ISTANBUL TECHNICAL UNIVERSITY
ELECTRICAL-ELECTRONICS FACULTY

SIGNAL PROCESSING TECHNIQUES FOR JOINT COMMUNICATION AND RADAR SENSING

SENIOR DESIGN PROJECT

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ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

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<u>İSTANBUL TEKNİK ÜNİVERSİTESİ</u>
<u>ELEKTRİK-ELEKTRONİK FAKÜLTESİ</u>

ORTAK İLETİŞİM VE RADAR ALGILAMA İÇİN SİNYAL İŞLEME TEKNİKLERİ

<u>LİSANS BİTİRME TASARIM PROJESİ</u>

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OCAK, 2025

We are submitting the Senior Design Project Report entitled as “SIGNAL PROCESSING TECHNIQUES FOR JOINT COMMUNICATION AND RADAR SENSING”. The Senior Design Project Report has been prepared as to fulfill the relevant regulations of the Electronics and Communication Engineering Department of Istanbul Technical University. We hereby confirm that we have realized all stages of the Senior Design Project work by ourselves and we have abided by the ethical rules with respect to academic and professional integrity .

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FOREWORD

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ABBREVIATIONS

AWGN	**:** Additive White Gaussian Noise
BER	: Bit Error Rate
BPSK	: Binary Phase Shift Keying
CP	: Cyclic Prefix
DFT	: Discrete Fourier Transformation
ERF	: Effective Radiated Power
FFT	: Fast Fourier Transform
IFFT	: Inverse Fast Fourier Transform
IDFT	: Inverse Discrete Fourier Transformation
JCR	: Joint Communication and Radar System
JRC	: Joint Radar and Communication System
LoS	: Line of Sight
OFDM	: Orthogonal Frequency Division Multiplexing
PMCW	: Phase Modulated Continuous Wave
PRBS	: Pseudo-Random Binary Sequence
PRF	: Pulse Repetition Frequency
QAM	: Quadrature Amplitude Modulation
RCS	: Radar Cross Section
RF	: Radio Frequency
SNR	: Signal-to-Noise Ratio
SVD	: Singular Value Decomposition

SYMBOLS

B	**:** Bandwidth
e	: Euler Constant
c	**:** Speed of Light
f	**:** Frequency
N	**:** Fast-Time Sampling Rate
M	**:** Slow-Time Sampling Rate
t	**:** Time
v	**:** Velocity of the targets
f_d	**:** Doppler frequency
H(f)	**:** Transfer function of a channel
Hz	**:** Hertz

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SIGNAL PROCESSING TECHNIQUES FOR JOINT COMMUNICATION AND RADAR SYSTEMS

SUMMARY

The development of a Joint Radar and Communication (JRC) system represents a cutting-edge approach to integrating radar and communication functionalities within a single framework. This project explores the design and simulation of such a system using MATLAB, focusing on achieving efficient resource utilization, reducing hardware complexity, and enhancing system performance. The motivation behind this integration lies in the increasing demand for technologies that support seamless communication and precise sensing capabilities in modern wireless systems. By combining these two functionalities, the JRC system aims to achieve spectrum efficiency, cost reduction, and improved network performance.

The radar subsystem is designed to detect and track targets by estimating critical parameters such as range, velocity, and angle. It operates at a carrier frequency of 24 GHz, utilizing a 100 MHz bandwidth to achieve high-resolution sensing. Advanced signal processing techniques, including range-Doppler analysis, are employed to ensure accurate target localization and motion tracking. On the other hand, the communication subsystem transmits modulated data streams to a user, prioritizing high data rates and reliable information transfer. By embedding communication data into Phase Modulated Continuous Waveforms (PMCW) and using Binary Phase Shift Keying (BPSK) modulation, the system achieves dual functionality without compromising either aspect.

One of the key innovations of this project is the multibeam optimization algorithm implemented using Singular Value Decomposition (SVD). This algorithm enables efficient resource allocation, allowing the system to prioritize either radar or communication functions based on the requirements of the application. Matched filter processing is applied to enhance communication data recovery, while Doppler processing ensures accurate estimation of target velocity. The system also addresses

real-world challenges, such as noise interference, multipath propagation, and Doppler shifts, by incorporating advanced channel modeling and equalization techniques.

Initial results demonstrate the system's robustness and reliability. The radar subsystem successfully detects and tracks targets within a maximum range of 200 meters, achieving precise velocity and range measurements. The communication subsystem maintains a low Bit Error Rate (BER) even in the presence of noise and channel impairments, ensuring high data transmission accuracy. A constellation diagram analysis further validates the system's performance, showing minimal deviations in the received symbols from their ideal positions.

Despite these achievements, the project acknowledges several challenges and areas for improvement. Residual channel impairments, such as amplitude and phase distortions, highlight the need for more sophisticated channel estimation techniques. Enhancing Doppler compensation capabilities and integrating noise reduction algorithms could further improve system performance. Future iterations of the project could explore the use of machine learning algorithms for adaptive channel estimation and advanced waveform design to optimize radar-communication coexistence.

The potential applications of the JRC system extend across various domains, including autonomous vehicles, military operations, and industrial IoT. In automotive systems, the technology could enable simultaneous navigation and vehicle-to-vehicle communication, enhancing safety and efficiency. Military applications could benefit from improved situational awareness and secure data transfer, while industrial systems could leverage the technology to integrate sensing and communication in smart infrastructure.

Overall, this project establishes a strong foundation for the development of integrated radar and communication systems. By leveraging advanced signal processing techniques and addressing the challenges of resource sharing, the JRC framework demonstrates its feasibility and potential for real-world implementation. Future work will focus on optimizing system parameters, validating simulation results with hardware prototypes, and expanding the system's capabilities to meet the demands of emerging technologies.

ORTAK İLETİŞİM VE RADAR ALGILAMA SİSTEMİ İÇİN SİNYAL İŞLEME TEKNİKLERİ

ÖZET

Ortak İletişim ve Radar Algılama (JRC) sistemi, radar ve iletişim işlevlerini tek bir çerçevede birleştiren yenilikçi bir yaklaşımı temsil eder. Bu proje, MATLAB kullanarak böyle bir sistemin tasarımını ve simülasyonunu incelemektedir ve kaynak kullanımında verimlilik, donanım karmaşıklığının azaltılması ve sistem performansının artırılmasına odaklanmaktadır. Bu entegrasyonun arkasındaki motivasyon, modern kablosuz sistemlerde kesintisiz iletişim ve hassas algılama yeteneklerini destekleyen teknolojilere olan artan taleptir. Radar ve iletişim işlevlerini birleştirerek, JRC sistemi spektrum verimliliği, maliyet azaltımı ve geliştirilmiş ağ performansı sağlamayı amaçlamaktadır.

Radar alt sistemi, mesafe, hız ve açı gibi kritik parametreleri tahmin ederek hedefleri tespit etmek ve takip etmek için tasarlanmıştır. Sistem, yüksek çözünürlüklü algılama sağlamak için 24 GHz taşıyıcı frekansında çalışır ve 100 MHz bant genişliği kullanır. Kesin hedef konumlandırması ve hareket takibi sağlamak için ileri sinyal işleme teknikleri, özellikle mesafe-Doppler analizi, kullanılır. İletişim alt sistemi ise modüle edilmiş veri akışlarını kullanıcıya iletir ve yüksek veri hızları ile güvenilir bilgi aktarımını önceliklendirir. İletişim verilerinin Faz Modüleli Sürekli Dalga (PMCW) sinyallerine gömülmesi ve Binary Phase Shift Keying (BPSK) modülasyonu kullanılması sayesinde sistem, her iki fonksiyonu da ödün vermeden gerçekleştirebilir.

Projenin kilit yeniliklerinden biri, Tekil Değer Ayrıştırma (SVD) kullanılarak uygulanan çoklu ışın optimizasyon algoritmasıdır. Bu algoritma, sistemin uygulamanın ihtiyaçlarına göre radar veya iletişim fonksiyonlarına öncelik vermesine olanak tanıyarak kaynak tahsisini verimli hale getirir. İletişim verilerinin kurtarılmasını iyileştirmek için eşleştirilmiş filtreleme işlemleri uygulanırken, Doppler işlemleri hedef hızının doğru tahmin edilmesini sağlar. Sistem ayrıca, gelişmiş kanal modelleme ve eşitleme tekniklerini entegre ederek gürültü girişimi, çoklu yol yayılımı ve Doppler kaymaları gibi gerçek dünya zorluklarını ele almaktadır.

İlk sonuçlar, sistemin sağlamlığını ve güvenilirliğini ortaya koymaktadır. Radar alt sistemi, maksimum 200 metre mesafede hedefleri başarıyla algılar ve takip ederken, hassas hız ve mesafe ölçümleri sağlar. İletişim alt sistemi ise gürültü ve kanal bozulmalarına rağmen düşük Bit Hata Oranı (BER) ile veri iletim doğruluğunu korur. Bir takımyıldız diyagramı analizi, sistemin performansını doğrular ve alınan sembollerin ideal konumlarına yakın olduğunu gösterir.

Bu başarılara rağmen, proje birkaç zorluğu ve iyileştirme alanını kabul etmektedir. Amplitüd ve faz bozulmaları gibi artık kanal bozulmaları, daha sofistike kanal tahmin tekniklerine olan ihtiyacı vurgulamaktadır. Doppler telafisi yeteneklerini geliştirmek ve gürültü azaltma algoritmalarını entegre etmek, sistem performansını daha da artırabilir. Projenin gelecekteki iterasyonlarında, adaptif kanal tahmini için makine öğrenimi algoritmalarının kullanımı ve radar-iletişim uyumunu optimize etmek için ileri dalga formu tasarımı araştırılabilir.

JRC sisteminin potansiyel uygulamaları, otonom araçlar, askeri operasyonlar ve endüstriyel IoT gibi çeşitli alanlara uzanmaktadır. Otomotiv sistemlerinde bu teknoloji, güvenliği ve verimliliği artırarak eşzamanlı navigasyon ve araçtan araca iletişim sağlayabilir. Askeri uygulamalar, gelişmiş durum farkındalığı ve güvenli veri aktarımından faydalanabilirken, endüstriyel sistemler bu teknolojiyi akıllı altyapılarda algılama ve iletişimi entegre etmek için kullanabilir.

Genel olarak, bu proje, entegre radar ve iletişim sistemlerinin geliştirilmesi için sağlam bir temel oluşturmaktadır. Gelişmiş sinyal işleme tekniklerinden yararlanarak ve kaynak paylaşımı zorluklarını ele alarak, JRC çerçevesi, uygulanabilirliğini ve gerçek dünya uygulamaları için potansiyelini göstermektedir. Gelecekteki çalışmalar, sistem parametrelerinin optimize edilmesine, simülasyon sonuçlarının donanım prototipleriyle doğrulanmasına ve sistemin ortaya çıkan teknolojilerin taleplerini karşılamak için genişletilmesine odaklanacaktır.

1. INTRODUCTION

The ever-growing demand for seamless communication and enhanced situational awareness necessitates innovative solutions that push the boundaries of conventional technologies. Joint Radar and Communication System (JRC) emerges as a promising approach, aiming to integrate communication and radar functionalities within a single system [1]. This unification offers significant advantages, including spectrum efficiency, hardware cost reduction, and improved network performance.

The JRC system demonstrates the feasibility of combining radar and communication functionalities, showcasing the potential for seamless integration in future technologies [2][3]. By leveraging shared resources, the system achieves cost and power efficiency while maintaining high performance in both radar sensing and communication tasks. This dual capability positions JRC systems as a critical component in emerging applications that demand high data rates and precise sensing capabilities [4].

1.1 Purpose of Project

This project delves into the implementation of JRC technology using a robust MATLAB program. A key challenge lies in optimizing beamforming and signal structures to cater to the inherent differences between communication and radar systems. The JRC system consists of two main components: a radar subsystem for detecting and tracking targets and a communication subsystem for transmitting data to a user [4]. The radar functionality includes the estimation of key parameters such as target range, velocity, and angle using high-resolution radar waveforms [2]. Simultaneously, the communication system transmits modulated data streams to a user while accounting for real-world impairments like noise, multipath propagation, and Doppler effects. Communication systems prioritize high data rates and reliable information transfer, while radar systems focus on accurate target detection and parameter estimation.

1.2 Literature Review

The integration of communication and radar systems, known as Joint Radar and Communication system (JRC), has garnered significant attention due to its potential to unify both functionalities into a single system. This convergence leverages shared hardware and signal processing techniques to enhance spectrum efficiency, reduce device size and cost, and improve performance for both communication and radar applications [1], [5]. Advanced signal processing methods are crucial for effectively merging these functionalities, encompassing aspects such as transmission signal design and receiver processing [6].

