A UNIFIED PLATFORM FOR RADAR AND COMMUNICATION SYSTEM

By

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DEDICATED TO:
My father,
My mother who recently passed away,
My wife and daughter SAMA,
My sisters and brothers,
My teachers,
My brother Haitham, who died during writing my thesis.

ABSTRACT

With recent developments of signal processing and digital hardware, radar has come to be a dynamic part of exploration and growth. For long time, both radar and communication were taken as two different systems with different signals. The notion of integrating radar and communication system on a single platform has gained much attention in the last few years. This interest stems from researchers attempt to find out creative solutions for different shared spectrum congestions among different RF services. This integration or hybridization allows both radar and communication systems to use the same structure and installation. This has the potential of becoming an effective technique for different applications in military, as well as, commercial. The significant benchmarks of radar system are how to make the radar system more precise in terms of range, angle /direction and speed measurements. At the same time, the robustness of wireless communication transmission through the wireless medium needs to be considered. Beside our comprehensive investigation of the literature so far, we have divided this dissertation into three parts.

First, we introduced our novel approach for radar communication integration based on spatial approach. The communication signal is designed and transmitted with radar function simultaneously. In this part we introduce two concepts. First was new technique for embedding communications to radar emission/radiation by employing frequency shift keying as orthogonal signals. Secondly, fighting the jammer available in side lobe and protecting the communication data transmitted. The result of this part is that, we got better performance in terms of jammer interference avoidance and bit error rate.

In the second part, we investigate and give a novel method on radar system based on temporal approach. In this approach, we exploit the radar rest mode to be used for communication transmission. Two beampatterns are designed for transmission. First one is transmitted during radar active mode, in which the mainlobe of this beam is used for radar functionalities. Whereas the other beampattern transmitted during the radar rest mode, is used for communication functionalities, in which the communication takes place in its main lobe. The frequency diverse array FDA radar is used in this scenario and the orthogonal frequency division multiplexing (OFDM) communication signal was constructed at physical layer from the FDA. Therefore, the low probability interception (LPI) has been achieved and the communication signal produced was achieved by securing the communication signal against any eavesdropper available outside the specified direction. The system is investigated under different parameters such as FDA-OFDM transmission against FDA radar transmission. The bit error rate BER , Cramer-Rao Lower Bound (CRLB), signal to noise ration (SNR) and SINR are achieved.

Finally, we introduced a novel approach of brining temporal and spatial approaches together. We used optimization problems to generate a communication in sidelobe to be transmitted simultaneously during radar active mode. When radar doges to sleep/silent/listening mode, the communication generated signal in sidelobe continue its transmission in the absence of radar beam. The radar has no hassle in its transmission. In this scenario, the communication throughput has been increased tremendously. Moreover, the system has been investigated under different scenarios. We transmitted the communication in sidelobe region with different communication locations with different

power levels. The communication is conducted through both radar modes and each sidelobe has its own distinct power level and transmitted to different directions.

PUBLICATIONS

Published Papers

1. Al-Salehi, A. R., Qureshi, I M., Malik, A. N., Khan, Z., & Khan, W. (2019). Throughput Enhancement for Dual-Function Radar-Embedded Communications Using Two Generalized Sidelobe Cancellers. IEEE Access, 7, 91390-91398 **(ISI with Impact factor = 4.089)**
2. Al-Salehi, A. R., Qureshi, I. M., Malik, A. N., Khan, W., & Basit, A. Dual-function radar–communications: information transmission during FDA radar listening mode. International Journal of Microwave and Wireless Technologies, 1-12.**(ISI with Impact factor =0.976**)

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3. Al-Salehi, AbdulRahman, Ijaz Mansoor Qureshi, Malik, A. N., Khan, Z. U., Khan, W," A Jammer Avoidance Approach for Dual-Function Radar-Communications Using FSK and Independent Null Steering" accepted in Digital signal processing Elsevier **(ISI with IF=2.87)**

Submitted papers

4. Al-Salehi, AbdulRahman, Ijaz Mansoor Qureshi, Malik, A. N., Khan, Z. U., Khan, W" A philosophy on radar-communication integration: From Theory to Application" submitted to IEEE Communications Surveys and Tutorials
5. Al-Salehi, AbdulRahman, Ijaz Mansoor Qureshi, Malik, A. N." Radar Embedded Communications using Independent Null Steering and waveform diversity" accepted in Digital signal processing Elsevier (ISI with IF=2.87)

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AbdulRahman Al-Salehi

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LIST OF ABBREVIATIONS

JRC	Joint Radar and Communication
DFRC	Dual-Function of Radar-Communication System
RadCom	Radcom
IRCS	Integrated Radar and Communication System
REC	Radar-Embedded Communication
RaCs	Joint Radar and Communication Systems
FDA	Frequency Diverse Array
PAR	Phased Array Radar
OFDM	Orthogonal Frequency Division Multiplexing
INS	Independent Null Steering
TMA	Time Modulated Array
IoT	Internet of Things
STMA	Sparse Time Modulated Array
ULA	Uniform Linear Array
DoI	Direction of Interest
DOA	Directional of Arrival
AOA	Angle of Arrival
LPI	Low Probability of Interception
LPID	Low Probability of Identification
INS	independent null steering
IMOP	Intentional Modulation On Pulse
INS-DFRC	Dual-Function Radar-Communications Based Independent Null Steering
AMRFC	Advanced Multifunction Radio Frequency
GSC	Generalized sidelobe canceller
PRI	Pulse Repetition Interval
C	Speed Of Light
SLL	Sidelobe Level
R	Communication Directions/ Receivers
ULA	Uniform Linear Array
FDA	Frequency Diverse Array
CRLB	Cramer Rao Lower Bound
AWGN	Additive White Gaussian Noise
EW	Electronic Warfare
LPI	Low Probability of Intercept
PCM	Pulse Coded Modulation
RCS	Radar Cross Section
TMA	Time Modulated Array
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
STMA	Sparse Time Modulated Array
QAM	Quadrature Amplitude Modulation
MIMO	Multiple Input Multiple Output
PSK	Phase Shift Keying
ASK	Amplitude Shift Keying
FSK	Frequency Shift Keying
MSE	Mean Square Error
PAR	Phased Array Radar

LIST OF SYMBOLS

t_w	Radar pulse width
τ_r	Radar rest mode time
T_t	Total time for one pulse repetition interval
GSC_1	First generalized sidelobe canceller
GSC_2	Second generalized sidelobe canceller
$\mathcal{R}_{\text{max}}$	The maximum unambiguous range
M	transmit antenna elements
D	Spacing between elements
$\mid\ \mid$	Absolute value or L1 norm
$\mathbf{w}_1$	M-by-1 weight vector of GSC1
^{H}	Hermitian operator
θ_t	Radar target angle
θ_{ci}	M-by-1 steering vector towards a pre-defined ith communication receiver located at angle (θ_{ci})
$\ominus$	Set of angles at which radar mainlobe operates.
Δ	communication power in sidelobe region
Ω	binary information bits
$\mathbf{C}_1$	Constraint matrix of GSC1
$\boldsymbol{B}_1$	Blocking matrix of GSC1
$\mathbf{f}_1$	Gain vector of GSC1
$\mathbf{w}_q$	Quiescent weight vector of GSC
$(.)^{-1}$	The inverse
$\mathbf{w}_a$	Adjustable weight vector of GSC
k	number of columns in C
$\boldsymbol{R}_x$	correlation matrix
χ	unit value gain along θ_t
$[.]^T$	Transpose operator
$\boldsymbol{R}_x$	Correlation matrix
$\{\sigma^2{}_i\}_i^M$	power of each transmitted signal
$\mathbf{w}_2$	M-by-1 weight vector of GSC_2
$\mathbf{C}_2$	Constraint matrix of GSC_2
$\mathbf{f}_2$	Gain vector of GSC2
$\mathbf{w}_{q2}$	Quiescent weight vector of GSC2
P_{GSC}	Output Power of GSC
q_w	achievable rate during active mode
q_w	achievable rate during rest mode
Q_w	Throughput during active mode
$Q_{increased}$	Throughput during rest mode
Q_{max}	Throughput during whole PRI

CHAPTER 1

INTRODUCTION

1.1 Overview

The system which is designed to allow both functions of radar and communication system to coexist in their functions or cooperate in their information or co-design into a single platform, is called radar-communication unification system or commonly known as Radcom. This technology is carrying different names, listed in this dissertation as found in the literature for broad aspect of the same technology as follows: ① Joint Radar and Communication System (JRC), ② Dual-Function of Radar-Communication System (DFRC) RadCom ④ Integrated Radar-Communication System (IRCS) ⑤ Radar-Embedded Communication (REC) and ⑥Radar-Communication Systems (RaCs).

Previously, the radar which is abbreviated from the radio detection and ranging was working as independent unit with main functions such as detection or tracking the target and measuring its range and velocity. It has been widely used in aircraft, vessels, directed missiles, climate formations and intelligent transportation systems etc. In contrast, the word wireless communication is used to transmit information or energy among two or more points which is not connected through any electrical connector. Similar to radar, this technology is using radio waves in their transmission.

With the advancement of digital signal processing, both radar and communication services came to work on a common platform. Recently various techniques are used to bring radar and communication systems to a common sharing spectrum. These types of techniques took many forms such as temporal, spatial and spatio-temporal techniques.

1.2 Background of Modern Radar and Communication Technologies

Previously, the researchers focused on radar and communication performance as independent system for so long time. Experts and specialists in radar are trying to find and enhance various parameters such as range estimation velocity, speed of the target, angle of arrival, directional of arrival, scanning and tracking surveillance, radar cross section and many others etc. also they focused on calculating the angle with respect to range fixation as in phased array radar. Others looked at the frequency diverse array in which one can calculate the range as well as the angle of the object which help to reduce range dependent interferences to calculate the range-angle of every object at each specific range-angle. Moreover, authors used cognition which proposed by Simon Hykin to allow the radar to know about its environment from its surround by using the feedback mechanism.

In contract to the fast developments in radar, the communication system is also progressing rapidly in different forms and applications. Researchers and experts, focusing on how to increase the data rate, how to mitigate the interferences, how to enhance the signal to noise ratio parameters. Even in recent technologies of the communication system such as the development of 4th and 5th generations experts/researchers are focused on the communication transmission speed as well as the quality and quantity of the data transmission.

In both technologies, radar and communication systems using similar mathematics and electromagnetic spectrum, as well as the concept of signal antenna arrays or multiple antenna arrays are used for both systems. Furthermore, the advancement in digital signal processing narrows the gap between these two technologies. These factors have led to the birth of a new type of radar having adaptation capability, and co-existence ability to work in the presence of another system side by side and benefit from each other. This new type of intelligent hybrid radars took many names and shapes, and allows the researchers and experts to focus on the basic objectives of both systems. In addition, researchers took advantage of the problems of each system, for example but not limited, there is no longer a need to mitigate the radar side lobe, but instead of that, the radar side lobe has been used to send a communication data.

This new radar using different forms based on different function required. Three famous categories of radar are used for both radar and communication functions. One is coexistence, in which both systems of radar and communication can be work together and find some degree of freedom as a common between them to reduce the interference. The second category is cooperation in which both systems shares some of information in order to reduce the interferences. Third category is called co-design method in which both systems built up totally together. In this case, researchers are trying to enhance the performance of both services by using different optimization techniques. Similarly, many researchers focused on time sharing, sub-band sharing and signal sharing among both systems. While others focused on spatial/ frequency sub-banding for both system. Another authors and researches focused on spatial-temporal approaches.

1.3 Motivation: A Unified Platform for Radar and Communication System

In fact, Radcom technology is still in its infancy stage and it needs a lot of investigation, scrutiny, research and development. Certainly, any valuable research in this area will help to develop this technology and improve its performance which in turn will fast it to be available in the real life application and market use. According to the previous discussion in the previous section, experts and researchers focused on conserving in finding and enhancing the performance of radar and communication while study this new technology.

Obviously, as there are a lot of researches now days in this area to enhance this new technology, but the system is not yet fully exploited. Bringing radar and communication together by developing new approaches is considering a step forward towards this advancement. For instance, focusing on temporal, spatial and spatial-temporal approach we emphasize that

For example, there is an urgent need to study this system from all different dimensions such as, temporal, spatial and spatiotemporal dimensions. We also emphasize that there is an urgent need to design new waveforms and new beampatterns for radcom technology and use it in different types of radars such as phased array radar PAR and frequency diverse array radar FDA. By this way we can construct new systems of intelligent systems of radar and communication. In order to achieve this, we must exploit the advancement of signal processing and all opportunities in the basics of radars and communication to be addressed and utilized.

The main goal of this thesis is to provide a comprehensive idea of what has been done to date and to develop new approaches and mechanisms that contribute in building a new generation of joint radar-communication system. This contribution will help in development of this technology to reach to its full maturity. It can also contribute effectively to the improvement of this technology by unifying two systems that have worked for a very long time separately from each other.

1.4 Objectives and Contribution of the dissertation

This dissertation is divided into three major topics that related to the dual function of radar and communication system. The first part discuss the recent of radar embedded communication and dual function of radar and communications (DFRC) problem. In second approach, the radar function considers as a primary function whereas the communication functions behalf as a secondary function. The second approach, investigates the current issues of the dual function radar and communication system with radar pulse repetition interval PRI exploitation. The temporal approach has have been introduced for the two radar mode (active and inactive radar modes) and introduced a new concept for radar-communication integration. The third approach, we used a spatiotemporal to introduce new concept to the existing unified systems. This approach based on exploiting both active and rest mode of radar. The proposed design allows the communication to be transmitted during the full pulse repetition interval in both active and rest modes. This technique also increased the communication throughput tremendously.

The three topics focused on three approaches. First is the spatial approach, in which the author fights the existing jammer in sidelobe region. In this section, we also introduce new information embedding technique based on frequency shift keying. Second approach was the temporal, we introduce new concept of radar-communication unification transmission in which the main lobe during active mode is carrying radar function, while the main lobe of the second beampattern transmitted during rest mode carrying communication signal. Third approach is the combination of temporal and spatial approach together in order to exploit the maximum allowable shared spectrum among the radar and communication without affecting their core functions in term of detection/surveillance assignment in radar or information throughput assignment in communication. The techniques which used in this dissertation are focused on three fundamental approaches Concept using sub-beams/multi-beams along with signal sharing will be used for RadCom. For sub-beams or multi-beams phased array radar, or frequency diverse array radar will be used. For signal sharing, a composite waveform or recursive for both radar and communication needs to be looked into. A hybridization of the communication and radar systems and bring them to be used as common platform for RadCom system also has been investigated. The main goal of our project is to improve the RadCom system. Different methods can be used to reduce the measureable gap between Radar and wireless communication systems and enhancing this technology by using signal sharing, and sub-beam sharing techniques based on waveform design techniques. We will use an interception and jamming techniques through integration process of the radar-communication system. This can help us to integrate and analyze our systems and bring a suitable support for radar-communication unification system for specific characteristics system toward real life application.

1.5 Organization of the dissertation

The dissertation has been organized as follows:

Chapter 2 gives an overall introduction about recent and current research in this field of integrating radar and communication system, and different terminologies that have been used for this paradigm. We discuss also the beam forming techniques in phased array radar and frequency diverse array that have been used in radcom system. We also discussed the reconfigurable system used orthogonal frequency division multiplexing and spread spectrum approaches. Furthermore, spatial and temporal approach has been discussed. Most of the information embedding and waveform diversity have been done so far in the literature has been studied in this dissertation. We introduced also the recent research in cognitive on radar-communication unification system. Finally we introduced the application areas this technology has been implemented so far.

Chapter 3 discuss the pervious techniques of information embedding have used so far. A new information embedding based on FSK has been investigated while fighting the jammer available in sidelobe region as well. In this chapter, we investigate that, how to steer the null independently without affecting the position of main lobe of radar as well as the other nulls in sidelobe region. By doing so, if jammer is moving towards the communication angle, then we move the null towards that jammer. In this case we only update the position of the null towards the new jammer position without affecting the other communication positions in sidelobe region. Furthermore, a part from using ASK, PSK or QAM modulations as found in the literature, we introduce a new method for the radar-communication integration based on frequency shift keying (FSK) modulation as orthogonal waveforms.

In **chapter 4**, we introduce three variables, first , we introduced the frequency diverse array to radar communication system. We analyzed the range and angle for radar- communication integration. We also exploit radar rest mode , in our scenario we used rest mode of frequency diverse array radar to be used for communication transmission. In this chapter, we designed two beam patterns to be transmitted sequentially, one during active mode carrying radar function only, whereas the other beam pattern bearing information and transmitted during frequency diverse array radar rest mode. Both main functions of radar and communication took place in the main lobe of its corresponding beam pattern. The transmission mode between radar and communication was based on temporal approach.

In **chapter 5**, we introduced new concept of transmitting communication in the radar rest mode as well as active mode. In other words, we exploit both, spatial approach and temporal approach to transmit a communication during both radar modes. In active mode we transmit communication signal via sidelobe radar levels. While in rest mode , we allow the communication signal produced in sidelobe to continue its transmission during radar rest mode. This technique has been produced by using generalized sidelobe cancellers.GSC.

Finally, **chapter 6** gives the overall conclusion and future work we have done in this dissertation. Moreover, we list down some of the future work and open problems that need to be addressed in order to enhance the technology.

Finally, in this chapter, we will present the current new modern of radars which has the ability to work with communication services. Then we presented the motivation and contribution of this thesis and lastly the organization of thesis.

CHAPTER 2

A PHILOSOPHY OF RADAR-COMMUNICATION INTEGRATION: FROM THEORY TO APPLICATIONS

2.1 Introduction:

Lately, the issues of radio frequency (RF) spectrum overcrowding due to the high demands of wireless communication have gained a substantial attention [1]. Many researchers, companies and authorities such as the Federal Communications Commission (FCC) are working to establish a common band for different services of RF spectrum to be multifunctional from a unified structure or common waveform[2]. The idea of radar-communications coexistence offers an interesting solution to the conventional RF spectrum issues[3-8].The developing idea of dual-function radar-communications (DFRC) as a type of this common band spectrum, in which communication signals are transmitted as secondary function to the primary radar function has emerged in recent the literature. These systems exploit the maximum advantages of the radar resources. The information embedding into the radar emission techniques allowing the communication to rise such as sidelobe control, time modulated arrays, waveform diversity etc. This information embedding into the radar emission took many forms such as spatial, temporal and signal sharing approaches. Before we go in deep study for joint radar-communication system and explore most of the literature work done in this field so far, let us first take a glance at the radar and communication systems, their evolutions and finally their differences and commonalities.

2.2 Radar and Communication Evolutions

The evolution of brining the radar and communication services to be unified weather in their hardware installation, frequency band or waveform design has gained intensive research in the few years. In this regards, due the focus of interest in RF spectrum congestion among radar and communication system, the radar is moving from military application towards the commercial application particularly towards commercial communication. The field of spectrum congestion and frequency assignment between radar and communication is a major challenge for researchers and requires new and bold concepts at the same time to protect services from interference.

2.2.1 Communication Signals:

In 1980s the development of first generation took place and completed its setup in 1990s. This first generation was an analog systems and the speed was in 2.4 Kbs only [9]. The second generation was a digital system with 64 Kbps . The third generation has been matured in 2005/2006 and it includes the global roaming, superior voice quality and video conferences. The transmission speed has been increased from 125 Kbps to 2 Mbps. The fourth generation has been setup and considered as higher capacity as compared to the previous generations. This generation is implemented to provide up to 1 Gbps at stationary systems. The fifth generation is the latest generation in wireless communication systems so far. This generation is expected to deliver higher data rate and lead the wireless communication for better performance. The 6th generation is just introduced in some papers. The 6th generation is supposed to connect all types of wireless communication together using artificial intelligence and machine learning. Internet of things IoT. Figure 1 shows the evolution with time in mobile wireless communication. In wireless communications systems, the transmitted signal usually unknown while the propagation channel is known or previously estimated. The trainmaster transmits the signal towards a receiver. This propagation takes place as one way communication transmission.

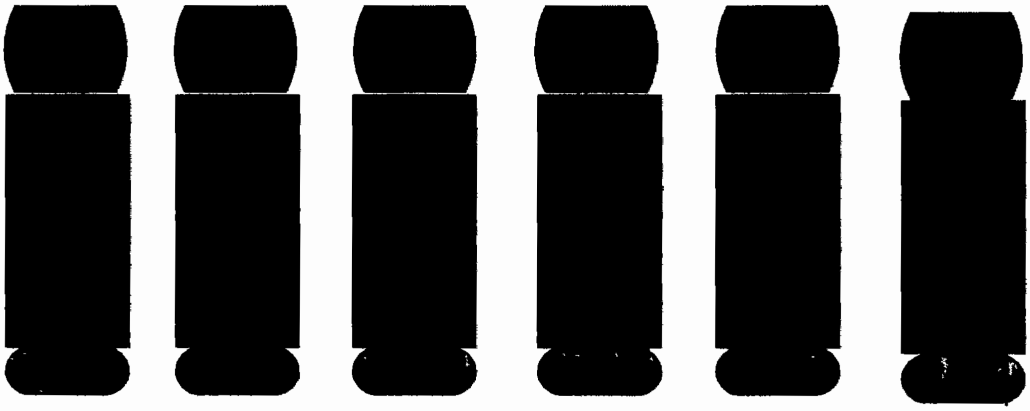


Figure 2-1 Mobile wireless communication evolution

2.2.2 Radar signals:

The terminology radar comes from radio detection and ranging. This radar is defined as the system that has the ability to do different functions such as detection of the target, its range, speed and direction. The received echo can give a shape, as well as, size and trajectory of the target. The radar was invented during World War II. Since that time, radar has passed through many developments. The modern forms of radars are used to find the shape, trajectory, ambiguity function of the detected target, accurate position and information of the target and Doppler shift of the received radar signal [10] . Finding the low probability of interception and identification (LPI and LPID) have also become important parameters of the modern radars[6]. Normally, radar transmits a known waveform to sense the environment. This signal hits the target and backscattered toward the receiver to be analyzed and extract the required information. Radars are used for military and commercial applications [4].

2.2.3 Comparison between Radar and Communication Systems

In this section we give a general comparison between radar and communication system based on their common and differences in terms of tasks, system transmission, channel, links capacity and signal propagation as defined in [11].

[redacted]	[redacted]	[redacted]
Common keys	• Use electromagnetic spectrum • Use similar mathematics	• Use electromagnetic spectrum • Use similar mathematics
Main difference	• Transmit data from a source to a receiver. The transmission of signals through a channel available between transmitter and receiver.	• Transmits an electromagnetic energy from transmitter to target, gathering information about the environment and receive the echo returns for parameter estimation.
	• In communication transmission, the propagation channel is estimated or with prior known while the signal sent is unknown	• In radar transmission, the transmitted waveform is known and the target channel needs to be estimated.
Tasks	• Wireless communications used to transmit information between from transmitter to receiver. And enhance the SNR,BER ,..etc.	• Radar used for detection of the targets at specific area and estimate the target parameter at that location such as velocity, Doppler, ambiguity, distance, time delay.
Input	• Communications Signal	• Radar waveform
Output	• The received signal is noisy and distorted from the transmitted version of signal	• The echo received signal is noisy due to objects/targets.
System	• Direct path and multipath	• Targets in environment
Transmission	• Data Transmission	• Carrier/energy transmission

Channel sounding	• The features of the channel are annoying parameters that need be taken into account, but have no inherent importance.	• The channel and its properties is considered as the main interest
	• Apply an equalizer to compensate	• Use multiple pulses to resolve in cross-range.
Links	• Communications may include direct path or reflections off surface.	• Radar returns are always due to scattering, it may require increased power for —small‖ targets.
Capacity	• The communication channel may have limited bandwidth, even if we increase the power transmission, the service still limited.	• The search volume in some type of radar can be increase and dwell time reduce if the radiated power is increased.
antenna	• Mobile components of communications usually use almost omnidirectional antennas.	• Radar usually uses a high-gain Antenna for determined surveillance area to be pictured.
Propagation loss	• The communication propagation takes one way channel and usually consider something on order of R2 / R3	• While the radar propagation takes two-way channel, therefore, the ERP should be calculated for R4 propagation loss.

Table 2-1 Comparison of radar and communication systems

2.3 Why Radar-Communication integration is Important?

The issue of spectral congestion among different RF technologies is motivating the conventional/ legacy radar band consumers to find new methods of permitting wireless communication technology to coexist, cooperate or co-design with the legacy radar. Instead of keeping the two systems working independently with huge power consumption, researchers, many firms and governmental bodies have started working for a common platform with the same structure and they would like to perform both functions.

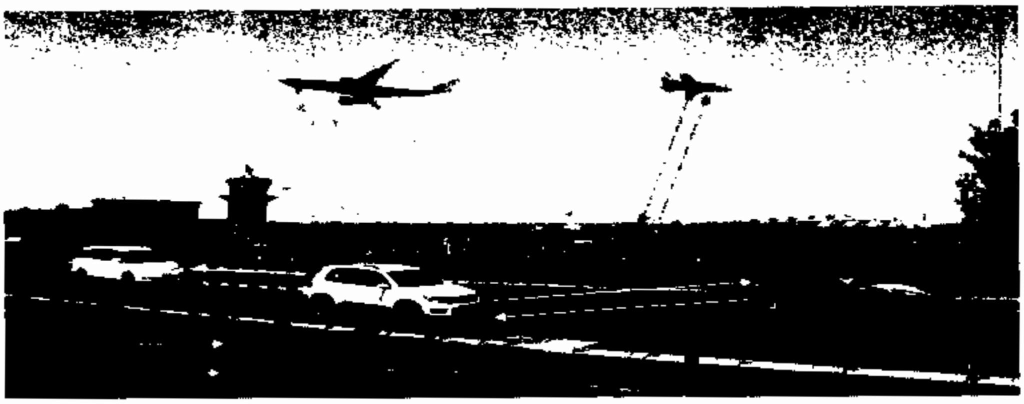


Figure 2-2 Scenario for joint radar-communication system. Solid lines represent radar operation. Dashed lines show the communications function

2.4 Definitions and Preliminaries

Before discussing the existing methods and surveying most of the papers found in the literature regarding this technology, we first define the most common terminologies used in the literature to describe the type of integration happening between radar and communications. These terminologies are co-existence, cooperation and co-design. Furthermore, we will investigate these methods under different types of sharing mechanisms used between the radar and communications systems, such as temporal, spatial and spatiotemporal sharing approaches.

