a balanced approach by distributing pilots at regular intervals in both the time and frequency domains. This provides comprehensive channel estimation, making it suitable for a wide range of channel conditions, including both fast and slow fading environments. The regular grid of pilots ensures that the channel state can be accurately tracked over time and frequency, offering adaptability to varying channel dynamics.

However, it introduces complexity in design. Finding the optimal pattern of pilot distribution requires careful consideration to balance the density of pilots in both dimensions. This complexity can increase the design and computational overhead.

Additionally, while it does not reduce the data rate as severely as the comb arrangement, the lattice pattern still occupies some subcarriers that could otherwise be used for data transmission, resulting in a moderate reduction in data rate.

1.8 **OFDM Sensing**

OFDM radar sensing generally is based on the use of pilot signals as reference to extract environmental information, mainly detection of targets and their properties of relative range and velocity. The conventional method used in all radar systems take in consideration these parameters to determine the performance measures of the system (Automotive Radars A review of signal processing techniques): [6] [7]

Table 1.5 : fundamental concepts that define the radar system's performance characteristics. [6] [7]

Radar Measures	**Equation**	**Description**
Maximum unambiguous range	$r\max = \Delta r N c$	the farthest distance a target can be located while still being correctly identified by the radar.
The range resolution	$\Delta r = \frac{c0}{2B} \mid \Delta r = \frac{c0}{Nc.\Delta f}$	it's the smallest difference in distance the radar can detect between two targets.
Maximum unambiguous relative velocity	$vmax = \frac{\pm \Delta v.Nsym}{2}$	This parameter specifies the highest relative velocity (speed and direction) of a target that the radar can determine accurately.
Velocity resolution	$\Delta v = \frac{c0}{2fc.Nsym(T0 + Tcp)}$ $\Delta v = \frac{1}{P.TN}$	This defines the smallest detectable change in a target's relative velocity that the radar can distinguish.

Where:

- ***B***: signal bandwidth.
- ***TN***: length of OFDM symbol (Tcp+T0)
- ***P**: number OFDM blocks of duration T0.*
- $\boldsymbol{\Delta f}$: sub-carrier spacing
- ***Nc***: number of sub-carriers.
- ***Nsym***: number of consecutively transmitted OFDM symbols.
- ***fc***: carrier frequency.
- ***Tcp***: length of the cyclic prefix (CP).

Taking a closer look at these equations we could conclude the following: [6] [7]

- **Range resolution** has a direct link to the spectral resources available, which means more bandwidth equals better range resolution.
- **Velocity resolution** has a direct link to the duration of the carriers, which means longer symbol duration equals better velocity resolution.

In terms of wave form design of radar systems these are the two main parameters that establishes the quality of detection in radar systems (regarding the only the waveform parameters). The problem this study is trying to deal with is the following:

There is a trade off at the cost of communication systems parameters, the full utilization of the band width can be computationally expansive specially in cases where the bandwidth is in the range of GHz, especially in the case of automotive radars which operate at GHz bandwidths and high frequencies [7].

This translates to expansive ADC hardware (OFDM Radar with Subcarrier Aliasing Reducing the ADC Sampling Frequency Without Losing Range Resolution), fast expensive storage and computational hardware if we analyze all the bandwidth with Nyquist criterion that ensure accurate representation of the signal's bandwidth:

$$fs \geq 2B \tag{1.7}$$

Where:

- fs is the sampling frequency.
- B is the bandwidth.

The same can be said for symbol duration, typical communication symbols operate at short durations while due to latency and channel non-stationery effects. Previous works regarding OFDM sensing: [6] [7]

In previous proposed methods that deal with the sampling problem in OFDM radar offer creative solutions that deal with the issue, but come with drawbacks regarding: higher hardware complexity, reduced velocity resolution, synchronization problems and data speeds reductio in some cases.

In [8], symbols were divided into M sub-symbols, with each sub-symbol being transmitted using a particular carrier frequency fc until the entire bandwidth was fully covered. This high range resolution way is achieved with lower sampling rates at both DAC and ADC. But at the expense of a lower maximal unambiguous velocity (vmax), a fast-settling time of the phase locked loop (PLL) for synchronization, and reduced data rate due to carrier-stepping.

The study of [9] incorporates random non-equidistant frequency hopping pattern using narrowband OFDM to preserve the maximum ambiguities with low sampling rate utilizing compressed sensing (CS). Nevertheless, CS algorithms adds more computational complexity to the radar system.

The paper [10] uses a frequency comb composed of L carrier frequencies at both ends to up convert (transmitter) and down convert (receiver) the signal, generating (L) sub-bands identical OFDM signals that span the desired RF bandwidth. However, it elevates RF hardware complexity significantly for the sub-bands generation and power consumption, along with strict synchronization requirements.

The author of [11] referred to as subcarrier aliasing OFDM (SA-OFDM), which leaves empty subcarriers between data subcarriers in each symbol, ensuring that when under-sampling a factor related to the empty subcarriers, the aliased subcarriers will slip into those empty subcarriers. Consequently, a low ADC sampling rate relative to μ is achieved, at the expense of downgraded maximum unambiguous range ($R_{max}$and low data rate).

In other papers such as [12], [13], the works are for reducing the OFDM sampling rate. However, they are related to the ones mentioned above and they differ only to the use of advanced algorithms or MIMO systems.

1.9 **Proposed solution**

The proposed solution introduces a new transceiver architecture that executes ISAC OFDM function without the sacrificing systems integrity. The transceiver design is focuses on two main parts: transmitter and receiver.

1.9.1 Transmitter

This part of work is considered as a conventional OFDM transmitter with costume pilot signal insertion that follows this succession between each consecutive communication symbol. These symbols at the receiver can help determine the channel state and the parameters environment, each succession of the pilot tones follow this equation at the frequency domain:

$$X_p(k_p, l) = X_p(k_p) \cdot e^{\frac{j2\pi k_p l \cdot L_{cp}}{N_{fft}}} \tag{1.8}$$

- $X_p(kp)$: represents the data symbols in the frequency domain.
- N_{fft}: number of subcarriers I the OFDM block
- L_{cp}: cyclic prefix length
- l: denotes the number of the OFDM symbol
- $X(k_p)$: is the complex coefficient of the pilot on the k-th subcarrier.

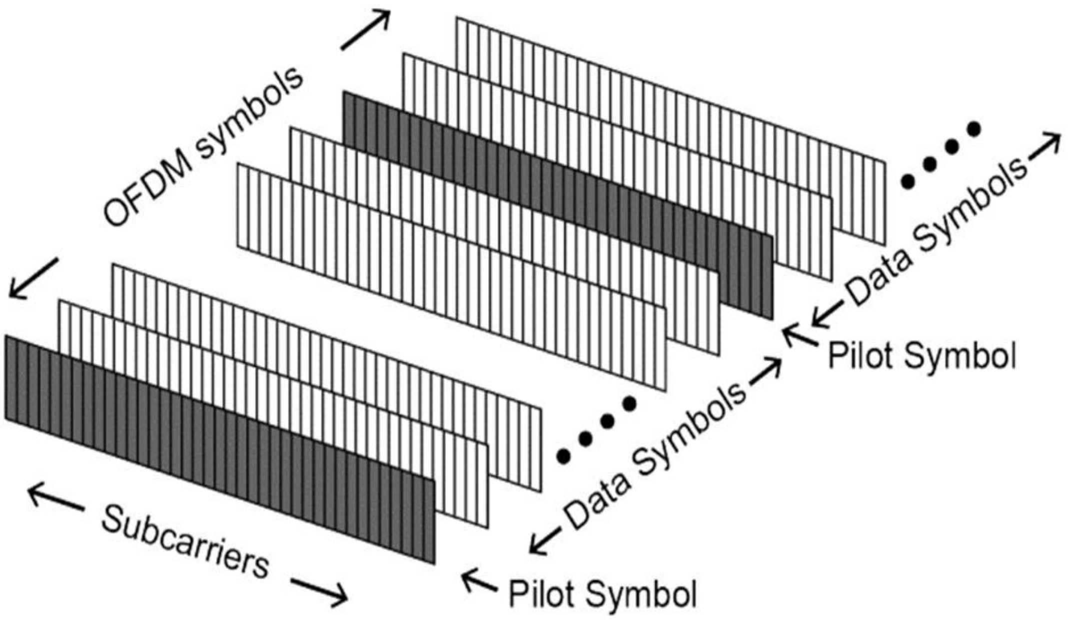

Figure 1.8 : OFDM comb structure used in this solution

The architecture employs having a conventional OFDM transmitter, with only slight change in the order of pilot wave insertion to allow for backwards compatibility with already exiting 4G and 5G systems.

1.9.2 Extremely low-complexity Sensing receiver

The receiver design leverages the sensing on the analog part before the digital conversion, making the sensing an analog operation, which can theoretically reduce power and computational resources compared to its digital counterpart.