The literature on JRC systems identifies three main approaches: communication-centric, radar-centric, and joint design and optimization. In communication-centric designs, radar sensing capabilities are integrated into existing communication systems with minimal changes to the primary communication signals. This often requires enhancements to hardware and algorithms to accommodate radar functions, though the sensing performance can vary based on specific scenarios [2]. Conversely, radar-centric designs embed communication functionalities into radar systems, maintaining the core radar operations largely intact. This allows for near-optimal radar performance but often limits the achievable data rates for communication [5]. The joint design and optimization approach represents a comprehensive integration where systems are developed from the ground up to balance both communication and radar functions. This approach employs techniques like waveform optimization to achieve a flexible trade-off between the two domains, ensuring efficient and adaptable system performance [1].

Despite the promising benefits, integrating communication and radar systems presents challenges such as achieving full-duplex operation, designing compatible signals, and addressing synchronization issues. However, the overlapping signal processing algorithms and hardware components offer opportunities for improved resource utilization and system efficiency [6]. Applications of JRC systems span various fields, including intelligent vehicular networks and broader Internet of Things (IoT) scenarios, demonstrating the wide-reaching implications and potential of this emerging research area [2].

Ongoing research and advancements in JRC systems emphasize the critical role of signal processing in achieving seamless integration of communication and radar functionalities [4]. These developments promise to enhance both the capabilities and applications of communication and radar technologies, paving the way for innovative solutions in various sectors [5].

2. JRC SYSTEM DESIGN

The progress of the project is divided into sub-topics in this part. Critical areas for implementation can be seen here as 5 categories:

1. Radar system.
2. Communication system.
3. JRC system.
4. JRC with PMCW.
5. JRC with OFDM.

2.1 Radar System

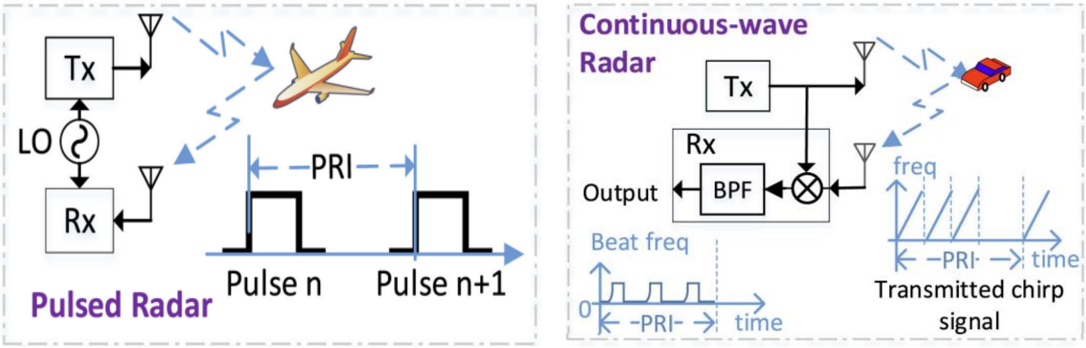

Figure 2.1 Illustration of Basic Pulsed Radar (left) & Continuous-wave Radar (right)[1].

The radar sensing component of the JRC system is responsible for detecting, localizing, and tracking targets in the environment. It operates using advanced radar waveforms and processing techniques to estimate key parameters such as range, velocity, and angles of the targets relative to the radar platform.

$$y_R(t) = \sum_{m=1}^{M_T} \sum_{l=1}^{L} b_l \psi_m(t-\tau_l) e^{j2\pi f_{D,l} t} a(M_R, \Phi_l) a^T(M_T, \theta_l) w_m \quad (2.1)$$

Equation in 2.1 models the received radar signal at time "$y_R(t)$" as a summation of contributions from multiple transmit antennas and multiple targets. "b_l" is the reflection coefficient of the "*l-th*" target. "$b_l \psi_m(t-\tau_l)$" defines the transmitted waveform from the m-th antenna, delayed by "τ_l", the time delay for the "*l-th*" target. This models the time-delay caused by the distance between radar and the target figure. "$e^{j2\pi f_{D,l} t}$" emphasizes the Doppler-shift term for the "*l-th*" target which accounts for the frequency shift caused by the relative velocities of the targets where $f_{D,l}$ is the Doppler frequency shift. "$a(M_R, \Phi_l)$" is the receive array steering vector for the targets which is dependent on the receive antenna configuration (M_R) and the arrival-angle (Φ_l). Likewise, "$a^T(M_T, \theta_l)$" is the transmit array steering vector for the targets, dependent on the transmit-antenna configuration (M_T) and departure-angle (θ_l). Finally, "w_m" defines the weights applied by the transmitted waveforms.

2.1.1 Radar parameters and components

○ **Carrier Frequency and Bandwidth**: Radar frequency is the oscillation rate of the electromagnetic wave emitted by a radar system and is usually expressed in Hertz (Hz). Radar frequency is defined by the carrier frequency of the system. Radar systems generally use the electromagnetic spectrum between 3 MHz and 300 GHz [3].

The bandwidth of the radar refers to the frequency range of the electromagnetic signal it emits and is directly related to the resolution of the signal. Higher bandwidth allows the radar to distinguish targets with higher resolution. Formulas for frequency and range can be seen in 2.2 and 2.3.

$$f = \frac{c}{\lambda} \tag{2.2}$$

$$\Delta R = \frac{c}{2B} \tag{2.3}$$

Frequency Band	Bandwidth
HF (3-30 MHz)	10-100 m
VHF (30-300 MHz)	1-10 m
UHF (300-1000 MHz	0.3-1 m
L (1-2 GHz)	15-30 cm
S (2-4 GHz)	8-15 cm
C (4-8 GHZ)	4-8 cm
X (8-12 GHZ)	2.5-4 cm
Ku (12-18 GHz)	1.7-2.5 cm
K (18-27 GHz)	1.2-1.7 cm
Ka (27-40 GHz)	0.75-1.2 cm
W (40-300 GHz)	1-7.5 mm

Table 2.1 Frequency Bands and Bandwidths of Radar Systems.

○ **Peak Power**: Peak power of the radar refers to the maximum instantaneous power level of the electromagnetic signal sent by the radar transmitter. Peak power directly affects the radar's ability to detect targets and its detection range. This parameter is critical to optimizing the performance of the radar. In 2.4 and 2.5, formulas for the operating cycle of radar and peak power can be seen.

$$D = \frac{\tau}{T} \tag{2.4}$$

$$P_{avg} = P_{peak} \cdot D \tag{2.5}$$

○ **Target Characteristics**: RCS is a parameter that determines the target detection and separation ability of the radar. The target's size, shape, material, orientation and radar frequency affect RCS. High RCS facilitates radar detection, while low RCS enables target concealment. Particularly in military and civilian radar applications, RCS analysis plays a critical role in target detection and radar performance. In 2.6, the RCS formula can be seen. In the formula, $P_{scattered}$ and $P_{incident}$ represent the power reflected back to the radar receiver by the target and power density of radar waves reaching the target, respectively.

$$\sigma = \frac{P_{scattered}}{P_{incident}} \cdot 4\pi R^2 \tag{2.6}$$

2.1.2 Waveform generation

To achieve high-resolution sensing, the radar system generates Phase Modulated Continuous Wave (PMCW) signals[2]. A Pseudo-Random Binary Sequence (PRBS) serves as the base waveform, providing desirable properties such as low autocorrelation and good range resolution. Autocorrelation is a mathematical concept used to measure the similarity or correlation of a signal with a delayed version of itself over varying time lags. It is often used in signal processing, time series analysis, and statistics to identify repeating patterns, detect periodicity, or determine the predictability of a signal. Autocorrelation measures how well a signal matches with its own shifted versions.

The waveform generation process includes:

○ A PRBS sequence modulated with binary phase shift keying (BPSK) to embed communication data.
○ A waveform structure designed to support both radar and communication, enabling dual functionality.
○ In order to test the communication part, an OFDM signal will also be generated and evaluated for the radar part.

2.1.3 Signal transmission and reception

The radar transmits waveforms using an isotropic antenna, which radiates the signal in all directions. The transmitted signal interacts with targets in the environment, reflecting back towards the radar receiver. The received signal contains critical information about the target, including range, velocity, and angle. Key components in the signal processing chain include:

$$\psi_m(t) = \sum_{n \in S_m} \widehat{w_{m,n}} e^{j2\pi n f_0 t} g(t - kT_0) \tag{2.7}$$

The formula in 2.7 represents a time-domain signal $\psi_m(t)$ synthesized by summing a set of modulated waveforms. Here, m denotes the index of the current signal or channel, and t is time. The summation is over the set S_m, which contains indices $n$relevant to the signal m. The term $\widehat{w_{m,n}}$ represents complex weighting coefficients for each component in the summation, contributing to the amplitude and phase of the resulting waveform. The exponential term $e^{j2\pi n f_0 t}$ denotes a complex exponential representing a carrier wave at frequency f_0 where j is the imaginary unit. The function $g(t - kT_0)$ is a time-shifted base waveform or pulse, where $g(t)$ is the original waveform, k is an integer index for discrete time shifts, and T_0 is the time period or interval between pulses. This formula is typically used in communication systems for generating complex signals by combining modulated waveforms, often for applications like orthogonal frequency-division multiplexing (OFDM) or pulse shaping in digital communication.

○ **Radiator and Collector**: The Radiator and Collector are essential components of a radar system, responsible for transmitting and receiving electromagnetic signals. These components work in tandem to ensure efficient signal propagation and reception, enabling the radar system to detect and track targets effectively.

1. **Radiator**:
    - The radiator is the subsystem that emits electromagnetic waves into the environment. It is typically implemented using an antenna designed to operate at the radar's carrier frequency.
    - The design of the radiator is critical for ensuring optimal signal coverage and directionality.
    - The radiator's beamforming capabilities allow the radar to focus energy in specific directions, improving detection accuracy and range resolution.
2. **Collector:**
    - The collector is responsible for capturing the reflected signals (echoes) from targets. It typically uses the same antenna as the radiator in a monostatic radar configuration or a separate antenna in bistatic systems.
    - The collector must be sensitive enough to detect weak signals reflected from distant or small targets. This requires low-noise amplifiers (LNAs) and high-gain antennas to enhance the received signal strength.
    - The collector also plays a role in determining the angular position of the target by analyzing the direction of the incoming signal.

○ **Free Space Channel**: Simulates the propagation of radar signals, accounting for two-way travel between the radar and targets.

$$H(t) \ = \ \sum_{l=1}^{L} \quad b_l \delta(t - \tau_l - \tau_o(t)) e^{j2\pi(f_{D,l} + f_0(t))t} a(M_R, \phi_l) a^T(M_T, \theta_l) \quad (2.8)$$

The general channel model for radar in a JRC setup is given in the 2.8. In this model, "$H(t)$" represents the time-varying channel response. The summation accounts for Lmultipath components, with each path characterized by a complex gain "b_l", which reflects amplitude and phase changes. The term "$\delta(t - \tau_l - \tau_o(t))$" is a Dirac delta function indicating the delay for each path, combining a fixed delay "τ_l" and a time-varying delay $\tau_o(t)$. The exponential "$e^{j2\pi(f_{D,l} + f_0(t))t}$" represents the Doppler shift "$f_{D,l}$" due to motion and a possibly time-varying carrier frequency "$f_0(t)$". The vectors "$a(M_R, \phi_l)$" and "$a^T(M_T, \theta_l)$" describe the receive and transmit array responses, which depend on the number of antennas "M_R" and "M_T", and the angles of arrival "ϕ_l" and departure "θ_l" for each path. This model captures the dynamic and multipath nature of radar channels in JRC systems.

○ **Thermal Noise**: Modeled using receiver noise figure and reference temperature, ensuring realistic performance evaluation. It originates from the thermal agitation of electrons in the system's components, leading to a base level of noise that limits the sensitivity of the radar receiver. This noise influences the Signal-to-Noise Ratio (SNR), a key metric for determining the clarity and reliability of received signals. Managing thermal noise is essential for accurately processing radar signals, particularly in scenarios where weak signals must be detected against a noisy background.

2.1.4 Signal Processing

The received signal undergoes extensive processing to extract radar-specific information. In 2.9, the received noise-free radar signal, after propagating through the channel, can be seen.

$$y_R(t) = \sum_{m=1}^{M_T} \quad \sum_{l=1}^{L} \quad b_l \psi_m(t - \tau_l) e^{j2\pi f_{D,l} t} a(M_R, \phi_l) a^T(M_T, \theta_l) w_m \quad (2.9)$$

- **Match Filtering:** Matched filtering is a fundamental signal processing technique used in radar systems to maximize the signal-to-noise ratio (SNR) for detecting a known signal in the presence of noise. The primary purpose of matched filtering is to enhance the detectability of weak signals by correlating the received signal with a template of the expected signal.