2.4.1 Coexistence Approach

Coexistence approach is defined as a spectral coexistence or the behavior of radar and communication transmitter/receiver to allow these systems to deal with each other as interference. In this case, there is no information shared among both systems to reduce each other interference, and this information must be estimated [12]. The drawback of the coexistence technique is that the interference alleviation consumes the system resources as well as bounds the degree of freedom existence. Figure 1 show that the cohabitation techniques between radar and communications to detect each other with some degree of freedom and adjustment to their relevant the interference mitigation. Many papers such as [8], [13]–[18] are discussed the coexistence techniques have been found in the literature. These papers will be discussed in the state of the art part.

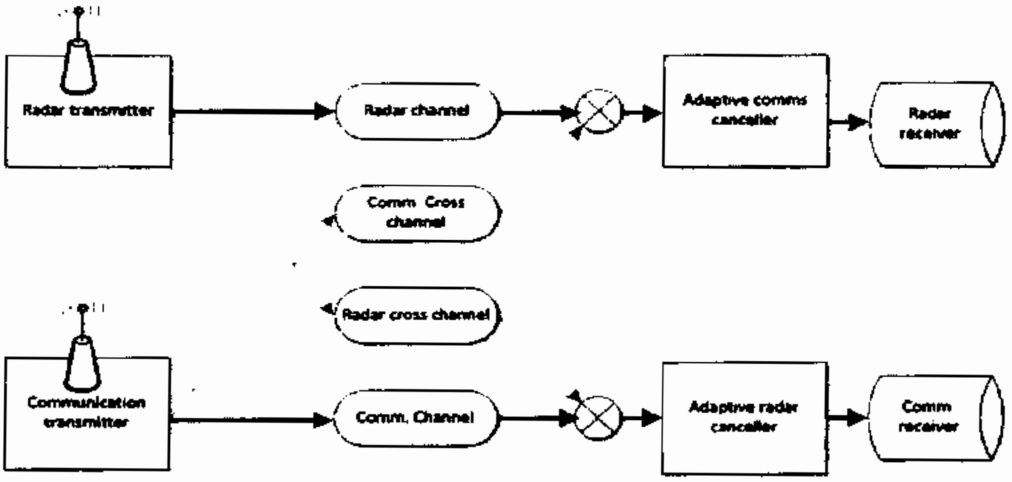


Figure 2-3 Block diagram of coexistence approach for joint radar and communication system

2.4.2 Cooperation Approaches

In this approach, some information is shared among the joint system for the purpose of interfering alleviation among one another. In this scheme, there is no significant change at the core operation of both systems rather than exchanging information in order to mutually alleviate interference[12,19,20].

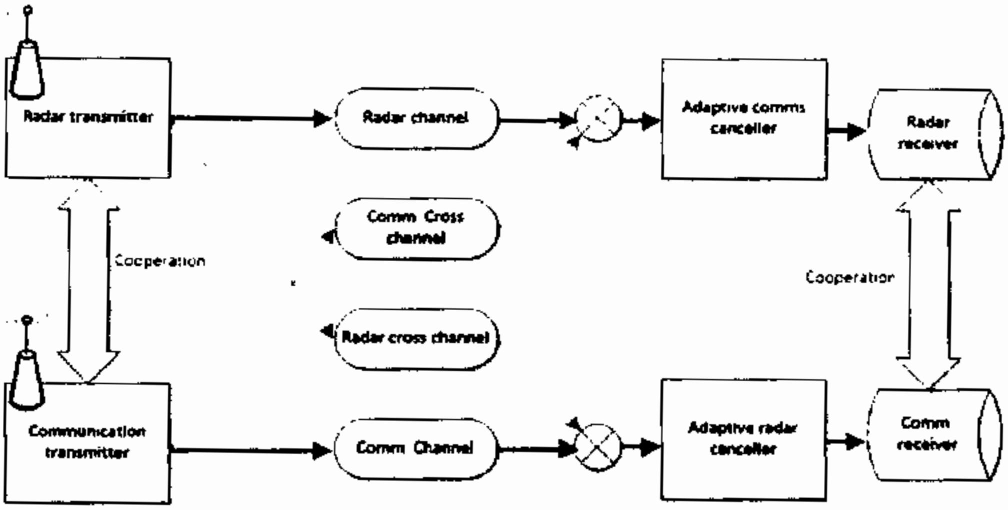


Figure 2-4 Block diagram of cooperation approach for joint radar and communication system

2.4.3 Co-Design (Joint Design and Optimization)

The main idea behind the code sign approach is how to perform radar and communication functions simultaneously via common transmitter/receiver, same bandwidth and joint waveform. Is defined as the approach that allow both systems (radar and communication) to be designed and functioning as a new joint system. In other words, this system is completely designed from ground up with keeping in mind that both systems must focus on maximizing their performance during their operation [12], [21-24]. Many techniques have been proposed for this paradigm such as intentional modulation on pulse (IMOP) [25]. A dual-function radar-communication (DFRC) system is an explicit example of this paradigm.

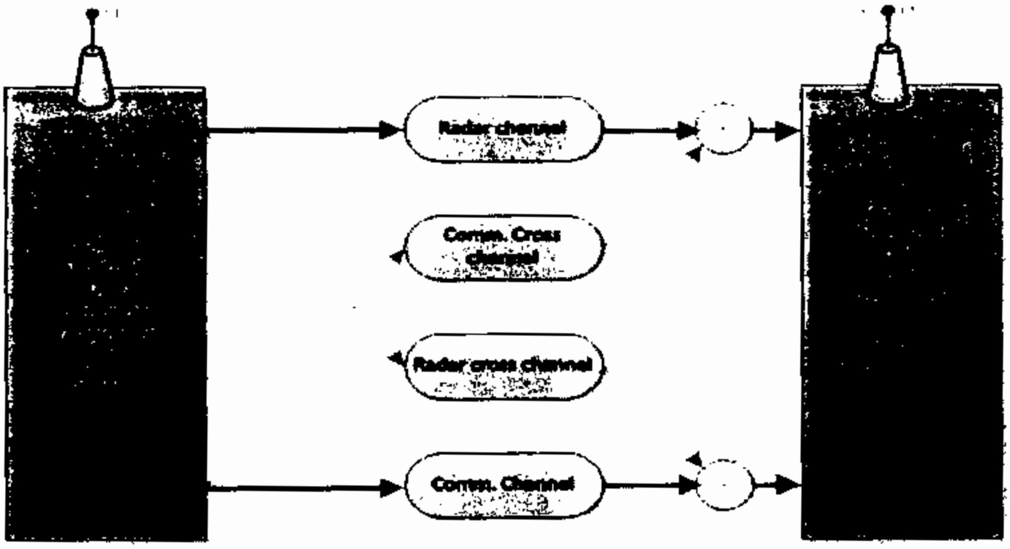


Figure 2-5 Block diagram of co-design approach for joint radar and communication system

2.5 State of The Art

We investigate the notion of integrating radar and communication system to be functional as a unified platform. This idea has been proposed since long time but never been properly implemented up to date. Initially was proposed for vehicle to vehicle communications, in which the possibility of transmitting a data and measure the ranges among vehicle has been proposed in[26-27]. As a result a number of studies with different scenarios and approach have been focused on the joint radar-communication integration and functions as shown in the next subsections.

2.5.1 Reconfigurable Systems Based OFDM Approaches

In order to design radar and communication system as one platform, researchers proposed and developed different algorithms, scenarios, waveforms and other many approaches to narrow the gap between the RF systems, and to fully exploit the their spectrum in efficient manner, to fulfill the demands of new era RF paradigms. For example, orthogonal frequency division multiplexing OFDM is configured to be used for short range either for radar or wireless communication [28-29]. The OFDM has taken many approaches in joint radar-communication integration. Simultaneous operation of radar and communication based OFDM via designing an intelligent system exploiting same hardware and same waveform to perform both systems is proposed in [30]. A multifrequency complementary phase coded (MCPC) modulation is used to simultaneous achievement of radar-communication system [31]. Extension of OFDM chirp signal to the radar by using communication codes for delay-Doppler was proposed in [32]. The combination of the advantage of multicarrier and phased coded signals is investigated to increase the Doppler shift accuracy and good range resolution in RadCom has been studied in [33]. However, researchers in OFDM focused on sidelobe reduction as in [34].

Others focused on maintaining constant envelop or reducing the peak average power ratio PAPR such in [35]and [36] respectively. A combination approach for OFDM with single input multiple outputs SIMO was proposed to study the range-Doppler-angle by using tensor disintegration method. The OFDM-MIMO was conducted and experimented in[37].Furthermore, a combination of MIMO radar and MIMO communication to fight the Doppler and range occurred in RadCom system OFDM based has been discussed in [38]. Moreover, MIMO radar integrations that employ different orthogonal waveform or OFDM signals in order to achieve a RadCom system having the ability to sense the environment and provide a communication has been proposed [39].OFDM consider as a good option for vehicle to vehicle communication (V2V) applications as investigated in many papers such as[40]. Interested researchers in this field can find more information in [30],[41-47]. From the discussion it's clear that, OFDM paradigm is a good choice for radar-communication system especially for 4G and 5G. OFDM considers as a good promising technique for 4G and 5G generations. This technique still need more study and investigation of finding robust waveform design for channel response correctness and objective scattering. In another direction of system reconfiguration, bandwidth allocation among a unified radar-communication has been discussed in [48]. The authors investigated the bandwidth sharing among both systems during the multimodal radar tracking and surveillances. The radar surveillance is segmented into many sectors/parts and the priorities given in each sector for radar and communication transmission. They determine these priorities of the bandwidth allocation either for radar or communications in each sector by using fuzzy logic. In [49], an OFDM robust approach has been proposed for specific scenario that when the radar and communication channel responses are known in order to enhance the system bandwidth and mitigate the side lobe interferences. In[50], authors presented two methods for designing optimal-waveforms for both radar and communication to work simultaneously, in which this design help to improve the radar and communication parameters such as range, speed and the communication channel capacity respectively. Studying the low probability of interception for Radcom system has been proposed in [51].

2.5.2 Spread Spectrum Approaches

In this section we introduce the spread spectrum technology that used in joint radar-communication system. The benefit of using spread spectrum technique is that it has similar noise autocorrelation properties. A waveform based on spread spectrum such as direction sequence spread spectrum was initially introduced in [52]and[53]. Other researchers studied the chirp spread spectrum to prevent a the conflict between consumers in terms of jamming avoidance [54],[55]. The issue of this technology is bounded and limited due to the time bandwidth multiplication [56]. Furthermore, the disadvantages of using m-sequences in RadCom is the absence of correlation perfection [57]. In [58] authors looked into the minimum shift keying MSK when combined with linear modulation frequency LMF to enhance the bandwidth and mitigate the sidelobe interferences.

2.5.3 Spatial Approach

Spatial means in this context, both systems are operating simultaneously, but each system has its own direction. In this section, we divide the spatial approach to three categories: Co-existence, cooperation and co-design techniques. Authors in [59], investigated the spectrum sharing among MIMO radar as well as the Long-Term Evolution (LTE) communication, and studied the feasibility of directing the radar waveform towards the null space of channel interference. Moreover, the projection of radar signal onto the null space to remove the interference of radar to the communication was investigated in [59-63]. In [61] investigation of MIMO radar in tandem with MIMO communication equalization was conducted. Other authors studied the spatial filtering techniques to reduce an interference of communication by exploiting the availability of degree of freedom in MIMO system as explained in [64]. However, spatial approaches are just a type of spatial isolation which has limited degree of freedom. The designers of this approach focus on how to steer the antenna radiations towards a specific directions for radar and other for communication. No doubt that, its simultaneous transmission, but every RF system is working in its given space. This technique leads for more cost and limited degree of freedom as studied in [65-66]. Other researchers, have investigated the mutual information MI using waveform design of MIMO radar to mitigate interference of communication co-existence in order to obtain, better radar detection , adequate correlation and reducing the peak to average power ratio PAPR [62,67].

Likewise, many researcher focused on the interleaved subcarrier orthogonal frequency division multiplexing methods to be used as MIMO radar when applied to conventional phased array systems[68]. Other approaches used the incremental frequencies in frequency diverse array as OFDM signal, in which the OFDM signal transmitted towards specific directional while the signal is scrambled in the unwanted directions. Likewise, the extension of MIMO radar-communication investigation has been discussed in [22]. In cooperative and no-cooperative approach based spatial technique, the matrix completion. MIMO radar techniques which has low sensitivity to interference was introduce in [24].

2.5.4 Time Approaches

The obvious approach for time sharing presented in many papers such as [69], in which the radar function takes place in mainlobe while the secondary function takes place in sidelobe region. The production of fixed mainlobe power, and variations in sidelobe levels is done by manipulating the variation of an intermidat beampattern. This is done by changing the number of elements which are on towards sidelobe directions. Authors optimized the duration of each element beampattern to maintain a regular time step among the beampattern in order to calculate the Doppler frequency for radar and to produce a chebycheve pattern. In this technique authors produce their results by using TMA or STMA. Moreover , TMA using differential evolution to eliminate the unused sidelobes was proposed in [70].

Time sharing approach based coexistence was introduced in many papers. Considering the radar function as a primary spectrum sharing and transmitting communication secondary spectrum sharing. The communication transmission takes place as possible as the interference does not exceed the allowable radar level.

Other authors looked at the co-designed as polarization approach in which they designed a single antenna that share a common transmitter for radar and communication. The down chirp continuous (CW) radar power is mixed with the up-chirp communication signal and transmitted from a common antenna. The received radar backscattered is matched filter using up mated filter to extract the radar parameters, while the communication signal is a pulse compressed using down chip filter to extract the communication information [71]. A communication transmission takes place when a certain level of radar to prevent any interference. The authors investigated the sharing spectrum among both systems, radar as primary function and communication as secondary function, particularly the communication utilizes this spectrum when traffic flow momentarily surpasses what can be maintained in the allocated spectrum [72]. Similarly the spectrum sharing between primary and secondary function has been investigated during radar rotation [73]. Furthermore, a grey space for spectrum sharing during radar rotation has been discussed in [74]. Others look at WLANs investigation during radar regular rotation by availing the time changing of the interference occurred due to the radar antenna rotation [75]. Some researchers exploit the temporal and spatial approach of spectrum sharing and use it in electronic intelligent as in [76].

2.5.5 Information Embedding Techniques

In this section, we investigate two information embedding techniques that have been used so far in radar-communication integration. These two types of information embedding are based on waveform diversity and directivity. In waveform diversity type, many papers discussed such as [77-84]. In [77], the event radar is altered into a number of K communication signal. These signals behave as communication information. The concept of intra radar pulse has been examined in [80]. A comprehensive study on waveform diversity has been conducted in [78]. Embedding information into the physical layer of the radar emission waveform is introduced in [79]. A phased modulated system was proposed for radar-communication emission to alleviate the influence the Doppler processing which occurred due to range sidelobe modulation (RSM) alteration from pulse to pulse as in [81]. More papers in radar emission based waveform diversity and their challenges have been discussed in[67], [68]and [69]. Moreover, some papers in waveform diversity techniques looked at the information embedding using fast time in which the communication data rate depend on every radar pulse as in [78][77]–[83]. Furthermore, new approaches based on implementing a set of waveforms at physical layer having multifunctional/multitasks used for far field purpose for radcom system. The idea behind these techniques is generating two different functions simultaneously transmitted from same aperture [85] and [86]. Another approach using quasi-orthogonality for different chirp rate to embed and transmit the communication signal while maintaining the radar performance intact[71].

The second type of the information embedding is based on communication receiver directivity in which the information embedding based communication receiver directivity known as dual function radar communication system and has been presented in many papers such as [69], [87-116] . In [113] and [109] many information embedding techniques have been presented to transmit a radar as primary function and communication as a secondary functions. MIMO radar for dual function radar communication system has been introduced in [115]. In this approach, authors shuffled the MIMO radar waveform throughout the antenna transmitter. The radar receiver knows this shuffling and the information can be extracted with the help of matched filter. Similarly MIMO radar for RadCom has been proposed in [102]. Furthermore, this section is well explained in the next three chapters. Moreover, information embedding used different digital modulation techniques such as beampattern amplitude modulation [101],or beam pattern phase modulation [95]–[97] in which the signal transmitted towards directions/users. QAM modulation in sidelobe region to produce different communication signal to different directions with different levels has been proposed in [104] . Index modulation is also used in [117]. The information embedding is done by shuffling the waveform. Similar approach is done for restricted scenarios of DFRC approach using code shift keying [118]. Others looked at the frequency hopping using specific codes.

2.5.6 Cognitive Approaches

In this section we discussed the recent publications that investigated the cognitive approach for radar-communication integration as in [119]–[125]. The word cognition found in the dictionary means, the method of obtaining information and understanding by thought, knowledge, and the feeling. The first cognitive radar proposed was by Simon Haykin [120]. The cognitive radio approach always checks the environment and learns from the surrounding. The ability of the system to use the feedback information between receiver and transmitter, as well as stores the data to enhance the performance of the system. It is worth noting that the feedback is the the main part in the cognition process. Some authors looked into the performance of communication system i.e WiMAX in the existence of S-band radar [123]. Others look into the overlapped frequency diverse arrays, in which the antenna arrays have been segmented to many part, each part represent specific orthogonal waveform. This technique used to easily control the sidelobe [122]. This technique is also used to obtain a better performance for the non-static target and communication. Others look into the designing of new waveforms for estimating target echo factors by and using Kalman filtering for ultra wideband transmission while calculating the communication data simultaneously [121]. Others in [124], looked at adjusting the radar waveform to signal dependent intervention from the communication service. In this approach, authors investigated the cognition approach in congested surroundings in which a number of frequency bands are common between radar and communications. They utilized the cognitive by Radio Environmental Map to produce spectral awareness for Ad-hoc environment and to expect the real scenario and Electronic Support Measurement. Some authors look at to the behavior of the cognitive radar and communication system when using the frequency band and they investigated the channel estimation parameters which define the manners of both systems under certain algorithms. Estimating the communication channel factors to reduce the common interfering among a primary communication function and radar which considers as a secondary function has been investigated in [126]. Different approaches for to maximize the mutual information characteristics have been proposed in [127]. In this work, authors control the inference by carefully designed the transmitted radar waveform. Authors conclude that increase the mutual information it not necessary assure the better performance of the radar system.

Calculating the cognitive radar parameters such as estimation and detection with the help of the communication channel present in the same band of radar has been discussed in [15]. Mitigating the interference of the operation of cognitive radar available with the wireless communication in the same band has been proposed in[128]. Furthermore, to transmit a MIMO radar function in the null space of communication with no interference has been studied in[67]. It is worth noted that, the above two papers mentioned tried to improve communication system with at the expense of radar. It is also worth mentioning that, most of the papers founds in the literature which discussed the spectrum sharing between radar and communication focused on solving the interference issues of one service but not both of them in the same time. For radar-communication system using FDA to differentiate between the moving radar target and communication receiver was introduced in[129]. Some authors looked at the cognitive DFRC using frequency hopping as in[130].

2.5.7 Joint Coding Approaches

Different radar-communication integration approaches used the coding techniques as a platform for their operation. Authors in[131], proposed Oppermann sequences for joint radar-communication system. Others in [57], used a complete complementary coding techniques for radar-communication integration. Using OFDM coding to permit the

Global Positioning system (GPS) and radar system to work simultaneously is proposed in [132]. Others looked to the combination of linear frequency LFM modulation when adjusted with the communication signal as in [133]. Using and optimizing radar performance using the pre-coding techniques have been investigated in[134]. Some research focused on implanting communication codes into the OFDM chirp radar as studied in [21].

2.5.8 Modern Co-Designed Method

In this section we present some modern techniques used as co-design approaches for radar- communication unification such as in [23]. Authors used a single waveform to perform both radar and communication system. This information has been encoded in in-band with the radar signal. Other approach used OFDM signal as sharing signal for both radar and communication system [30,40, 44-47].

2.5.9 Sparse and Compressed Sensing Methods

In this section we investigate some papers focused on radar-communication integration based compressed sensing such as [17], [135-139], and [105]. Authors in[140]introduced investigated the modulation Symbol-Domain and spares representation integration into a common platform, this method used is helped out to solve the range Doppler. They propose a random subcarrier mechanism to be integrated with OFDM to enhance the radar performance while keeping the multiuser spectrum in its minimal stage. For more information in this field, one can refer to [139-142].

2.5.10 FDA RadCom Methods

Most of the previous approaches for dual function radar communications system have investigated this technology on the basis of phased array beam patterns in which only angle parameter was taken into account during the radar and communication transmission/reception. Using frequency diverse array for radar-communication integration has been proposed in many papers such as [122],[88],[108],[100],[111],[143],[93] [73], [75], [113]–[117]. The advantage of this new approach is the range and angle parameters are calculated due to frequency incremental in every antenna element. Recently subarray has been introduced as in [122]. Transmission of communication information in the null depth of sidelobe region of FDA beampattern has been introduced in [129].

2.5.11 Neural Network Methods

Neural network methods has been introduced in[106]. The neural network was proposed to minimize the BER. Both radar-communication operations at the same time has been proposed on existing spectrum band between 2.38GHZ up to 2.42 GHz. The advantage of using neural network that there is no priority of one system over the other, the concept of primary-secondary user is not applied in such system.

2.5.12 Modern Co-Design Radar-Communication Based on Rest Mode and Beamforming

This has been introduced in [110],[108],[107]. In [108], we investigate the frequency diverse array for joint radar and communication systems. The basic idea is to use the transmitter/receiver modules of the radar system for communication purpose during listening mode as a secondary function. The radar will be performing its routine functions during the active mode as primary function. A Frequency Diverse Array (FDA) at the transmitter side will be used to produce an Orthogonal Frequency Division Multiplexed (OFDM) signal, which is proposed for communication system. The directivity of radar antenna, FDA in this case, provides an additional advantage to mitigate the interferences other than the Direction of Interest (DoI). The proposed technique allows two beampatterns to be transmitted sequentially from the same FDA structure. Due to the communication signal transmission in the mainlobe of the second beampattern, the Bit Error Rate (BER) achieved in this work is better than BER of the existing techniques used the sidelobe transmission for communications. At the receiver, both incoming signals of radar and communication will share different spatial angle. Simulation results indicate the novelty of idea to suppress the interferences in terms of direction of interest. Another approach based on radar rest mode exploitation presented in [107], in which, we introduced a new method for radar communication integration. The methods found in the literature regarding radar and communication system unification were mostly focused only on the DFRC/RADCOM transmission during the radar active mode. These available methods limited the communication throughput transmission as it is bounded by the short time of radar pulse in active mode. To increase the throughput of communications without disturbing the radar task, we designed a new system that allows the communication transmission during the entire pulse repetition interval. This approach has been achieved by designing two generalized sidelobe cancellers (GSCs) to work together. We exploit two radar modes to transmit the DFRC system. The first mode is the active mode, the radar task is accomplished in mainlobe, and communications transmission occurred in sidelobes. During this active mode, only one GSC is working. In rest mode, both the GSCs are working. The first GSC has the mainlobe and sidelobe levels as in active mode, and the second GSC has the same mainlobe level but double the power in the sidelobes. The output of both is the difference of the two generalized sidelobe cancellers, in which the mainlobe is cancelled, while the sidelobes have the same power, as in the case of active mode. The proposed system permits the wireless communication to be transmitted during the entire pulse repetition interval. Therefore the throughput achieved has been enormously.

2.6 Applications of Radar-Communication Unification System

Radar-communication unification has many applications for 4th and 5th generation. This application depends up on the scenario the system implemented for such as vehicle to vehicle communication, internet of things, automotive radar applications in intelligent transportations. It can be applied to radar that used to sense the environment and transmit data from base station to ground as SAR operates. Also in radar network that gather information with one another and performed a communication between them. Again for intelligent transportation system, the radcom application can be used advancing crash cautionary, eyeless crossing cautionary, susceptible street customer detection, bird's eye view, automatic overtake. All these application and many others can reduce the vehicle crashes upto 80% [144].