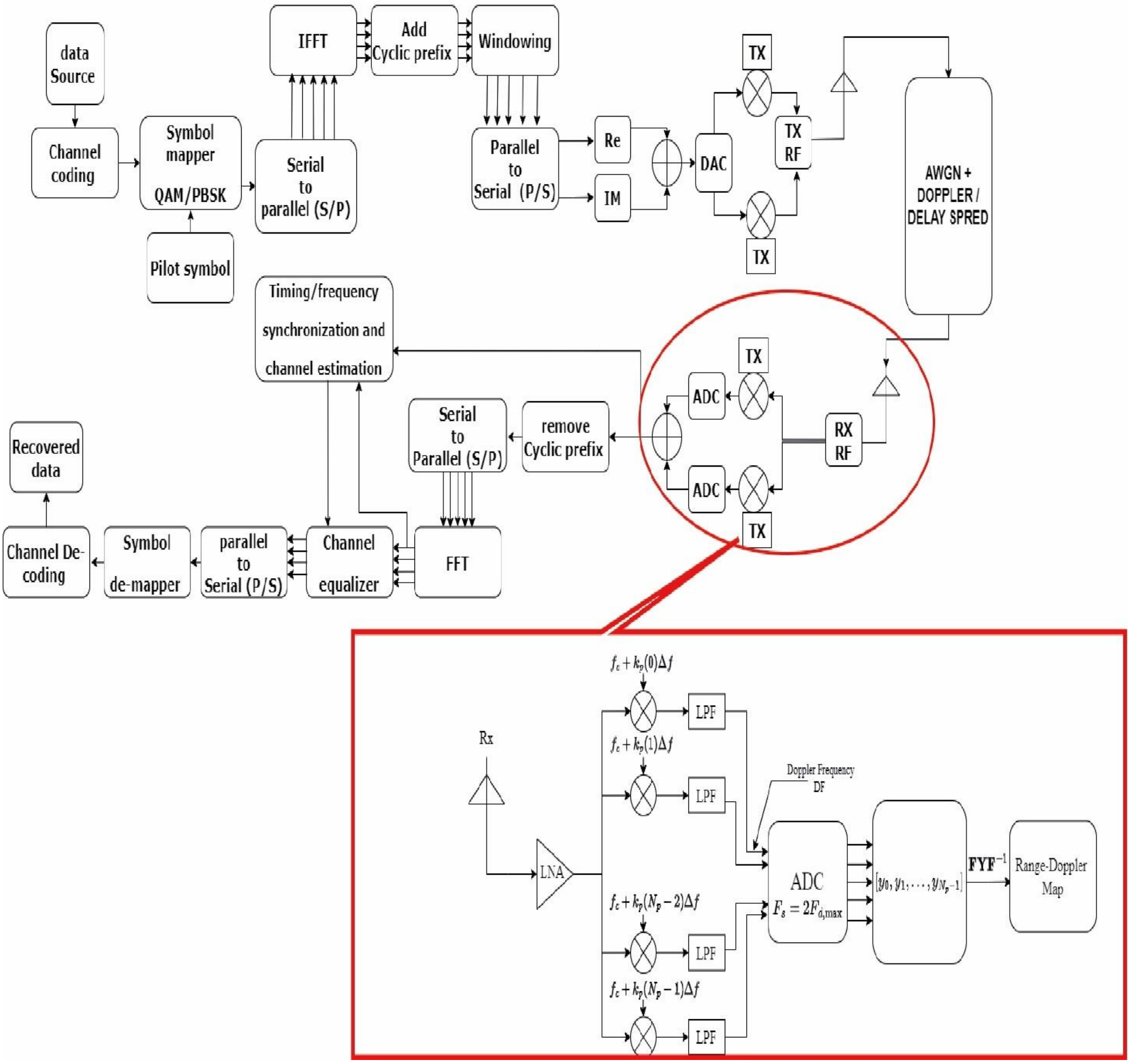

Figure 1.9 : The Sensing Receiver design

In Figure 1.10 shows the detailed architecture of the low complexity receiver, this type of architecture takes advantage of analog signal processing and chirp detection technics in order to implement polit signal detection at very specific subcarrier frequencies, we will explain each block:

Table 1.6 : Description of low-complexity Sensing receiver

Number	Name	Function
100	Rx	Receiver antenna
105	LNA	Low Noise Amplifier: a type of filter that is commonly used to filter out unwanted noise and interference from the received signal improves the receiver sensitivity and allows for the detection of weak signals.
110	Local oscillator	**Down conversion: The** received chirp radar signal is down converted to the (DF) Dopler Frequency band through mixing with a local oscillator signal with step frequencies corresponding the pilot subcarriers: $f = fc + \mathrm{Xp}(k\mathrm{p}).\Delta f$ Δf is the subcarrier spacing. The LO signal is usually generated by a stable and tunable oscillator. Mixing involves multiplying the received signal with the LO signal, resulting in the desired frequency shift to the DF band (120). This process is called Signal .
115	Low pass filter	**Filtering:** After down conversion, a lowpass filter is applied to remove unwanted noise and interference outside the desired DF band. The filter's characteristics are chosen to match the bandwidth of the maximum Doppler frequency to preserve the relevant information.
125	ADC	**Sampling**: The signal is then sampled at a sufficiently high rate using an analog-to-digital converter (ADC). The sampling rate is chosen based on the Nyquist criterion to ensure accurate representation of the signal's bandwidth $$fs \geq 2f\mathrm{dmax}$$ F(d,max) is the maximum doppler frequency that correspond to the target with the highest velocity. Generally, it is in the order of few KHz.
135	Dopler range map	**Digital Signal Processing:** The sampled data is processed digitally to extract the desired information. Then it is converted to range-Doppler map. **Detection and Estimation:** Following digital signal processing, detection algorithms are applied to identify targets based on the processed data. Velocity estimation is performed by analyzing the frequency shift between the transmitted pilot tones and the received echoes. Range estimation is achieved by analyzing the frequency echoes corresponding to the same time delays. And the design can still function as a normal OFDM signal receiver that extracts the data information from the received symbols.

1.10 **Conclusion**

This novel type approach in OFDM RADAR SENCING offers very low complexity, more energy efficient, very resource efficient, backwards compatible and accurate sensing that can offer enhanced sensing ability to already existing ISAC based OFDM communication systems. In addition, it offer sthe radar capability to conventional Communication systems, making it one of the most suitable candidates for future 6G waveform designed for automotive radar communication systems.

Chapter 2
Simulations and Results

2.1 Introduction

In this chapter, we present a systematic approach to simulating a low-complexity OFDM-based ISAC system in MATLAB. Firstly, we introduce a detailed block diagram that illustrates the new architecture, outlining the function of each component and their interaction within the system. Following this, we provide a comprehensive mathematical description of the architecture, elucidating the underlying principles that govern its operation.

Subsequently, we display the simulation counterpart of the architecture, showcasing how theoretical concepts are translated into practical implementation within the MATLAB environment. Lastly, the chapter concludes with a presentation of the results obtained from the simulation, offering insights into the system's performance and efficacy under various conditions.

2.2 Block Diagram of the Simulation

The simulation will follow the sequence outlined in Figure 2.1. Where the diagram illustrates the steps taken to execute the simulation presented in this thesis.

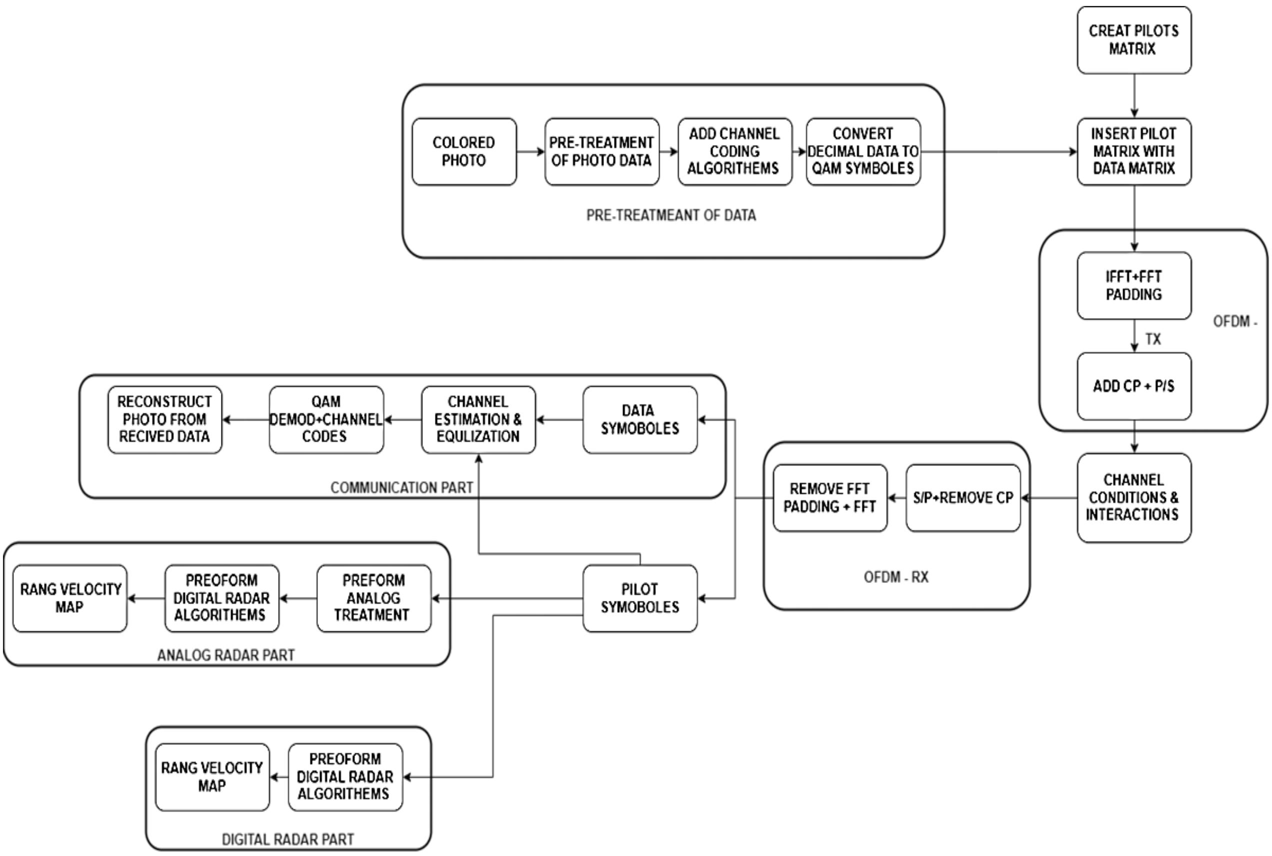

Figure 2.1 . Flowchart Diagram of The OFDM ISAC Simulation

2.3 **Simulation Parameters**

For the simulation at hand, we will take into consideration the parameters of Table 2.1:

Table 2.1 : The numeric parameters taken for this simulation

N	number of subcarriers	1024	Number of subcarriers per a single time frame
M	number of time frames	140 (14*10)	Number of time sub-frame per 1 ms.
CP	cyclic prefix length	(N/8)	//
PDR	Pilot to data ratio	(N/16)	The ration between the number of pilot symbols compeered to data symbols.
(Δf)	subcarrier spacing	240 Khz (5G NR standards)	///
(fc)	carrier frequency	76 Ghz (long rang radars standard)	//
Mod	modulation type	$2^{number\ of\ bits\ per\ symbol}$	Number of possible symbols N-bits = [2:8]
N-tap	Number of targets in the environment	[4:8]	//
SNR value	Signal to noise ratio	[0:20]	//

This table represents the different simulation parameters assigned for this simulation , some values above have been chosen based on initialization parameters such as the number of subcarriers and the cyclic prefix and pilot to data ratio and number of taps, other parameters such as subcarrier frequency, number of times ,and carrier frequency are taken from 5G standards and automotive radar .

2.4 **Process**

We will go through the diagram in more detail-oriented fashion, starting with the steps taken in the block diagram in (figure 1.2 Block diagram of transmitter and receiver in an OFDM system).

2.4.1 Data Pre-Processing

In Figure 2.2 shows the initials steps taken for data processing before OFDM modulation.