  The received radar signal typically includes echoes from targets, represented as:

$$y(t) = \sum_{l=1}^{L} s(t - \tau_l)h_l + n(t) \tag{2.10}$$

  In 2.10, $s(t)$ is the transmitted signal, τ_l is the delay corresponding to each target, $h_l$is the channel coefficient, and $n(t)$ is the noise.

  The matched filter is designed to match the expected signal $s(t)$. It is essentially the time-reversed complex conjugate of the expected signal:

$$h_{MF}(t) = s^*(-t) \tag{2.11}$$

  The received signal $y(t)$ is convolved with the matched filter $h_{MF}(t)$ as shown below:

$$r(t) = y(t) * h_{MF}(t) \tag{2.12}$$

  This operation correlates the received signal with the template, effectively summing the signal components while spreading out the noise.

$$r(t) = \sum_{l=1}^{L} s(t - \tau_l)h_l + n_{filtered}(t) \tag{2.13}$$

  The output of the matched filter is a series of peaks corresponding to the echoes of the transmitted signal. Each peak indicates the presence of a target, with its position (delay) corresponding to the target's range.

  For its properties such as maximizing SNR, time delay estimation and robustness to noise, match filtering is applied.

- **FFT Analysis**: Fast Fourier Transform (FFT) is used in radar systems to convert received signals from the time domain into the frequency domain. This transformation is crucial for isolating reflected radar signals from the clutter of other data, such as noise, interference, or embedded communication signals, and for extracting meaningful information about the target.

FFT allows radar systems to isolate reflected signals that correspond to specific targets. This is done by focusing on the frequency shifts introduced by the target's motion or distance.

Communication data embedded in the radar waveform is often spectrally separable from the reflected radar signal. By analyzing the frequency spectrum, the FFT helps differentiate and filter out communication-related components.

- **Range-Doppler Analysis**: Range-Doppler analysis is a radar signal processing technique used to estimate and visualize the range and velocity of one or more targets. The output is presented as a range-Doppler map, a 2D matrix where one axis represents the target range and the other axis represents its relative velocity.

  The range-Doppler map is a visualization that combines range and velocity data for all detected targets. Each point in the map represents a detected target with its associated range and velocity. The intensity at each point indicates the signal strength or reflectivity of the target.

2.1.5 Radar performance

The simulation effectively demonstrates the radar’s ability to:

- Identify and localize targets in a 3D space.
- Track target motion in real time, including velocity and direction.
- Resolve multiple targets simultaneously using high-resolution waveforms.

By integrating advanced waveform design and signal processing techniques, the radar sensing component achieves high accuracy and reliability, making it a vital part of the JRC system. The flexibility and efficiency of this radar design showcase its potential for real-world applications, including automotive safety, surveillance, and smart infrastructure.

2.2 Communication System

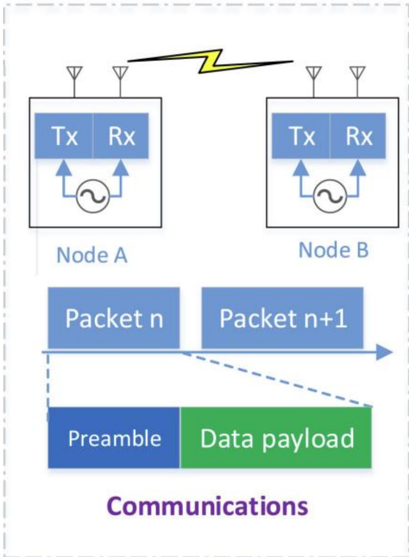

Figure 2.2 Illustration of Communication Systems. [1]

The communication subsystem uses advanced waveform design, signal processing, and channel modeling to simulate real-world transmission scenarios and evaluate performance under various conditions [3].

2.2.1 Waveform design for communication

The communication system employs the same waveform structure used by the radar, integrating communication data within the radar's PMCW signal. In order to test the radar part, an OFDM signal will also be generated and evaluated for the communication part[2]. Binary Phase Shift Keying (BPSK) modulation is used to encode the transmitted data, ensuring robustness and efficient use of bandwidth[2]. Key features of the waveform design include:

- **Data Embedding:** Communication data is modulated onto the radar waveform using BPSK [7]. This ensures compatibility with radar operations while transmitting information to the user.
- **Orthogonal Frequency Division Multiplexing (OFDM):** The base OFDM

waveform provides properties like low autocorrelation, which are beneficial for both radar sensing and communication[2]. It is combined with the BPSK-modulated data to create a dual-purpose waveform.

- **Frame Structure:** Each PMCW frame carries a set of transmitted bits, with the waveform designed to minimize interference between radar and communication functions.

2.2.2 Communication channel modeling

The communication channel is modeled to reflect real-world propagation effects, including line-of-sight (LOS) transmission, multipath reflections, and Doppler shifts. Key parameters include:

- **Line-of-Sight Delay**: The delay caused by the distance between the radar platform (JRC) and the user is calculated based on the speed of light. The LOS delay is determined by the distance vector.
- **Multipath Propagation**: The channel accounts for multiple paths with varying delays and gains, simulating the scattering and reflection effects commonly observed in wireless communication. The multipath components are defined with delays relative to the LOS path and corresponding average path gains.
- **Doppler Effects**: The maximum two-way Doppler shift is computed based on the relative velocity of moving targets and the user. This accounts for frequency shifts introduced by motion, which are critical for accurate signal decoding.

2.2.3 Signal transmission and reception

The communication waveform is transmitted through the modeled channel, where it experiences various impairments such as noise, fading, and Doppler shifts. The received signal is then processed to recover the transmitted data. Key steps in this process include:

- **Additive White Gaussian Noise (AWGN)**: The received signal is further degraded with AWGN to simulate realistic noise conditions. A certain user-defined Signal-to-Noise Ratio (SNR) is applied, ensuring that the signal quality is within an operational range.

- **Reshaping and Separation**: The received signal is reshaped into its original frame structure, and the communication data is separated from the radar-specific components using the known PRBS sequence.

2.2.4 Channel response and equalization

To mitigate the effects of multipath propagation and Doppler shifts, the system computes the channel response:

- **FFT Analysis**: The FFT of the received PRBS sequence is divided by the FFT of the transmitted PRBS to estimate the channel response.
- **Channel Equalization**: The received signal's frequency domain representation is equalized by compensating for the channel response. This step ensures accurate demodulation of the transmitted data [3].

2.2.5 Demodulation and decoding

The equalized signal is passed through an inverse FFT to retrieve the time-domain data. The system then performs the following steps:

- **Symbol Detection**: The maximum-likelihood detection of BPSK symbols is performed to identify the transmitted bits. The received symbols are normalized by the PRBS chip length for accurate decoding.
- **Demodulation**: The detected symbols are demodulated to recover the transmitted binary data.
- **Error Analysis**: A bit error rate (BER) calculation is conducted by comparing the transmitted data with the recovered data. This provides a quantitative measure of the communication system's performance.

2.2.6 Constellation diagram

A constellation diagram is a graphical representation used in digital communication systems to evaluate the performance of modulation schemes. It shows the received symbols as points in a complex plane, providing insight into the effects of noise, distortion, and channel impairments on the transmitted signal.

Components of a constellation diagram are:

- Reference points on the diagram represent the ideal positions of symbols in the modulation scheme.
- The actual points plotted on the diagram correspond to the received signal after demodulation.
- Noise and impairments cause these points to deviate from their reference positions.
- The spread of points around the reference positions indicates the level of distortion or noise in the system.
- A narrow spread indicates a high-quality signal, while a wide spread suggests significant noise or channel impairments.

2.2.7 Performance evaluation

The communication subsystem is evaluated for its ability to:

- Transmit and decode data accurately in the presence of noise and multipath effects.
- Maintain low bit error rates (BER) under realistic conditions.

By integrating advanced channel modeling, equalization techniques, and waveform design, the communication system demonstrates robust performance alongside the radar subsystem. This dual-purpose approach highlights the efficiency and versatility of the JRC system in simultaneously addressing sensing & communication demands.

2.3 JRC System

The Joint Radar and Communication (JRC) system is a cutting-edge approach to integrating radar and communication functionalities on a single platform. This integration addresses the challenges posed by an increasingly congested frequency spectrum and the growing demand for large bandwidths by both radar and communication systems. In a JRC system, radar and communication share the same platform and utilize a common transmit waveform, enabling efficient spectrum usage and hardware simplification.

Two primary approaches to waveform design for JRC systems are explored:

1. **PMCW-Based JRC System:** This approach is radar-centric, as Phase Modulated Continuous Wave (PMCW) is a waveform specifically tailored for

radar applications. It prioritizes radar sensing while embedding communication data within the radar waveform.

2. **OFDM-Based JRC System:** This approach is communication-centric, as Orthogonal Frequency Division Multiplexing (OFDM) is a waveform designed for communication. It adapts the communication waveform to perform radar functions, ensuring compatibility with communication requirements.

2.4 PMCW based JRC system

To explore advanced radar techniques, the system includes a preliminary implementation of Phase-Modulated Continuous Waveform[6][5]. The process of generating a Range-Doppler map with PMCW signal can be seen in Figure 2.4.

2.4.1 Radar Part

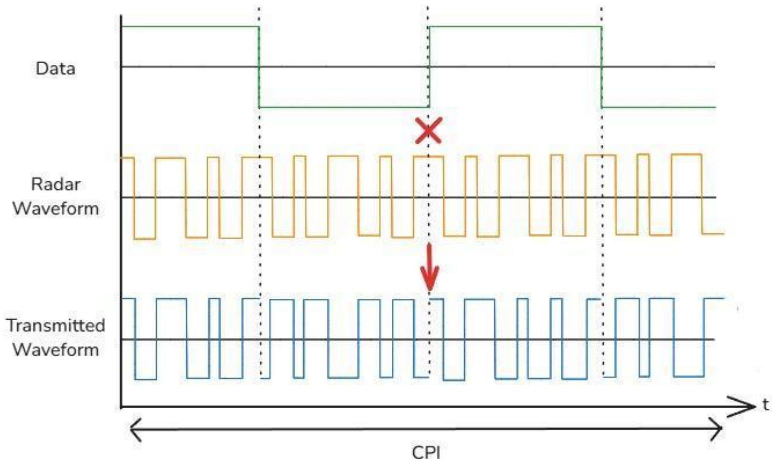

Figure 2.3 Modulation of PMCW signal with PRBS.

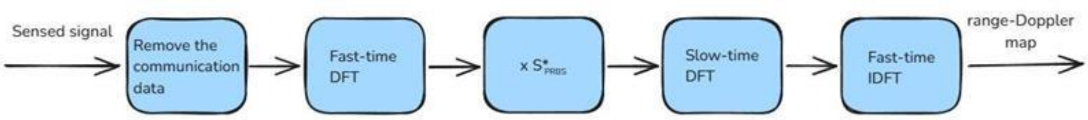

Figure 2.4 The Process of Generating a Range-Doppler Map with PMCW Signal.

1. **Remove the Communication Data**

- Radar signals can often also carry communication data (e.g. in integrated radar and communication systems). However, in order to focus on target information for radar analysis, the communication data must be removed. This step is done to isolate only the part of the signal that is suitable for radar processing.

$$r(t) = s_{radar}(t) + s_{comm}(t) + n(t) \tag{2.14}$$

$$s_{comm}(t) = \int_T r(t)p^*(t)dt \tag{2.15}$$

$$s_{radar}(t) = r(t) - \int_T r(t)p^*(t)dt \tag{2.16}$$

In 2.14, 2.15 and 2.16, the removal of the communication data from the sensed signal $r(t)$ can be seen. Here, $s_{radar}(t)$ represents the signal with information about radar targets, $s_{comm}(t)$ represents the communication data, $n(t)$ is the noise caused by the environment and $p^*(t)$ is a reference signal.

- The characteristics of the communication data are identified (e.g. a known pilot signal or coding method). Using this information, the communication data is extracted from the signal and the radar information is cleaned for processing.
- After this process, the signal contains only the part that will be used for radar target detection and analysis.

2. Fast-Time DFT

- In this step, the signal is converted from time domain to frequency domain. The term Fast-Time usually refers to the pulse data of the transmitted signal sampled in time. Information on the range of the targets is extracted from these fast-time samples.

$$S(f,m) = \sum_{n=0}^{N-1} s_{radar}(n,m)e^{-j2\pi f_n \Delta t} \tag{2.17}$$

In 2.17, $S(f,m)$ represents the signal in frequency domain while $s_{radar}(n,m)$ represents the signal in the time domain. N is the fast time sampling rate.

$$R = \frac{c \cdot \Delta t}{2} = \frac{c \cdot f}{2 \cdot B} \tag{2.18}$$

In 2.18, R is the distance between JRC system and targets and Δt is the return time of the radar signal.