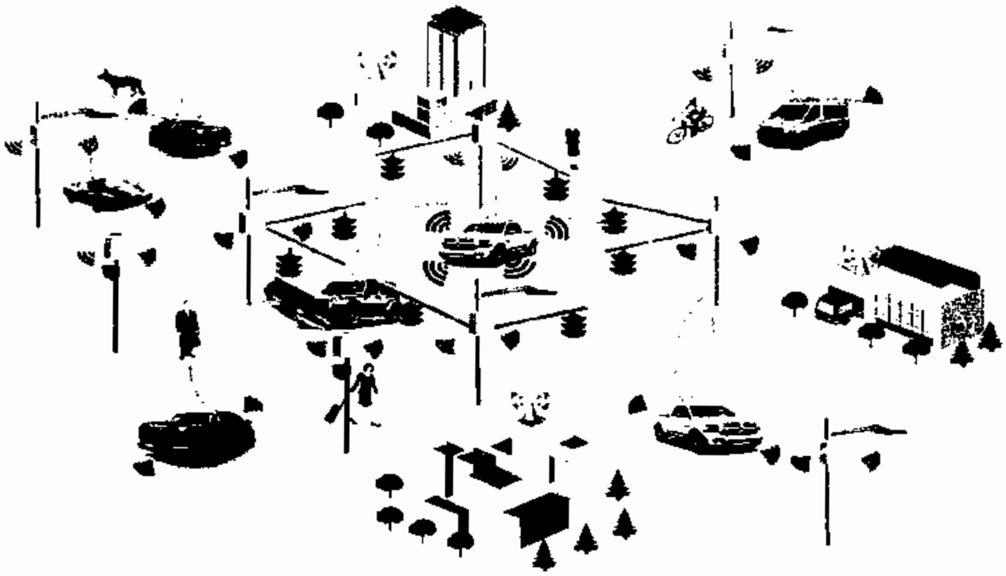


Figure 2-6 An illustrative diagram shows the applications radar-communication unification for vehicle to vehicle communication

DFRC system is a type of co-design paradigm that functions of radar communication simultaneously using for the same hardware at transmitter or receiver side and waveform. The main aim of the DFRC system is to allow the communication to use the information of radar system without influence/affect the radar performance or degrade the radar mission. The exploited radar infrastructure which can be used by communication includes bandwidth, beam forming, multisensory, antenna arrays and its gains and configurations as well as power gain. The application of DFRC can be implemented and applied in recent technologies which require reallocating the spectrum or those technologies which demands many services to work together without interference between them. Such applications are vehicle to vehicles communication, automotive radar applications in intelligent transportations. It can be applied to radar that used to sense the environment and transmit data from base station to ground as SAR operates. Also in radar network that gather information with one another and performed a communication between them. Furthermore, the radcom system can be used in internet of things (IoT). In this approach, the designers connect different type of complements such as machine to machine communication with wireless sensor networks to allow a communication transmission and radar detection as well. This and many applications for radar-communication unification can be found in [145] and references therein.

CHAPTER 3

A JAMMER AVOIDANCE APPROACH FOR DUAL-FUNCTION RADAR-COMMUNICATIONS USING FSK AND INDEPENDENT NULL STEERING

3.1 Abstract

In this work our focus is on radar being used for communications in parallel to conventional target tracking and/or surveillance assignment. In proposed setup, the main beam is directed toward the targets, whereas, the additional tasks of communications is performed through the sidelobes. In addition, the nulls are used to avoid the jammers. A sophisticated null steering feature has been incorporated to deal with jammers changing their positions. These null shifting is kept independent, that is, only the proposed null will be shifted whereas, rest of the antenna radiation pattern including main beam and sidelobes will remain undisturbed. We also propose a new information embedding to transmit the communication signal in the radar emission by using the frequency shift keying (FSK) as orthogonal waveforms to transmit binary information towards the communication receivers. Simulations are carried out and the results indicate the validity and performance of the proposed idea in terms of interference mitigation as well as Bit Error Rate (BER) as presented in this chapter.

3.2 Introduction

The era of multifunction Radio Frequency (RF) system is approaching rapidly. In the earliest form of radar and communication systems, they implemented as different units to work as separate systems. Despite the fact that both systems are a family of

RF spectrum and have many similar properties, they generally use different frequency bands for their operations[84] and [1]. Recent growing demands of (RF) spectrum management encouraged the future developments to focus on sharing spectrum between multiple RF functions such as radar and communications to be unified in their hardware installations and sharing/exchanging information as well as narrowing their gaps. Recent design methods used for this joint system focused on their coexistence, cooperation, and co-design techniques. The co-existence method focused on the operation of the two systems as odd functions and sources of interference to each other[146]. This joint platform allows both systems to use the same bandwidth either simultaneously or consecutively with the continuous exploration and utilization of the existing spectrum [113]. In cooperation method [20], researchers focused on the mitigation of mutual interference among the two systems by allowing them to share information and adjust their presence to each other. The structure of this method may not drastically change their real function rather than focusing on their information exchange.

In co-design method, the system integration is taken place from ground up, to enhance the spectral efficiency of the unified platform as discussed in [23] and reference therein. Other types of co-design methods are embedding communication information in radar radiation which introduced in [77], [78], [80], [83], where authors investigated that how to embed information bits/symbols in to the radar radiation by varying the waveform through every radar pulse. A tradeoff between radar and communications performance by embedding information bits, while keeping the waveform envelop constant with good power spectral efficiency, has been considered in[79].

Another technique investigated the time modulated array (TMA) as in [69]. The authors investigated the radar operation through main lobe and the communication information symbol embedding in sidelobe region. The authors introduced two methods, first is based on the sparse time modulated array (STMA) in which the antenna elements are switched on and off to produce a sideloble level variation. Second method is based on phase only synthesis TMA in which the variation of sidelobe level are achieved by adjusting the phases of the transmit array. In general, the joint platform is beneficial in terms of less installation, hardware costs reduction, and Radio frequency (RF) spectrum exploitation. The dual-function of radar-communications (DFRC) for unified platform needs to identify the priority of both systems based on directivity and power allotment i.e, between the main lobe as primary function and sidelobe as secondary function [112]. In [90], Hassanein el at. used a linear combination between principle and associated weight vectors to produce different beampatterns to send the information through the deep null towards a communication receiver. A robust technique based on quadratic and linear optimization to achieve a desired tradeoff between the main lobe and sidelobes have been proposed in [147],[148],[99]. The problem with papers mentioned above is that if the direction of one null has been shifted to a particular angle, then all the other nulls will also be shifted.

In this chapter, we introduce a new method for DFRC system using independent null steering by decoupling weights. Communication receivers and jammer are located in sidelobe region and receiving a distinct sidelobe directed to them independently. In order to avoid the jammer, the nulls are shifted according to the movement of jammer. To prevent the movement of other null from their actual positions, a structure has been used for decoupling all transmitted weight vectors [149]. As a result, all the nulls can be retained at their actual positions except the null which has been shifted to the direction of jammer. This contribution gives more degree of freedom to the null movement and allows for adaptive manipulation based on jammer movement. The contribution of this chapter can be summarized as follow:

1. Developed a new method a new information-embedding for dual-function radar-communications system based FSK modulation transmission as orthogonal waveforms in sidelobe of each radar pulse, while keeping the radar in mainlobe doing its functional routine.
2. Investigate the concept of independent null steering by decoupling weights for the DFRC to protect the communication system in sidelobe region from the jammers, while keeping the radar functions intact in the main lobe. Thus fighting the jammer located in sidelobe region
3. Developed the communication receiver for the proposed system. The communication can be delivered to single or multiple communication receivers as long as they are available in the sidelobe region.
4. Investigate the computational radar range at receiver side.

The proposed method is tested against the jammer movement in sidelobe region of DFRC systems. We conduct two scenarios, first when jammer is static state regarding the transmitter. In this case, we keep weight vectors at their position in the same angle as far as the jammer's look angle/directional of arrival towards the null is fixed. The second scenario is tested and conducted when the jammer is moving. In this case, we move the null according the jammer movement without affecting radar position and other communications available insidelobe region. It is shown that moving the null towards jammer to secure our communication transmission results Bit Error Rate enhancement as compared to the traditional DFRC systems.

This chapter is organized as following: In section 3.3, we introduce the background of INS and discuss the proposed formulation for system for joint radar and communication and the information embedding at the transmitter. Section 3.4, we drive the proposed design at receiver side, section 3.5 provides simulation results, and Section 3.6 concludes the chapter and discuss the future directions.

3.3 System Modeling

In this section we present the preliminaries about the independent null steering by decoupling weights followed by formulation of proposed dual function radar and communication system.

3.3.1 Preliminaries

Assume that, we have a uniform linear array (ULA) radar with N elements and half wavelength spacing d. In our case, by taking the first element of the array as reference, and putting $z_k = e^{j\gamma_k}$

where $\gamma = \frac{2\pi}{\lambda} d \cos\theta$ for k=1,...N-1. The array factor for ULA is defined in [149] as

$$AF = \sum_{k=1}^{N} e^{-j(k-1)\gamma} = \sum_{k=1}^{N} z^{(k-1)} == 1 + z + \cdots + z^{(N-1)} \qquad 3.1$$

As the polynomial has $(N-1)$ degree in (1), there exists zeros which represents the nulls are $(N-1)$. To steer these nulls, the array factor may be re-written as

$$AF = A_0 + A_1 z + \cdots + A_{N-1} z^{N-1} \qquad 3.2$$

In factorized form, the above equation may be written as:

$$AF = (z - z_1)(z - z_2)(z - z_{N-1}) \qquad 3.3$$

Here,$z_1, z_{2,} \ldots\ldots z_{N-1}$ corresponds to nulls positions in the array factor along fixed angles, $A_0, A_1 \ldots., A_{N-1}$ are the coefficient weights. These exist zeros at $z_1, z_{2,} \ldots\ldots z_{N-1}$ are used to steer $N-1$ null along the desired directions. In figure 1.1, For the time being we will focus on explaining the independent null steering structure (INS) concept, while the communication module integration with INS will be discussed in details in the next heading of this chapter.

Each adder has two inputs with four stages are shown in figure 1. In the first stage , two inputs are added together after multiplying the first input by $(-z_1)$ where z_1 represents the position of the first null in the array factor. The result of this stage can be represented as

$$x_{1,1} = (z - z_1)$$

$$x_{1,2} = z(z - z_1)$$

$$x_{1,3} = z^2(z - z_1)$$

and

$$x_{1,4} = z^3(z - z_1)$$

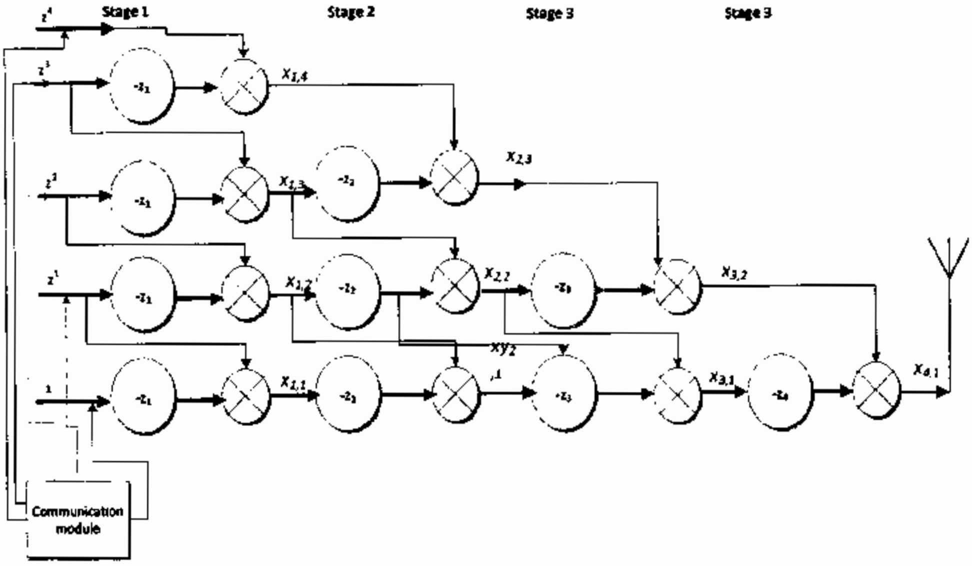


Figure 3-1 Transmitting terminal for independent null steering of four nulls and 5 element arrays

The output of this stage for k=1,...N-1 can be written in general form as

$$x_{1,k} = z^{k-1}(z - z_1) \qquad 3.4$$

Similarly, the second stage has two inputs added together after multiplying the first input by $(-z_2)$ where z_2 represents the position of the 2nd null in the array factor and the output can be written as

$$x_{2,1} = (z - z_1)(z - z_2)$$

$$x_{2,2} = z(z - z_1)(z - z_2)$$

$$x_{2,3} = z^2(z - z_1)(z - z_2)$$

And in general form for *k=1,...N-2* can be expressed as:

$$x_{2,k} = z^{k-1}(z - z_1)(z - z_2) \qquad 3.5$$

Likewise, the third stage represents the position of the 3rd null output in the array factor can be written as

$$x_{3,1} = (z - z_1)(z - z_2)(z - z_3)$$

$$x_{3,2} = z(z - z_1)(z - z_2)(z - z_3)$$

Which in general form for *k =1,...N-3* can be expressed as:

$$x_{3,k} = z^{k-1}(z - z_1)(z - z_2)(z - z_3) \qquad 3.6$$

Finally, the 4th stage represents the position of the 4th null in the array factor and the output can be written as $x_{4,1} = (z - z_1)(z - z_2)(z - z_3)(z - z_4)$ or it can be written in general form for *k =1,...N-4* as

$$x_{4,k} = z^{k-1}(z - z_1)(z - z_2)(z - z_3)(z - z_4) \qquad 3.7$$

3.3.2 Problem Formulation

We assume a unified radar-communication equipped with N radiated antennas towards a spatial radar direction denoted by $\Theta = [\ \theta_s \pm \Delta\theta]$ and towards multiple communication receivers located in sidelobe region denoted as $\overline{\Theta} = [\ \theta_{c1}, \theta_{c2}\ ]$.The transmitter and receiver are co-located with each other so they look at same spatial angle from far field point. The proposed idea is to steer the null independently without affecting the position of main lobe of radar as well as the other nulls in sidelobe region. By doing so, if jammer is moving towards the communication angle, then we move the null towards that jammer. In this case we only update the position of the null towards the new jammer position without affecting the other communication positions in sidelobe region. We develop a set of complex weight vectors with two input adders to maintain the same power in the mainlobe with distinct sidelobe. The null in each stage of the array is responsible to cancel a particular interference accordingly i.e from $\theta_{n1}$to θ'_{n1} . If the position of a specific null is required to be updated, then the set of same weight in the corresponding stage is updated accordingly. The null movement should be changed within a certain limit. To embed communication data into the radar emission, the frequency shift keying

(FSK) used as multiple orthogonal waveforms to transmit binary information towards the communication receivers in sidelobe regions. Each beampattern uses this FSK as orthogonal waveforms to embed M bits of information. This M bits or block of M-ary FSK are subjected to a threshold decision at receiver side..

3.3.3 Proposed Information Embedding

For the same structure in Fig.3.1, we consider the output of the array elements is designed to steer the null towards jammer and direct the sidelobe power towards a communication receivers during one pulse repetition interval. The transmitted radar signal takes place in main lobe represented by the spatial direction θ_s and range bin R_s. Due to the decoupling weights, the mainlobe power kept unity towards the target and doesn't influences by the sidelobe movement. At the same time, the communication waveform takes place in sidelobe region represented by a spatial direction θ_c and the range bin R_c. These two functions can be represented in a general form as two simultaneous transmitted functions. To embed communication signal to the array factor, we use frequency shift keying (FSK) modulation. Consider two orthogonal waveforms are transmitted simultaneously in each radar pulse. These two waveforms are orthogonal in their frequencies and can be expressed as

$$\psi_i(\mathrm{t}) = \begin{cases} \sqrt{\dfrac{2\varepsilon_b}{T_b}} \cos 2\pi f_1 t & 0 \leq t \leq T \\ \sqrt{\dfrac{2\varepsilon_b}{T_b}} \cos 2\pi f_2 t & 0 \leq t \leq T \end{cases} \qquad 3.8$$

Here $\psi_i(\mathrm{t})$ is an orthogonal having a distinct frequency f_1 or f_2 during each transmission. ε_b represents an energy of each bit, T_b is the pulse duration of each bit, f_1 and f_2 are two different frequencies and representing the information bits being transmitted in each signal. Both pulse above having a unit energy. The embedding information is done by switching the frequencies among both f_1 which represents the binary information bit "one" and f_2 represents the binary information bit "zero". By doing so, if the received signal corresponds to f_1 then the transmitted bit is one and if f_2 is transmitted, the received bit is zero. In other words, one is obtained from the other by shifting in frequency. In order to increase the throughput, we transmit M bits per pulse and we use a threshold decision at receiver side. In this case, we use M-ary-FSK and assume that $q=\log_2 M$ a block of bits per signal waveform. Hence , the above Eq. can be written as

$$\psi_i(\mathrm{t}) = \sqrt{\frac{2q\varepsilon_b}{T}}\cos 2\pi \Upsilon \Delta f t \qquad 3.9$$

where $q = 1,..,Q$ and $q\varepsilon_b$ denotes the energy per symbol, Δf is the frequency separation among two successive frequencies and Υ is the number of frequency separations between successive frequencies Δf and T is the interval of the symbol. In order to satisfy the orthogonality condition among these two transmitted waveforms, we must keep $\Delta f = {}^{1}/_{2T}$ which yield to

$$\mathrm{s(t)_{FSK}} = \int_{-\infty}^{+\infty} \psi_m(\mathrm{t})\psi_n(\mathrm{t})\mathrm{dt} = 0\,, \mathrm{m} \neq \mathrm{n} \qquad 3.10$$

We also consider $\{\lambda_i\}_{i=1}^{M}$ as a threshold values that use to decide either the received block of M bits which transmitted along with each orthogonal waveform $\psi_i(\mathrm{t})$ waveform is binary bit one or zero. In doing so, if the received M bits greater than the threshold value, then the transmitted signal was carrying information bit "one" otherwise the received signal carrying a zero bits. Furthermore, the orthogonal waveform at receiver side helps for better matched filtering. Such threshold can be written as

$$\lambda_i \underset{0}{\overset{1}{\gtrless}} Threshold$$

By looking into the above structure, the output of first stage for *(k=1,..,N-1)* may be written as

$$s(t,\tau)_{1,k} = z^{k-1}(z - z_1) \cdot \sum_{i=1}^{M} \lambda_i(\tau)\, \psi_i(t) \tag{3.11}$$

Here τ represents the pulse number (slow index) and t represent the pulse width (fast index). The summation here in $\psi_i(t)$ for i=1,..,M, represents the number of the transmitted orthogonal waveforms per pulse. Again by looking to the structure, the output at second stage for *(k=1,..,N-2)* , the transmitted baseband signal can be written as

$$s(t,\tau)_{2,k} = z^{k-1}(z - z_1)(z - z_2) \cdot \sum_{i=1}^{M} \lambda_i(\tau)\, \psi_i(t) \tag{3.12}$$

Third stage output for the third null for *(k=1,..,N-3)* may be expressed as

$$s(t,\tau)_{3,k} = z^{k-1}(z - z_1)(z - z_2)(z - z_3) \cdot \sum_{i=1}^{M} \lambda_i(\tau)\, \psi_i(t) \tag{3.13}$$

Finally, for the fourth null for $k = 1, \dots, N - 4$, the output stage can be written as

$$s(t,\tau)_{4,k} = z^{k-1}(z - z_1)(z - z_2)(z - z_3)(z - z_4) \cdot \sum_{i=1}^{M} \lambda_i(\tau)\, \psi_i(t) \tag{3.14}$$

In general form, back to Eq.(3), the baseband transmitted signals at the input of antenna array may be written as:

$$s(t,\tau)_{j,k} = AF. \sum_{i=1}^{M} \lambda_i(\tau)\, \psi_i(t) \tag{3.15}$$

It is worth mentioning that, baseband transmitted signal at any stage of the proposed design is having an array factor of the antenna elements which contains the radar radiation as well as an independent communication signal transmitted along with this array factor.

In order to steer the null towards jammers, we implement a decision maker algorithm with a simple scenario that, if the receivers are static and jammer is moving. In this case, we find the direction of arrival (DOA) of the jammer first, and then making decision as to which null to be moved accordingly. Table I summaries the directional of arrival of the jammer on the transmitter of DFRC system.

TABLE I. DOA OF THE JAMMER BASED INDEPENDENT NULL STEERING ALGORITHM

```
Initialize: Inputs: N, d, c, f, $\Theta=\theta_s$ and $\bar{\Theta}=\theta_c$ .
1. Initialize the transmitting elements N
2. For each transmitted beam,
3. check each the directional of arrival angle of the jammer $\theta_j$
4. If $\theta_{n2} < \theta_j \leq \theta_{n3}$
5. Calculate the movement of the null to the right side of the null $\theta_{n3}$ or left side of the null $\theta_{n2}$.
6. If $\theta_{n2} < \theta_a \leq \frac{\theta_{n3}+\theta_{n2}}{2}$
   Then move the null $\theta_{n2}$ towards $\theta_{n3}$ and update $\theta_j=\theta'_{n2}$ , where $\theta'_{n2}$ is the new position of the previous null $\theta_{n2}$.
7. Else If $\frac{\theta_{n3}+\theta_{n2}}{2} \leq \theta_a < \theta_{n3}$
8. Calculate the movement of the null towards $\theta_{n2}$
9. Update $\theta_j=\theta'_{n3}$ , where $\theta'_{n3}$ is the new position of the previous null $\theta_{n3}$.
End
```

Table 3-1 DOA OF THE JAMMER BASED INDEPENDENT NULL STEERING ALGORITHM

3.4 Receiver Analysis

In this part we discuss first the communication received signal at the communication receiver. Then we see the impact of different frequencies transmitted with radar emission.

3.4.1 Detection at the Communication Receiver

At the receiver side, for the l^{th} communication receiver, the baseband-received vector can be expressed as

$$y_{l,m}(t,\tau) = \left\{\beta_l \alpha_l(\theta_l) \left[AF.\sum_{i=1}^{M} \lambda_i(\tau)\,\psi_i(t)\right]\right\} + n_l(t,\tau) \qquad 3.16$$

Here β_l is the propagation factor, $\alpha_l(\theta_l)$ is the reflection coefficient, (θ_l) is the angle of directional of arrival for lth communication receiver and $n_l(t,\tau)$ the additive white Gaussian noise with zero mean and variance σ^2. We assume that, bank of matched filters at the receiver are implemented as shown in Fig.2 These matched filters having a perfect knowledge about the transmitted waveforms. The received signal to each of the transmitted waveform $\psi_i(t)$ may be expressed as

$$y_{l,m}(t,\tau) = \beta_l \alpha_l(\theta_l)\left[AF.\int_0^T \sum_{i=1}^{M} \lambda_i(\tau)\,\psi_i(t)\psi_m(t)\,dt\right] + \check{n}_l(t,\tau) \tag{3.17}$$

$$y_{l,m}(t,\tau) = \beta_l \alpha_l(\theta_l)\left[AF.\sum_{i=1}^{M} \lambda_i\,\delta_{im}\right] + \check{n}_l(t,\tau) \tag{3.18}$$

where T is the pulse width and $\check{n}_l(t,\tau)$ is the noise at the output of the matched filter whose variance is the same as $n_l(t,\tau)$. If the received signal corresponds to f_1 then the transmitted bit is one and if the transmitted signal was f_2, the received bit is zero. In other words, one is obtained from other, by only shifting in their frequency. By applying the receive beamforming vector, it can be written as

$$y_{l,m}(t,\tau) = \beta_l \alpha_l^H(\theta_l)\alpha_l(\theta_l)\left[AF.\sum_{i=1}^{M} \lambda_i\,\delta_{im}\right] \tag{3.19}$$

Here $m = 1, \ldots\ldots, M$ the orthogonal waveforms at matched filters, so the above Eq. can be written as

$$y_{l,m}(t,\tau) = \beta_l\left(AF.\sum_{i=1}^{M} \lambda_i\,\delta_{im}\right) = \beta_l(AF.\lambda_m) \tag{3.20}$$

At the end of each pulse, we are remaining only with the binary bits which need to pass through a decision threshold, and β_l which is a constant value. It is also worth mentioning that, the power of the array factor in side lobe region is designed to be used for a communication transmission purpose and it has been selected carefully by the designers. the followed decision detection which made regarding the digital information threshold λ_i shows that the large magnitude of M bits transmitted with f_1 output p_{th} leads for binary ones binary information and the smaller magnitude of M bits correspond to f_2 and leads to binary zeros detection as follow

$$\lambda_i = \begin{cases} 0, & \lambda_i < p_{th} \\ 1, & \lambda_i > p_{th} \end{cases} \qquad 3.21$$

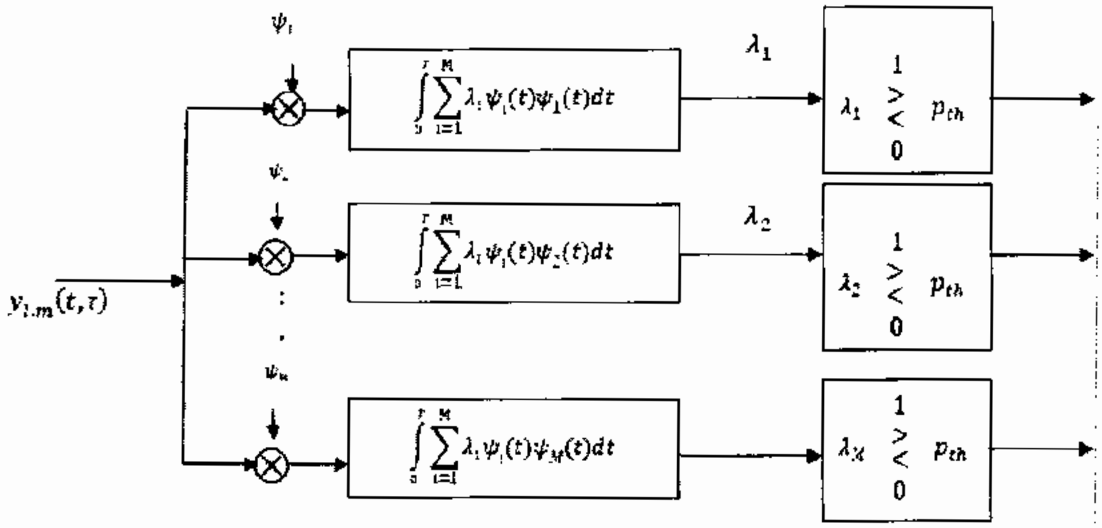


Figure 3-2 Matched filter at receiver end for the proposed technique

3.4.2 Radar Computation Range Analysis

We assume that the radar receiver is co-located near to the DFRC transmitter. In this proposed design, multiple frequencies are transmitted during each radar emission which can help in computing the range of radar echo signal. Therefore, the backscattered radar signal may be written as

$$\psi_i(\mathrm{t}) = \sqrt{\frac{2q\varepsilon_b}{T}} \cos\left(2\pi f_c t - \frac{4\pi f_c R}{c}\right) \qquad 3.22$$

where, R is the target range of the received signal. The value of this range can be written as

$$\mathrm{R} = \left(\frac{c}{4\pi f_c}\right) \tag{3.23}$$

If we calculate the range of the two frequencies , we get for the first orthognal waveform having f_1 , then we get the following formula as

$$\Psi_1(\mathrm{t}) = \sqrt{\frac{2q\varepsilon_b}{T}} \cos\left(2\pi f_1 t - \frac{4\pi f_1 R}{c}\right) \tag{3.24}$$

Similarly for computing the rang of the second received orthogonal waveform carrying f_2 the following formula is written as

$$\Psi_2(\mathrm{t}) = \sqrt{\frac{2q\varepsilon_b}{T}} \cos\left(2\pi f_2 t - \frac{4\pi f_2 R}{c}\right) \tag{3.25}$$

Therefore, the phased difference between the two signals after mixing these two frequencies with the carrier at the receiver side can be written as

$$\nabla\Phi = (f_2 - f_1)\frac{4\pi R}{c} = \frac{4\pi R\Delta f}{c} \tag{3.26}$$

It is clear that from the above equation, the range of the target can be extracted such as

$$R = \frac{c\nabla\Phi}{4\pi\Delta f} \tag{3.27}$$

From the above equation, R is considered an unambiguous when it has a maximum value that $\nabla\Phi = 2\Phi$ and the above equation may be written as

$$R_{\text{unambiguous}} = \frac{c}{2\Delta f}$$

where, $R_{\text{unambiguous}}$ is the maximum unambiguous range. Moreover, if the difference between the two frequenciesis large, this will lead to range accuracy due to the proportionately change in Δf with $\nabla\Phi$. Therefore, the radar range resolution depends on the duration of each frequency and Δf is used to determine the maximum unambiguous range. We noted that the range of the target depends on the difference among frequencies which leads to better range resolution that depend on time span of every frequency such as.

$$\nabla = \frac{ct_p}{2\Delta f}$$

We noted that the range of the target depends on the difference among frequencies. Therefore, the radar range resolution depends on the duration of each frequency and Δf is used to determine the maximum unambiguous range. In conclusion of the above analysis,the difference between the two frequencies, determines the R-unambiguous. Moreover, the range is calculated from the phase difference of the backscattered signal of the two transmitted frequencies consecutively.