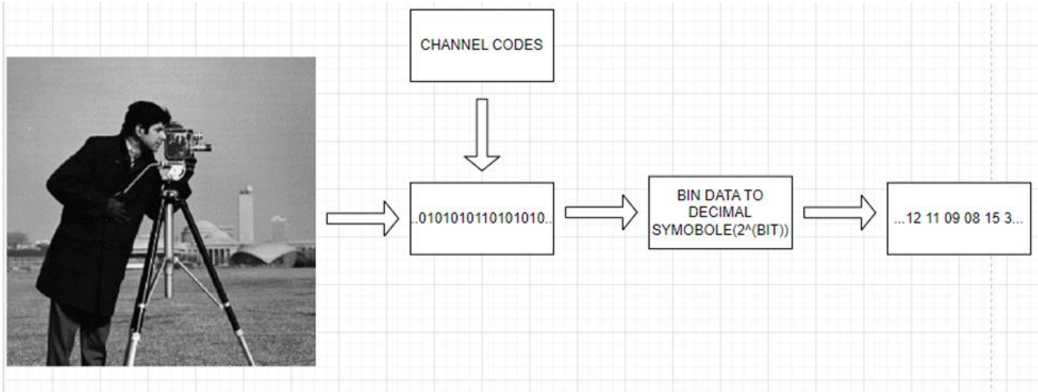

Figure 2.2 : Flowchart of pre-treatment of the image data

We begin by using a 256 by 256 grayscale image as our input, which serves as our transmitted data. The image is then converted from an 8-bit form to a binary form. Following this, error correction algorithms are applied to the binary data stream to mitigate the effects of the channel. Next, we utilize the input parameter MOD to convert the binary sequence to decimal form by manipulating each consecutive bit: 01101011 is transformed to 001 101 11, with the possibility of adding padding of zeros at the beginning, if necessary. The next step involves the conversion from decimal symbols to QAM symbols. This enables the representation of each sequence of bits by quadrature symbols, and then the conversion of decimal symbols to digital QAM symbols.

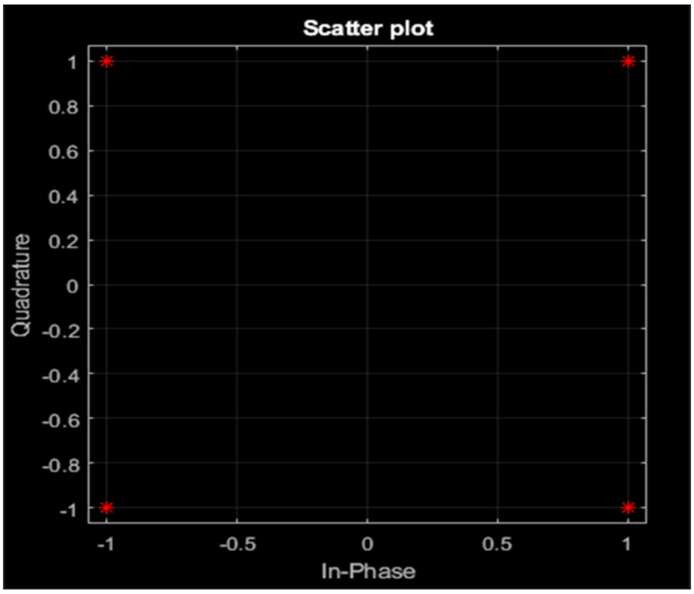

Figure 2.3 : Chosen modulation type

2.4.2 Create the pilot symbols:

This process will involve making the proper arrangement of the pilots and properly inserting them in their positions using this equation:

$$X_p(k_p, l) = X_p(k_p) \cdot e^{\frac{j2\pi k_p l \cdot L_{cp}}{N_{fft}}} \quad (2.1)$$

Where each line of subcarriers is bean placed to achieve the comb structure following this indexing the ration of pilots devised by number of subcarriers. $X_p(k_p)$: is the initial value of the pilot symbol that we will use estimation and equalization of the channel.

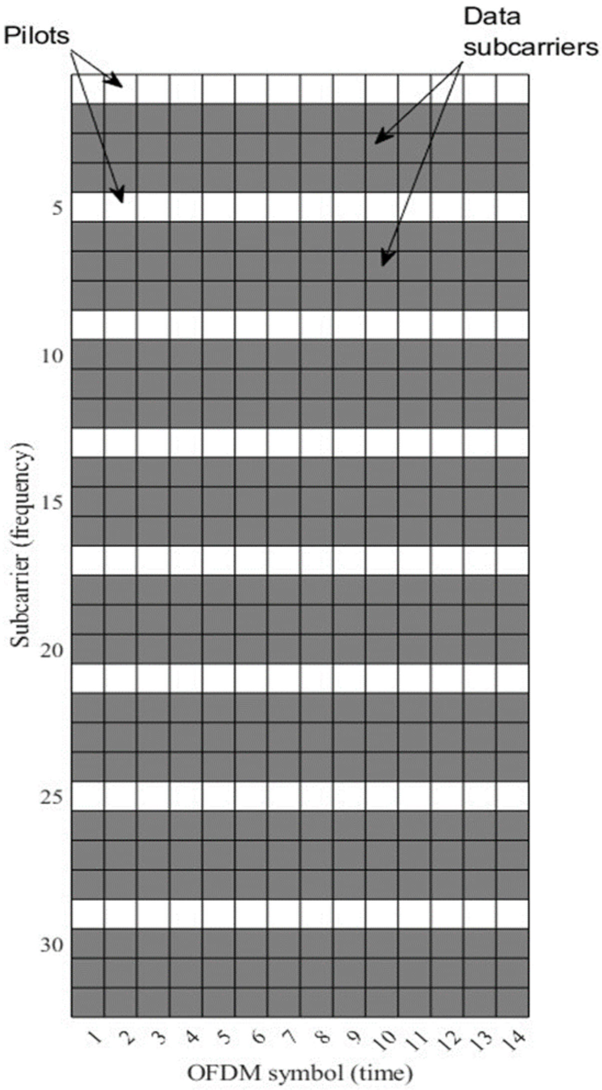

Figure 2.4 : The used comb type of pilot structuring

This form of pilot structure aids in the right utilization of time resources for very reliable doppler resolution, as well as proper frequency resources for good accuracy in long-range radars.

2.4.3 Operation & Cyclic prefix addition

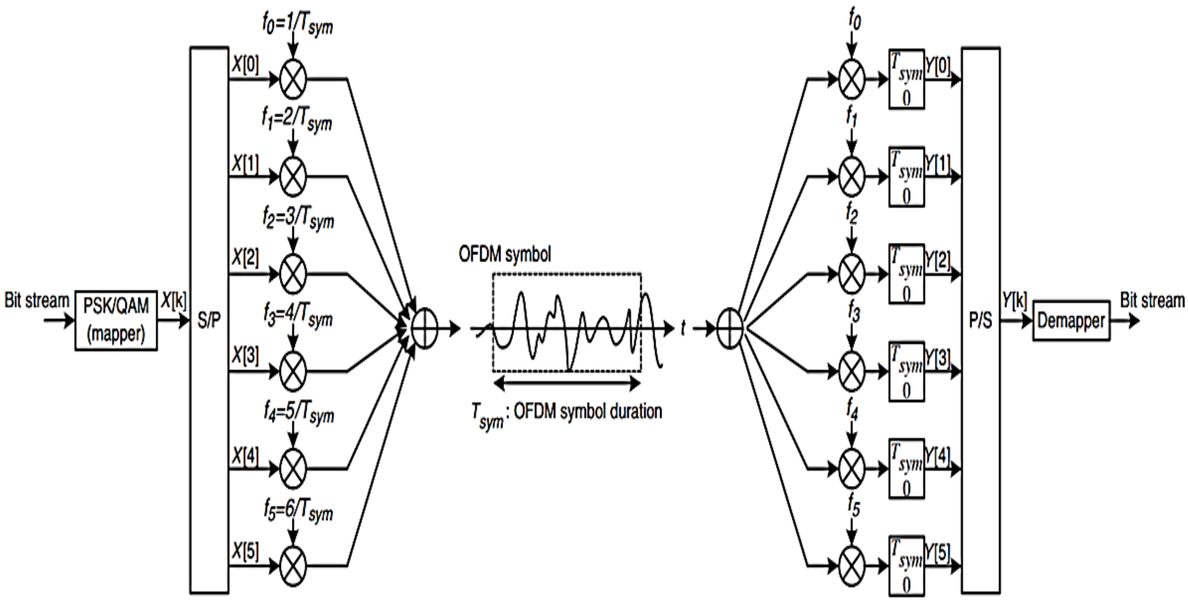

Figure 2.5 : base of OFDM modulation [4]

Orthogonal frequency-division multiplexing (OFDM) modulation fundamentally relies on the utilization of multicarrier signal processes to enhance spectral efficiency and overall performance. By dividing the available bandwidth into multiple orthogonal subcarriers, OFDM optimizes the use of the spectrum, allowing for higher data rates and improved resilience to frequency-selective fading.

Additionally, incorporation of a Cyclic Prefix (CP) in the time domain serves as a crucial mechanism for mitigating Inter-Symbol Interference (ISI). The CP is a repetition of the end of the OFDM symbol appended to its beginning, which effectively absorbs multipath delays and maintains the orthogonality of the subcarriers.

This practice not only provides protection against ISI but also simplifies equalization at the receiver, enhancing the robustness of the communication system. These benefits, along with other advantages, are discussed in detail in subsection 1.6 of the previous section. Furthermore, the use of CP allows for simpler receiver design and reduces the complexity associated with channel estimation and synchronization, making OFDM a preferred choice in modern wireless communication systems.

2.4.4 Channel generation and characteristics

The channel will be characterized according to the use case of automotive radars, this means the nature of the channel is dynamic relative to both the RX/TX, this is characterized by the multipath fading:

Multipath propagation, a major cause of signal deterioration in wireless communications, occurs when transmitted signals arrive at the receiver via several routes due to reflections, diffractions, and scattering. This leads to small-scale fading, which is defined by fast signal strength variations over short distances, and frequency-selective fading, in which various signal frequencies experience varying levels of fading, resulting in (ISI).

Fast fading occurs with strong relative motion, resulting in substantial Doppler shifts and that leads to (ICI). Whereas slow fading is caused by gradual environmental changes. Multipath effects raise the bit error rate (BER), which implies that the crucial need for channel estimation and equalization in this case. The channel is generated and according to:

The number of taps in the environment + the range and velocity of each tap in the environment.