- A Discrete Fourier Transform (DFT) or the more efficient Fast Fourier Transform (FFT) is applied to the signal received in the fast time axis. This transform extracts the frequency components used to obtain the target range information.
- Fast-time DFT is used to determine that targets are at different distances depending on the transmission and return times of the radar waves. The distance information corresponding to each target is revealed in this step.

3. **Multiplication with S*(PRBS)**

- PRBS (Pseudo-Random Binary Sequence) is a random binary sequence that serves as a reference for the modulation used in the radar signal. S*(PRBS) is the complex conjugate of this sequence.
- By multiplying the received radar signal by a known reference signal (e.g. correlation), the signal returned from targets can be more clearly analyzed. This process allows the signal to be free of interference and to focus on target information.

$$S'(f,m) = S(f,m) \cdot S^*_{PRBS}(f) \tag{2.19}$$

In 2.19, $S^*_{PRBS}(f)$ represents the complex conjugate of the PRBS and $S'(f,m)$ is the signal free of PRBS effects.

- The radar signal is multiplied by the complex conjugate of the transmitted PRBS code. This multiplication helps to clarify the target information in the signal and to separate it from other unnecessary information such as noise.
- The multiplication process reveals more distinct features in the signal related to the targets.

4. **Slow Time DFT**

- In radar systems, the slow time axis refers to the longer time scale between signal transmission times (e.g. the time between radar pulse transmissions). Data on this axis is used to analyze the Doppler shift.

- The purpose of this step is to extract velocity information of targets by analyzing Doppler frequencies.
- DFT is applied to the signal in the slow time axis. This process reveals the frequency components associated with the Doppler shifts of the targets. The Doppler shift represents the relative motion (i.e. velocity) of the target with respect to the radar antenna.

$$S(f,v) = \sum_{m=1}^{M-1} S'(f,m)e^{j2\pi vm\Delta t_s} \quad (2.20)$$

In 2.20, $S(f,v)$ represents the slow-time DFT result expressing Doppler frequency and Δts represents the slow-time sampling rate.

$$v = \frac{f_D\lambda}{2} \quad (2.21)$$

According to the formula in 2.21, Velocities of each target can be calculated.

- The slow-time DFT provides the velocity information of the targets and this information is used to generate the range-Doppler map.

5. Fast-Time Inverse Discrete Fourier Transform

- The Inverse Fourier Transform (IDFT) transforms the signal from the frequency domain back into the time domain. This process allows for easier interpretation of the signal in the time domain after frequency analysis.

$$s(n,v) = \frac{1}{N}\sum_{f=0}^{N-1} S(f,v)e^{j2\pi f_n\Delta t} \quad (2.22)$$

In 2.22, $s(n,v)$ represents the radar signal in the time domain.

- Once the processing in the frequency domain is complete, the signal is returned to the time domain, making it suitable for further processing. In addition, the IDFT signal is converted into data to be used in the range-Doppler map.

6. Range-Doppler Map

- This map shows the range and Doppler shift (velocity) of the targets in two dimensions. This is the most important output of the radar system for target detection and tracking.

$$\text{Range-Doppler Map} = |s(n, \upsilon)|^2 \tag{2.23}$$

Using the formula in 2.23, a Range-Doppler Map is calculated.

- Range information from Fast-Time DFT and Doppler information from Slow-Time DFT are combined. This information is visualized on a two-dimensional map. In this map, X-axis represents the Doppler frequency and the Y axis shows the range.

2.4.2 Communication Part

After the signal is received by radar, it is time to forward the information to the downlink user. The process of communication with the PMCW signal can be seen in Figure 2.5.

Figure 2.5 The Process of Communication with PMCW Signal.

1. **Fast-Time Discrete Fourier Transform**

- At this stage, the information of the signal on the time axis is converted to the frequency axis. The term “Fast-Time” refers to sampled data based on the transmission time of the signal and range information is usually obtained on this axis. The formulas for fast-time DFT and range calculation can be seen in 2.13 and 2.14.
- DFT is a mathematical tool that analyzes the time-domain components of a signal and converts them into frequency-domain components. Through this transformation, different frequency contents of the signal can be extracted. It is used in radar systems, especially to determine range information.
- This step yields the frequency components of the received signal. This information is used in the next steps to analyze target information and channel distortion.

2. Multiplication with S*(PRBS)

- The multiplication with S*(PRBS) process reveals more distinct features in the signal related to the targets. The formula for this step can be seen in 2.15.

3. Channel Equalization

- Radar signals are distorted from transmitter to receiver by the atmosphere, obstacles and multipath effects. These effects can change the amplitude, phase and timing information of the signal.
- The channel equalization process corrects these distortions and ensures that the signal is restored as close as possible to its original form. It is a critical step for the accurate extraction of target information.
- The transfer function of the channel is estimated. According to this transfer function, the received signal is corrected. Mathematically, the effects caused by the channel are inverted.

$$Z(f) = \frac{X\prime(f,m)}{H(f)} \tag{2.24}$$

In 2.24, $Z(f)$ represents the signal after channel equalization process and $X'(f,m)$ represents the signal after the multiplication with S*(PRBS).

- As the effects of the channel are corrected, the signal becomes more reliable for further processing.

4. Fast-Time IDFT

- Once the processing in the frequency domain is complete, the signal is returned to the time domain, making it suitable for further processing. In addition, the IDFT signal is converted into data to be used in the range-Doppler map. The formula for fast-time IDFT can be seen in 2.18.

5. Demodulation

- Demodulation is a process to remove the information-carrying part (the modulated component) from the received signal [7]. In radar or communication systems, modulation is usually performed on a carrier frequency and this carrier frequency needs to be removed.

2.5 OFDM based JRC system

To explore advanced communication techniques, the system includes a preliminary implementation of Orthogonal Frequency Division Multiplexing (OFDM) [6][5]. The process of generation a Range-Doppler Map with OFDM signal can be seen in Figure 2.6.

2.5.1 Radar Part

Figure 2.6 The Process of Generating a Range-Doppler Map with OFDM Signal.

1. **Removal of Cyclic Prefix[8]**

- The cyclic prefix is added at the beginning of symbols carrying data in OFDM signals and is used to reduce the effects of multipath propagation in the time domain.
- The receiver removes the cyclic prefix from the incoming signal to get to the actual symbol.

$$x_{rx}[n] = x_{rx,CP}[n + N_{CP}], n = 0,1,\ldots,N-1 \tag{2.25}$$

- This step is necessary to make the signal suitable for DFT because without the cyclic prefix the subcarriers in the frequency domain cannot be decomposed correctly [6].

2. **Fast-time DFT**

- This process allows the subcarriers to be decomposed and the data on each carrier can be used to study the effects of the channel or to decode the information content [9]. The formulas for fast-time DFT and range calculation can be seen in 2.17 and 2.18.

- In the context of radar, this step is done to increase the distance resolution of the signal. By being able to process the subcarriers independently of each other, the distance of multiple targets can be accurately measured.

3. Division by QAM Transmit Signal

- The transmitted QAM modulated signal is used to normalize the phase and amplitude information of the signal detected at the receiver.

$$H[k] = \frac{X[k]}{qamTx[k]} \tag{2.26}$$

In 2.26, $X[k]$ represents the signal obtained after fast-time DFT, $qamTx[k]$ is the transmitted OFDM symbol and $H[k]$ represents the channel response.

- This process allows the effects of the transmitted signal to be removed at the receiver. In particular, by removing the effects of the channel (e.g. attenuation, delay or phase shift), it allows the processing chain at the receiver to work more accurately [7].
- In the context of radar, this process allows the echo to be compared with the transmitted signal to extract target characteristics [6].

4. Slow-time DFT

- In this step, DFT is applied on multiple OFDM symbols to calculate the Doppler frequency components [9].
- The Doppler frequency represents the speed of the target relative to the radar source. Formulas for slow-time DFT and target velocities can be seen in 2.20 and 2.21.

5. Fast-time IDFT

- Once the processing in the frequency domain is complete, the signal is returned to the time domain, making it suitable for further processing. In addition, the IDFT signal is converted into data to be used in the Range-

Doppler map. The formula for fast-time IDFT can be seen in 2.22.

6. **Range-Doppler Map**

- This map shows the range and Doppler shift (velocity) of the targets in two dimensions. This is the most important output of the radar system for target detection and tracking. The formula for obtaining a Range-Doppler map can be seen in 2.23.
- Range information from Fast-Time DFT and Doppler information from Slow-Time DFT are combined. This information is visualized on a two-dimensional map. In this map, X-axis represents the Doppler frequency and the Y axis shows the range.

2.5.2 Communication Part

After the signal is received by radar, it is time to forward the information to the downlink user. The process of communication for the OFDM signal can be seen in Figure 2.8.

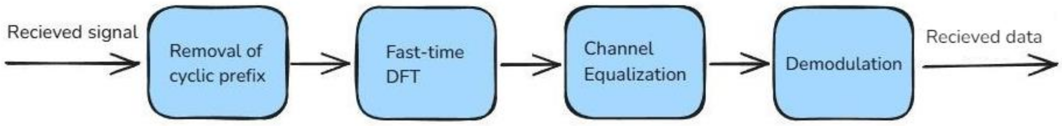

Figure 2.7 The Process of Communication with OFDM Signal.

1. **Removing of Cyclic Prefix [8]**

- This step is necessary to make the signal suitable for DFT because without the cyclic prefix the subcarriers in the frequency domain cannot be decomposed correctly [6]. The formula for this step can be seen in 2.25.

2. **Fast-Time DFT**

- In this stage, the time information in the received signal is converted into frequency information. This is a critical step, especially when analyzing range information and Doppler shifts of targets. The formulas for fast-time

DFT and range calculation can be seen in 2.17 and 2.18.

3. Channel Equalization

- The channel equalization process corrects the distortions from transmitter to receiver, caused by environmental effects, and ensures that the signal is restored as close as possible to its original form. It is a critical step for the accurate extraction of target information [6]. The formula for this step can be seen in 2.24.

4. Demodulation

- Demodulation is a process to remove the information-carrying part (the modulated component) from the received signal [7]. In radar or communication systems, modulation is usually performed on a carrier frequency and this carrier frequency needs to be removed.

The comparison of PMCW and OFDM waveforms can be seen in Figure 2.9.

Feature	PMCW	OFDM
Focus	Radar-centric	Communication-centric
Data Rate	Low	High
Range Accuracy	Strong	Moderate
Doppler Tolerance	Moderate	High

Table 2.2 The comparison of PMCW and OFDM waveforms.

3. PRACTICAL APPLICATION

The MATLAB code developed for the JRC system has been successfully implemented, as shown in the image below. The system's radar and communication functions are executed over two different waveform types. When the PMCW waveform is employed, a radar centric JRC system is established due to the inherent characteristics of the wave. Conversely, when the OFDM waveform is utilized, a more communication centric JRC system is formed. Through the radar system, target object detection, distance estimation, and Doppler estimation are performed. Meanwhile, data transfer is conducted as a result of the communication system. Subsequently, all these results undergo joint processing, and outputs for radar performance and communication performance are generated. In Figure 3.1, algorithmic flow of the practical application part can be seen.