3.5 Simulation Results and Discussions

In In our simulation, we consider a uniform linear transmitted array of 10 elements for simulation purpose, having a half wavelength spaced antenna apart. Two functions take place beside the radar operation i.e. communications in sidelobe region and jammer mitigation approach. We consider different examples for fighting the jammer in sidelobe region by moving the null towards the look angle of that jammer without affecting the radar performance as well as communications available in sidelobe region. Three scenarios are presented in the following simulation. First, when jammer is not moving. Second scenario conducted when one jammer is moving in sidelobe region. Third scenario studied the case when multiple jammers are moving in sidelobe region. For this purpose, our design can steer four nulls independently. We also show the radar performance within main beam and communication performance under the proposed system in sidelobe region. We keep the radar power in main lobe to be unity, while the sidelobe power level is designed to a certain level based on the requirement. The carrier frequency fc=3e9. We use the carrier frequency for binary information bit “one”f1=br*8 and the carrier frequency for the binary information bit “zero” f2=br*2 in which br is the bit rate and its given as bp=.000001. The proposed scheme is compared with the previous DFRC schemes based sidelobe level controls as in [69] and [12]. Our proposed scheme (DFRC based INS) outperforms the existing conventional DFRC schemes found in the literature in terms of probability of resolution and bit error rate. Simulation results showed that the proposed method has better performance when compared with the previous DFRC systems at different levels as shown in the following examples. We consider different examples for fighting the jammer in sidelobe region by moving the null towards the look angle of that jammer without affecting the radar performance as well as communications. For this purpose, our design can steer four nulls independently. We also show the radar performance within a main beam and communication performance under the proposed system in sidelobe region outperforms the existing techniques.

Example 1: Fixed/Static Jammer: To get better insight into INS, we considered an example for null movement in case of jammer. In the first case shown in Fig. 3.3, the jammer is not moving, therefore, both weight vectors keep their position in the same angle. In second case shown in Fig. 3.4, the jammer moved from $\theta_{n1} = 40°$, to its new position $\theta'_{n1} = 45°$, then the first null will be shifted accordingly. Clearly, the rest of nulls for both beampattern are imping in the same angle.

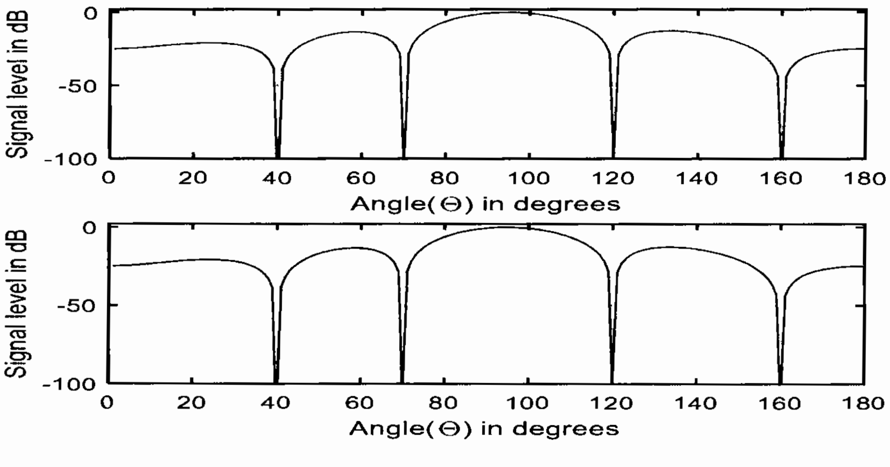


Figure 3-3 Both weights are fixed with the same angle in case of jammer is static

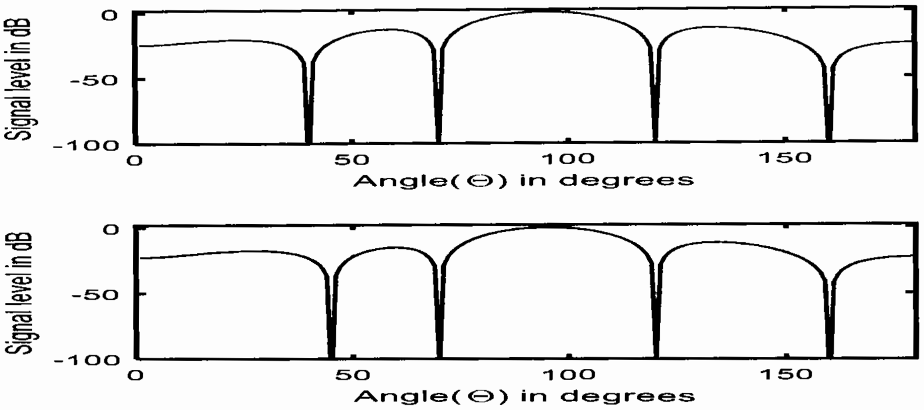


Figure 3-4 Second weight changed the angle from 40 deg to 45 based on the jammer movement.

Example 2 In case the jammers are moving. Consider a jammer number 1 moves from $\theta_{n1} = 40°$ to its new position $\theta'_{n1} = 45°$ as shown in figure 3.5.The first null updates its new position according to the jammer movement without any affection of this movement on radar function, communications transmission or other nulls. The movement of the first null will cause a change in its corresponding weight only in which $z_1 = -0.7983 + 0.6023i$.

Similarly, figure 3.6 shows the second null movement from angle 70° to 75° degrees. The updated weight for the second null will be $z_2 = 0.4652 + 0.8852i$. The radar operation at the desired angle will not be affected as well as the communications direction at 60° .

If the third jammer moved to angle 125° as shown in figure 3.7, the fourth null moved to its corresponding position and the updated weight for the fourth null will be $z_3 = 0.0877 - 0.9961i$. Finally, if the fourth jammer moved to angle from 150° to 160° as in figure 3.8 , the fourth null moved to its corresponding position and the updated weight for the fourth null will be $z_4 = -0.8946 - 0.4469i$. It worthy noted that as far as the null away from the main beam, as maximum as the main beam is secured from any compression or distortion. In all the above mentioned cases the main beam keeps its radiation towards the desired angle.

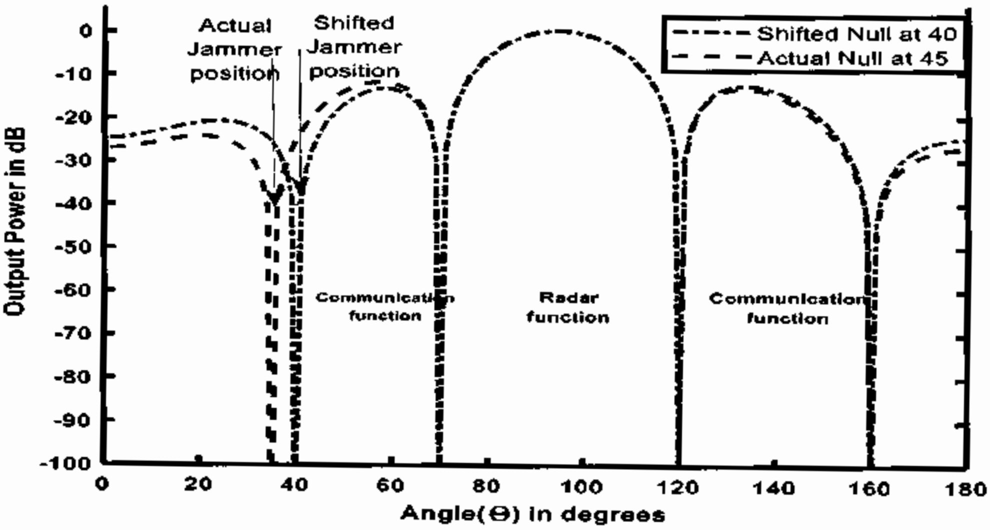


Figure 3-5 First independent null movement from angle 40°to 45° while the communication directions and target are fixed.

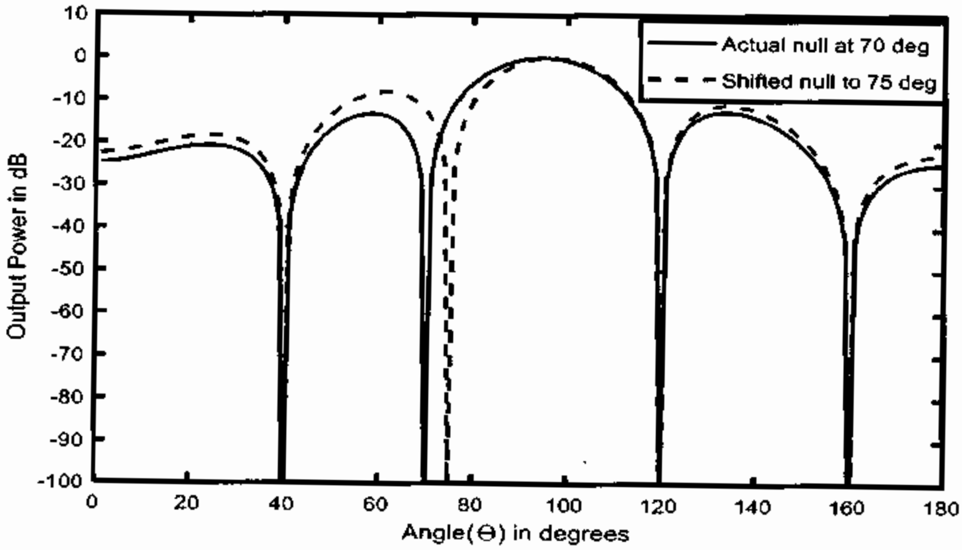


Figure 3-6 Second independent null movement from angle 70°to 75° while the communication directions and target are fixed.

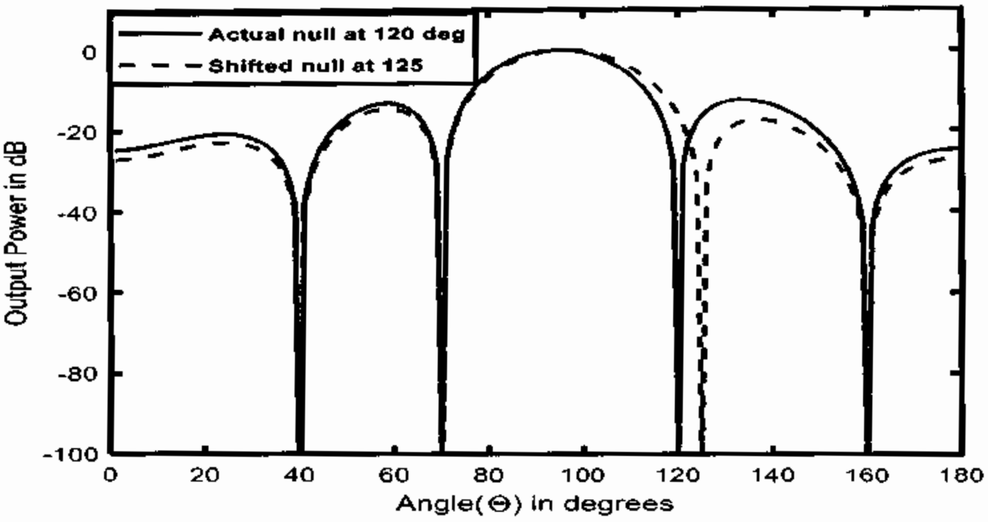


Figure 3-7 Third independent nulls movement from angle 120°to 125° while the communication directions and target are fixed.

It's worth noted that if the desired direction has been changed, then all the weights have to be change accordingly.

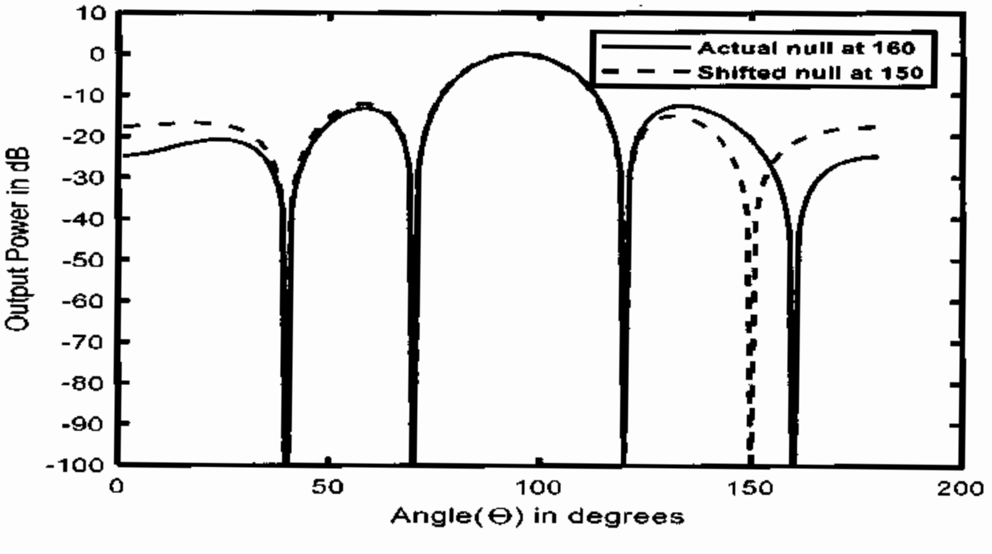


Figure 3-8 Fourth independent nulls movement from angle 150° to160°,while the communication directions and target are fixed.

To conclude the above discussion, we proposed that one beampattern is used as reference beampattern having a fixed look angle towards the communication receivers and radar target. A sophisticated null steering feature has been incorporated to deal with the moving jammers insidelobe region for the rest four beampatterns as in Fig. 3.9 . In this scenario of null shifting, only the proposed null will be shifted, whereas, rest of the antenna radiation pattern including main beam and the other sidelobes will remain undisturbed. . If the jammer is moving towards the communication angle, then update the position of the null towards the new jammer position without affecting the other communications positions in sidelobe region.

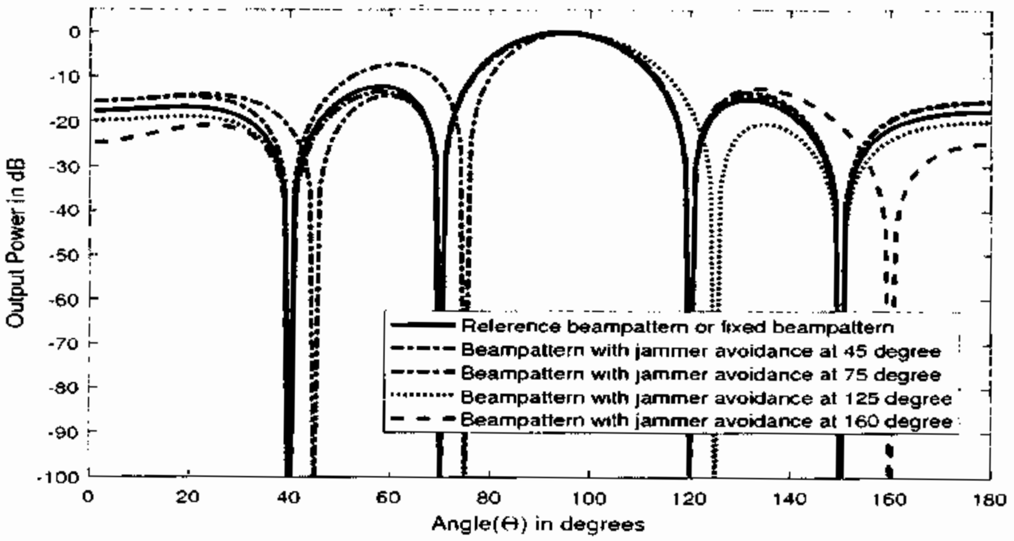


Figure 3-9 five beampatterns with jammer avoidance at different DOA in sidelobe regions.

Example 3 Radar performance within main beam

We evaluate the directional of arrival (DOA) estimation for the radar function. Suppose two targets are closely located 3^0 and 5^o · We assume that, the coefficient in every radar pulse is fixed. These coefficients differ from pulse to another. We note that, the radar performance for the proposed method dual-function radar-communications using independent null steering (INS-DFRC) with waveform diversity outperforms other than schemes in [69] and [112]in terms of root mean square error and probability of resolution shown in figure 3.10 and figure 3.11 . The method in [69] used single waveform in every given pulse, while in [112] used two orthogonal waveforms, one associated with the high sidelobe beam pattern and the other associated with the lower side lobe. Whereas in our proposed we used M=4 orthogonal waveform, which makes the data received depends on the sidelobe level. In our proposed method, we used M orthogonal waveforms that transmitted simultaneously with every radar pulse which leads to better performance in terms of DOA as compared to the existing methods. We used M=4 as proposed in [112]which gives the same identical result to our proposed techniques. When we increase the number of orthogonal waveform we found better result.

Example 4 Bit Error Rate Performance:

We simulate the BER performance of the proposed technique. During every radar pulse, M of communication information bits is transmitted towards the communication directions placed in the sidelobe region. We compared our result with the existing method in [69] and [112]. Furthermore, we used M orthogonal waveforms to deliver M bits per pulse i.e., four orthogonal waveforms to deliver four bits per pulse and we can use more orthogonal waveforms because our designed waveform is totally is independent from being affected by the number of antenna elements. We compare our result with those proposed by authors in [69] and [112], in which authors used one waveform per bit in method 1 and four orthogonal waveforms to deliver two bits per bits per pulse in method 2. Our proposed method outperform better than the existing mentioned methods as shown in figure 3.12

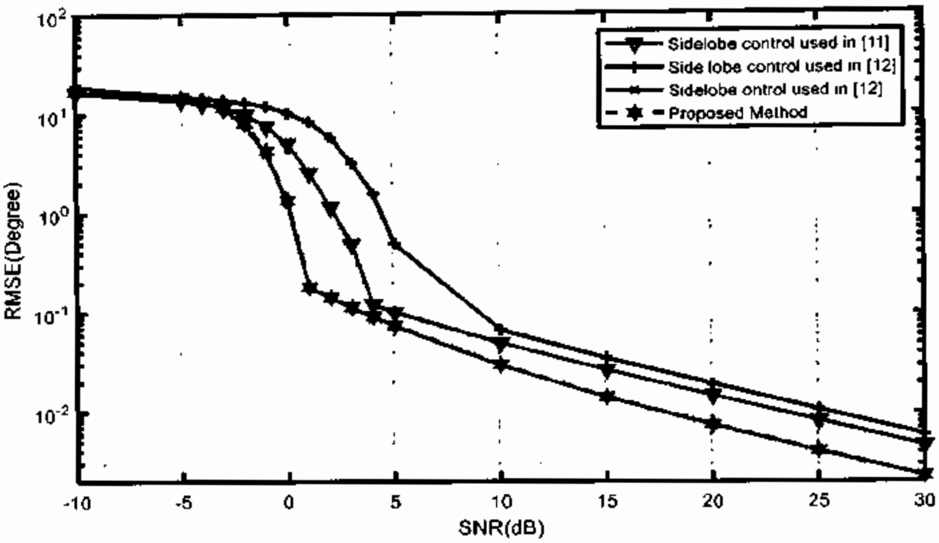


Figure 3-10 RMSEs of DOA estimation vs SNR (example3)

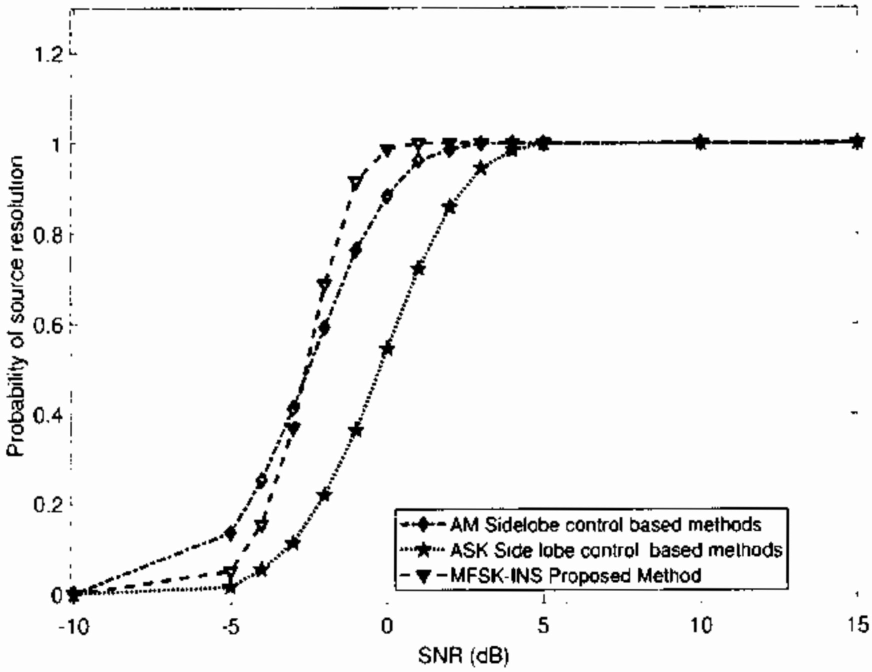


Figure 3-11 probability of resolution as a function of SNR (example 3)

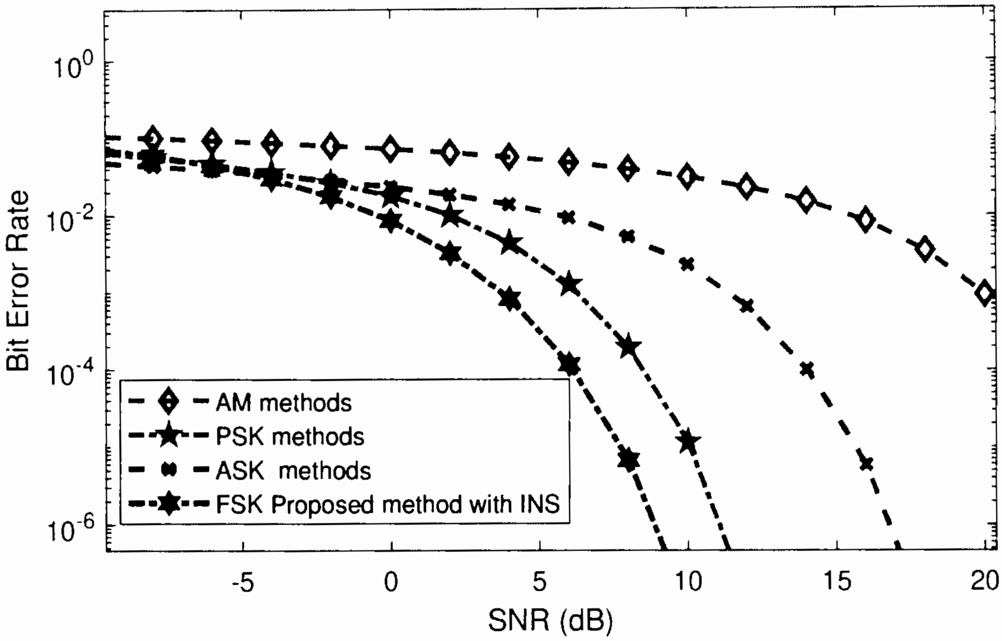


Figure 3-12 The BERs versus the SNR for the four methods

3.6 Conclusion

In this chapter, we proposed a new dual-function radar-communications system with a spatial null steering capability in the beam pattern to mitigate the impact of interferers, where each null in the beam pattern is set independently. We measured three parameters radar, communications and jammer control. The presented approach has first performed the radar functionalities via main beam, communications function via sidelobes and jammer avoidance by null controls. If the jammer is moving towards the communications angle, then we move the null towards that jammer by updating the position of the null towards the new jammer position without affecting the other communications positions in sidelobe region. We used multiple orthogonal waveforms to embed M bits of information transmitted simultaneously with their corresponding threshold values. The results in terms of transmitted beam pattern for the joint system have been presented to show the freedom movement of the null towards the interference/jammer direction.