- **Doppler Shift Calculation:**

$$X_p\left(k_p, l\right) = X_p\left(k_p\right) \cdot e^{\frac{j2\pi k_p l \cdot L_{cp}}{N_{fft}}} \tag{2.2}$$

Where: λ is the wave length of the *fc*

- **Time Delay Calculation**

$$\tau = \frac{2 \times range}{C0} \tag{2.3}$$

- **Channel Coefficients**

$$\text{chan\_coef} = \sqrt{}(\frac{1}{2})(\text{rand}(1,\text{taps}) + \text{j} \cdot \text{randn}(1,\text{taps})) \tag{2.4}$$

- **Doppler Effect**

$$\text{d} = \text{TXsignal} \cdot \exp(\frac{\text{j}2\pi}{M}(0{:}\,\text{length}(\text{TXsignal}) - 1) \cdot \frac{\text{Lcp}.\,fD)}{Nfft + Lcp} \tag{2.5}$$

- **Channel-Affected Signal**

$\text{output channel} = \text{AWGN} + \text{chan\_coef} \cdot \text{circshift}([\text{d}; \tau(1\text{: end})], \tau)$ the above equations give a general mathematical description of the interaction between the generated channel that replicates the effects of multipath channel and the transmitted TX signal.

2.4.5 Channel reception and treatments

In this part, we will separate it to three parts: analog radar receiver, digital radar receiver and communication system receiver, each of them will be described in terms of results of the simulation.

2.4.5.1 Analog receiver

The sensing receiver design as shown in figure (11), the receiver will take three main steps to accomplish its task:

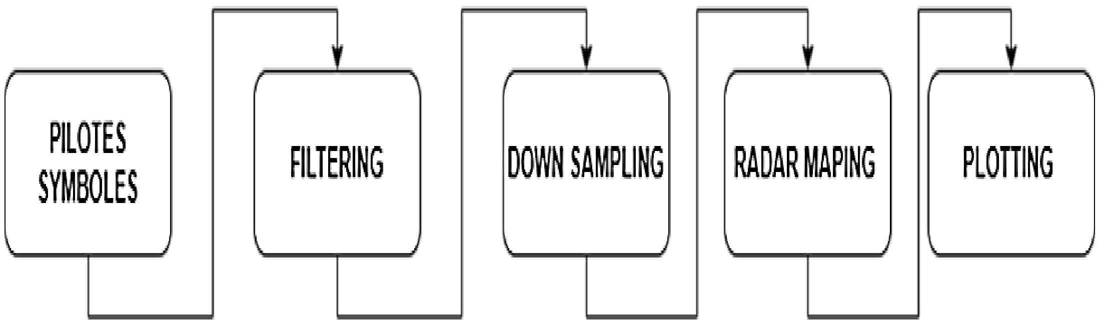

Figure 2.6 : Flowchart Diagram of Analog Processing for OFDM Rader

The first step is to effectively remove the phase distortion, aligning the received signal's phase with the original transmitted signal's phase. This acts as both channel equalization and multiplication with received subcarrier frequencies.

The second step is to introduce a filtering; the filter function applies different kinds of filters according to the needed requirement.

In this simulation, a moving average filter is applied to smooth the signal, reducing the high-frequency noise components. This results in a cleaner version of the received signal.

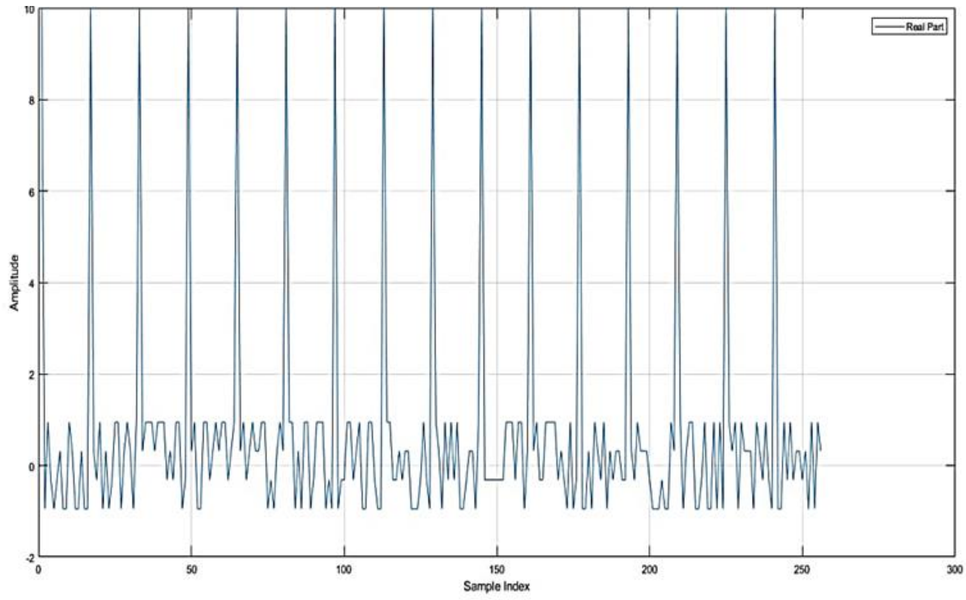

Figure 2.7.real part of pilot signals before channel interaction

Figure 2.7 shows the shape of the pilots before transition, this will be as reference for both the equalization and radar part.

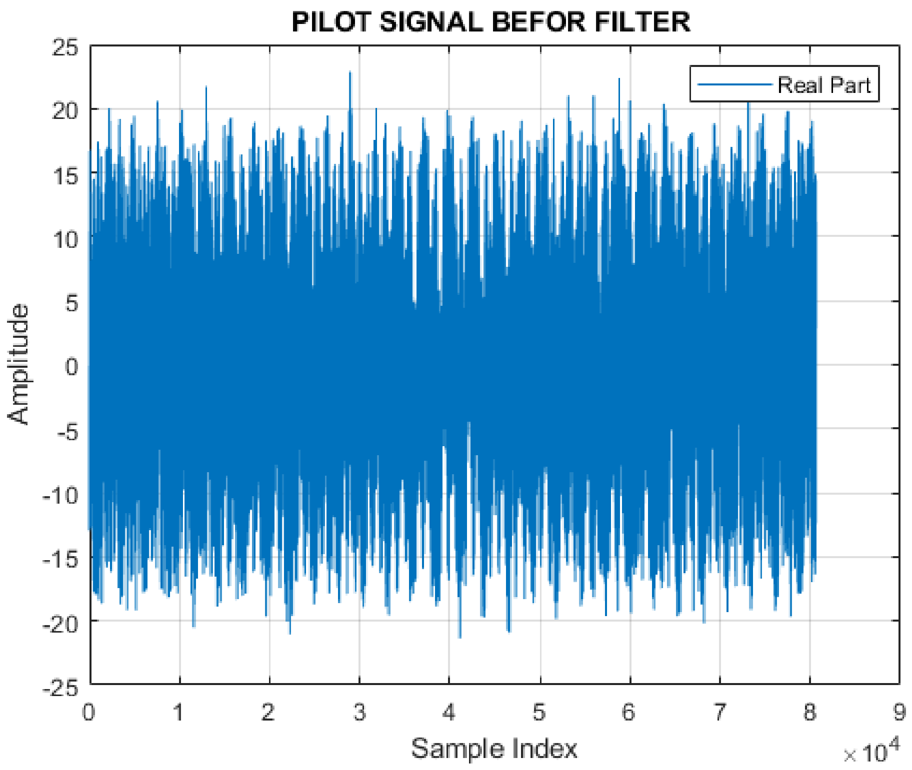

Figure 2.8 : Real part of pilot signal at reception for 8 taps channel

The figure 2.7 shows the real part of the complex pilot signal after the multipath channel interaction, this shows random and disfigured effects of the channel on the signal.

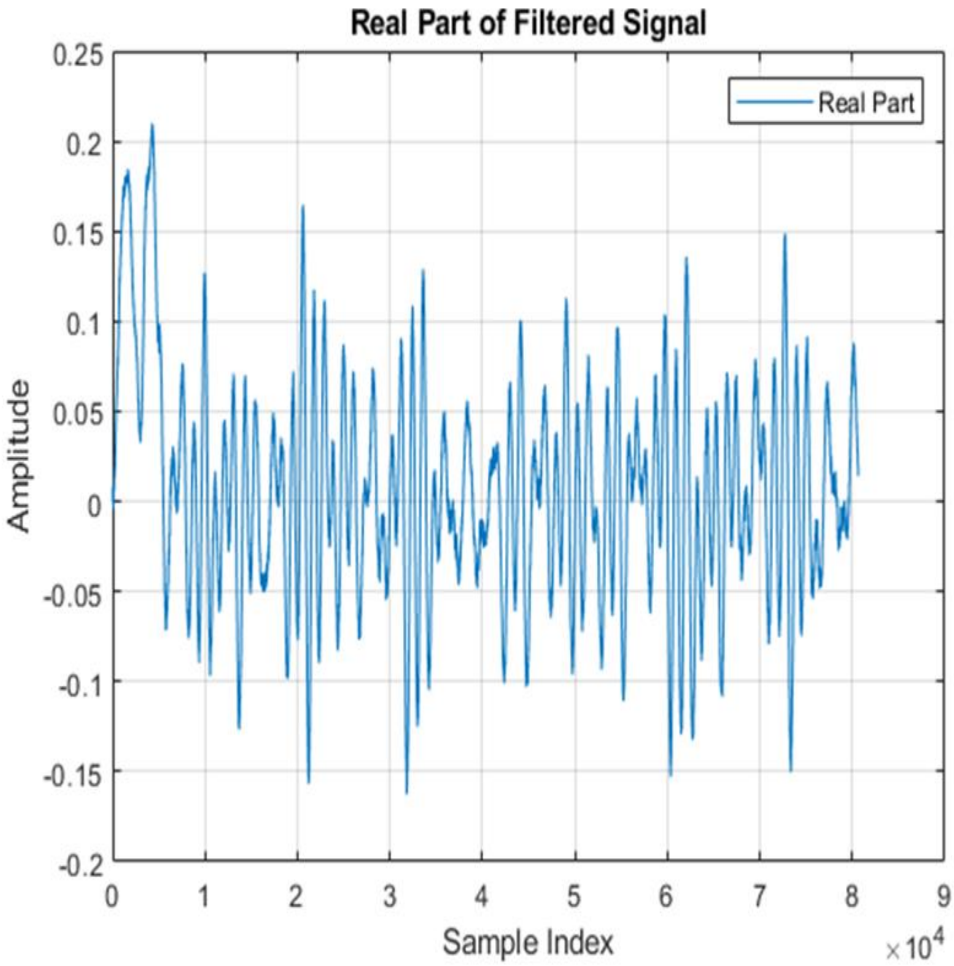

Figure 2.9 : Real part of filtered signal for 8 taps channel

This figure depicts the filtered echo signal, which demonstrates a smooth output achieved through the application of a moving average filter. This filter effectively mitigates the channel effects, such as noise and interference, and restores the general shape of the original signal.