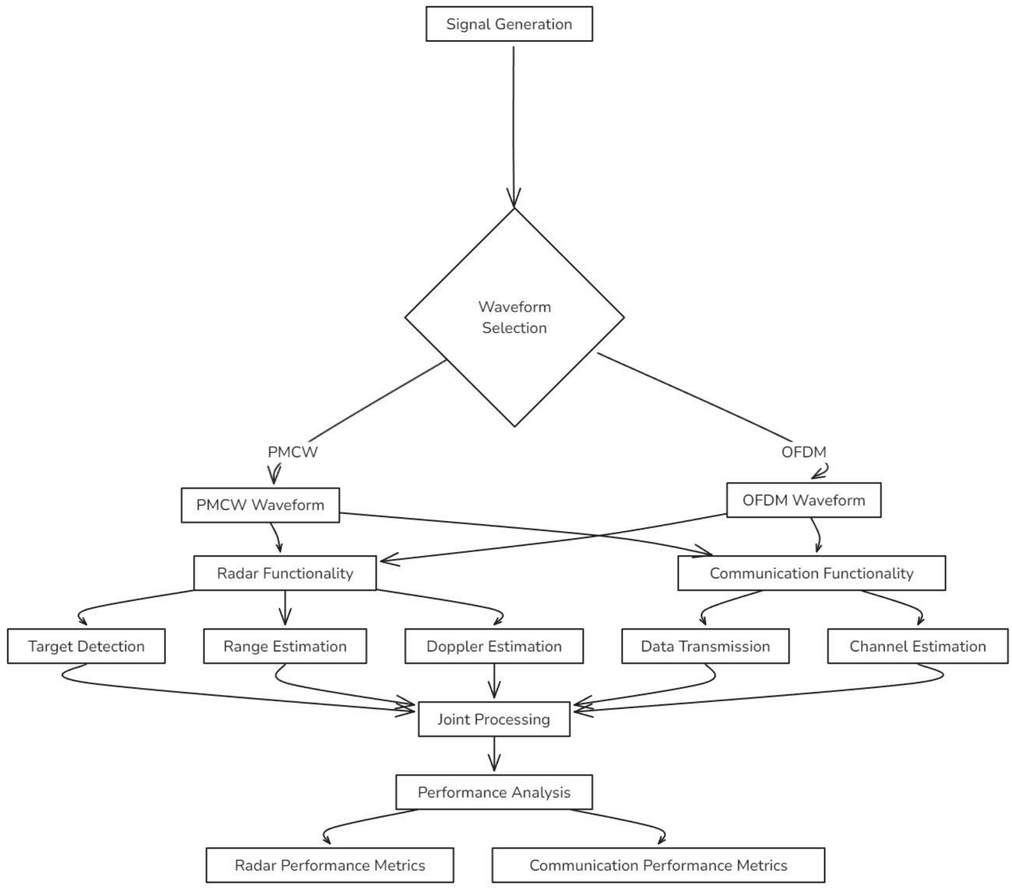

Figure 3.1 Diagram of the Algorithmic Flow.

3.1 MATLAB Simulation

In the first stage of the MATLAB simulation, the JRC system parameters and the location, speed and radar cross section properties of the target objects were determined.

- JRC system efficiency and observability were also taken into account;
- Carrier Frequency: 24GHz
- Bandwidth: 100 MHz
- Peak Power: 0.01 Watt
- Transmitter Antenna Gain: 20 dB
- Receiver Antenna Gain: 20 dB
- Noise Figure: 2.9 dB
- Reference Temperature: 290 K
- Maximum Range: 200 m
- Maximum Relative Velocity: 60 m/s

The JRC system is positioned motionlessly at the center point, namely [0,0,0], on the platform so that the system performance can be easily measured.

Three target objects were positioned on the platform at coordinates [85,15,0], [60,-5,0] and [45,0,0], and the velocities of these objects were given as [10,0,0], [-20,0,0] and [-18,0,0], respectively. The properties of target objects are assigned using the “phased toolbox”.

User coordinates are determined as [50,50,0].

```
rng('default');

basicParams = struct( ...
    'carrierFreq', 24e9, ...
    'bandwidth', 100e6, ...
    'peakPower', 0.01 , ...
    'TxAntennaGain', 20, ...
    'RxAntennaGain', 20, ...
    'noiseFigure', 2.9,...
    'refTemperature',290,...
    'maxRange',200,...
    'maxRelVelocity', 60 ...
);
```

```
JRCMotion = struct( ...
        'position', [0; 0; 0], ...
        'velocity', [0; 0; 0] ...
    );

JRCPlatform =  phased.Platform('InitialPosition',
JRCMotion.position , 'Velocity', JRCMotion.velocity);

target = struct( ...
         'positions' , [85 60 45; 15 -5 0; 0 0 0],...
         'velocities' ,  [10 -20 -18; 0 0 0; 0 0 0],...
         'radarCrossSection' ,  [1.8 5.3 3.8]...
    );

targetMotion = phased.Platform('InitialPosition',
target.positions, 'Velocity', target.velocities);

radarTarget = phased.RadarTarget('Model', 'Swerling1',
'MeanRCS', target.radarCrossSection, 'OperatingFrequency',
basicParams.carrierFreq);

userCoordinates = [50; 50; 0];

JRCGraph(JRCMotion.position, target.positions, userCoordinates,
target.velocities);
```

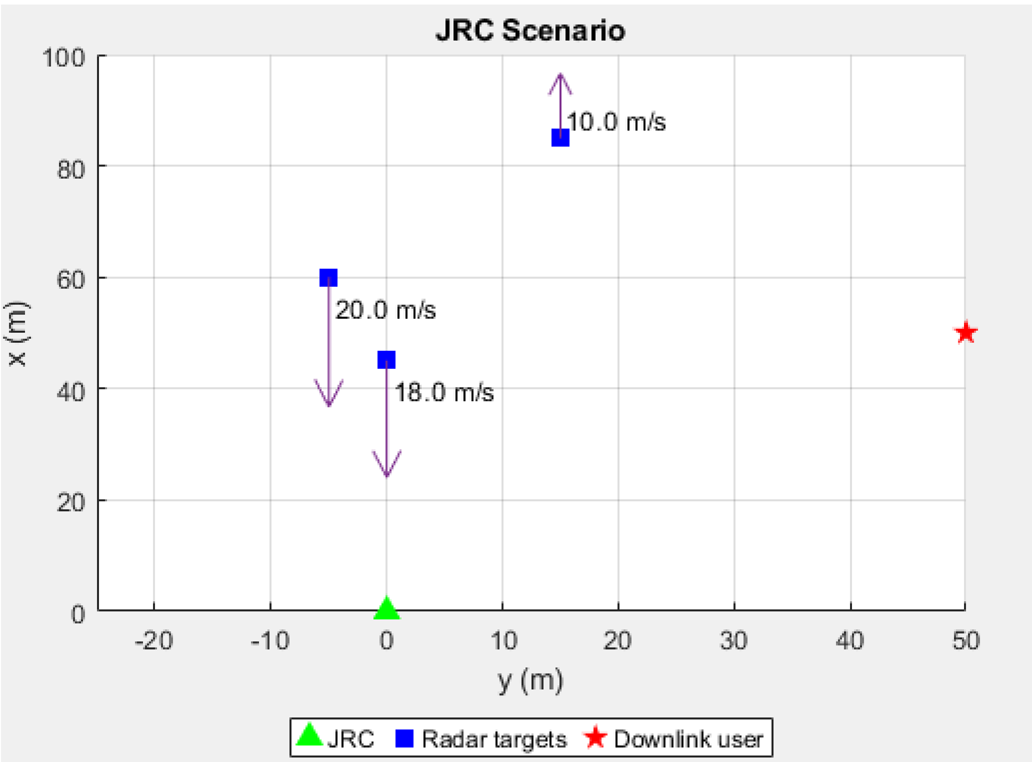

Figure 3.2 Platform that Shows JRC System, Targets and Downlink User.

3.2 PMCW Waveform

This MATLAB code initializes parameters and constructs waveforms for a communication system using Signal Processing Toolbox and custom functions. It defines a PRBS structure with properties such as the sequence order (PRBS.a), the generated sequence, the number of chips, the chip duration, and the modulation period. The PRBS sequence is generated using a helper function helperMLS, which produces a Maximum Length Sequence (MLS) based on the given order.

The Communication Data structure defines the transmitted data's properties, including the number of bits and a randomly generated binary sequence using randi. These binary bits are modulated into Phase-Shift Keying (PSK) symbols using the "pskmod" function.

The TransmitWaveform structure combines the PRBS sequence with the PSK-modulated symbols to form the transmitted waveform. The structure concatenates the PRBS sequence with the PSK symbols to create a two-dimensional waveform, where each row corresponds to a different signal component. The waveform's periodicity is set to twice the modulation period. This setup enables efficient generation and transmission of PSK-modulated waveforms with PRBS for synchronization or spreading purposes in a communication system.

```
PRBS = struct();
    PRBS.a = 8;
    PRBS.sequence = helperMLS(PRBS.a);
    PRBS.chipNumber = numel(PRBS.sequence);
    PRBS.chipDuration = 1/basicParams.bandwidth;
    PRBS.modPeriod = PRBS.chipNumber *  PRBS.chipDuration;

CommData = struct();
    CommData.bits = 256;
    CommData.binary =  randi([0, 1], [CommData.bits 1]);
    CommData.pskSymbols = pskmod(CommData.binary, 2);

TransmitWaveform = struct();
    TransmitWaveform.xWave = [PRBS.sequence * ones(1,
CommData.bits); PRBS.sequence * CommData.pskSymbols.'];
    TransmitWaveform.period = 2*PRBS.modPeriod;
```

3.2.1 Radar System

This MATLAB code simulates a radar system designed for transmitting and receiving waveforms, utilizing the Phased Array System Toolbox to model various system components and processes. The radar system is encapsulated within the RadarSim structure, which includes critical elements such as a transmitter (phased.Transmitter) configured with antenna gain and peak power, an isotropic antenna element (phased.IsotropicAntennaElement), and components for signal radiation and collection (phased.Radiator and phased.Collector). Additionally, a receiver (phased.ReceiverPreamp) is implemented to amplify incoming signals while introducing thermal noise, and a free-space channel model (phased.FreeSpace) is used to simulate two-way signal propagation.

The simulation runs in a loop for a series of bits specified in CommData.bits, where the motion of the radar platform (JRCMotion) and targets (targetMotion) is updated at each iteration. Range and angles to the targets are calculated using the rangeangle function. The transmitted signal undergoes various stages, including transmission, propagation, reflection, and reception, modeled within the TransmittedSignal structure. Noise is added to the received signals to simulate real-world conditions. The received signals are then processed into the FilteredSignal structure, where they are combined with PSK-modulated symbols to enhance signal quality. Fast Fourier Transform (FFT) is applied to both the received signal and the PRBS sequence to filter and analyze the signals, resulting in a frequency-domain signal (FilteredSignal.FDomSignal).

The range-Doppler response is computed using the phased.RangeDopplerResponse object, which applies FFT in the slow-time domain and inverse FFT in the fast-time domain to generate a range-Doppler map. This map provides insight into the target's range and relative velocity, with parameters such as operating frequency, sample rate, and PRF tailored to the transmitted waveform's period. Finally, the range-Doppler response is visualized using a 2D plot (imagesc), where the x-axis represents relative velocity, the y-axis represents range, and the color intensity in dB indicates signal strength. This comprehensive simulation integrates advanced signal processing and radar modeling techniques, making it a robust framework for developing and analyzing radar algorithms.

```
RadarSim = struct();
RadarSim.sampleFreq = basicParams.bandwidth;
RadarSim.transmitter = phased.Transmitter('Gain',
basicParams.TxAntennaGain, 'PeakPower', basicParams.peakPower);
RadarSim.antenna = phased.IsotropicAntennaElement;
RadarSim.radiator = phased.Radiator('Sensor', RadarSim.antenna,
'OperatingFrequency', basicParams.carrierFreq);
RadarSim.collector = phased.Collector('Sensor', RadarSim.antenna,
'OperatingFrequency', basicParams.carrierFreq);
RadarSim.reciever = phased.ReceiverPreamp('SampleRate',
RadarSim.sampleFreq, 'Gain', basicParams.RxAntennaGain,
'NoiseFigure', basicParams.noiseFigure, 'ReferenceTemperature',
basicParams.refTemperature);
RadarSim.channel = phased.FreeSpace('SampleRate',
RadarSim.sampleFreq, 'TwoWayPropagation', true,
'OperatingFrequency', basicParams.carrierFreq);
RadarSim.recievedYWave =  zeros(size(TransmitWaveform.xWave));



for loop = 1:CommData.bits


    [JRCMotion.position, JRCMotion.velocity] =
JRCPlatform(TransmitWaveform.period);
    [target.positions, target.velocities] =
targetMotion(TransmitWaveform.period);


    [targetRange, targetAngle] = rangeangle(target.positions,
JRCMotion.position);

    TransmittedSignal = struct();
    TransmittedSignal.signal =
RadarSim.transmitter(TransmitWaveform.xWave(:, loop));
    TransmittedSignal.radiatedSignal =
RadarSim.radiator(TransmittedSignal.signal, targetAngle);
    TransmittedSignal.channelEffect =
RadarSim.channel(TransmittedSignal.radiatedSignal,
JRCMotion.position, target.positions, JRCMotion.velocity,
target.velocities);
    TransmittedSignal.reflectedSignal =
radarTarget(TransmittedSignal.channelEffect, false);
    TransmittedSignal.receivedSignal =
RadarSim.collector(TransmittedSignal.reflectedSignal,
targetAngle);



    RadarSim.recievedYWave(:, loop) =
RadarSim.reciever(TransmittedSignal.receivedSignal);
end

FilteredSignal = struct();
FilteredSignal.recivedYWave =
RadarSim.recievedYWave(PRBS.chipNumber+1:end, :) .*
(CommData.pskSymbols.');
FilteredSignal.recivedYWave = FilteredSignal.recivedYWave +
RadarSim.recievedYWave(1:PRBS.chipNumber, :);
```

```
FilteredSignal.fftYWave = fft(FilteredSignal.recivedYWave);
FilteredSignal.fftSequence = fft(PRBS.sequence);
FilteredSignal.FDomSignal = FilteredSignal.fftYWave .*
conj(FilteredSignal.fftSequence);


RangeDopplerResponse = phased.RangeDopplerResponse( ...
    'RangeMethod', 'FFT', ...
    'SampleRate', RadarSim.sampleFreq, ...
    'SweepSlope', -basicParams.bandwidth / PRBS.modPeriod, ...
    'DopplerOutput', 'Speed', ...
    'OperatingFrequency', basicParams.carrierFreq, ...
    'PRFSource', 'Property', ...
    'PRF', 1 / TransmitWaveform.period, ...
    'ReferenceRangeCentered', false ...
);


[response, rangeGrid, dopplerGrid] = step(RangeDopplerResponse,
FilteredSignal.FDomSignal);

figure;
imagesc(dopplerGrid, rangeGrid, 10*log10(abs(response)));
set(gca, 'YDir', 'normal');
xlabel('Relative Velocity (m/s)');
ylabel('Range (m)');
colorbar;
title('Range-Doppler Response');
xlim([-basicParams.maxRelVelocity basicParams.maxRelVelocity]);
ylim([0 basicParams.maxRange]);
```