CHAPTER 4

DUAL-FUNCTION RADAR-COMMUNICATIONS: INFORMATION TRANSMISSION DURING FDA RADAR REST MODE

4.1 Abstract

In this chapter, we examine the frequency diverse array to be used for a unified platform of radar and communication system. Since every pulsed radar, has two modes, one is an active mode, in which the radiation of radar function towards a target takes place. And the other is rest/silent/listening mode, in which radar goes to listening mode to wait for the echo to comeback from the target. During this sleeping/listening mode time, the radar only goes for listening mode. This listening mode time is much higher than the active mode time. Therefore, we propose a new idea to exploit this time of spectrum occupied by radar, to transmit and received a communication signal as a secondary function. The radar operation will keep its routine function as a primary function. A Frequency Diverse Array (FDA) transmitter is used to generate an OFDM signal, which is used here as communication signal transmitted towards an intended communication receiver. The directivity of radar antenna, FDA in this case, provides an additional advantage to mitigate the interferences other than the Direction of Interest (DoI). The proposed technique allows two beampatterns to be transmitted sequentially from the same FDA structure. Due to the communication signal transmission in the mainlobe of the second beampattern, the Bit Error Rate (BER) achieved in mainlobe is better than the existing techniques using the sidelobe

transmission for communications. At the receiver, both incoming signals of radar and communication will share different spatial angle. The proposed idea has been carried out through intensive simulation to prove the originality of the idea. Furthermore, we investigated the SINR and CRLB to estimate the angle and range.

4.2 Introduction

Radar and communication system have been worked since they existed as independent systems to avoid the potential dangers of their combination. However, this scenario is changed dramatically in the last few years due to an inadequate accessibility to the radio spectrum. This issue cause a huge pressure for the radar system to be reinvestigated and redesigned to become one of the promising candidate to solve the spectrum congestion[1]. Moreover, the requirements of bringing both systems together to allow their co-existence and solve the contention issues between radar and communication system as well as to redraw the RF spectrum to be used for different categories of services, urged many research groups to conduct an intensive research on this new technology. Hence, based on similar waveform designs and front-end architectures of these technologies, researchers get the maximum by integration in terms of cost, size, space, and functional reconfiguration [150].

Different progress efforts are conducted to unify radar and communication system and allow them to coexist. This coexistence/unification has been widely deliberated at various conferences and forums. At early stage of this unification, three categories occurred such as time sharing in which the time dimension in this coexistence between both systems is the key point. The second category is based on sub-beam as presented in chapter two. Third category of this unification is based on signal sharing. These types and their advancements have been discussed in the second chapter as well in these papers [151],[52],[152],[30]. Based on the scenario required, the integration process may allow the communication to be used as secondary function and radar is consider the primary function, or the communication can be the primary function while radar is the secondary function. [77],[84],[153],[112].

In [150], authors introduced temporal approach for joint radar and communication based on time-domain duplexing. In contrast , signal sharing as a form of co-design system was proposed in Waveform design for fusion of OFDM signal is considered as signal sharing mechanism, where the communication signal is transmitted to the intended receiver, while the backscattered signal gets analysed for radar measurement as in [30] and [152]. Spread spectrum techniques are also analysed for the joint radar and communication systems (RadCom) [52]. Moreover, the integration can also occur based on the embedding information bits to the radar echoes. This approach used a tag/transponder, which is located in the coverage area of radar illumination. This tag/transponder is used to remodulate the radar echoes with information bits and then send it back to the desired receiver [77]. In spite of the enormous development and much mature radar technology, there is great potential and demand for techniques that use spectrum in a more intelligent and efficient way between radar and communication systems [84]. Moreover, the spectrum sharing management for efficient bandwidth utilization of radar and communication systems can play an important role in this field [153], [125]

In [112], authors introduced a dual function system for radar and communication based on power allotment and directivity of the transmitted signal of each system. They used optimization problem to control the power transmission in sidelobe regions and to be used for communication purpose while the radar signal takes place in the mainlobe with unity power. In [90], designed multiple beamforming weight vectors, one weight vector consider as the a principle beamforming weight vector. This principle weight vector is used to produce a mainlobe radar function as primary function. Whereas the other weight vectors generated is used for communication transmission by enforcing the deep null insidelobe region to be used for communication information embedding.

Similarly, the concept of Advanced Multifunction Radio Frequency (AMRFC) is one the earliest technique that used to divide the spectrum as sub-beam sharing among different RF services, i.e radar-communication as well electronic warfare etc.[154]. After that, dividing the frequency as sub-banding spectrum among radar-communication is presented in many papers such as [151] and [155] where it has been used as an active phased array radar to integrate radar and communication systems into unified platform. The drawback of phased array radar is the steering beam angle fixation for all ranges. This limitation is overcome by FDA radar [156], which possess a spatial variation in the signal field pattern due to the range-angle dependence. The idea of FDA was proposed for first time by Antonik in [156], [157]and has been investigated in the last decade for its applicability in areas, such as radar and wireless communication and other applications can be found in [143], [158]–[163] [16-19]. In an FDA, an array antenna is based on using a small incremental frequency across the array elements, unlike phased array, which uses identical frequencies among all elements within the array. In [164], authors used spread spectrum sequences and time modulated frequency diverse multiple-input-multiple output for dual functionality of radar-communication system. The communication embedding is achieved by spread sequence in every radar pulse. In [100] Costas signal waveforms is used to embed information into FDA-multiple-input multiple-output MIMO radar. In [111], the incremental frequency of FDA has been embedded with information during radar emission. The drawback of all papers mentioned above, the information embedding took place during radar active mode only, which leads to low throughput/less-achievable data rate. To increase the achievable data rate/throughput we transmit the communication signal during FDA radar listening mode.

In [93], authors used Butler matrix over FDA to transmit a communication signal in the null direction of the radar mainlobe. Moreover, information embedding using spread sequence for every radar pulse and time modulated FDA with MIMO techniques was proposed in [100]. Using mainlobe for radar functionalities, while transmitting amplitude shift keying (ASK), phase shift keying (PSK) and quadrature amplitude modulation (QAM) communication signals in sidelobe region was investigated in [104]. This approach allows the designers to transmit a distinct communications towards different communication receivers available at distinct locations in sidelobe regions.

In this chapter, we mainly focused on some variables achievments such as (1)- how to use the FDA radar listening mode for communication (2) instead of transmitting a communication signal insidelobe region as in DFRC existing scenarios, the communication signal is transmitted via second beam pattern. This technique allows two waveforms to be transmitted sequentially (3) this approach increase the data rate of communications and in the same time keeps the radar functionalities intact. (4) We produce the communication signal (OFDM in this scenario) from the FDA incremental frequencies by converting the FDA frequencies to an orthogonal frequencies and send the signal toward a specific direction to increase the LPI property. The number of transmitted communications uplinks depends on the number of radar pulses transmitted waveform during the radar active mode. It worth noting that the time taken for one pulse communication transmission during FDA radar rest/listening mode is larger than the time for one FDA radar pulse transmission during its active mode. This mechanism increases the communication throughput in terms of time transmission as well as in terms of transmission of the communication signal in mainlobe. At receiver side, we analysed the radar echo and communication signal coming from different radcom transmitter. Moreover, we have used orthogonal waveforms for each pulse for better matched filtering at the receiver side. The proposed technique enjoys the BER improvement, as well as, the low probability of interception (LPI) in terms of directional of arrival secrecy and preserves the communication signal towards specific direction. Furthermore, the performance of the proposed system is analyzed in terms of SINR and CRLB to show its effectiveness.

The rest of this chapter is organized as follows. In section 4.2, we describe the proposed scenario and the system model for dual-function radar-communication DFRC system. Section 4.4 describes the simultaneous signal reception and the SINR performance analysis for both systems. Section 4.5 provides simulation results and discussions, and section 4.6 concludes the chapter and discusses the future directions.

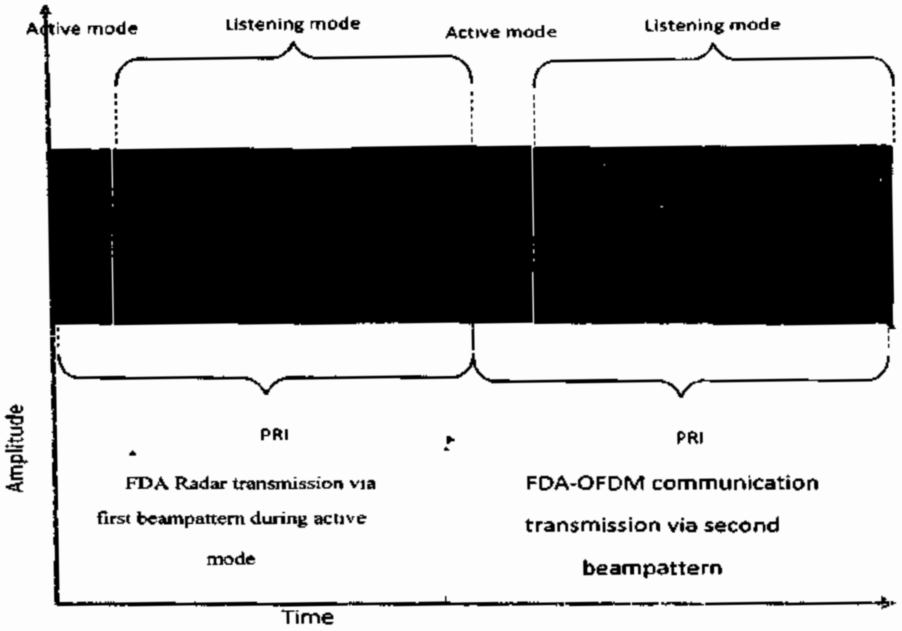


Figure 4-1 Modes transmission diagram for the proposed joint radar-communication systems

4.3 Problem Formulation and System Model

In conventional radar system, the radar transmits energy for only a small period during each pulse repetition interval (PRI), and then keeps silent with no transmission known as radar listening time, as shown in figure 4.1 and expressed as

$$T_t = T_t - t_b \qquad 4.1$$

$$T_s = T_t - t_b \qquad 4.2$$

where t_b is the radar pulse width , T_s is the radar listening time mode and T_t is the total time.

In our scenario, we consider two joint radar and communication systems (RaC_1 and RaC_2) shown in figure 4.2. Each RaC performs a dual-function of radar-communication systems by transmitting a radar pulse during its active mode and communication signal during its listening mode. Two colocated receivers with N elements are placed close to their respective transmitters, RaC_1 and RaC_2. When the RaC_1 sends a radar pulse towards a far field target, the echo received by RaC_1 receiver is matched-filtered to extract the radar measurements. On the other hand, the communication signal coming from RaC_2 towards RaC_1 receiver will be detected as the desired communication signal, while the radar echo coming from RaC_2 is considered as interference to the RaC_1 receiver. We have used orthogonal waveforms for each pulse for better matched filtering at the receiver side.

Consider an FDA radar with M elements and uniform spacing d shown in figure 4.3. The radar radiated waveform by the m^{th}element during one pulse repetition interval is transmitted towards a spatial direction $\Theta \in [\theta_{min}, \theta_{max}]$ and range bin $R \in [R_{min}, R_{max}]$.The communication waveform corresponds to a spatial region $\bar{\Theta} \in [\bar{\theta}_{min}, \bar{\theta}_{max}]$ and the range bin $\bar{R} \in [\bar{R}_{min}\ \bar{R}_{max}$ .These two waveforms can be represented in a general form as two functions in time domain in the following expression.

$$s(t) = \left\{ \begin{array}{ll} s_1(t, r_0, \theta_0) & \begin{array}{c} 0 \leq t \leq t_b \\ \Theta: \theta_{min} \leq \theta_0 \leq \theta_{max} \\ R: R_{min} \leq r_0 \leq R_{max} \end{array} \\ s_2(t, r_c, \theta_c) & \begin{array}{c} t_b < t \leq T_s \\ \bar{\Theta}: \bar{\theta}_{min} \leq \theta_c \leq \bar{\theta}_{max} \\ \bar{R}: \bar{R}_{min} \leq r_c \leq \bar{R}_{max} \end{array} \end{array} \right\} \qquad 4.3$$

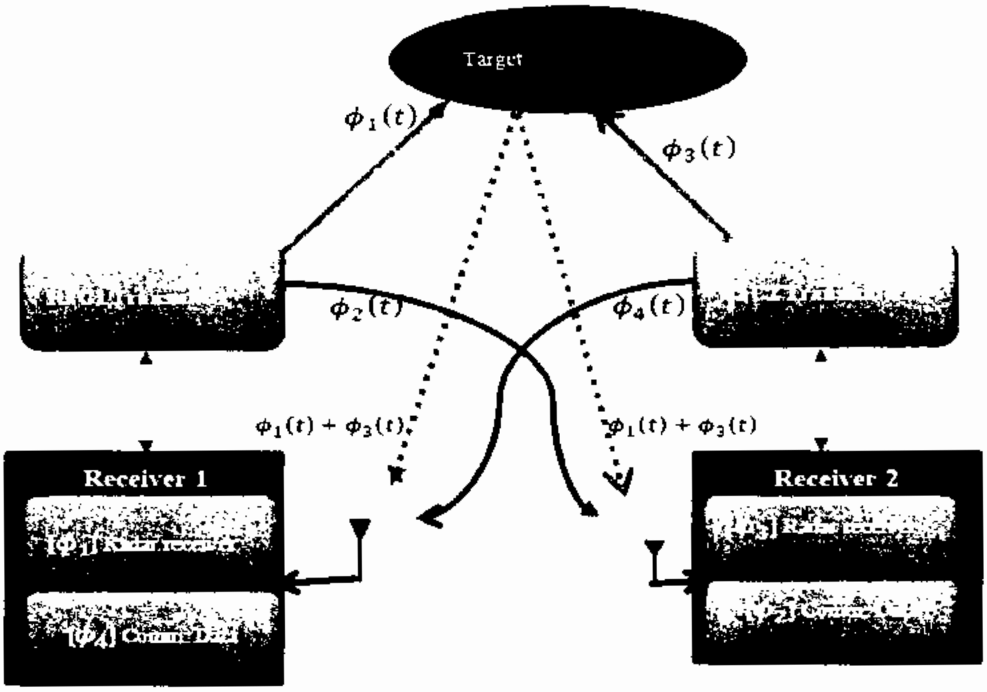


Figure 4-2 The proposed scenario for joint FDA radar-communication systems

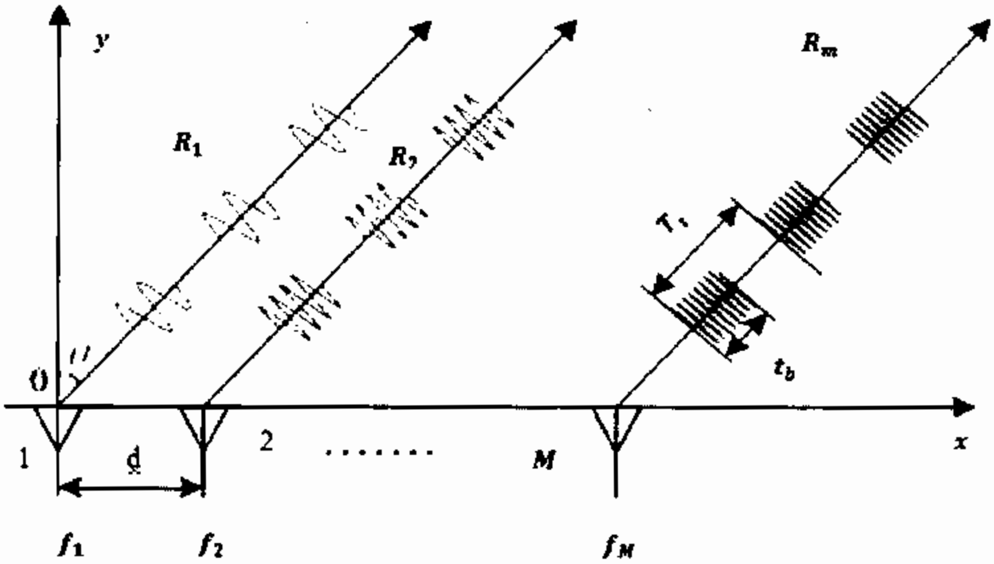


Figure 4-3 FDA array elements

where $s_1(t, r_0, \theta_0)$ is the baseband representation of the FDA radar during the active mode, and $s_2(t, r_c, \theta_c)$ denotes the communication baseband transmitted signal during the listening time mode of FDA radar.

The radiated waveform from m^{th}element can be expressed as

$$X_m(t) = \mathbf{w}_m^H \ e^{j2\pi f_m t} \qquad 4.4$$

where $f_m = f_1 + (m-1)\,\Delta f$, f_m is the respective frequency from m^{th} element of FDA radar, f_1 is the reference frequency, and Δf is the incremental frequency and w_m^H is the weighting function pattern to a specific range r_0 and angle θ_0 given as [163]

$$\mathbf{w}_m^H = e^{j2\pi f_m (\frac{r_0}{c} - \frac{md\sin\theta_0}{c})} \qquad 4.5$$

where d is the elements spacing, c is the speed of light .The arrived signal at target may be expressed as

$$s_1(t) = \sum_{m-1}^{M} X_m\left(t - \frac{r_m}{c}\right) = \sum_{m=1}^{M} \mathbf{w}_m^H \ e^{j2\pi f_m\left(t - \frac{r_m}{c}\right)}$$

$$= \sum_{m=1}^{M} \mathbf{w}_m^H \ e^{j2\pi f_m\left(t - \frac{r}{c} + \frac{md\sin\theta}{c}\right)} \qquad 4.6$$

And

$$r_m = r - md\ \sin\theta \qquad 4.7$$

r is the slant range between the reference element and the target, and θ is the direction angle.

The equation (6) can be written as

$$s_1(t) = \sum_{m=1}^{M} e^{j2\pi f_m t} e^{-j2\pi f_m}\left[\left(\frac{r - r_0}{c}\right) - \frac{md}{c}\,(\sin\theta - \sin\theta_0)\right] \qquad 4.8$$

For a far field target, equation (8) can be written as

$$s_1(t) = e^{j2\pi f_1 t} e^{-j\Psi f_1} \sum_{m=1}^{M} \left(e^{-j\Delta f \Psi}\right)^{m-1}$$

$$= e^{j2\pi f_1 t} e^{-j\Psi f_1}\ e^{-j(M-1)\frac{\Psi}{2}} \left(\frac{\sin\left(\frac{M\Delta f \Psi}{2}\right)}{\sin\left(\frac{\Delta f \Psi}{2}\right)} \right) \quad 4.9$$

where

$$\Psi = 2\pi\left[\left(\frac{r - r_0}{c}\right) - \frac{d}{c}\,(\sin\theta - \sin\theta_0)\right] \quad 4.10$$

By putting (10) into (9), it can be further written

$$s_1(t) = e^{j2\pi f_1 t} e^{-j\Psi f_1}\ e^{-j(M-1)\Psi/2}$$

$$\times \left[\frac{\sin(M\pi\Delta f\left(\frac{r - r_0}{c}\right) - \left(\frac{\pi\Delta f d}{c}\right)(\sin\theta - \sin\theta_0)}{\sin(\pi\Delta f\left(\frac{r - r_0}{c}\right) - \left(\frac{\pi\Delta f d}{c}\right)(\sin\theta - \sin\theta_0)}\right] \quad 4.11$$

4.3.1 FDA Transmit Beam Forming during Radar Active Mode

Consider the FDA structure shown in figure 3.The phase of the signal transmitted from the reference element (first element) to a far field target given in [163] as

$$\gamma_1 = \frac{2\pi f_1\, r}{c} \quad 4.12a$$

where r is the target range from first element. Similarly, the phase of the signal radiated from the second element can be written as

$$\gamma_2 = \frac{2\pi f_2\, r_2}{c} = \frac{2\pi(f_1 + \Delta f)(r - md\ \sin\theta)}{c} \quad 4.12b$$

We calculate the difference between two elements as

$$\gamma_2 - \gamma_1 = \frac{2\pi f_2 r_2}{c} = \frac{2\pi(f_1 + \Delta f)(r - md \sin\theta)}{c} - \frac{2\pi f_1 r}{c}$$
$$= \frac{-2\pi f_1 d \sin\theta - 2\pi\Delta f d \sin\theta}{c} - \frac{2\pi\Delta f r}{c} \qquad 4.13$$

Likewise, the difference between the mth and reference elements can be given as

$$\gamma_m - \gamma_1 = \gamma_{m-1} = -\frac{2\pi f_1(M-1)d \sin\theta}{c} - \frac{2\pi(M-1)\Delta f r}{c} \qquad 4.14$$

For a given target at far field, the transmit steering vector can be represented as

$$\mathbf{a}_\Theta(\theta, r) = \begin{bmatrix} 1 \;\; e^{-j\left(\frac{2\pi f d \sin\theta}{c} + \frac{2\pi\Delta f d \sin\theta}{c} - \frac{2\pi\Delta f d r}{c}\right)} \ldots\ldots \\ \ldots e^{-j\left(\frac{2\pi f(M-1)d\sin\theta}{c} - \frac{2\pi(M-1)\Delta f r}{c}\right)} \end{bmatrix}^T \qquad 4.15$$

$$= \begin{bmatrix} 1 & e^{-j\left(\frac{2\pi f d \sin\theta}{c} + \frac{2\pi\Delta f d \sin\theta}{c}\right)} \ldots\ldots\ldots e^{-j\left(\frac{2\pi f(M-1)d\sin\theta}{c}\right)} \end{bmatrix}^T$$

$$\odot \begin{bmatrix} 1 & e^{j\left(\frac{2\pi\Delta f d r}{c}\right)} \ldots\ldots\ldots e^{j\left(\frac{2\pi(M-1)\Delta f d r}{c}\right)} \end{bmatrix}^T$$

$$= \mathbf{a}_\Theta(\theta, r) = a_\Theta(\theta) \odot \mathbf{a}_R(r) \qquad 4.16$$

where $\odot$ is the Hadamard product. The beam pattern towards direction θ_0 and range r_0 can be written as

$$s_1(t, \theta_0, r_0) = [\mathbf{w}^H \mathbf{a}_\Theta(\theta_0, r_0)]\phi_1 \qquad 4.17$$

where $\phi_1(t)$ is the orthogonal waveforms associated with radar signal to help for better detection at the receiver side, $\mathbf{w}^H$ is the radar weighting vector.

Suppose another radar transmitter from RaC$_2$ located at $a_\Theta(\theta_i, r_i)$ is radiating a pulse towards the same target of RaC$_1$, which is located at (θ_0, r_0) .The echo arriving from RaC$_2$ is assumed to be as interference to the radar receiver of RaC$_1$. The beam pattern of RaC$_2$ in an interference direction θ_i and range r_i can be written as

$$s_3(t, \theta_i, r_i) = [\mathbf{w}^H \mathbf{a}_\Theta(\theta_i, r_i)] \phi_3(t) \qquad 4.18$$

where $\phi_3(t)$ is the orthogonal waveforms associated with radar signal radiated from RaC$_2$.

4.3.2 FDA -OFDM Communication during Radar Listening Mode

In the proposed system, the communication transmission takes place during FDA radar listening mode, the communication signal used in this scenario is the FDA-OFDM which is produced from FDA elements. This signal sent to the intended receiver located at predefined communication direction given in [17] as

$$\begin{aligned} s_2(t) &= \sum_{m=1}^{M} \mathbf{b}_m^H \, e^{j2\pi f_m\left(t-\frac{r_m}{c}\right)} \, e^{-j\varphi_m} \\ &= \sum_{m=1}^{M} \mathbf{b}_m^H \, e^{j2\pi f_m t} \, e^{-j\left[2\pi f_m\left(\frac{r-md\sin\theta}{c}\right)+\varphi_m\right]} \end{aligned} \qquad 4.19$$

where b_m is the information bit, and φ_m is the initial phase of mth RF carrier.

The FDA-OFDM signal could gain low probability of intercept by setting the summation for each m along the predefined direction to be a constant value Φ_m given as [143]

$$\Phi_m = 2\pi f_m(r - md \sin\theta_c/c) + \varphi_m \qquad 4.20$$

The dynamic mapping needs to be updated dynamically to satisfy the condition in (20) along the intended angle. By doing so, the OFDM will be preserved along θ_c which will be distorted in other directions which leads to safety against any eavesdropper or interceptor. Therefore (19) can be written as

$$s_2(t) = \sum_{m=1}^{M} \mathbf{b}_m^H \, e^{j2\pi f_m t} \, e^{-j\Phi_m} \qquad 4.21$$

Moreover, we can write (21) in a vector form as

$$s_2(t) = [b_1 \;\; b_2 \;\; b_3 \;\; .. b_m]^H \begin{bmatrix} 1 \\ ej2\pi ft \\ e^{j2\pi\, f_2 t} \\ e^{j2\pi\, f_3 t} \\ . \\ . \\ e^{j2\pi(M-1)\, f_m t} \end{bmatrix} e^{-j\Phi_m} \qquad 4.22$$

In FDA, the incremental frequencies among element arrays makes the array radiation changes as a function of angle, range, and time [143] and [122]. By doing so, if the communication signal transmitted towards a specific angle, then the FDA still has different ranges. Hence, even if the eavesdropper and communication user are located in the same direction, they will still have different ranges. Moreover, authors in [165] investigated the superiority of the FDA communication performance over the phased array communication in terms of range dimension. In this chapter we investigate the FDA-OFDM communication transmission signal to a predefined direction to protect our transmitted signal from any eavesdropper located outside the intended direction as in [143].This is clear in equation (21), where the intended signal can only obtained by the concern receivers available along the direction of the desired communication transmission. The FDA-OFDM hybridization allows the transmission of distinct carriers through FDA elements towards the desired range-angle position (θ_c, r_c) and enhances the probability of interception reduction.