By averaging the data points over a specified window, the moving average filter reduces fluctuations and enhances signal clarity, leading to more accurate and reliable signal representation. This step involves applying different types of analog filters to execute different task depending on the intended results, for this simulation we used this or better visual representation and to extract higher signal details for more accurate processing.

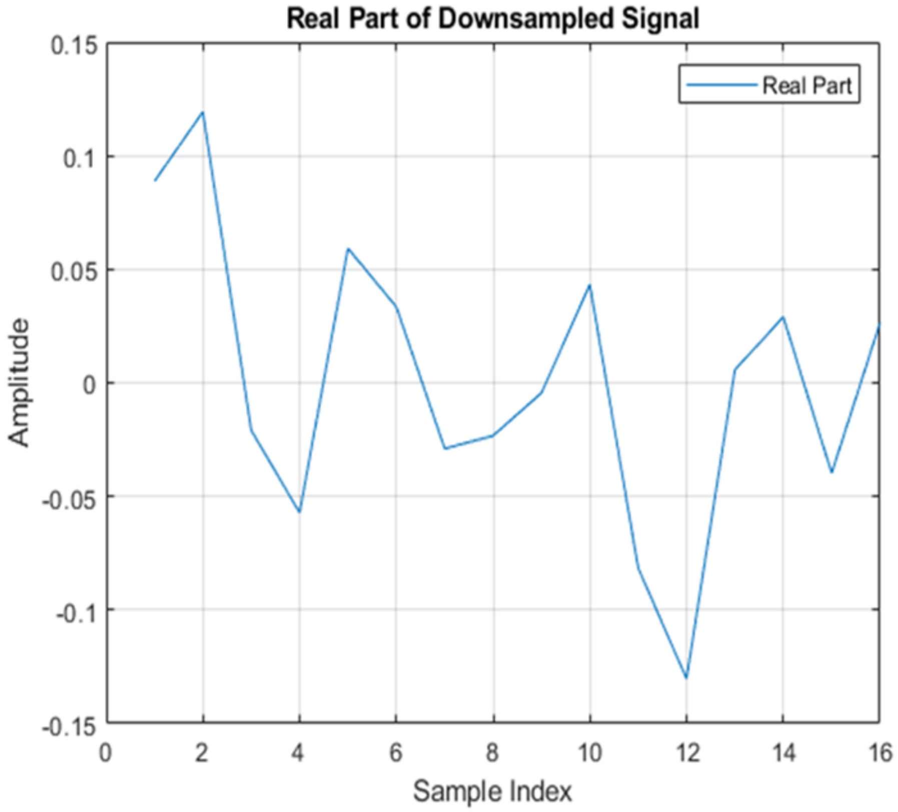

Figure 2.10 : Real Part of Down sampled Signal for 8 taps channel

In this figure, we executed down sampling at 16 equally distributed intervals, where a single value from the original signal was sampled at each interval, this can translate to more intervals more details captured and more accurate sensing. This process optimizes performance while maintaining the integrity of the important signal features providing several key benefits. Firstly, it captures and preserves the essential details of the signal, ensuring that only the most critical information is retained, which is particularly important for accurately representing the signal's characteristics. Secondly, significantly reduces the computational complexity and storage requirements for subsequent radar signal processing.

By focusing on key data points, this method enhances both efficiency and enables faster data analysis and processing, which is crucial in real-time applications. Additionally, it helps in reducing the bandwidth required for transmitting the signal, making it more suitable for communication systems with limited bandwidth.

Finally, down sampling involves extracting samples from the filtered signal at intervals specified by the down sampling factor.

This operation captures the essential information necessary for executing sensing functionalities while reducing the sampling rate, thereby decreasing computational complexity and memory requirements for subsequent processing stages.

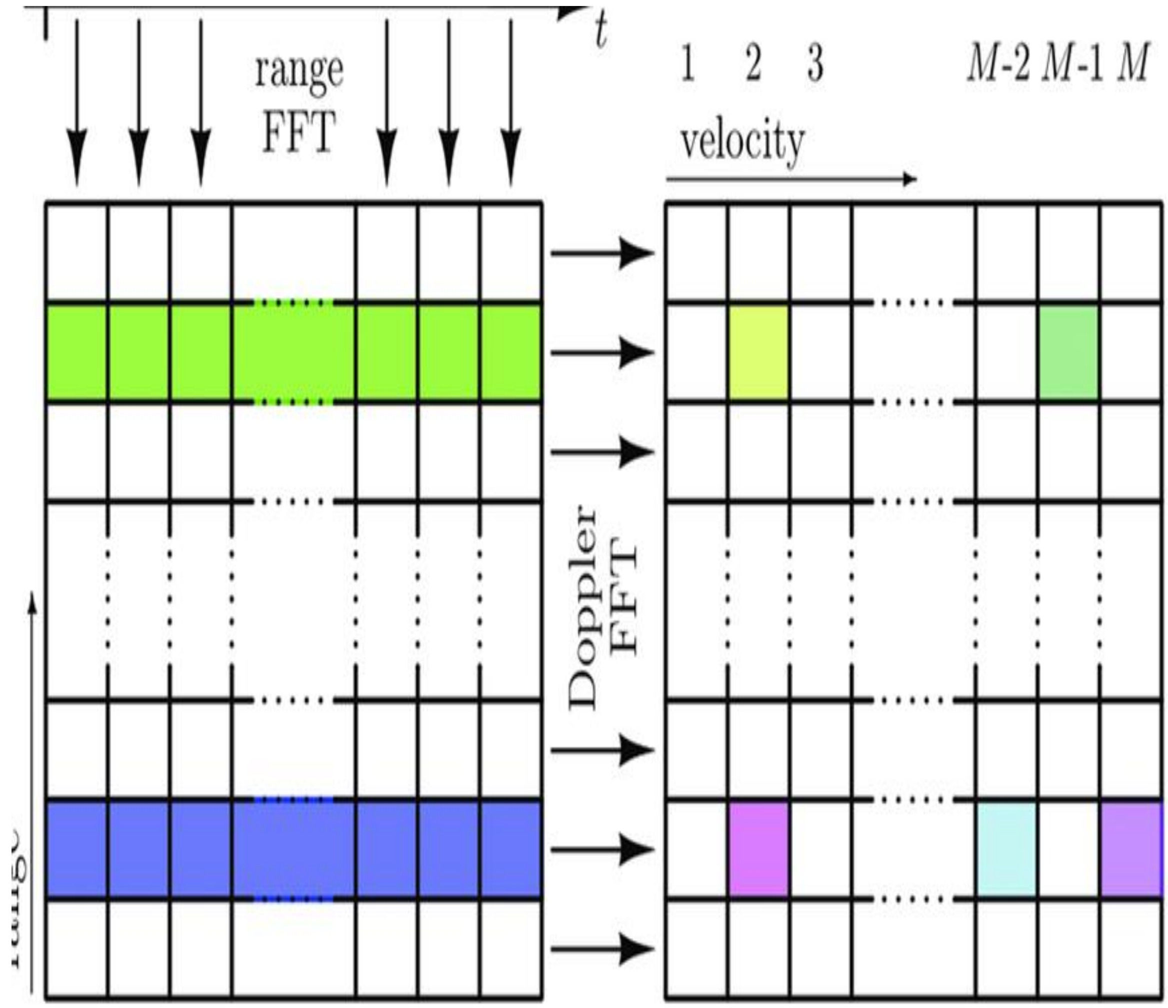

figure 2.11 Radar Mapping of Rage Doppler Properties of Dowsammpleed Signal

The next step involves taking preforming FFT/IFFT operation on the sampled signal to map out the fast/slow time variations of the received signal, also known as range velocity map, were each Colom is mapped properly to extract the slight variation that indicate the range and velocity of the targets ,After wards, the filtered and down sampled signal is plotted to visualize its characteristics, using normal fft/ifft properties to extract range Doppler information This is done by taking the real part of the signal and plotted against the sample index to observe its amplitude variations over time.

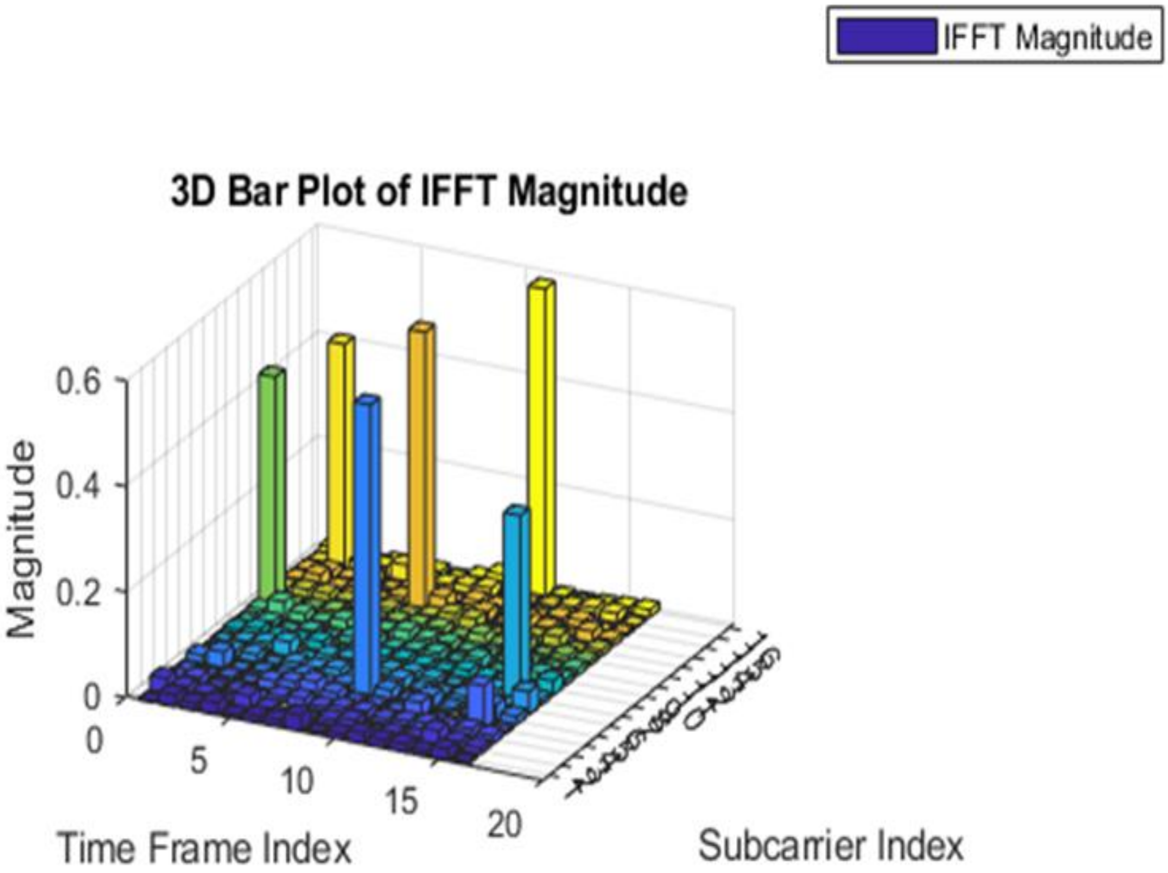

Figure 2.12 : 3D Bar Plot of IFFT Magnitude 8 taps

The image above presents a 3D bar plot illustrating the efficacy of the solution in detecting targets and identifying their range and velocity properties, each peak at the bar plot represents a single target with its range velocity properties. It shows that the systems has detected 6 unique targets from the generated environment with high data accuracy represented as the magnitude of each bar.