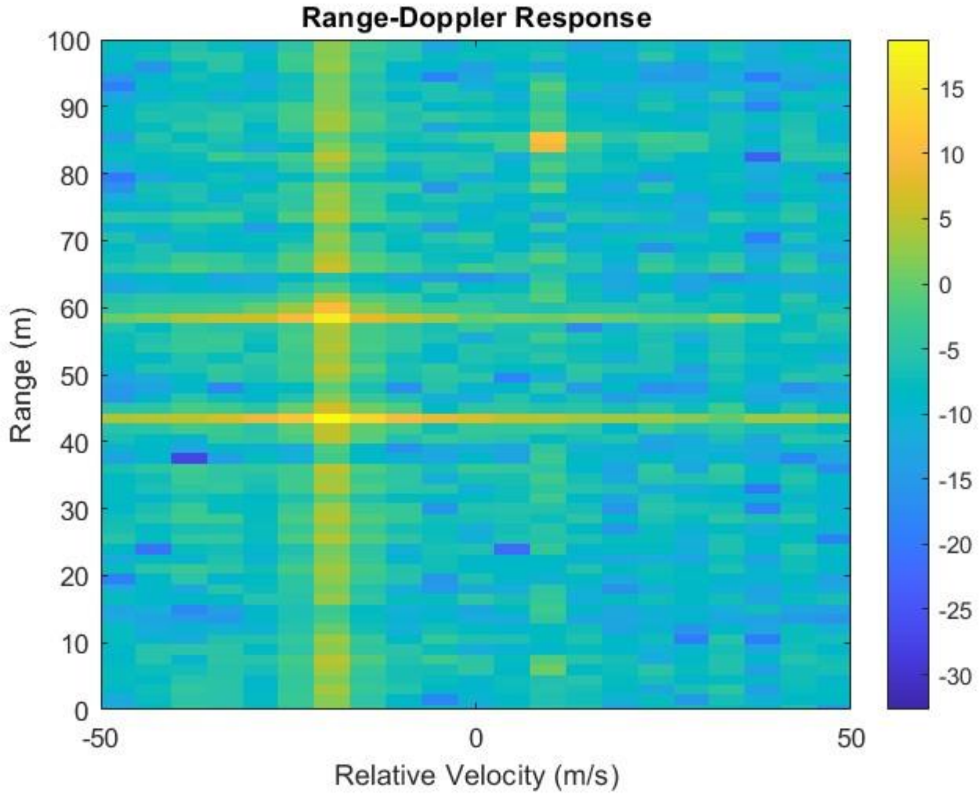

Figure 3.3 Range-Doppler Response of PMCW Waveform.

The Map presented in Figure 3.3 is a key output of the firstradar subsystem, providing a two-dimensional representation of target range and relative velocity. This map is generated by combining range information obtained from the Fast-Time Discrete Fourier Transform (DFT) and Doppler information derived from the Slow-Time DFT, enabling precise detection and tracking of targets.

The vertical axis as the range resolution axis of the map represents the range of detected targets. The radar system demonstrates high range resolution, which is achieved through the use of a wide bandwidth waveform. This allows for accurate separation of targets located at different distances.

The horizontal axis as Doppler Resolution represents the Doppler frequency, corresponding to the relative velocity of the targets. The map shows clear separation of Doppler shifts, indicating the radar's ability to distinguish between targets moving at different speeds.

Finally, the intensity of the colors in the map reflects the strength of the received signals, typically measured in decibels (dB). Brighter regions correspond to stronger reflections, which are often associated with larger or closer targets. This visualization is crucial for identifying and tracking targets, as it provides both spatial and motion information in a single map.

3.2.2 Communication System

This MATLAB code defines a CommSim structure to model the communication aspects of a joint radar-communication (JRC) system, including path delay, gain, and Doppler effects using the **Communications System Toolbox**. The system first calculates the line-of-sight (LOS) delay based on the Euclidean distance (vecnorm) between the radar's motion coordinates (JRCMotion.position) and user-defined coordinates (userCoordinates), divided by the speed of light (physconst('LightSpeed')). Multipath effects are introduced by adjusting the LOS delay with a set of predefined scaling factors and corresponding path gains.

The channel model is implemented using the comm.RicianChannel function, which accounts for both the LOS and multipath components. The channel includes parameters such as maximum Doppler shift, derived from the radar's maximum relative velocity (speed2dop) and the wavelength of the carrier frequency (freq2wavelen), as well as the predefined path delays and average path gains. The transmitted waveform (TransmitWaveform.xWave) is passed through the channel, and Additive White Gaussian Noise (AWGN) is added to simulate real-world signal degradation. The noisy transmitted signal is reshaped into a 2D array for further processing.

To analyze the received signal, FFT is applied to the first portion of the transmitted signal corresponding to the PRBS sequence, yielding the frequency response of the signal (CommSim.freqResponse). Similarly, the FFT is applied to the remaining part of the transmitted signal, which represents the frequency-domain received signal (CommSim.freqDomRecievedSig). The time-domain signal is reconstructed using the Inverse FFT (ifft), incorporating the frequency response to compensate for channel effects.

The signal's peak is identified using the maximum absolute value (max(abs())) in the time domain, and the received data is demodulated using Phase Shift Keying (PSK) demodulation (pskdemod). Finally, a constellation diagram (comm.ConstellationDiagram) is plotted to visualize the received PSK symbols, referencing a binary PSK constellation (pskmod([0 1], 2)). This process integrates radar and communication signals, demonstrating their coexistence in a shared framework, with robust handling of multipath effects, Doppler shifts, and noise.

```
CommSim = struct();
CommSim.DownlinkLOS = vecnorm(JRCMotion.position -
userCoordinates);
CommSim.LOS = CommSim.DownlinkLOS/physconst('LightSpeed');
CommSim.Delay = CommSim.LOS * [1 1.6 1.1 1.45] - CommSim.LOS;
CommSim.Gain = [0 -1 2 -1.5];
CommSim.dopplerFreq = 2 * speed2dop(basicParams.maxRelVelocity,
freq2wavelen(basicParams.carrierFreq));
CommSim.channel = comm.RicianChannel( ...
        'PathGainsOutputPort', true, ...
        'DirectPathDopplerShift', 0, ...
        'MaximumDopplerShift', CommSim.dopplerFreq / 2, ...
        'PathDelays', CommSim.Delay, ...
        'AveragePathGains', CommSim.Gain, ...
        'SampleRate', RadarSim.sampleFreq ...
    );
CommSim.SigNoiseRatio = 40;
CommSim.TXSignal =
reshape(awgn(CommSim.channel(TransmitWaveform.xWave(:)),
CommSim.SigNoiseRatio, 'measured'), 2*PRBS.chipNumber, []);
CommSim.freqResponse = fft(CommSim.TXSignal(1:PRBS.chipNumber,
:))./FilteredSignal.fftSequence;
CommSim.freqDomRecievedSig = fft(CommSim.TXSignal(PRBS.chipNumber
+ 1:end, :));
CommSim.timeDomSig = ifft((CommSim.freqDomRecievedSig .*
conj(FilteredSignal.fftSequence))./CommSim.freqResponse);


[~, index] = max(abs(CommSim.timeDomSig), [], 'linear');
CommSim.recievedData = pskdemod(CommSim.timeDomSig(index).' /
PRBS.chipNumber, 2);

diagConst = comm.ConstellationDiagram(...
    'NumInputPorts', 1, ...
    'ReferenceConstellation', pskmod([0 1], 2), ...
    'ChannelNames', {'Received PSK Symbols'});

diagConst(CommSim.timeDomSig(index).'./ PRBS.chipNumber(:));
```

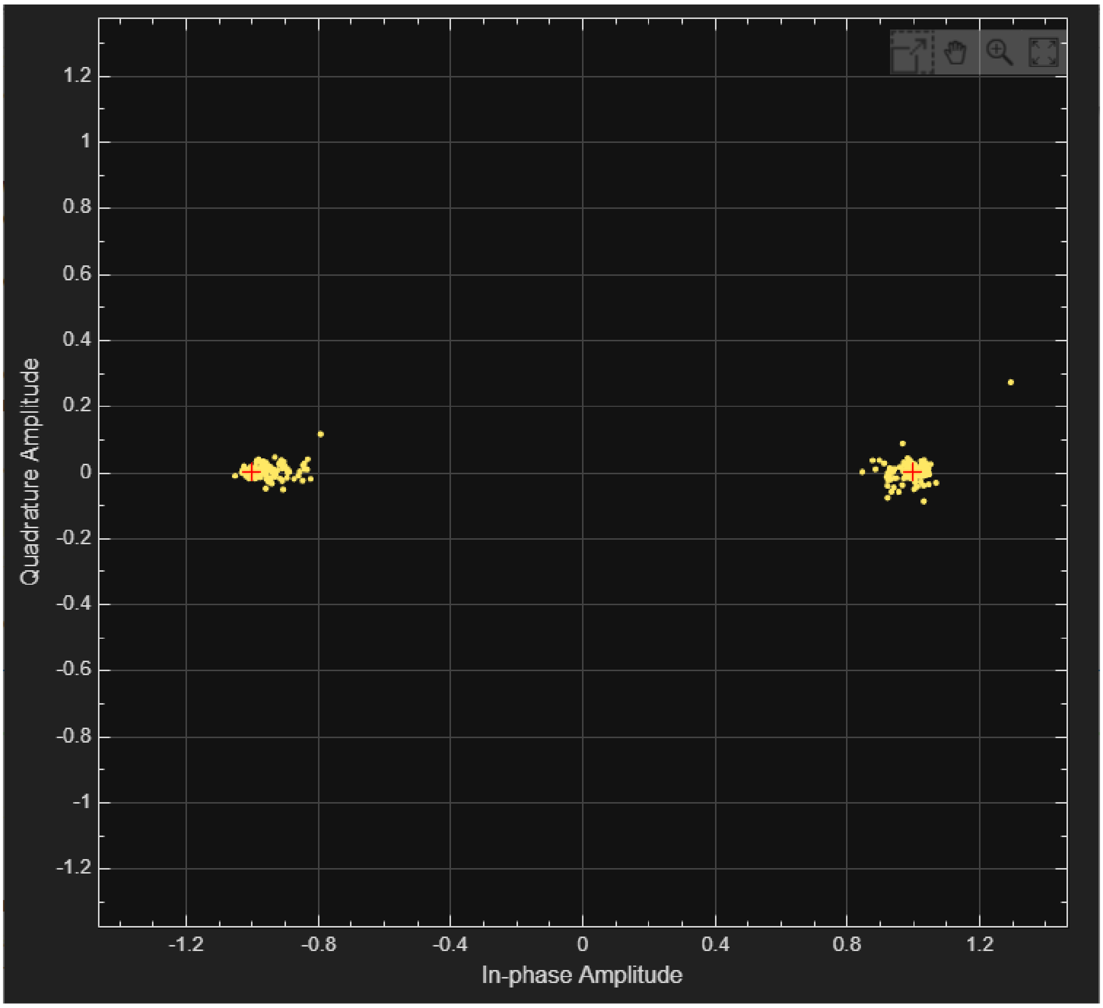

Figure 3.4 Constellation Diagram of the PMCW Waveform.

As a result, the Constellation Diagram presented in Figure 3.4 provides a graphical representation of the received symbols in the complex plane, allowing for an analysis of the effects of noise, distortion, and channel impairments on the transmitted signal.