For a receiver located at far field, the transmitted steering vector for communication purpose may be expressed as

$$\mathbf{a}_{\bar{\Theta}}(\theta, r) = \mathbf{a}_{\bar{\Theta}}(\theta_c) \odot \mathbf{a}_{\bar{R}}(r_c) \qquad 4.23$$

Where

$$\mathbf{a}_{\bar{\Theta}}(\theta_c)$$

$$= [1 \quad e^{-j\left(\frac{2\pi f d \sin\theta_c}{c}+\frac{2\pi \Delta f d \sin\theta_c}{c}\right)} \ldots\ldots\ldots e^{-j\left(\frac{2\pi f (M-1) d \sin\theta_c}{c}\right)}]^T \qquad 4.24$$

$$\mathbf{a}_{\bar{R}}(r_c) = [1 \quad e^{j\left(\frac{2\pi \Delta f d r_c}{c}\right)} \ldots\ldots\ldots e^{j\left(\frac{2\pi (M-1) \Delta f d r_c}{c}\right)}]^T \qquad 4.25$$

By applying the orthogonal waveforms $\phi_2(t)$ and $\phi_4(t)$ to the baseband transmitted communication signals from RaC$_1$ and RaC$_2$ respectively towards a specific angle θ_c and range r_c, the equations may be written as

$$s_2(t, \theta_c, r_c) = [\mathbf{b}^H \mathbf{a}_{\bar{\Theta}}(\theta_c, r_c)]\phi_2(t) \qquad 4.26a$$

$$s_4(t, r_c, \theta_c) = [\mathbf{b}^H a_{\bar{\Theta}}(\theta_c, r_c)]\phi_4(t) \qquad 4.26b$$

where $\phi_2(t)$ and $\phi_2(t)$is the orthogonal waveforms associated with the communication signals for better matched filtering at the receiver side.

4.4 Simultaneous Signal Reception

We assume that the receiver elements are closely located to the RaC$_1$ and RaC$_2$ transmitters such that both transmitters and receivers look at the same spatial angle from the far field point. The total received signal at the first receiver of RaC$_1$ will be the combination of radar and communication signals and is modelled as

$$x(t) = r_{d-echo}(t) + r_i(t) + c(t) + n(t) \qquad 4.27$$

where $r_{d-echo}(t)$ is the radar desired echo, $r_i(t)$ is the interference echo transmitted from RaC$_2$, c(t) is the communication signal and n(t) is the additive white noise vector with zero mean.

4.4.1 Radar Received Signal Analysis

At radar receiver, the downlink communication signal is assumed as interference to the incoming radar echo and vice versa. The total received signal by RaC_1 receiver may be expressed as

$$\begin{aligned} x(t) = {} & \boldsymbol{\alpha}_0[\mathbf{w}^H\mathbf{a}_\Theta(\theta_0, r_0)]\mathbf{v}_\Theta(\theta_0, r_0)\phi_1(t) \\ & + \boldsymbol{\alpha}_i[\mathbf{w}^H a_i(\theta_i, r_i)]\mathbf{v}_i(\theta_i, r_i)\phi_3(t) \\ & + \boldsymbol{\alpha}_c[\mathbf{b}^H\mathbf{a}_{\bar{\Theta}}(\theta_c, r_c)]\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c)\phi_4(t) + n(t) \end{aligned} \qquad 4.28$$

Here, $\mathbf{v}_\Theta(\theta_0, r_0)$ is the receive steering vector of the desired radar echo, $\mathbf{v}_i(\theta_i, r_i)$ is the receive steering vector of the interferer echo transmitted from another radar (in this example RaC_2 transmitter), $\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c)$ is the receive steering vector of the communication signal coming from RaC_2. The parameters α_0 α_i, α_c are the complex amplitudes of the received radar, interference and communication signals. In this regard, each of the received signals has it own orthogonal waveform $\phi(t)$. These signals (radar echo, communication and interference signals) are considers as interference to each other, and they are depending on their own orthogonal waveforms transmitted with them by RaC transmitter arrays. These orthogonal waveforms are designed at transmitter to help in better detection and separation of the received desired signals at receiver side. Therefore, the first two terms in (28) are radar signal dependent. They depend on the signals radiated by the joint platform and backscattered by targets and clutters as well as they depend on their corresponding orthogonal waveforms. Using the matched filter, the received radar desired echo to the transmitted signal $\phi_1(t)$ may be written as

$$Y_0(t) = \frac{\int_{t_b} x(t)\phi_1^*(t)dt}{\int_{t_b} |\phi_1^*(t)|^2 \, dt} = \alpha_0[\mathbf{w}^H a_\Theta(\theta_0, r_0)]\mathbf{v}_\Theta(\theta_0, r_0) + \mathbf{n}_{i+n} \qquad 4.29$$

where t_b is the pulse width duration, and the (n_{i+n}) is the interference and noise observed by the radar receiver and can be written as

$$\mathbf{n}_{\mathbf{rad(i+n)}} = c(t) + r_i(t) + n(t)$$

$$= \boldsymbol{\alpha}_i[\mathbf{w}^H\mathbf{a}_i(\theta_i, r_i)]\mathbf{v}_i(\theta_i, r_i)\phi_3(t) \qquad 4.30$$

$$+\boldsymbol{\alpha}_c[\mathbf{b}^H\mathbf{a}_{\bar{\Theta}}(\theta_c, r_c)]\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c)\phi_4(t) + n(t)$$

$$\mathbf{n}_{\mathbf{rad(i+n)}} = \boldsymbol{\alpha}_i\mathbf{u}(\theta_i, r_i) + \boldsymbol{\alpha}_c\mathbf{u}(\theta_c, r_c) + n(t) \qquad 4.31$$

where $\mathbf{u}(\theta_i, r_i)$ is the respective virtual steering vector defined as $[\mathbf{w}^H a(\theta, r)]\mathbf{v}_\Theta(\theta, r)\phi_3(t)$ and $\mathbf{u}(\theta_c, r_c)$ is the respective virtual steering vector defined as$[\mathbf{b}^H a_{\bar{\Theta}}(\theta_c, r_c)]\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c)\phi_4(t)$. We assume that the additive white Gaussian noise vector with zero mean is $\delta^2 I$.

The FDA radar transmit/receive beampattern in [20] is given as

$$\mathbf{G}_\Theta(\theta, r) = \frac{|[\mathbf{a}_\Theta(\theta).\mathbf{a}_\Theta(r)]^H \cdot \mathbf{a}_\Theta(\theta_0).\mathbf{a}_\Theta(r_0)|^2}{|\mathbf{a}_\Theta(\theta_0) \otimes \mathbf{a}_\Theta(r_0)|^4} \qquad 4.32$$

The covariance matrix for the radar received signal is

$$\mathbf{C}_{\mathbf{0(i+n)}} = \boldsymbol{\alpha}_i^2[u(\theta_i, r_i)\mathbf{u}^H(\theta_i, r_i)] + \boldsymbol{\alpha}_c^2[\mathbf{u}(\theta_c, r_c)\mathbf{u}^H(\theta_c, r_c)]$$
$$+ \boldsymbol{\delta}^2\mathbf{I} \qquad 4.33$$

The output of signal to interference ratio for FDA radar is given in [20] as

$$\mathrm{SINR}_{\mathrm{radar}} \triangleq \frac{\boldsymbol{\delta}^2\left|\mathbf{u}_\Theta^H(\theta_0, r_0)\mathbf{u}_\Theta(\theta_0, r_0)\right|^2}{\mathbf{u}_\Theta^H(\theta_0, r_0)\mathbf{C}_{\mathbf{0(i+n)}}\mathbf{u}_\Theta(\theta_0, r_0)} \qquad 4.34$$

To investigate the performance of the received signal after matched filtering as in (29), we consider a target is present at (θ_0, r_0). In case the range is known and angle is unknown, the corresponding CRLB is equivalent to the inverse of Fisher Information matrix FIM and has been given in [160] as

$$CRLB_{angle} = \mathbf{\Gamma}^{-1}$$

$$= \frac{1}{8\pi^2 d^2 sin^2(\theta).SNR \left\{ \frac{\sum_{n}^{N-1}(n-1)^2}{\lambda^2} + \frac{\Delta \mathrm{f}^2 \sum_{n}^{N-1}(n-1)^4}{c^2} + \frac{2\Delta \mathrm{f} \sum_{n}^{N-1}(n-1)^3}{\lambda c} \right\}} \qquad 4.35$$

where Γ^{-1} is the inverse FIM. In [111]. the radar emission is containing information bits which limit the CRLB for angle to some extent and keeps the FDA RadCom fluctuating between FDA and phased array systems, because when $\Delta \mathrm{f}$ multiplied by binary information "one" it gives FDA system and when multiplied by binary information "zero" it gives phased array system, so this approach keeps the system performance in between both conventional systems. Therefore, they bound the CRLB for angle to a certain value only such as

$$CRLB_{angle}^{Lower\ bound} < CRLB_{FDA\,radcom} < CRLB_{angle}^{Upper\ bound}$$

In contrast, our proposed system allows the CRLB to be achieved without any deterioration exactly like the conventional FDA conventional system. In case the angle is known parameter and we need to estimate the range parameter. The CRLB is again the inverse of Fisher Information Matrix of range(r_0) and defined as

$$CRLB_{range} = \mathbf{\Gamma}^{-1} = \frac{1}{8\pi^2.SNR \left\{ \frac{\Delta \mathrm{f}^2 \sum_{n}^{N-1}(n-1)^2}{c^2} \right\}} \qquad 4.36$$

Hence the information embedding in [111] has no significant influence on the range, but our system gives as identical result to FDA conventional system.

4.4.2 Communication Downlink Signal Analysis

In this part, we analyze the communication signal that received at RaC$_1$ receiver. The receiver will receive the communication signal, radar signal and the noise as well. Mathematically this can be expressed as

$$x(t) = \boldsymbol{\alpha}_c[\mathbf{b}^H a_{\bar{\Theta}}(\theta_c, r_c)]\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c)\phi_4(t) + r(t) + n(t) \qquad 4.37$$

in this equation, $r(t)$ is the radar backscattered /echoes signal which is assument as an interference to the received communication signal. To detect the communication signal only, we use matched filter to the transmitted signal $\phi_4(t)$ and this may be written as

$$Y_c(t) = \frac{\int_{t_b} x(t)\phi_4^*(t)dt}{\int_{t_b} |\phi_4^*(t)|^2\, dt} = \boldsymbol{\alpha}_c[\mathbf{b}^H \mathbf{a}_{\bar{\Theta}}(\theta_c, r_c)]\mathbf{v}_{\bar{\Theta}}(\theta_c, r_c) + \mathbf{n}_{i+n} \qquad 4.38$$

At this point, the communication receiver deals with the radar and interference signals as a noise components. The total noise signal with respect to the communication receiver point of view is

$$n_{com(i+n)} = r(t) + n(t) = \boldsymbol{\alpha}_i[\mathbf{w}^H \mathbf{a}_{\Theta}(\theta_i, R_i)]\mathbf{v}_{\Theta}(\theta_i, R_i)\phi_i(t) + n(t) = \boldsymbol{\alpha}_i \mathbf{u}(\theta_i, R_i) + n(t) \qquad 4.39$$

where $u(\theta_i, R_i) = [\mathbf{w}^H \mathbf{a}_{\Theta}(\theta_i, R_i)]\mathbf{v}_{\Theta}(\theta_i, R_i)\phi_i(t)$

The covariance matrix for the communication received signal is

$$\mathbf{C}_{c(i+n)} = \delta^2[\mathbf{u}_{\bar{\Theta}}(\theta_c, R_c)]\mathbf{u}^H{}_{\bar{\Theta}}(\theta_c, R_c) + \boldsymbol{\delta}^2\mathbf{I} \qquad 4.40$$

The output of signal to interference ratio for communication is given as

$$\mathrm{SINR}_{com} \triangleq \frac{\boldsymbol{\delta}^2|\mathbf{u}_{\Theta}(\theta_c, R_c)^H \mathbf{u}_{\Theta}(\theta_c, R_c)|^2}{\mathbf{u}_{\bar{\Theta}}^H(\theta_c, R_c)\mathbf{C}_{c(i+n)}\mathbf{u}_{\bar{\Theta}}(\theta_c, R_c)} \qquad 4.41$$

To summarize this section , the received waveforms steps can be concluded as in the following table

```
Table I : ALGORITHM
------------------------------------------------------------------------
1. Initialize: Inputs: N, d, c, f, $\Theta = \theta_1 \& \theta_3$ and $\bar{\Theta} = \theta_c$ , $R = r_0$ and $\bar{R} = r_c$
2. Initialize the FDA receiving elements
3. Use non-adaptive beam forming for each receive signals
4. Use the matched filter for $\phi_0(t)$ to extract the radar measurements using equation (4.29)
5. if the receive signal is communication signal: Then apply second matched filter to the waveform $\phi_c(t)$ for the communication processing using equation (4.38)
6. Otherwise, the received signal is interferences and $n(t)$.
```

Table 4-1 Algorithm

Finally, we analyze the link budget of our proposed system of joint radar and communication system based on silent mode. In our proposed system, the maximum radar range is important parameter. Let the distance between joint radar-communication receivers denoted as d_{max}. The link budget for maximum radar range can be calculated as given in [166] as

$$r_{max} = \left(\frac{P_t G_{t,radar}\, G_{r,radar}}{\tau\, PRF\, F_{radar}} \times \frac{\rho}{(4\pi^3)} \frac{\lambda^2 L_{loss}}{k_0\, B_w\, SNR_r} n^{0.5} Gsp \right)^{1/4} \qquad 4.42$$

From the above equation, the radar receives echo signal power inversely proportional of the 4th power of distance, while in communications this becomes stronger and it goes to 2nd power. The communication link budget can be given as

$$d_{\max} = \left(\frac{P_t G_{t,comm} \, G_{r,comm}}{\tau \, PRF \, F_{comm}} \times \frac{\rho}{(4\pi^3)} \, \frac{\lambda^2 L_{loss}}{k_0 \, B_w \, SNR_r} \right)^{1/2} \qquad 4.43$$

where $d_{\max}$ is the maximum radar-communication receiver distance .The link parameters are listed in table II as under

Table II: link Budget Parameters

Parameter	**Description**	**Value**
PRF	Pulse repetition frequency	3KHz
Pt	**Transmit average power**	**0 dB**
K	Boltzman's constant	1.38×10^{-23}
T_o	**Noise reference temperature**	**290 k**
SNR_{radar}	SNR at radar receiver side	10dB
SNRcomm	**SNR at comm. receiver**	**-10dB**
N	Number of radar pulses	200
λ	**Wavelength**	**0.5 cm**
Gt,radar	Radar transmitting antenna gain in the mainlobe	0 dB
Gr,radar	**radar receiver antenna gain**	**0 dB**
ρ	Radar cross section	1 m^2
Ls	**Loss factor**	**0.2**
N	Number of pulses	200
Gsp	**Signal processing gain**	**37 dB**
F_{radar}	Radar receiver noise figure	4 dB
F_{comm}	**Comm receiver noiser figure**	**10 dB**
Rmax	Maximum range	9 km
d_{max}	**Distance between receivers**	**22.2 km**
Gt,comm	Comm. transmitting antenna gain in the mainlobe during listening mode (fig 4.6)	-5 dB
Gr,comm	**Comm receiver antenna gain**	**-5 dB**
Δf	Incremental frequency	60 KHz
f_c	**Carrier frequency**	**10 GHz**

Table 4-2 Link Budget Parameters

4.5 Simulation Result

In this section, we performed extensive simulation to illustrate the performance features of the proposed scheme.

Example 1. Communication Performance Within Radar Active Mode:

In this example, we compared the transmission during radar active mode as well as during radar listening mode. We have first proposed a communication transmission via radar sidelobes during the active mode to show the simultaneous operation for dual-function radar-communication system. We synthesized the power radiation towards the target and proposed four communication directions in sidelobe region. We consider 11 elements at FDA transmitter with the same number at the receiver side and all elements having a half wavelength spaced antenna apart. In this example, we use an optimization problem for the simultaneous transmission of desired radar waveform in the main lobe (as primary function) and communication waveform in sidelobe region (as secondary function) is given by the following expressions

$$\underset{\mathbf{w}_1\ \ \theta}{\min\max} |\mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}(\theta)| \qquad 4.44a$$

$$\mathrm{s.t}\quad \mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}(\theta_{\mathrm{radar}}) = 1\,,\ \ \theta_{\mathrm{t}} \in \Theta \qquad 4.44b$$

$$\mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}(\theta_{\mathrm{ci}}) = \Delta_i \quad \mathrm{for}\ 1 \leq i \leq k-1 \qquad 4.44c$$

In above expressions, $\mathbf{w}_1$ is M X 1 weight vector, $\mathbf{a}(\theta_{\mathrm{t}})$ is M by 1 steering vector towards the target at θ_{radar} in radar spatial sector Θ, $\mathbf{a}(\theta_{\mathrm{ci}})$ is M X 1 steering vector towards a pre-defined i^{th} communication receiver at angle (θ_{ci}).

For communication purpose, we changed the sidelboe level by changing the sidelobe power and kept the radar beam with unity power. The power of the two transmitted beam patterns of main lobe assumed to be directed towards a radar target at $\theta_{radar} = 0°$, and four communication receivers assumed to be located at $\theta_{\mathrm{c1}} = -60°, \theta_{\mathrm{c1}} = -40°\ \theta_{\mathrm{c3}} = 40°$ and $\theta_{\mathrm{c4}} = 60°$ respectively. The variation of sidelobes levels of the two beam patterns as in figure (4.4a) represents the communications information transmitted towards the communication directions. The communications achieved in sidelobe level (SLL) associated with the higher beam pattern (red line) is constrained at (-10 dB) and represents the transmitted bit "1". Whereas the communication in sidelobe level associated with the lower beam pattern (blue dashed line) is constrained at -14 dB and represents the transmitted bit "0". Even if we increase the number of information bits or throughput as in figure (4.4b), then we have to increase the number beam patterns transmission, which means more sidelobes levels (SLL) occurrence at SLL_1=-10 dB, SLL_2=-12 dB,SLL_3=-14 dB and SLL_4=-15 dB . By doing so, the system performance in terms of direction of arrival (DOA) will be degraded. However, the throughput of the amount of data rate transmitted is limited in such systems. In order to increase the achievable data rate while reducing the number of beampatterns and improve the DOA performance, we exploit the radar listening mode for communication transmission. This technique allowed for high throughput in terms of more bits per second that can be transmitted and leads to the directional of arrival improvement as well as explained in the next examples. Moreover, for the sake of comparison, we implement the ASK and QAM used in [104], as shown in Fig.4.4(c) and Fig.4.4(d) in which the authors synthesized the power in one sidelobe region only towards one or two communication receivers. Whereas in our example mentioned in Fig. 4.4(a) and Fig.4.4(b) we transmit the communication signals during active mode towards four communication receivers which definitely leads for throughput increment and BER enhancements.

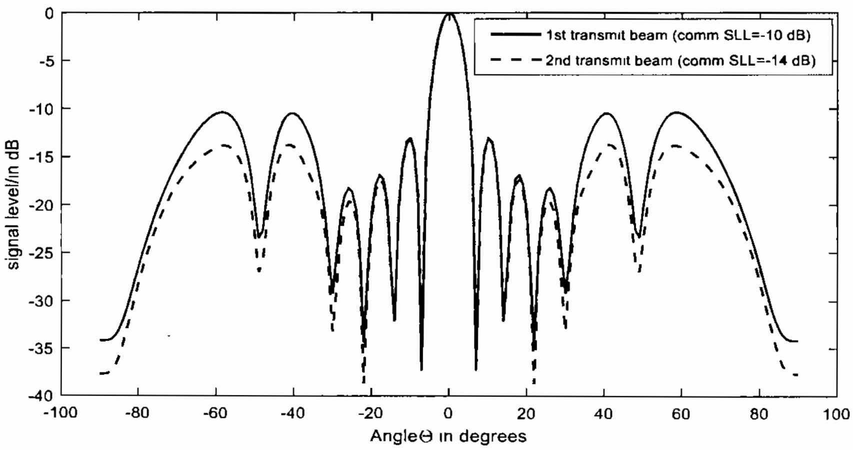


Fig.4.4 **(a)** Power beampattern vs spatial angle with two sidelobe levels using ASK transmission

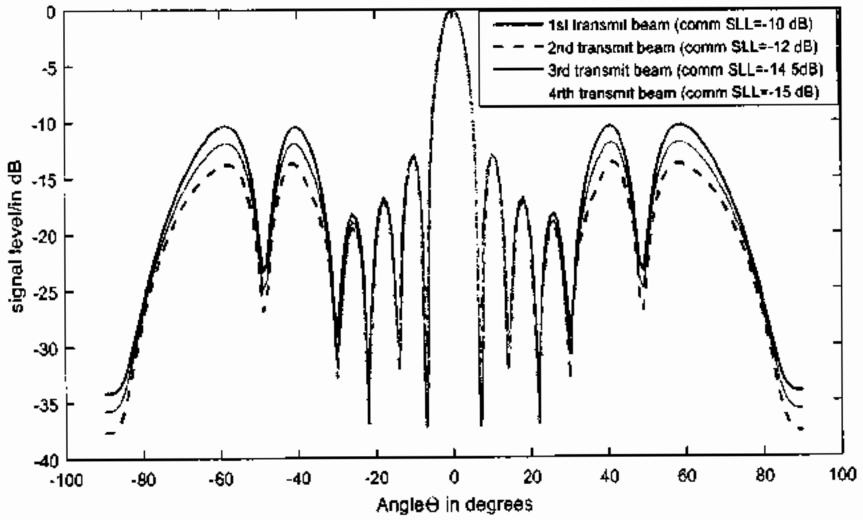


Fig.4.4 **(b)** Power beam pattern vs spatial angle with four SLLs using ASK transmission

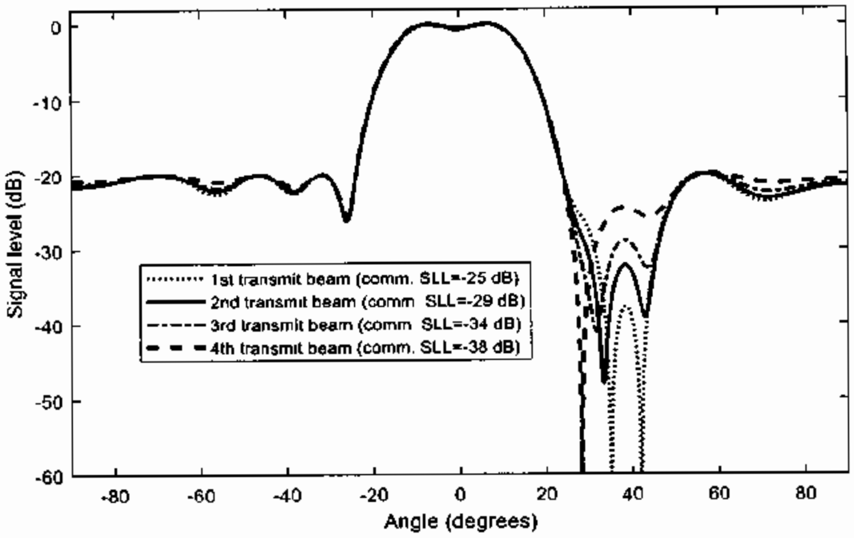


Fig.4.4 **(c)** Power beam pattern vs spatial angle with four SLLs using ASK transmission

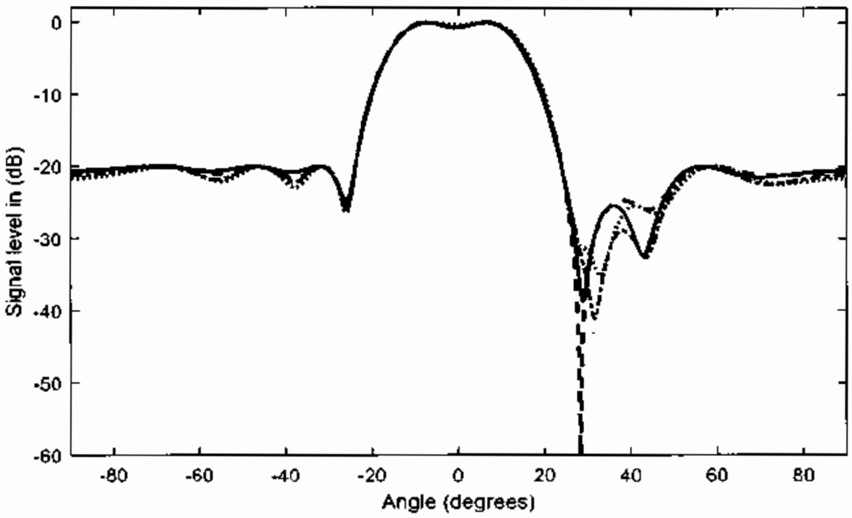


Fig.4.4 (d) Power beam pattern vs spatial angle with four SLLs using QAM transmission

Figure 4-4(a)-(d) Power beam pattern vs spatial angle for different modulation schemes

Example 2. Radar system Performance Within Active Mode: For the same setup in example 1, except that two beampatterns are considered to be transmitted sequentially according to our proposed design. In this example, we used two different beam-patterns, one radiated during the radar active mode as primary radar function, followed by the second beam-pattern carrying OFDM communication signal in listening mode as a secondary function.