This method demonstrates suitability for detection scenarios under diverse forms and channel conditions, particularly when multiple targets are in close proximity to one another. It is well-suited for far and mid-range automotive radar simulations, providing reliable performance in complex detection environments.

The 3D plot effectively visualizes how the solution can distinguish between targets with varying velocities and distances, showcasing its robustness in handling overlapping signals. Furthermore, this approach enhances target resolution and accuracy, making it invaluable for applications such as collision avoidance, adaptive cruise control, and autonomous driving systems. By offering precise detection capabilities.

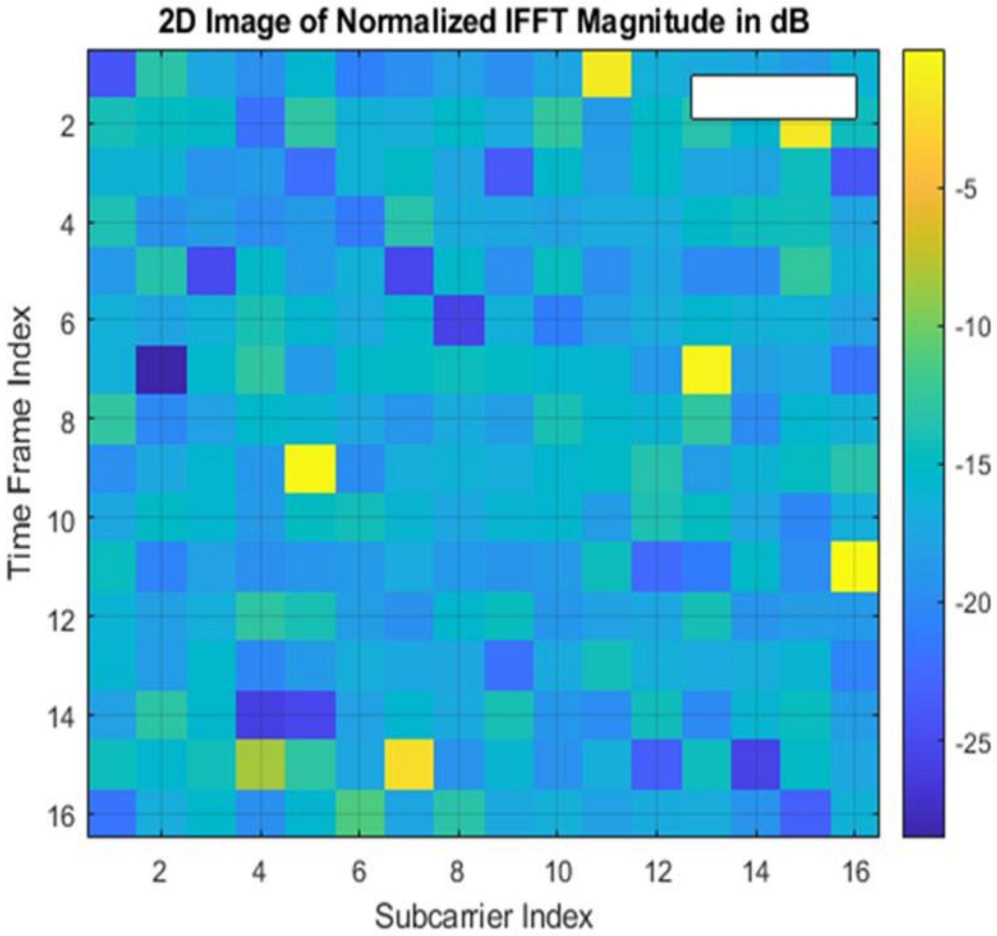

Figure 2.13 : 2D Image of Normalized IFFT Magnitude in dB 8 taps

This image is an above view of the 3D bar plot that shows the detection of 7 targets with their properties, helping in improving the probability of detection of targets by highlighting them in yellow for more better visual representation. This map helps in targets display in the environment The figures show the target properties from the received echo signal of each path generated by the channel function, with the received signal power comparison of each target as well.

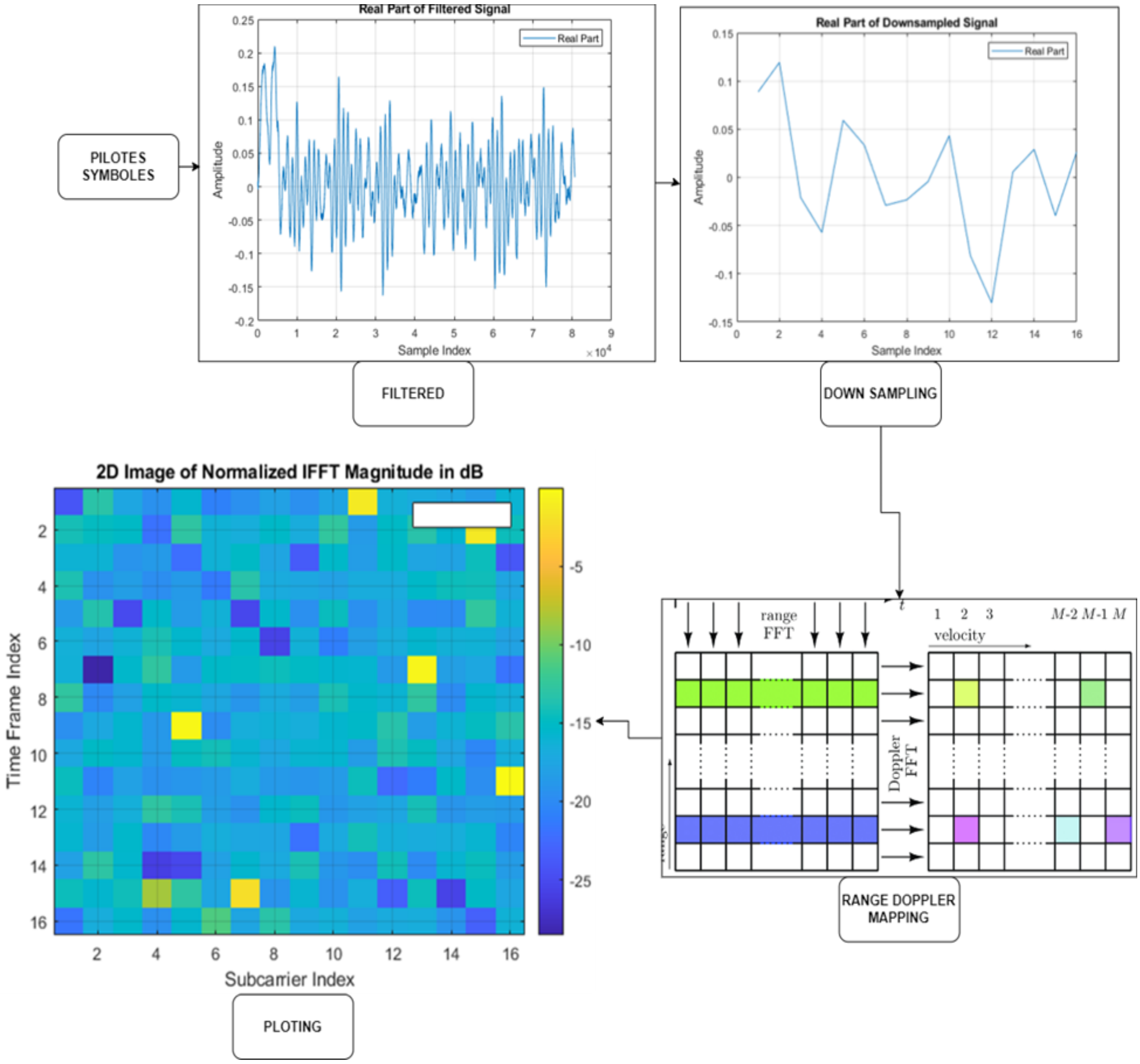

Figure 2.14 : Flowchart diagram of the proposed method

Figure 2.14 shows the main step by step process that takes place in order to perform the analog pre-processing needed before the digital processing.

2.4.5.2 Digital receiver

In this section, the complete received signal is sampled and processed through the entire allocated bandwidth, as well as advanced algorithms are applied to the pilot signals, offering a significant advantage to radar functionality at the expense of more computationally complex algorithms and processing.

This requires increased sampling rates, which in turn necessitates more hardware-intensive processing, translating to higher costs, especially for commercial automotive radars with large bandwidth allocations.

This approach leverages the capabilities and computational cost of digital signal processing to enhance performance. Specifically, in the context of Orthogonal Frequency-Division Multiplexing (OFDM) sensing, integrating the previous analog radar components can significantly improve the accuracy of digital radars.

This combined approach ensures more precise target detection and characterization, benefiting from the strengths of both analog and digital radar technologies in diverse and challenging environments.

The fusion of analog and digital techniques allows for superior resolution and robustness, making it highly effective for applications such as advanced driver assistance systems (ADAS) and autonomous vehicles. Despite the higher cost and complexity, the enhanced detection capabilities and reliability in various operational conditions justify the investment in more sophisticated hardware and algorithms.

This shows radar detection using standard digital signal processing methods for radar detection & range velocity estimation of 4-tap channel that.