The diagram shows the ideal positions of the transmitted symbols as reference points, which are determined by the modulation scheme used in the communication system. In this case, Binary Phase Shift Keying (BPSK) or Quadrature Amplitude Modulation (QAM) is likely employed.

The actual received symbols are plotted around the reference points. The spread of these points indicates the level of distortion or noise introduced during transmission and reception.

The tight clustering of the received symbols around the reference points suggests a high Signal-to-Noise Ratio (SNR), indicating that the communication system is robust against noise and interference.

Finally, Minimal deviations from the reference points imply a low Bit Error Rate (BER), which is a key performance metric for digital communication systems. This demonstrates the system's ability to reliably transmit data even in the presence of channel impairments.

This Figure highlights the effectiveness of the communication system in maintaining signal integrity. The minimal spread of the received symbols around their ideal positions indicates that the system successfully mitigates the effects of noise and distortion. This is achieved through advanced signal processing techniques, such as matched filtering, equalization, and channel estimation.

The diagram also validates the performance of the modulation scheme used. In the case of BPSK, the two distinct clusters of points (representing binary "0" and "1") are clearly separated, ensuring reliable demodulation. If QAM is used, the distinct grid-like structure of the constellation points confirms the system's ability to handle higher data rates while maintaining accuracy.

3.3 OFDM Waveform

This MATLAB code defines the structure for simulating an Orthogonal Frequency Division Multiplexing (OFDM) system using functions from the Communication System Toolbox. The OFDM structure configures the system's parameters, including the number of subcarriers, subcarrier separation, symbol duration, and cyclic prefix (CP) duration. It calculates the CP length based on the maximum range and sampling frequency, and defines the total symbol duration and data subcarriers by excluding reserved subcarriers. The TransmitData structure defines parameters for the transmitted data, such as the number of bits per symbol, modulation order, and number of OFDM symbols. The binary data to be transmitted is generated randomly using the randi function, creating a matrix of binary values with dimensions based on the number of data subcarriers and symbols. This setup provides the foundation for OFDM signal processing and transmission.

```
OFDM = struct();
OFDM.subcarrier = 1024;
OFDM.sep = basicParams.bandwidth/OFDM.subcarrier;
OFDM.duration = 1/OFDM.sep;
OFDM.CPDuration = range2time(basicParams.maxRange);
OFDM.CPLength = ceil(RadarSim.sampleFreq*OFDM.CPDuration);
OFDM.CPDuration = OFDM.CPLength/RadarSim.sampleFreq;
OFDM.symDur = OFDM.duration + OFDM.CPDuration;
OFDM.symNum = OFDM.subcarrier + OFDM.CPLength;
OFDM.dataSubcarrier = OFDM.subcarrier-length([1:9
(OFDM.subcarrier/2+1) (OFDM.subcarrier-8:OFDM.subcarrier)]');

    empIndex = [1:9 (OFDM.subcarrier/2+1) (OFDM.subcarrier-
8:OFDM.subcarrier)]';

TransmitData = struct();
TransmitData.bits = 6;
TransmitData.order = 2^TransmitData.bits;
TransmitData.numofSym = 128 ;

CommData.binary = randi([0,1],
[OFDM.dataSubcarrier*TransmitData.bits TransmitData.numofSym]);
```

3.3.1 Radar System

The MATLAB code which is shown below , simulates a JRC system using OFDM signals and the Phased Array System Toolbox. It begins by modulating the binary data using QAM and OFDM, creating the transmitted signal with cyclic prefix included. The radar simulation involves resetting the platform objects for the transmitter and targets. Within a loop for each OFDM symbol, the code updates the positions and velocities of the radar platform and targets, computes their ranges and angles (rangeangle), and processes the signal through transmission, radiation, channel effects, reflection, and reception using objects like RadarSim.transmitter, RadarSim.radiator, RadarSim.channel, and RadarSim.collector. The received radar signal is stored in receivedRadarSig.

The received signal is reshaped and demodulated using *ofdmdemod* and filtered by dividing it with the modulation symbols. Finally, phased.RangeDopplerResponse is used to compute the Doppler spectrum and range estimation via FFT in the slow-time domain and IFFT in the fast-time domain. The plotResponse function visualizes the range-Doppler map, showing Doppler vs. range performance for the transmitted OFDM signal. The plot limits are set based on the system's maximum relative velocity and range. This process enables the evaluation of radar and communication performance in a JRC framework.

```
TransmitData.modulated = reshape(ofdmmod(qammod(CommData.binary,
...
                                     TransmitData.order,
'InputType', 'bit', 'UnitAveragePower', true), ...
                                     OFDM.subcarrier,
OFDM.CPLength, empIndex), ...
                                     OFDM.symNum, ...
                                     TransmitData.numofSym);

recievedRadarSig =
zeros(size(TransmitData.modulated/max(sqrt(abs(TransmitData.modula
ted).^2), [], 'all')));


reset(JRCPlatform);
reset(targetMotion);


for loop = 1:TransmitData.numofSym
    [JRCMotion.position, JRCMotion.velocity] =
JRCPlatform(OFDM.symDur);

    [target.positions, target.velocities] =
targetMotion(OFDM.symDur);

    [targetRange, targetAngle] = rangeangle(target.positions,
JRCMotion.position);

    TransmittedSignal.signal =
RadarSim.transmitter(TransmitData.modulated(:, loop));

    TransmittedSignal.radiatedSignal =
RadarSim.radiator(TransmittedSignal.signal, targetAngle);

    TransmittedSignal.channelEffect =
RadarSim.channel(TransmittedSignal.radiatedSignal,
JRCMotion.position, target.positions, JRCMotion.velocity,
target.velocities);

    TransmittedSignal.reflectedSignal =
radarTarget(TransmittedSignal.channelEffect, false);

    TransmittedSignal.receivedSignal =
RadarSim.collector(TransmittedSignal.reflectedSignal,
targetAngle);

    recievedRadarSig(:, loop) =
RadarSim.reciever(TransmittedSignal.receivedSignal);
end

recievedRadarSig1 = reshape(recievedRadarSig,
OFDM.symNum*TransmitData.numofSym, 1);


TransmitData.demodulated = ofdmdemod(recievedRadarSig1,
OFDM.subcarrier, OFDM.CPLength, OFDM.CPLength, empIndex);
```

```
TransmitData.filtered =
TransmitData.demodulated./qammod(CommData.binary,
TransmitData.order, 'InputType', 'bit', 'UnitAveragePower', true);

RangeDopplerResponse2 = phased.RangeDopplerResponse('RangeMethod',
'FFT', 'SampleRate', RadarSim.sampleFreq, 'SweepSlope', -
basicParams.bandwidth/OFDM.symDur,...
    'DopplerOutput', 'Speed', 'OperatingFrequency',
basicParams.carrierFreq, 'PRFSource', 'Property', 'PRF',
1/OFDM.symDur, ...
    'ReferenceRangeCentered', false);

figure;
plotResponse(RangeDopplerResponse2, TransmitData.filtered, 'Unit',
'db');
xlim([-basicParams.maxRelVelocity basicParams.maxRelVelocity]);
ylim([0 basicParams.maxRange]);
```

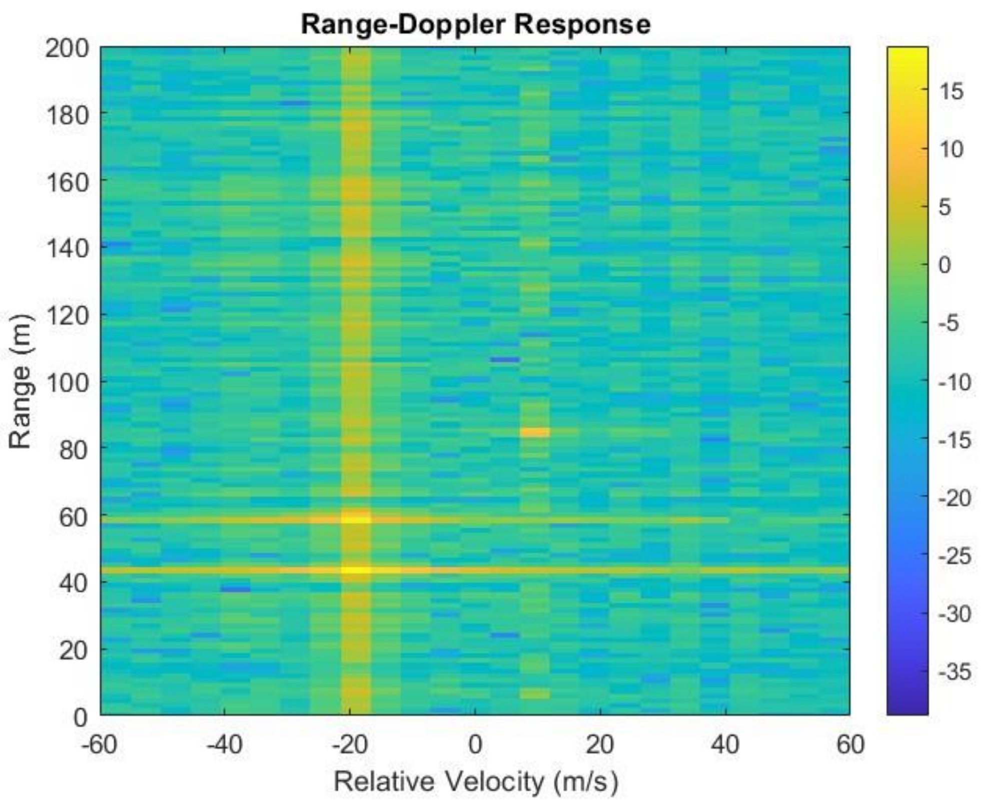

Figure 3.5 Range-Doppler Response of the OFDM Waveform.

The map presented in Figure 3.5 combines range information obtained from the Fast-Time Discrete Fourier Transform (DFT) and Doppler information derived from the Slow-Time DFT, providing a two-dimensional representation of the target's range and relative velocity.

The horizontal axis represents the Doppler frequency, which corresponds to the relative velocity of the target with respect to the radar system. Clear separation of Doppler shifts indicates the radar's ability to distinguish between targets moving at different velocities.

The vertical axis represents the range, or the distance of the target from the radar. The map demonstrates precise range resolution, which is achieved through the high bandwidth of the radar waveform.

The color intensity in the map, which is measured in decibels (dB), indicates the strength of the reflected signal. Stronger reflections correspond to brighter regions, which are likely caused by larger or closer targets.

In general the Figure 3.5 highlights the radar subsystem's capability to detect and track multiple targets simultaneously. The distinct peaks in the map suggest that the radar can effectively resolve targets in both range and velocity domains. The high resolution in both axes is a result of advanced signal processing techniques, including the use of Fast-Time DFT for range estimation and Slow-Time DFT for Doppler analysis. These techniques ensure accurate detection of target parameters, even in the presence of noise and interference. Also, the minimal noise artifacts in the map indicate that the radar system is robust against environmental disturbances and channel impairments. This robustness is further enhanced by the integration of matched filtering and Doppler compensation techniques.

3.3.2 Communication System

The MATLAB code, which can be seen below , models the channel response for an OFDM-based communication system using Communication System Toolbox and related utilities. The transmitted signal is generated by modulating binary data using QAM and OFDM. The OFDM signal passes through a Rician channel, which returns the channel-propagated signal and path gains. Additive white Gaussian noise is added to the signal using "*awgn*" to simulate real-world noise conditions.

The channel information, such as filter coefficients and filter delay, is extracted using the "*info*" function. The OFDM channel response is computed using a custom function *"ofdmChannelResponse"*, considering the subcarrier indices and channel delay.

The received signal is processed by demodulating the OFDM signal, followed by zero-forcing equalization to mitigate channel effects using the computed OFDM channel response. The equalized signal is then demodulated back to binary data using QAM demodulation.