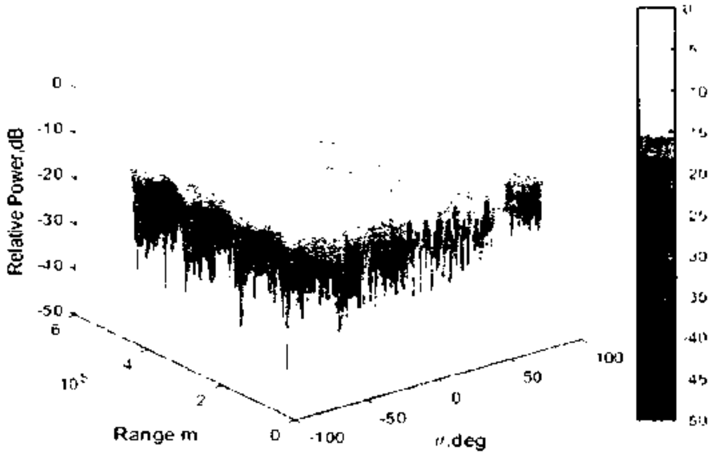


Fig.4.5(a) FDA transmit beam pattern.

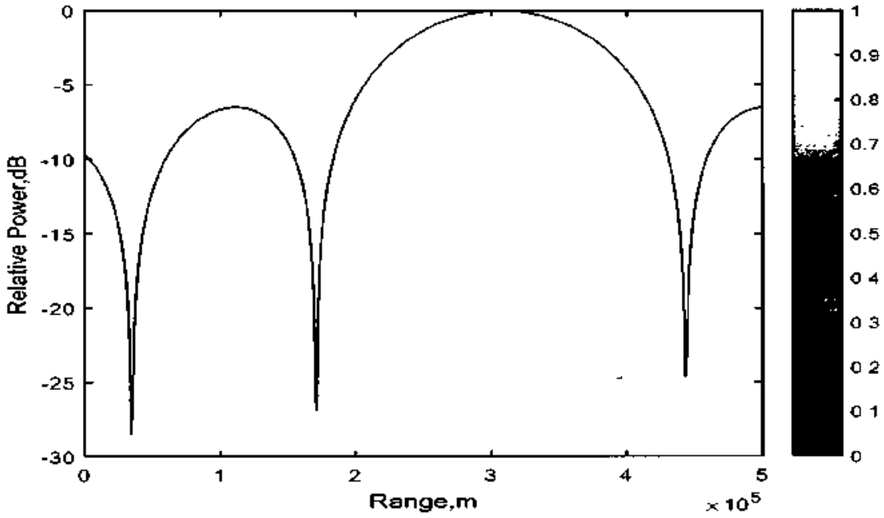


Fig. 4.5 (b) Slant range vs relative power of FDA

Figure 4-5 (a)-(b) beampatterns during radar active mode

The performance of the first beampatterns for radar transmission during the active mode is bounded by $(0 \leq t \leq t_b)$ interval, whereas the second beam pattern bearing communication during the radar listening mode is bounded by $(t_b < t \leq T_r)$ interval. As both systems running in different time modes, the radar beam will not be affected by the second beam bearing information and will operate as the conventional FDA radar as shown in Fig. 4.5(a) and 4.5(b). By doing so, the performance of DOA estimation is improved.

Example 3. Communication Performance Within Radar listening Mode: A part from example (1), we analyze here the performance of the second beampattern during the radar listening mode. Figure 4.6 shows two main lobes having distinct functions. The mainlobe with black dashed line represents the radar beam pattern with spatial sector [-90 90] and power maximization towards the target at $\theta_{\text{radar}} = 40°$. Whereas the mainlobe with red line represents the information embedded in second beam pattern as a communication signal with power maximization towards a communication receiver located at $\theta_{\text{com}} = -30°$ The maximum peak power transmitted from the array is 0 dB for radar beam, while the second beam which carrying communication is less than radar in term of power by -5 dB. It's worth mentioned that, there is no interference between radar and communication signal as shown in figure 4.6, because they are running in different time interval modes. The communication signal is secured at physical layer level due to the angle fixation towards a specific receiver by directing the energy radiation towards a specific direction. This will enhance the low probability of interception LPI property against any eavesdropper located outside the boreside transmission.

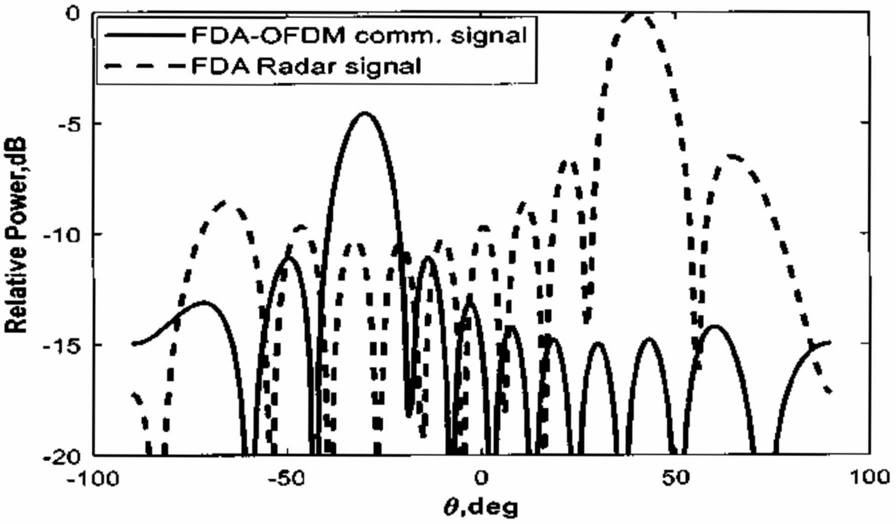


Figure 4-6 FDA & FDA-OFDM transmitted beampatterns vs spatial angle toward a specific angle for LPI property

***Example4. Data Rate Analysis*:** Here we evaluate the communication performance operation during radar listening mode, to recover the information data transmitted during this mode, we re-call equation (21) as

$$s_2(t) = \sum_{m=1}^{M} b_m^H \; e^{j2\pi f_m t} \, e^{-j\Phi_m}$$

For the purpose of checking the orthogonal property of the above equation, we may be re-write it as

$$s_2(t) = \sum_{m=1}^{M} \mathbf{b}_m^H \; e^{-j\Phi_m} \, e^{\frac{j2\pi f_m R m}{c}} \times \int_{\frac{\varepsilon}{\Delta f}}^{\frac{\varepsilon+i}{\Delta f}} e^{j2\pi(m-1)\Delta f t} \; e^{j2\pi(n-1)\Delta f t} dt \qquad 4.45$$

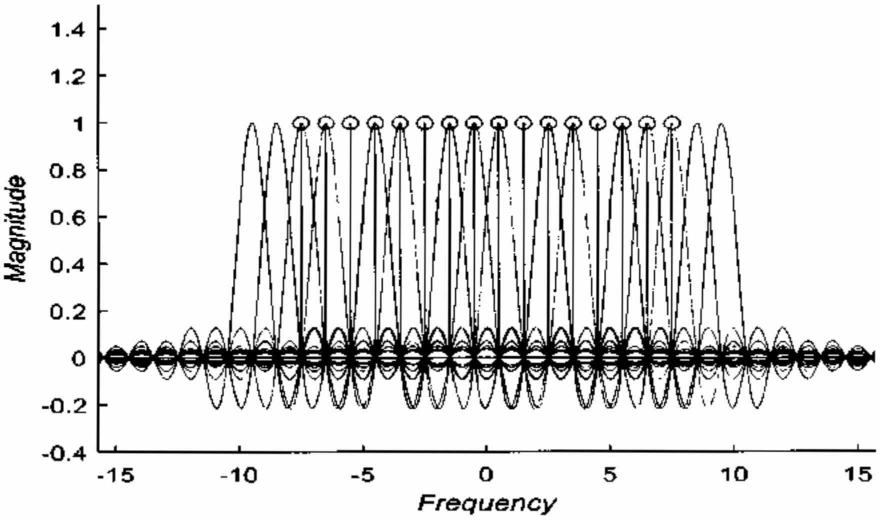


Figure 4-7 Frequency spectrum of each carrier shows the confined symbol duration within a range timing

where ε represents a positive real number and n & m represents different frequencies to show the orthogonality among them, where $\square \neq m$ in case of zero and $n = m$ in case of one. Taking the Fourier transform after multiplying the above equation by rectangular function we get

$$z(t) = \int_{-\Delta T/2}^{\Delta T/2} s_2(t)\, rect(\frac{t}{\Delta T})\, e^{j2\pi f_m t}\, dt$$

The corresponding result after analysis is

$$z(t) = \sum_{m=1}^{M} b_m^H\, e^{-j\Phi_m}.\Delta T. sinc(f + f_m)\Delta T \qquad 4.46$$

The above equation shows that, each carrier frequency is orthogonal with each other in the frequency domain for the second beam during radar listening mode and confined within a limited range time ΔT as shown in figure 4.7.

The bit error rate for this system may be given as

$$\mathrm{BER} = Q(\sqrt{2.E_s/N_o}) \qquad 4.47$$

where E_S/N_o is the signal to noise ratio and Q(.) is the complementary Gaussian error function. Hence, the achievable data rate can be calculated as the number in bits per symbol transmitted during radar listening mode time. Where the radar pulses T_p are associated with their corresponding time intervals T_s available for listening mode. So the achievable data rate in bits per second can be defined as: the number in bits per symbol B times the number of symbols Q times the duration intervals T_s available for uplink transmission times In figure 4.8, the communication transmission occurred in main lobe of second beam pattern leads to improve the BER as compared to the sidelobe design of the previously existing systems [112], [111],[116] and [104]. To test BER, a sequence of 10^5 symbols is transmitted. It's evident that our proposed system having better achievement and shows some improvement of overall throughput or sum data rate because the transmission occurred in the main lobe of communication during for longer time rather than that which used in active mode. In our proposed scheme the communication transmission gone through the high gain transmission of second beampattern. The BER is improved, when high gain lobe transmitted towards a communication receiver. This also proved the superiority of the proposed system among existing techniques. It is very vivid from figure above that utilization of high gain main lobe for communication in the absence of radar target yields a better BER as compared to sidelobe based communication.

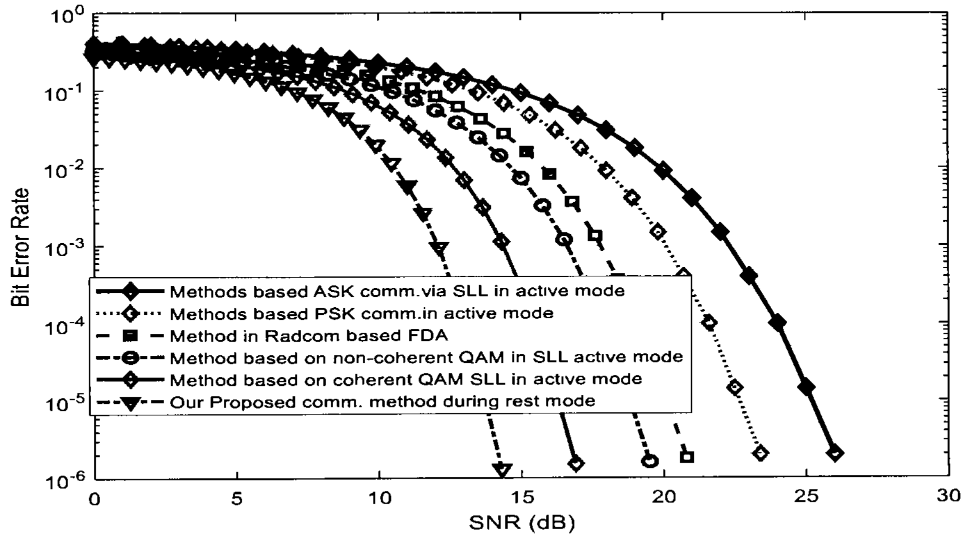


Figure 4-8 . BER vs SNR for joint function radar-communication

.*Example 5. SINR versus SNR Performance Analysis For the joint FDA platform:* In this example, the performance analysis of our proposed RadCom system in terms of SINR is shown and compared with the performance FDA conventional, phased array system and FDA RadCom proposed in [111]. The SINR for these systems has been plotted against SNR as shown in Fig. 4.9(a). For radar evaluation, we consider an interference located at (-30^0,9km).Hence the proposed system is capable to suppress the interference in both angle and range dimensions, the estimated result are outperforms the phased array techniques. Moreover our system doesn't alter the radar waveform with any binary information embedding during radar active mode, this leads to identical result of the FDA conventional. Our proposed system radiated toward the intended area and gives better SINR versus SNR as compared with [111]. We have achieved a slight improved performance than conventional FDA. Similarly, for communication evaluation we consider the second beampattern transmission with interference located at 40^0. The SINR versus SNR simulation in Fig. 4.9(b) shows that our proposed system during radar listening mode outperforms the conventional communication transmission. Overall our proposed system has better robustness characteristics against any eavesdropping and noise occurrence.

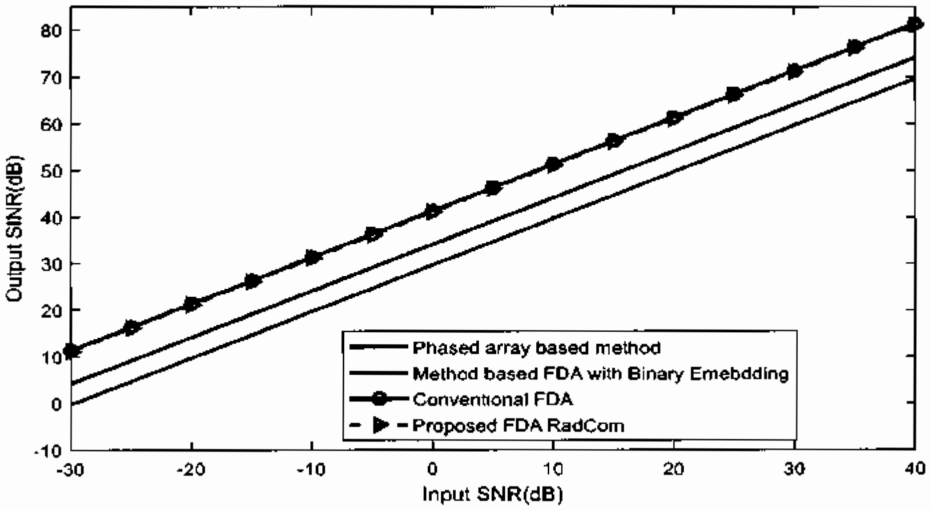


Fig.9. **(a)** SNR vs SINR for FDA functionalities under both cases (conventional and RadCom)

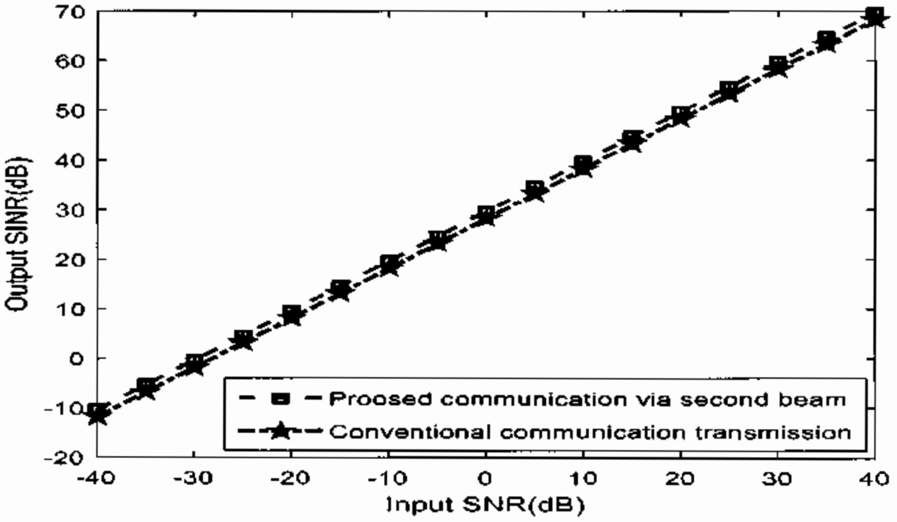


Fig.4.9. **(b)** SNR vs SINR for second beam-pattern bearing communication.

Figure 4-9 (a)-(b) SNR vs SINR for FDA 1st and 2nd beampattern

Example 6. ***Cramer-Rao lower bounds (CRLBs)-*** To investigate the radar performance system within active mode, Cramer-Rao lower bounds has been plotted in both angle and range as shown in Fig. 4.10 (a) and 4.10(b) respectively. We comparatively simulate the following radar systems: (i) phased array system; (ii) FDA RadCom given in [111]; (iii) our proposed RadCom scheme. By using equation (35) we simulate the target signal of interest reflected from angle 30^0 and equation (36) to compute the range for the proposed system at 9*km*. The CRLB for three radars is quite good, however the proposed RadCom outperforms the phased array radar and FDA RadCom in [111]

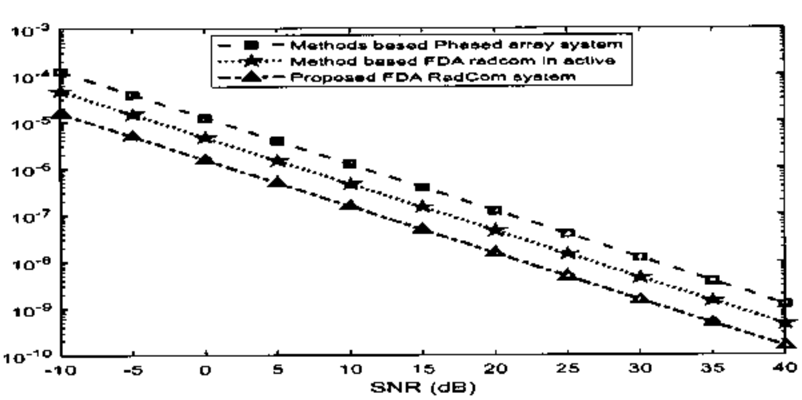


Fig. 10. **(a)** CRLB for estimating angle versus SNR

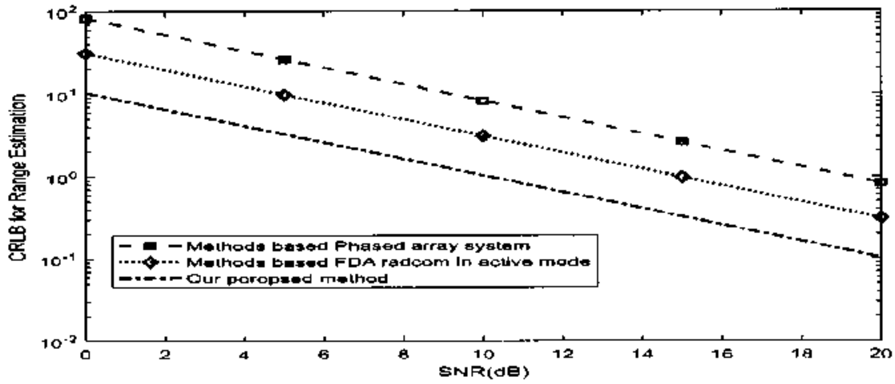


Fig.4.10. (b) CRLB for estimating Range versus SNR

Figure 4-10 (a)-(b) CRLB for estimating SNR vs angle and range

This improvement in estimation performance occurred because we did not alter or embed any communication signal during radar active mode radiation as authored did in [111]. They used to alter the radar functionalities during active mode, which led to keep the system ranging in the middle between conventional FDA and Phased array systems. Therefore, they limited their results by upper and lower bound of angle to maintain an adequate performance. It's worth noted that, the increasing or decreasing the incremental frequency doesn't have a sever influence on CRLB, while that the CRLB can be improved if the antenna elements are increased.

4.6 Conclusion

In this chapter, we have designed a novel approach for dual-function of FDA radar-communications system. We have exploited the listening mode of FDA pulsed radar for the communication transmission in order to get a unified transmitter/receiver platforms. Communication transmission is achieved via radiating a communication signal during the radar listening mode. The uplink/downlink of communication takes place when the radar is in listening mode. The approach has first performed the radar functionalities during the active mode and steers the main beam towards a target. Then, the hybridization based FDA-OFDM information-bearing communication beanpattern was transmitted during the FDA listening mode towards pre-defined receiver. At receiver side, two matched filters are used to separate the incoming beampatterns of radar and communication from different spatial angle. Results in terms of transmit/receive beampattern for the joint system has been presented to show the feasibility of the proposed system. We have achieved good results in communication side with high capability of interference rejection and improved BER. Finally, we showed that the designed joint system does not suffer from the interference emissions of each other in their main beams directions. Simulation results have shown the effectiveness of the proposed scheme.

CHAPTER 5

THROUGHPUT ENHANCEMENT FOR DUAL-FUNCTION RADAR EMBEDDED COMMUNICATIONS USING TWO GENERALIZED SIDELOBE CANCELLERS

5.1 Abstract

In this chapter, in which, we introduced a new method for radar communication integration. The methods found in the literature regarding radar and communication system unification were mostly focused only on the DFRC/RADCOM transmission during the radar active mode. These available methods limited the communication throughput transmission as it is bounded by the short time of radar pulse in active mode. To increase the throughput of communications without disturbing the radar task, we designed a new system that allows the communication transmission during the entire pulse repetition interval. This approach has been achieved by designing two generalized sidelobe cancellers (GSCs) to work together. We exploit two radar modes to transmit the DFRC system. The first mode is the active mode, the radar task is accomplished in mainlobe, and communications transmission occurred in sidelobes. During this active mode, only one GSC is working. In rest mode, both the GSCs are working. The first GSC has the mainlobe and sidelobe levels as in active mode, and the second GSC has the same mainlobe level but double the power in the sidelobes. The output of both is the difference of the two generalized sidelobe cancellers, in which the mainlobe is cancelled, while the sidelobes have the same power, as in the case of active mode. The proposed

system permits the wireless communication to be transmitted during the entire pulse repetition interval. Therefore the throughput achieved has been enormously.

5.2 Introduction

The ever-increasing demands for radar and communication systems to be unified on a single platform has gained great attention from researchers in the area of spectrum sharing. This fusion is required to provide the efficient usage of the shared spectrum to obtain a high-throughput measurement of both services[1], [2], [84], [167]. The obvious approach techniques used in radar –communication unification are: first, time sharing in which the integration between the two systems are based on time. Second approach based on frequency or sub band sharing, in which the frequency band is divided among different services/systems. Third approach is signal sharing and coding in which a common designed signal is used for both systems [81]. These methods involve novel techniques for waveform diversity management which has an easy implementation, a hardware cost reduction, and radio frequency (RF) spectrum exploitation[78], [113]. Further mover, new approaches and method used in recent publications using the same common structure and resource allocation to perform the radar and communication functions simultaneously to get the required bandwidth. These new methods/techniques they have been known as co-existence, cooperation and co-design methods[12]. The coexistence method is the method used for both radar and communication as interference to each other[20]. In this approach, the designers always try to minimize the interference of one system on the other. The cooperation method is based on exchanging the mutual information between the two systems. In this technique there is no significant change in the core operation of both systems radar than exchanging information in order to mutually alleviate the interferences as in [18].A co-design approach is defined as how to perform radar and communication functions simultaneously via common transmitter/receiver, same bandwidth and joint waveform. Is defined as the approach that allow both systems (radar and communication) to be designed and functioning as a new joint system. In other words, this system is completely designed from ground up with keeping in mind that both systems must focus on maximizing their performance during their operation as in [22], [23], [168]and the references therein. Moreover, in the explicit form of the co-design method, the information is embedded into the radar emission by varying the waveform in every radar pulse[77], [79], [83]. A tradeoff between the radar and communication performance by embedding information bits and keeping the waveform envelope constant with good power spectral efficiency was introduced in[79]. One of the pioneering approaches in this field is the idea of designing the mainlobe for radar primary functionalities and the sidelobe for communications as a secondary function in which both of these two systems/services are working within a same band, signal and common structure. These techniques are known as dual-function radar communication (DFRC) and presented in many papers such as[69], [90], [95], [97]–[99], [104], [112], [113], [115], [116]. The amplitude modulation (AM) with different sidelobe levels have been introduced in [69]. In this approach, authors introduced the information embedding using TMA as phased modulation (PM) synthesis by studying the time modulated arrays (TMAs for radar-communication integration. Two techniques have been introduced, one is based on a sparse time modulated array (STMA), in which the antenna elements are moved on and off to produce a variation in the sidelobe level. The other technique established on phase only synthesized a TMA, which is similar to an

STMA, except that the variation in the sidelobe level is achieved by adjusting the phases of the transmitting array. Others in [112] designed a DFRC system by using convex optimization to dedicate the mainlobe for radar while the side lobes for communications. The authors in this approach generate multiple beam forming weight vectors and each beam forming weight vector has its own orthogonal waveform. The amplitude shift keying ASK is used as modulation scheme, in which the communication information is embedded in each sidelobe level and transmitted towards a specific receiver located in side lobe radar region. Another approach used a linear the combination among the reference and accompanying weight vectors to generate multiple weight vectors, these weight vector are transmitted through the deep null in the direction of a communication receiver [90]. Other researchers designed a robust methods by using quadratic and linear optimization to find a tradeoff the mainlobe for radar and in the sidelobes for communications as in [99], [147], [148]. In [88], Butler matrix is designed to allow communication transmission into the null of the radar waveform based on frequency diverse array which has the properties of transmission of the beam pattern to different ranges and directions. In [164], the authors used a time-modulated frequency diverse multiple-input and multiple-output (MIMO) array method for the DFRC system, in which the information embedding occurred via spread sequences through every radar pulse. Moreover, different radar communication integration techniques can be found in [3]. In the previous papers and the literature which was already introduced up to date in the field of radar-communication integration, the data rate produced was totally based on radar active mode transmission, therefore , the data rate was very low. Therefore, we thought out of the box, about, what will happened if we used radar rest/listening/silent mode for communication transmission beside the transmission of communication in active mode such as the previous techniques introduced so far. Generalized sidelobe cancellers (GSCs) are an effective approach for spatial-temporal transmission. The generalized sidelobe canceller has been examined widely in radar and communication systems in areas where the desired signal needs to be measured either in time or at the amplitude level [169]. In this chapter, we suggest a novel method to DFRC using both radar modes to transmit communication information in a sidelobe region. The contribution of this chapter can be summarized as follows:

1- We develop two generalized sidelobe cancellers, GSC_1 and GSC_2. GSC_1 operates in active radar mode to perform a radar task in the mainlobe and a communication task in the sidelobe region. In rest mode, GSC_2 is functional in parallel and produces identical power in the mainlobe at the position of the mainlobe of GSC_1 but double power in the sidelobe region. Subtracting one function from the other function eliminates the mainlobe, while the sidelobes with proper power are available for the communication transmission.