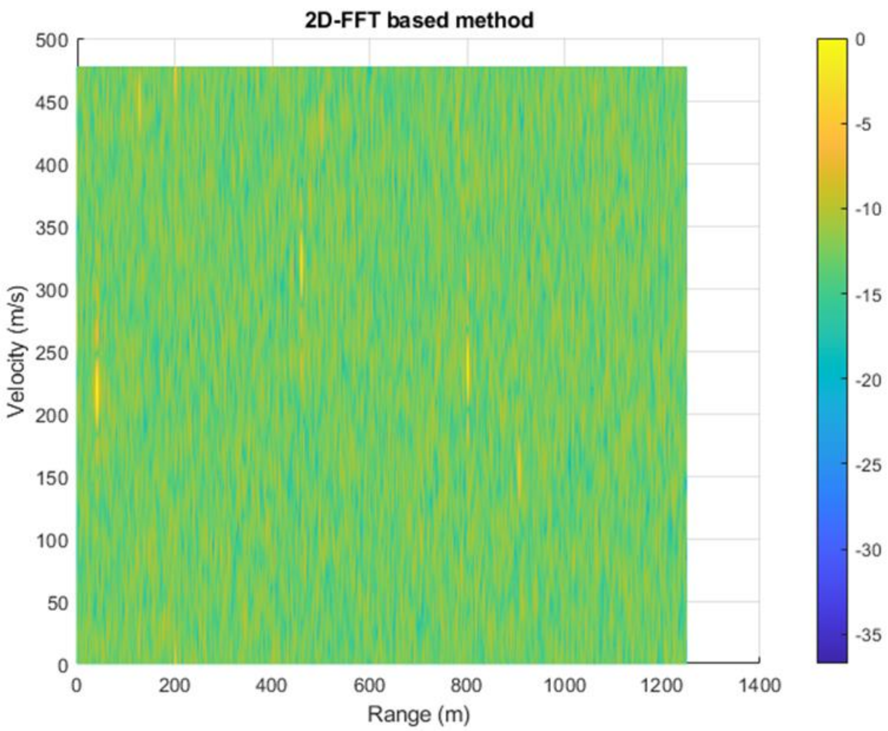

Figure 2.15 : Result Radar detection of 4-tap (FFT Method)

This figure shows the range-velocity map of the standard 4-tap channel, where four targets can be detected along with their properties. This particular method represents the most basic and straightforward approach in radar applications, where the FFT algorithm is simply applied to the received signal to extract radar information. However, despite its simplicity, this method lacks in scenarios where multiple closely packed targets with similar ranges but varying properties may be incorrectly considered as one target, leading to a deficiency in range resolution criteria. In such cases, the limited resolution of the FFT-based approach can result in merged target representations, hindering accurate target identification and characterization. To overcome this limitation, more advanced signal processing techniques, such as adaptive beamforming or multi-resolution processing, may be employed to enhance range resolution and distinguish between closely spaced targets. By incorporating these techniques, radar systems can achieve improved performance in target detection and tracking, especially in complex and cluttered environments. Thus, while the FFT-based method provides a fundamental basis for radar signal processing, it often necessitates supplementary techniques to address the challenges posed by dense target scenarios.

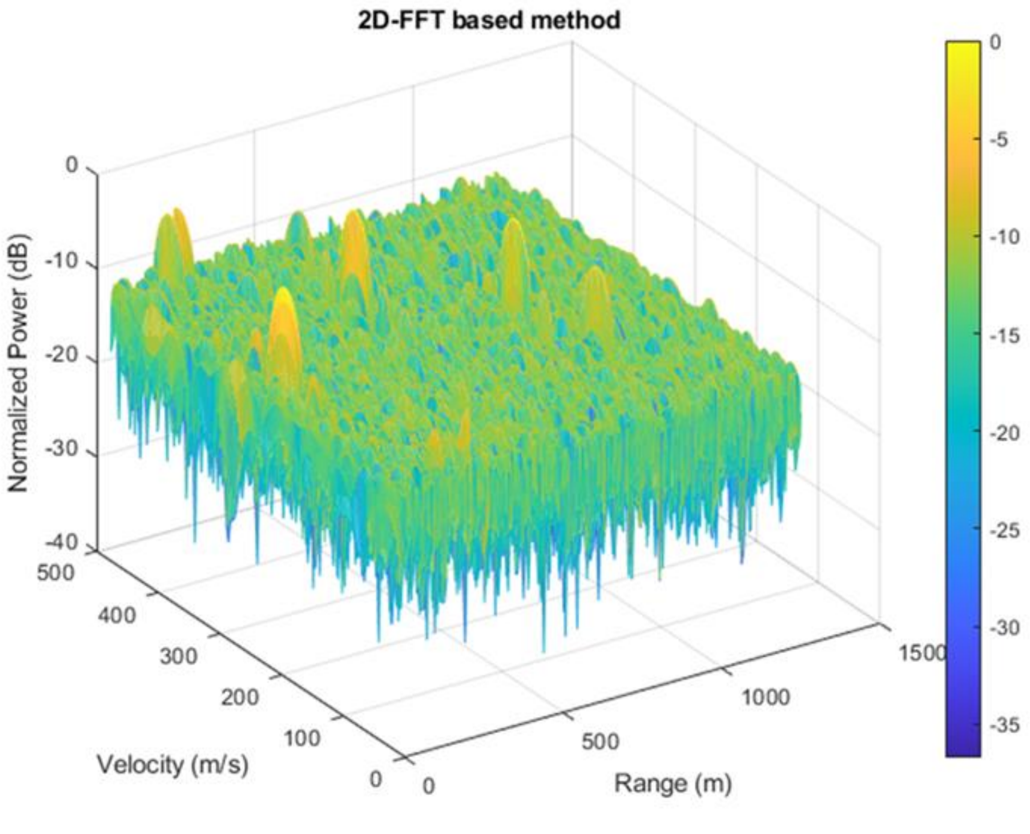

Figure 2.16 : Result radar range velocity estimation of 4-tap (FFT Method)

This figure shows a side view of the previous range velocity map, this view opposite to the previous one helps depict the targets in the environment more clearly compared to the environment clutter by showing approximately 4 peaks that can determent the presence of clutter (random variations created by the channel function). But just like the previous map this method sacrifices some of its accuracy in determining range and velocity due to very high bandwidth ADC conversion costs.

The Figures 2.15, 2.16 show the velocity range map of several targets relative to the Transmitter using the Cycle Cross-Correlation based sensing algorithm, offers robust target detection and tracking capabilities, particularly in scenarios with multiple targets, clutter, and varying environmental conditions.

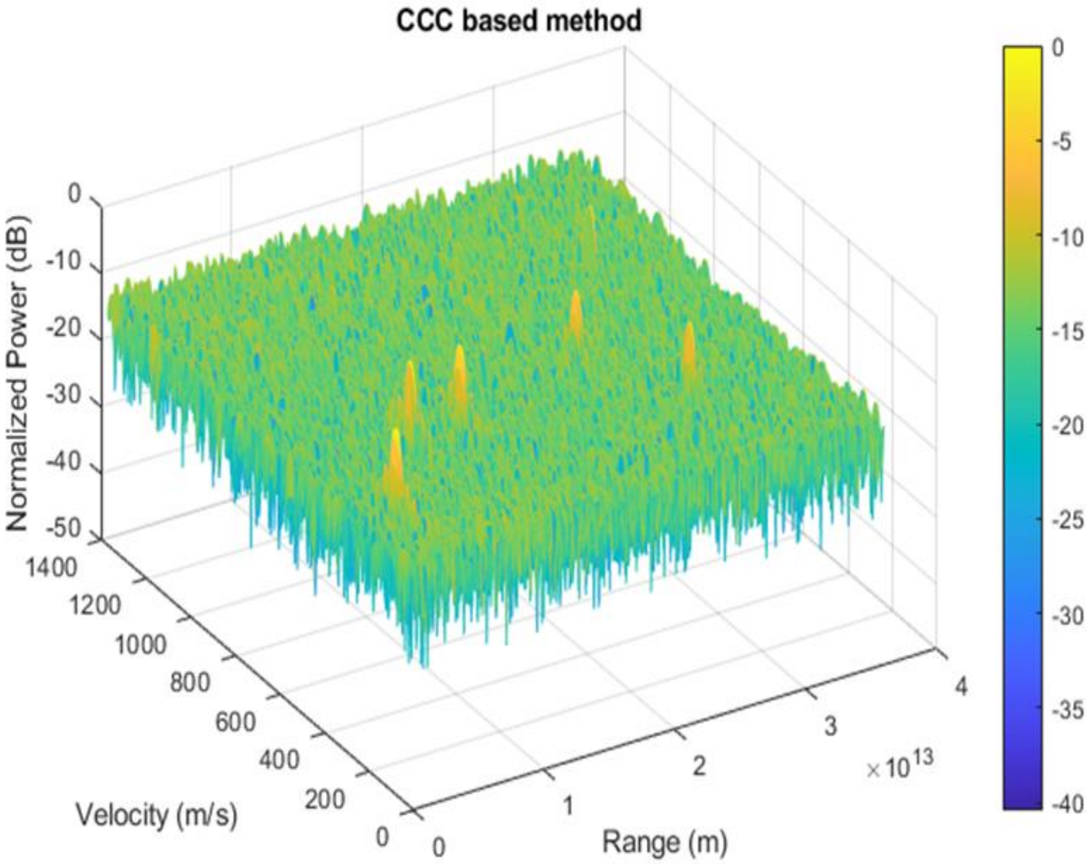

Figure 2.17 : Result radar range velocity estimation (CCC Method)

The figure shows the rage velocity map with same channel conditions as the previous figure, using a different more accurate algorithms, this algorithm offers better detection and tracking of targets I the environment, but trades off with more computational complexity and power consumption, the peaks that show in this figure are relatively the same peaks in the previous figure that depict the same targets. The improved part is that these peaks are much narrower, making this algorithm determent the properties of targets much more accurately.

In this part, we will determine the quality of information that is revived, in this case we will be using aa image before and after transmission threw the multipath channel. We will use both the QAM constellation map, BER and the visual image to see how well can the communication preform in the selected channel conditions. We took the following conditions as a reference:

The following communication system uses simple channel estimation and equalization using a pilot to data ratio of ratio Nfft/16.

These images take into consideration different conditions and their impact on the information quality at the receiver.