To visualize the system's performance, the received QAM symbols are plotted on a constellation diagram using the "*comm.ConstellationDiagram object*", with reference symbols based on the modulation order. This allows for performance analysis of the received signal, showing deviations from the ideal constellation points due to channel impairments and noise.

```
ChannelResponse = struct();


[propagation, PG] =
CommSim.channel(ofdmmod(qammod(CommData.binary, ...
                                     TransmitData.order,
'InputType', 'bit', 'UnitAveragePower', true), ...
                                     OFDM.subcarrier,
OFDM.CPLength, empIndex));

ChannelResponse.propagation = awgn(propagation,
CommSim.SigNoiseRatio, "measured");


ChannelResponse.PF =
info(CommSim.channel).ChannelFilterCoefficients;
ChannelResponse.OF = info(CommSim.channel).ChannelFilterDelay;
ChannelResponse.ofdm = ofdmChannelResponse(PG, ChannelResponse.PF,
OFDM.subcarrier, OFDM.CPLength, setdiff(1:OFDM.subcarrier,
empIndex), ChannelResponse.OF);

ChannelResponse.QAMEqualized =
ofdmEqualize(ofdmdemod([ChannelResponse.propagation(ChannelRespons
e.OF+1:end,:); ...
                    zeros(ChannelResponse.OF, 1)],
OFDM.subcarrier, OFDM.CPLength, OFDM.CPLength/2, empIndex), ...
                    ChannelResponse.ofdm(:), 'Algorithm', 'zf');


CommSim.recievedData = qamdemod(ChannelResponse.QAMEqualized,
TransmitData.order, 'OutputType', 'bit', 'UnitAveragePower',
true);


diagConst = comm.ConstellationDiagram('NumInputPorts', 1, ...
    'ReferenceConstellation', qammod(0:TransmitData.order-1,
TransmitData.order, 'UnitAveragePower', true), 'ChannelNames',
{'Received QAM Symbols'});
```

```
diagConst(ChannelResponse.QAMEqualized(1:OFDM.dataSubcarrier*10).'
);
```

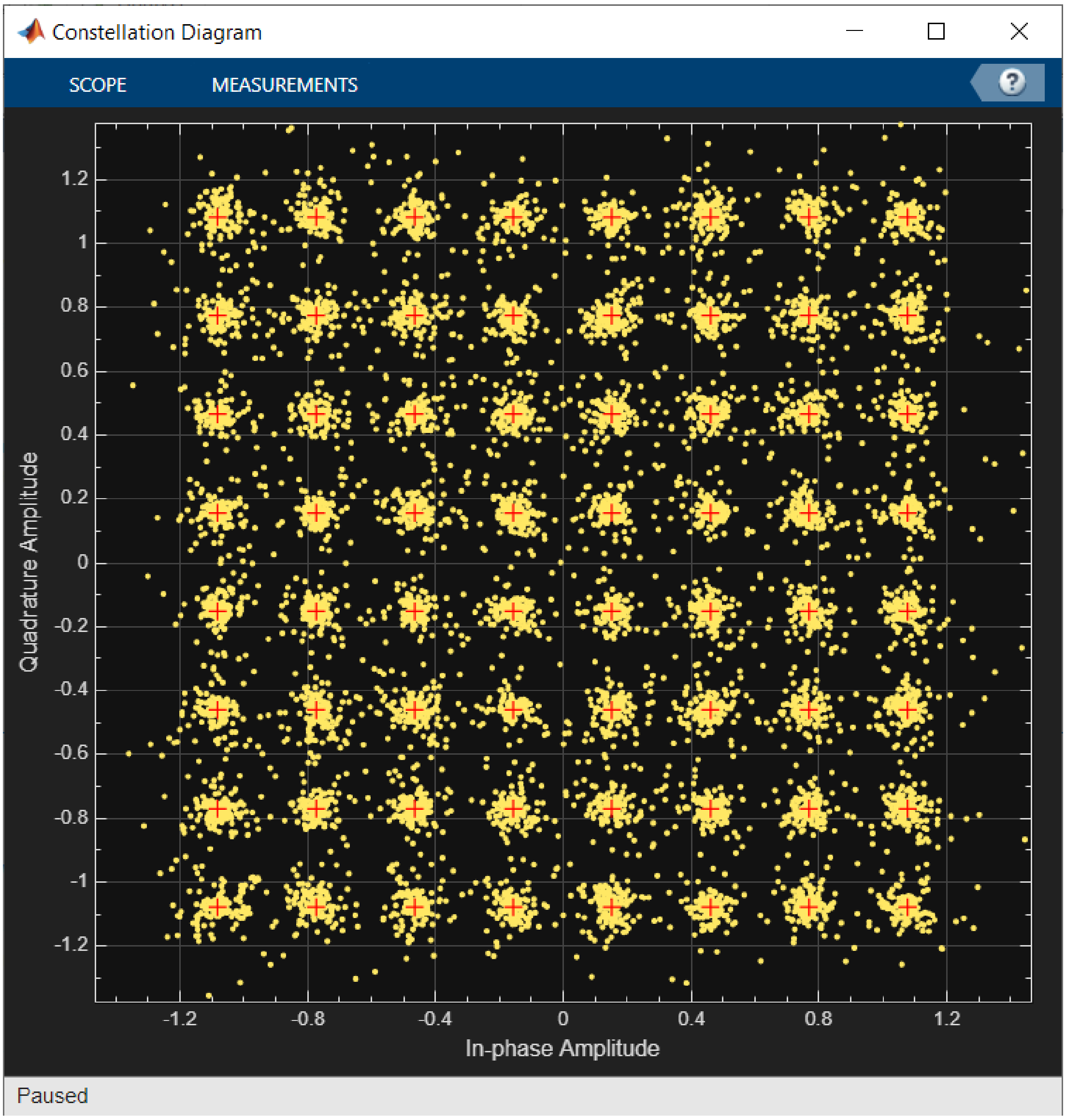

Figure 3.6 Constellation Diagram of the OFDM Waveform.

The constellation diagram as an output demonstrates the effectiveness of the implemented modulation scheme, particularly Binary Phase Shift Keying (BPSK) for the PMCW waveform and Quadrature Amplitude Modulation (QAM) for the OFDM waveform. The received symbols are plotted near their ideal reference positions, indicating minimal deviations caused by noise and channel impairments. This suggests that the system maintains a low Bit Error Rate (BER), even under challenging conditions, ensuring reliable data transmission.

The spread of the points around the reference positions is minimal, which highlights the system's ability to mitigate the effects of amplitude and phase distortions. However, the analysis also acknowledges residual impairments, such as slight deviations due to channel imperfections. These deviations underline the need for further optimization, such as advanced channel estimation techniques and noise reduction algorithms, to enhance overall performance.

To conclude, the constellation diagram validates the system's robustness and reliability, showcasing its potential for real-world applications. The results confirm that the implemented signal processing techniques effectively address noise and distortion, ensuring high communication accuracy.

4. REALISTIC CONSTRAINTS AND CONCLUSIONS

Hardware Complexity:

- Implementing both OFDM (Orthogonal Frequency Division Multiplexing) and PMCW (Phase Modulated Continuous Wave) waveforms requires sophisticated hardware capable of handling wideband signals, precise synchronization, and rapid waveform switching. This increases design complexity and cost.

Computational Load:

OFDM and PMCW involve extensive digital signal processing, such as FFT/IFFT operations for OFDM and correlation for PMCW. High computational requirements may lead to latency issues, especially in real-time applications.

Power Efficiency:

Operating dual waveforms may demand high power, straining the power budget of mobile or energy-constrained platforms like drones or vehicles.

Interference Management:

Coexistence of OFDM communication and PMCW radar signals may cause mutual interference, particularly when bandwidth is shared, degrading both radar detection and communication performance.

Time-Frequency Resource Allocation:

Joint operation necessitates careful resource allocation to balance the needs of communication (data throughput) and radar (target detection and tracking), potentially leading to trade-offs in system performance.

Channel Sensitivity:

OFDM is sensitive to Doppler effects, which can impact radar performance at high target velocities. Similarly, PMCW performance may degrade in highly dynamic or cluttered environments due to multi-path and noise.

System Integration Challenges:

Merging OFDM and PMCW functionalities into a single Joint Radar-Communication (JRC) system involves aligning waveform generation, synchronization, and signal processing architectures while maintaining compatibility with existing communication and radar standards.

4.1 Practical Application of the Project

The Joint Radar and Communication (JRC) system developed in this project has significant practical applications across various domains. By integrating radar and communication functionalities into a single framework, the system offers enhanced efficiency, reduced hardware complexity, and spectrum sharing capabilities.

- Autonomous Vehicles: The JRC system can enable simultaneous navigation and vehicle-to-vehicle communication, improving safety and efficiency in autonomous driving systems.
- Military Applications: The system can enhance situational awareness by providing precise target detection and secure data transmission in real-time.
- Industrial IoT: In smart infrastructure, the JRC system can integrate sensing and communication functionalities, enabling efficient monitoring and control of industrial processes.
- Healthcare and Emergency Services: The system can be adapted for applications such as remote patient monitoring or disaster response, where simultaneous sensing and communication are critical.

The project demonstrates the feasibility of such a system through MATLAB simulations, validating its performance in both radar and communication domains.

4.2 Realistic Constraints

The design and implementation of the JRC system are subject to several realistic constraints, including social, environmental, and economic impacts, cost considerations, adherence to engineering standards, and health and safety concerns.

4.2.1 Social, Environmental and Economic impact

The JRC system has the potential to improve public safety and quality of life. For example, in autonomous vehicles, it can reduce traffic accidents by enabling precise navigation and communication. In military applications, it can enhance national security by improving target detection and secure communication. However, the widespread adoption of such systems may raise concerns about privacy and data security, which must be addressed.

The system's environmental impact is minimal compared to traditional radar and communication systems, as it reduces hardware requirements and energy consumption by integrating both functionalities. However, the production and disposal of electronic components must be managed responsibly to minimize e-waste.

The JRC system offers cost savings by reducing the need for separate radar and communication systems. Its implementation in industries such as automotive and IoT can lead to significant economic benefits by improving efficiency and reducing operational costs. However, the initial development and deployment costs may be high, particularly for hardware prototyping and testing.

4.2.2 Cost Analysis

The cost analysis for the JRC system includes the following components:

- **Design and Simulation Costs:**
  Since the educational MATLAB license was used for this project, there was no design and simulation cost for computational resources to contribute to the overall cost.
- **Hardware Cost:**
  While this project focused on simulations, hardware implementation would require components such as antennas, signal processors, and power amplifiers. The estimated cost for prototyping is $1,000.
- **Total Estimated Cost:**
  The total cost for the project, including design, simulation and hardware, is approximately $1,000. Future iterations may reduce costs through optimization and mass production.

4.2.3 Standards

The JRC system adheres to several engineering standards to ensure reliability, safety, and interoperability:

- **IEEE Standards:**
  The system complies with IEEE standards for radar and communication systems, including waveform design, signal processing, and electromagnetic compatibility.

- **IET and EU Standards:**
  European standards for wireless communication and radar systems are followed to ensure the system's applicability in global markets.
- **Turkish Standards:**
  The project aligns with national standards for electronic systems, ensuring compliance with local regulations.
- **Engineering Code of Conduct:**
  The project adheres to ethical guidelines, prioritizing safety, reliability, and environmental responsibility in its design and implementation.

4.2.4 Health and Safety Concerns

The JRC system is designed with health and safety considerations in mind:

- **Electromagnetic Radiation:**
  The system operates within safe frequency ranges and power levels to minimize exposure to harmful electromagnetic radiation.
- **Hardware Safety:**
  All components are designed to meet safety standards, reducing the risk of electrical hazards or malfunctions.
- **User Safety:**
  In applications such as autonomous vehicles, the system enhances safety by providing accurate navigation and communication. However, rigorous testing is required to ensure reliability under all conditions.
- **Potential Risks:**
  The system must be tested for potential risks, such as interference with other devices or unintended signal propagation, which could pose safety concerns.

4.3 Future Work and Recommendations

The project establishes a strong foundation for the development of integrated radar and communication systems. However, several areas for improvement and future research remain:

- **Hardware Prototyping:**
  The next step is to develop and test hardware prototypes to validate the simulation results in real-world scenarios.
- **Advanced Waveform Design:**
  Exploring new waveform designs, such as adaptive or hybrid waveforms, can further optimize radar-communication coexistence.
- **Machine Learning Integration:**
  Implementing machine learning algorithms for adaptive channel estimation, resource allocation, and interference mitigation can enhance system performance.
- **Doppler Compensation:**
  Developing more robust Doppler compensation techniques will improve the system's ability to track high-speed targets.
- **Environmental Testing:**
  Conducting field tests in various environmental conditions will ensure the system's reliability and robustness in real-world applications.
- **Cost Optimization:**
  Future iterations should focus on reducing hardware and implementation costs to make the system more accessible for commercial applications.

By addressing these areas, the JRC system can be further refined and expanded to meet the demands of emerging technologies and applications

4.4 CONCLUSION

The integration of OFDM and PMCW waveforms in a Joint Radar-Communication (JRC) system presents a promising solution for applications requiring simultaneous target detection and high data-rate communication. OFDM excels in communication with its spectral efficiency and flexibility, while PMCW provides robust radar performance due to its high range resolution and resilience to interference. However, the successful implementation of such a system depends on addressing key constraints, including hardware complexity, computational demands, interference management, and resource allocation. Despite these challenges, advancements in signal processing and hardware technologies are paving the way for efficient and reliable JRC systems, enabling seamless operation in dynamic environments for future autonomous platforms, smart vehicles, and wireless communication networks.

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