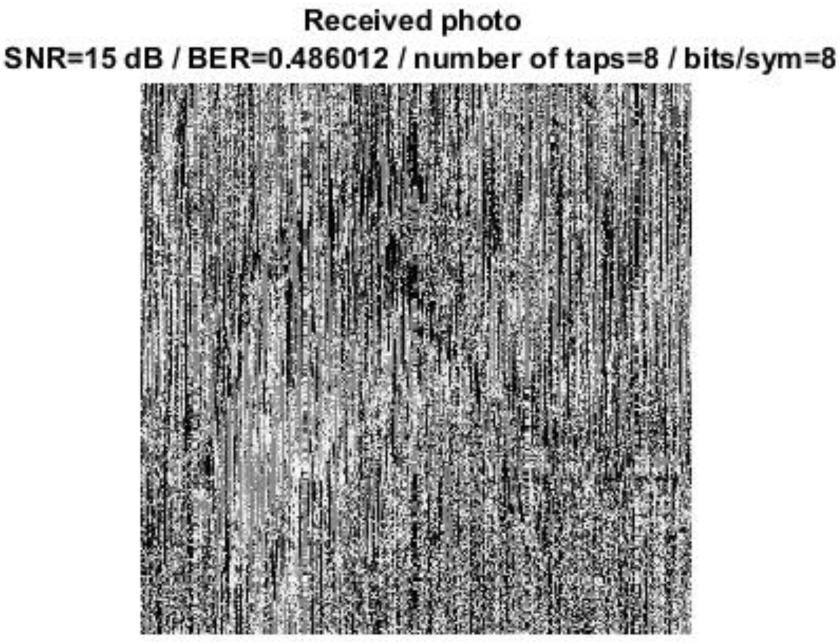

Figure 2.18 : Result of Received Picture with 8-taps and SNR = 15 dB

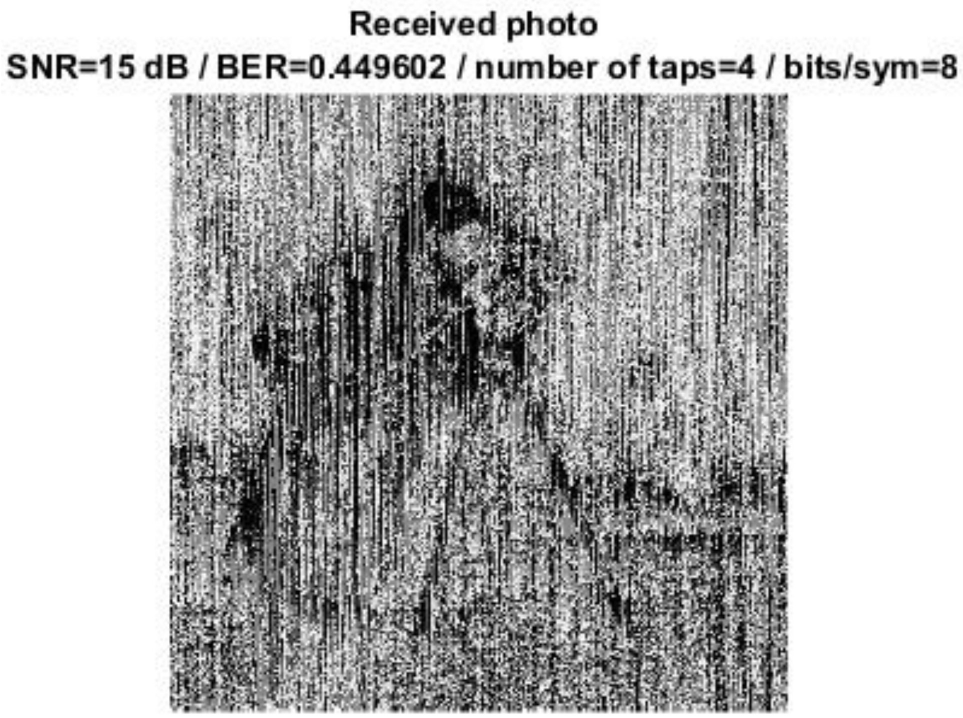

Figure 2.19 : Result of Received Picture with 4-taps and SNR = 15 dB

Figure 2.20 : Result of Received Picture with 2-taps and SNR = 15 dB

From the Figure 2.18 to 2.20 depicts the final received data signal after equalization and reconstruction, which shows the destructive nature of the multipath channel with dynamic conditions, with the orthogonality of the signals is severely destroyed due to ICI, in this figure we fix the number of taps, bits per symbol part and SNR, while varying the number of taps to 8,4,2. , we notice more taps give more destructive results , compared to channels with less taps .

A discernible trend emerges as the number of taps increases, signaling a heightened degree of channel degradation and consequently diminishing information received by the receiver. This observation underscores a fundamental principle: as channel conditions veer towards the extreme end of the spectrum, the deleterious effects amplify correspondingly.

Figure 2.21 : Result of Received Picture with 3-taps and SNR = 35 dB

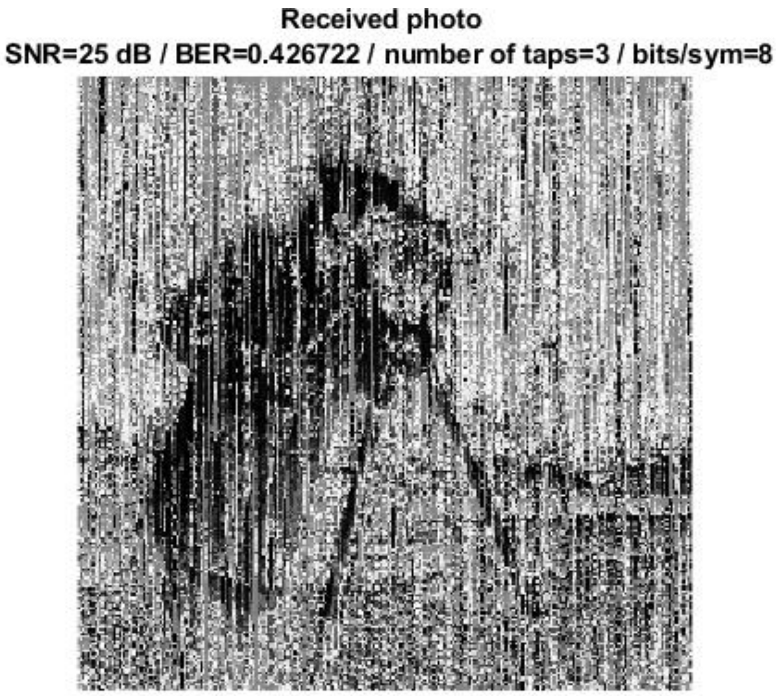

Figure 2.22 : Result of Received Picture with 3-taps and SNR = 25 dB

Figure 2.23 : Result of Received Picture with 3-taps and SNR = 20 dB

From figure 2.21 to 2.23 shows a discernible pattern emerges when examining the sequence of images in relation to Signal-to-Noise Ratio (SNR) values. Notably, a direct correlation manifests between SNR levels and image quality. Elevated SNR levels yield superior resolution and outcomes, whereas lower SNR levels precipitate diminished image quality and fidelity.

Figure 2.24 : Result of Received Picture with 3-taps and SNR = 20 dB

Figure 2.25 : Result of Received Picture with 3-taps and SNR = 20 dB

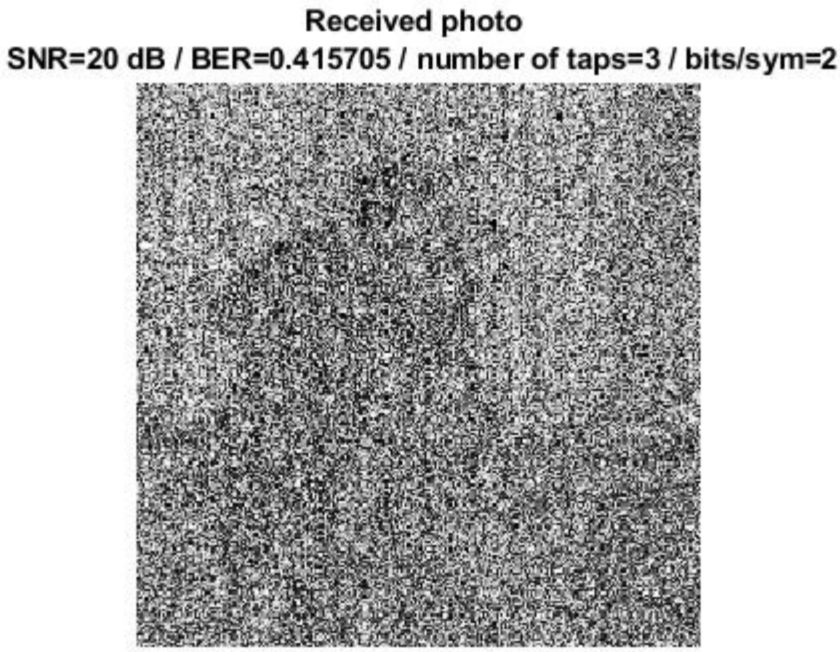

Figure 2.26 : Result of Received Picture with 3-taps and SNR = 20 dB

In figures 2.24 to 2.26 an intriguing insight emerges regarding the role of constellation types in data reception. Remarkably, higher constellation orders are observed to significantly enhance the received signal compared to their lower counterparts. This finding underscores the pivotal role of constellation type in adapting to varying channel conditions, offering a versatile solution to accommodate the fluctuations inherent in channel dynamics.

The images above show the destructive nature of the channel. The most noticeable difference is that with increased number of taps the more destructive the channel becomes the increased BER it results, showing the need for better error correction and channel equalization algorithms to mitigate channel effects. The second change that can be noticed is: power allocation is plays a noticeable role in decreasing the BER of the system.

2.5 **Conclusion**

The simulation shows the base concept of the proposed low complexity OFDM based ISAC architecture that can achieve enhanced both higher radar sensing accuracy and provide dissent communication requirements under high mobile scenarios. Additionally, this novel method proves to achieve very high Doppler resolution suitable for automotive radar applications, taking full advantage of provided spectral and computational resources while maintaining higher accuracy sensing.

General Conclusion

General Conclusion

In this thesis, we have presented a novel approach for very low complexity OFDM-based integrated sensing and communication (ISAC) tailored for 6G automotive radar waveform design. Our methodology leverages the inherent advantages of OFDM, such as robustness to multipath fading and efficient spectrum utilization, to create a unified system that meets the demanding requirements of next-generation automotive applications.

By optimizing OFDM parameters and employing advanced signal processing techniques, our approach maintains low computational complexity ad solves the over sampling problem related to ultrawide band spectrums, making it suitable for real-time automotive environments.

The proposed system demonstrates significant improvements in sensing performance, achieving high data rates while providing accurate radar sensing capabilities. our simulation model achieved acceptable communication performances with only standard OFDM error correctio methods and simple channel estimation and equalization algorithms, our low complexity OFDM-based ISAC system represents a significant advancement in 6G automotive radar waveforms, reducing system complexity and enhancing performance, thus paving the way for safer and more efficient transportation systems.

Our findings provide a robust foundation for further research and development in ISAC for automotive applications, contributing to the advancement of 6G technologies and beyond.

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