2- We achieve increased throughput by using even the rest mode of the radar for communications.

The rest of this chapter is organized as follows. Section 5.3 describes the fundamentals of radar, and Section 5.4 introduces the problem formulation and system modeling for the joint platform. Section 5.5 analyzes the communication throughput per pulse repetition interval. Section 5.6 provides the simulation results. Section 5.7 concludes the chapter and discusses the future directions.

5.3 Fundamentals

In a conventional radar system, the radar transmits energy for only a small period during each pulse repetition interval (PRI) and then remains silent with no transmission in radar rest mode, as shown in Fig. 5.1. Mathematically, this can be expressed as

$$T_t = t_w + \tau_r \qquad 5.1$$

where t_w is the radar pulse width, τ_r is the radar rest mode time for the transmitted pulse reflection from the target during one PRI, and T_t is the total time for one pulse repetition interval. To calculate the time taken by the target echo, one should know the distance of the target and the time associated with the pulse width during each PRI. In doing so, two parameters need to be considered. The first parameter involves the relation between the active mode and rest mode time duration during each PRI according to the following equation:

$$\tau_r = T_t - t_w \qquad 5.2$$

The second parameter is the rest mode time based on the target distance. The target distance corresponds to the two-way propagation time of the transmitted pulse during each PRI from the radar transmitter to the target, which is backscattered and received before the next pulse is transmitted. This relation is given as

$$\mathcal{R}_{max} = \frac{(t_w + \tau_r)C}{2} \qquad 5.3$$

where C is the speed of light~~,~~ and $\mathcal{R}_{max}$ is the maximum unambiguous range. Hence, the maximum time given for rest mode based on the maximum unambiguous range can be given as

$$\tau_r = \frac{2\mathcal{R}_{\max}}{C} - t_w \qquad 5.4$$

5.4 Problem Formulation and System Model

The communication data rate for information embedding based on the sidelobe remains unchanged and bounded only by the sidelobe occurrence in radar active mode. To increase the communication throughput, we propose a technique that allows communication transmission during the radar active and rest modes. In active mode, GSC_1 works and tracks the signal for the radar via the mainlobe and communication signal via the sidelobe.

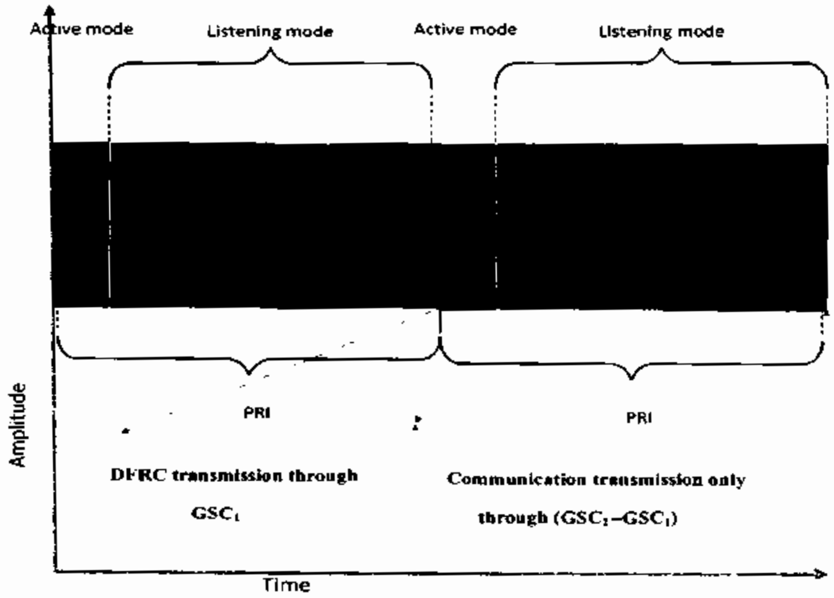


Figure 5-1 Illustrative diagram of the proposed transmission signaling of the (PRI)

The processing time in active mode is t_w. In rest mode, GSC_1 and GSC_2 work together; having identical amplitude powers in the mainlobe and different amplitude powers in the sidelobe region. The subtracted resulting power of both GSCs (GSC_1 and GSC_2) is transmitted during the timeτ_r.

In this chapter, we consider a uniform linear array of M transmit antenna elements with a spacing of d. These elements simultaneously transmit the radar waveform and communication signal in radar active mode, while they carry out only the communication process in radar rest mode, i.e., with no radar transmission. It is worth mentioning that we consider the case of a single target in this chapter.

5.4.1 DFRC in Radar Active Mode

The optimization problem for the simultaneous transmission of the desired radar waveform through the mainlobe (as a primary function) and the communication waveform through the sidelobe region (as a secondary function) is given by the following expressions-:

$$\min_{\mathbf{w}_1}\max_{\theta} |\mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}_1(\theta)| \qquad 5.5(a)$$

$$\text{s.t}\quad \mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}_1(\theta_{\mathrm{t}}) = 1, \qquad \theta_{\mathrm{t}} \in \Theta \qquad 5.5(b)$$

$$\mathbf{w}_1{}^{\mathrm{H}}\mathbf{a}(\theta_{\mathrm{ci}}) = \Delta_{1,i}\, e^{\Omega_i} \;\; \text{for } 1 \le i \le k-1 \qquad 5.5(c)$$

In the above expressions, $\mathbf{w}_1$ is an M-by-1 weight vector, $(.)^{\mathrm{H}}$ is a Hermitian operator, $\mathbf{a}_1(\theta_{\mathrm{t}})$ is an M-by-1 steering vector towards the target at θ_t in radar spatial sector Θ, $\mathbf{a}_1(\theta_{\mathrm{ci}})$ is an M-by-1 steering vector towards a predefined i^{th} communication receiver located at angle (θ_{ci}) and $\Delta_{1,i}\, e^{\Omega_i}$ is the desired communication signal strength in the relevant sidelobe region.

To implement this optimization problem, we use a generalized sidelobe canceller (GSC_1) as shown in Fig.5. 2 for the transmission in radar active mode. The parameters for the proposed GSC_1 are given as follows:

The constraint matrix is:

$$\mathbf{C_1} = [\bar{a}(\theta_t) \quad \bar{a}(\theta_{c1}) \quad \bar{a}(\theta_{c2})\ldots \quad \bar{a}(\theta_{k-1})] \qquad 5.6$$

The blocking matrix is:

$$\boldsymbol{B_1} = \mathrm{null}[\mathbf{C_1}^{\mathrm{H}}] \qquad 5.7$$

The gain vector is:

$$\mathbf{C_1}^{\mathbf{H}}\mathbf{w_1} = \mathbf{f_1} \qquad 5.8$$

The quiescent weight vector is:

$$\mathbf{w}_{\mathrm{q1}} = \mathbf{C_1}(\mathbf{C_1}^{\mathbf{H}}\mathbf{C_1})^{-1}\boldsymbol{f_1} \qquad 5.9$$

The adjustable weight vector is:

$$\mathbf{w}_{\mathrm{a1}} = (\mathbf{B}_1^H \boldsymbol{R_x}\, \mathbf{B_1})^{-1}\mathbf{B_1}\, \mathbf{R}\, \mathbf{w}_{\mathrm{q1}} \qquad 5.10$$

where k denotes the number of columns in $\mathbf{C_1}$, $k-1$ represents the—number of communication directions, and $\mathbf{C_1}$ is the M-by-k constraint matrix of the total steering vectors. $\boldsymbol{B_1}$is the M-by-(M-k) blocking matrix of the space spanned by the columns of the steering vector contained in the matrix, and $(.)^{-1}$ is the inverse operator. $\mathbf{f_1}$ is the gain vector for k constraints (in our scenario, k=5), and $\boldsymbol{R_x}$ is the correlation matrix. The transmitted steering vector towards the direction i can be expressed in general form as

$$\bar{a}(\theta_i) = [1 \quad e^{-\mathrm{j}\left(\frac{2\pi \sin\theta_i}{c}\right)}, \ldots\ldots\ldots e^{-\mathrm{j}\left(\frac{2\pi(M-1)\sin\theta_i}{c}\right)}]^T \qquad 5.11$$

where $[.]^{\mathrm{T}}$ is the transpose operator. For our approach, the optimum weight vector that minimizes the mean square value of the beamformer output is subject to multiple linear constraints and may be expressed as

$$\mathbf{f_1} = \mathbf{C^H w_1} = \begin{bmatrix} \chi \\ \Delta_{1,1}\, e^{\Omega_1} \\ \Delta_{1,2}\, e^{\Omega_2} \\ \Delta_{1,3}\, e^{\Omega_3} \\ \Delta_{1,4}\, e^{\Omega_4} \end{bmatrix} \qquad 5.12$$

where

$$e^{\Omega_i} = \begin{cases} e^0, & for\ \Omega = 0 \\ e^1, & for\ \Omega = 1 \end{cases} \qquad 5.13$$

Here, $\chi = 1$ represents the unit value gain along θ_t for the radar signal power towards the target. $\Delta_{1,i}\, e^{\Omega_i}$ is the desired communication signal, where the Δ values in the column represent the communication power in the sidelobe region and $\Omega \in [0,1]$ represents binary information bits associated with each sidelobe level. If the received beampattern has a higher sidelobe level, then the transmitted bit is one; otherwise, it is zero.

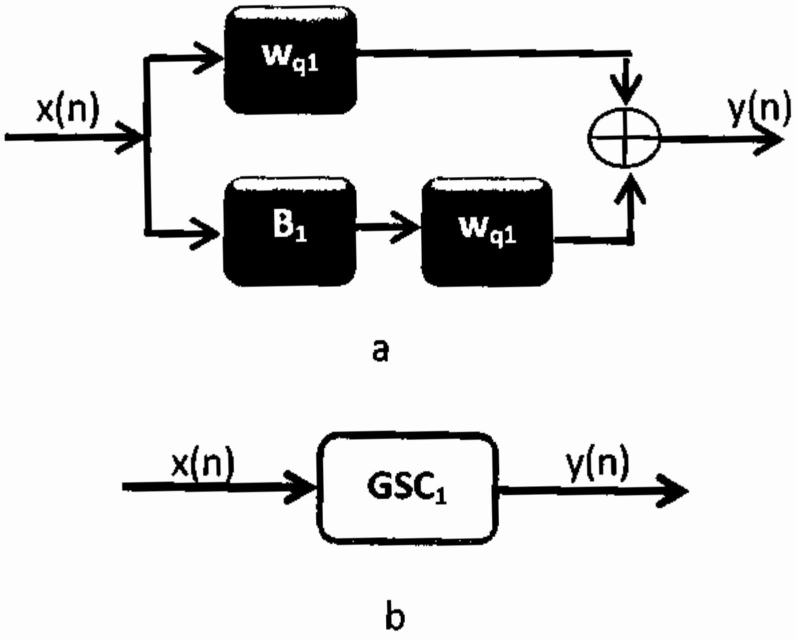


Figure 5-2 (a) Block diagram of the generalized sidelobe canceller (GSC). (b) is equivalent to (a).

To find the blocking matrix, as given in [170], the orthogonal complement is written as

$$\mathbf{C_1}^{H}\boldsymbol{B}_{\mathbf{1}} = \mathbf{0} \qquad 5.14$$

where **0** denotes the null matrix. Thus, the gain vector may be rewritten as

$$\mathbf{C^H}(\mathbf{w}_{\mathrm{q1}}) = \begin{bmatrix} \chi \\ \Delta_{1,1}\, e^{\Omega_1} \\ \Delta_{1,2}\, e^{\Omega_2} \\ \Delta_{1,3}\, e^{\Omega_3} \\ \Delta_{1,4}\, e^{\Omega_4} \end{bmatrix} \qquad 5.15$$

where $\mathbf{w}_{\mathbf{q1}}$ is the quiescent beamformer that guarantees the communication signal in the desired direction. $\mathbf{w}_{\mathbf{q1}}$ is fixed and is not affected by the lower branch of GSC$_1$. For an unconstrained optimization problem, we should only adjust the weight vector available in the lower branch i.e., $\mathbf{w}_{\mathrm{a1}}$. If we consider the output signal of the first *GSC$_1$* given as

$$\mathbf{w}_{\mathrm{q1}}^{\mathbf{H}}\mathbf{x}(\mathrm{n}) - \mathbf{w}_{\mathbf{a1}}^{\mathbf{H}}\mathbf{B}_{\mathbf{1}}^{\mathbf{H}}\mathbf{x}(\mathrm{n}) = y_1(n) \qquad 5.16$$

then its corresponding output power is written as

$$\mathrm{E}|y_1(n)|^2 = (\mathbf{w}_{\mathrm{q1}} - \mathbf{B_1}\mathbf{w}_{\mathrm{a1}})^{H}\boldsymbol{E}[\mathbf{x}^*(\mathrm{n})\mathbf{x}(\mathrm{n})](\mathbf{w}_{\mathrm{q1}} - \mathbf{B_1}\mathbf{w}_{\mathrm{a1}})$$

$$\mathrm{E}|y_1(n)|^2 = (\mathbf{w}_{\mathrm{q1}} - \mathbf{B_1}\mathbf{w}_{\mathrm{a1}})^{H}\boldsymbol{R}_{\boldsymbol{x}}(\mathbf{w}_{\mathrm{q1}} - \mathbf{B_1}\mathbf{w}_{\mathrm{a1}}) = P_{GSC_1} \qquad 5.17$$

-Here, the correlation matrix $\boldsymbol{R}_{\boldsymbol{x}}$ of the five constraints can be expressed as

$$\boldsymbol{R}_{\boldsymbol{x}} = \boldsymbol{R}_{\boldsymbol{t}} + \boldsymbol{R}_{\boldsymbol{c1}} + \boldsymbol{R}_{\boldsymbol{c2}} + \boldsymbol{R}_{\boldsymbol{c3}} + \boldsymbol{R}_{\boldsymbol{c4}} \qquad 5.18$$

-where $\boldsymbol{R}_{\boldsymbol{t}}$—_is the radar correlation matrix; and $(\boldsymbol{R}_{\boldsymbol{c1}} + \boldsymbol{R}_{\boldsymbol{c2}} + \boldsymbol{R}_{\boldsymbol{c3}} + \boldsymbol{R}_{\boldsymbol{c4}})$ are the communication correlation matrices. The correlation matrix of these signals is given as

$$R_x = \begin{bmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \sigma_2^2 & \vdots \\ 0 & \cdots & \sigma_i^2 \end{bmatrix} \qquad 5.19$$

$\{\sigma^2{}_i\}_i^M$ is the power of each transmitted signal. $R_x = \sigma^2 \mathbf{I}$ in the case of white noise only, where $\mathbf{I}$ is the M-by-M identity matrix and σ^2 is the noise variance. Thus, Eq. (10) may be rewritten as

$$\mathbf{w_{a1}} = (\mathbf{B_1}^H \mathbf{B_1})^{-1} \mathbf{B_1} \mathbf{w_{q1}} \qquad 5.20$$

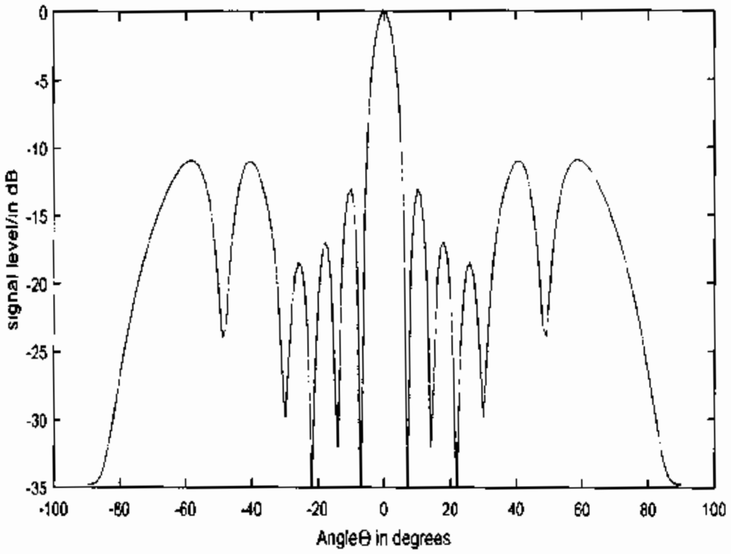


Figure 5-3 Beampattern during GSC1 to transmit a radar signal towards the target and four communication signals.

5.4.2 Transmission in Radar Rest Mode

During radar rest mode, there is no signal transmitted towards the radar target. The radar goes to listening mode. In this case, only the designed communication signal is transmitted towards the intended receivers located in the sidelobe region. The communication signal transmitted here is the signal that produced as a different in powers between two GSCs having equal main lobe power and different sidelobe power. In other words, GSC_2 starts operating in parallel toGSC_1. To remove the radar function in mainlobe , the signal powers of both GSCs in the mainlobe are remained equal. Ideally, the subtraction of the signals of these GSCs shown in Fig.5.4 will result in no signal in the mainlobe region. On the other hand, the signal strength of GSC_2 in the prescribed sidelobe regions is kept double that of GSC_1. Therefore, the overall signal strength after the subtraction will be the same as in radar active mode for the sidelobe communication. To formulate this problem, we design a weight vector $\mathbf{w_2}$ that adjusts the GSC_2 radiation power to be identical to that of GSC_1 except that the sidelobe power of GSC_2 is double that of GSC_1. Such a weight vector can be designed according to the following optimization problem.

$$\min_{\mathbf{w}_2}\max_{\theta} |\mathbf{w}_2{}^{H}\mathbf{a_2}(\theta)| \tag{5.21(a)}$$

$$\text{s.t} \quad \mathbf{w}_2{}^{H}\mathbf{a_2}(\theta_t) = 1 , \quad \theta_t \in \Theta \tag{5.21(b)}$$

$$\mathbf{w}_2{}^{H}\mathbf{a_2}(\theta_{ci}) = \Delta_{2,i}\, e^{\Omega_i} \quad \text{for } 1 \le i \le 4 \tag{5.21(c)}$$

where $\mathbf{w}_2$ is the M-by-1 weight vector of GSC$_2$. In our case, both *GSCs* have overlapping main beams and communication sidelobes. Thus, $\mathbf{C_1} = \mathbf{C_2}$ and $\mathbf{B_1} = \mathbf{B_2}$. The blocking matrix of the space spanned by the columns of the steering vector matrix **C** of GSC_2 is identical to that in GSC_1; therefore, the GSC_2 parameters can be written as follows.

The constraint matrix is:

$$\mathbf{C}_2 = [\bar{a}(\theta_t) \quad \bar{a}(\theta_{c1}) \quad \bar{a}(\theta_{c2}) \ldots \quad \bar{a}(\theta_{k-1})] \tag{5.22}$$

The blocking matrix is:

$$\boldsymbol{B}_2 = \text{null}[\mathbf{C}_2{}^{H}] \tag{5.23}$$

The gain vector is:

$$\mathbf{C_2}^{\mathbf{H}}\mathbf{w}_2 = \mathbf{f}_2 \qquad 5.24$$

The quiescent weight vector is:

$$\mathbf{w}_{q2} = \mathbf{C}_2(\mathbf{C_2}^{\mathbf{H}}\mathbf{C}_2)^{-1}f_2 \qquad 5.25$$

The adjustable weight vector is:

$$\mathbf{w}_{a2} = \left(\mathbf{B}_2^H R_x\, \mathbf{B}_2\right)^{-1}\mathbf{B}_2\, R_x\, \mathbf{w}_{q2} \qquad 5.26$$

$$\mathbf{w}_{a1} = (\mathbf{B_2}^{\mathbf{H}}\mathbf{B}_2)^{-1}\mathbf{B}_2\mathbf{w}_{q2} \qquad 5.27$$

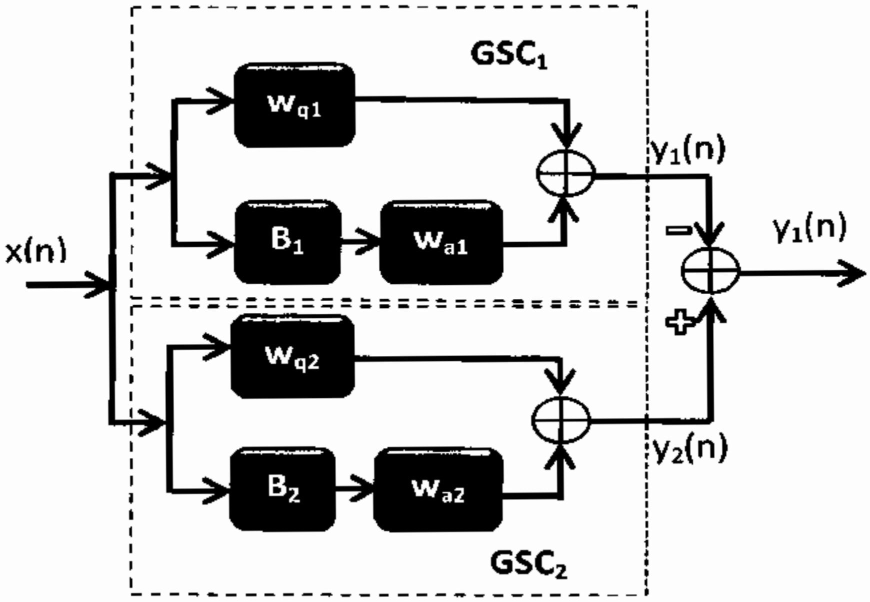


Figure 5-4 Proposed technique for the joint transmitter system

The gain vector $\mathbf{f_2}$ for the multiple linear constraints of the second *GSC* may be expressed as

$$\mathbf{C_2}^{\mathbf{H}}\mathbf{w}_2 = \mathbf{f}_2 = \begin{bmatrix} \chi \\ 2\Delta_{2,1}\, e^{\Omega_1} \\ 2\Delta_{2,2}\, e^{\Omega_2} \\ 2\Delta_{2,3}\, e^{\Omega_3} \\ 2\Delta_{2,4}\, e^{\Omega_4} \end{bmatrix} \qquad 5.28$$

Similar to the previous gain vector in GSC_1, in which the first value in the column represents the normalized radar power towards the target and the rest of the values are the communication powers in the sidelobe region. The values of this communication gain vector are double those in the first gain vector $\mathbf{f}_1$.

For an unconstrained optimization problem, one should adjust the lower branch, the weight vector $\mathbf{w}_{a2}$. The signal power of the second GSC_2 can be written as

$$\mathbf{w}_{q2}^{\mathbf{H}}\mathbf{x}(\mathrm{n}) - \mathbf{w}_{a2}^{\mathbf{H}}\mathbf{B}_2^{\mathbf{H}}\mathbf{x}(\mathrm{n}) = y_2(n) \qquad 5.29$$

By taking the expected value of the above equation, its corresponding output power is written as

$$\mathrm{E}|y_2(n)|^2 = (\mathbf{w}_{q2} - \mathbf{B}_2\mathbf{w}_{a2})^H \boldsymbol{E}[\mathbf{x}^*(\mathrm{n})\mathbf{x}(\mathrm{n})](\mathbf{w}_{q2} - \mathbf{B}_2\mathbf{w}_{a2})$$

$$\mathrm{E}|y_2(n)|^2 = (\mathbf{w}_{q2} - \mathbf{B}_1\mathbf{w}_{a2})^H \boldsymbol{R}_x(\mathbf{w}_{q2} - \mathbf{B}_1\mathbf{w}_{a2}) = P_{GSC_2} \qquad 5.30$$

It is worth mentioning that we have assumed the same power in the mainlobes for both GSCs, but GSC_2 has double the power in the sidelobe region compared to GSC_1. Hence, the resultant power of both GSCs can be written as

$$\mathrm{E}|y_2(n)|^2 - \mathrm{E}|y_1(n)|^2 = \Delta \qquad 5.31$$

This Δ represents the net power in the sidelobe region, i.e., with no power in the mainlobes in radar rest mode, as shown in Fig.5.5 . Note that this power in the sidelobe region is equal to the power in the sidelobe region of GSC_1. Moreover, a comparison of the proposed system with the present DFRC approaches in terms of radar operating modes is shown in Table I.

TABLE I:RADAR OPERATING MODES FOR DIFFERENT DFRC SYSTEMS				
Radar Mode	**In Active Mode**		**In Rest Mode**	
Transmission type	Radar Tx	Comm. Tx	Radar Tx	Comm. Tx
All existing DFRC transmissions	On: in mainlobe	On: in sidelobe	Off	Off
PE-MU-DFRC[29]	On: in mainlobe	On: in sidelobe	Off	Off
Proposed technique: GSC-DFRC	On: in mainlobe	On: in sidelobe	Off	On: in sidelobe

Table 5-1 TABLE I:RADAR OPERATING MODES FOR DIFFERENT DFRC SYSTEMS

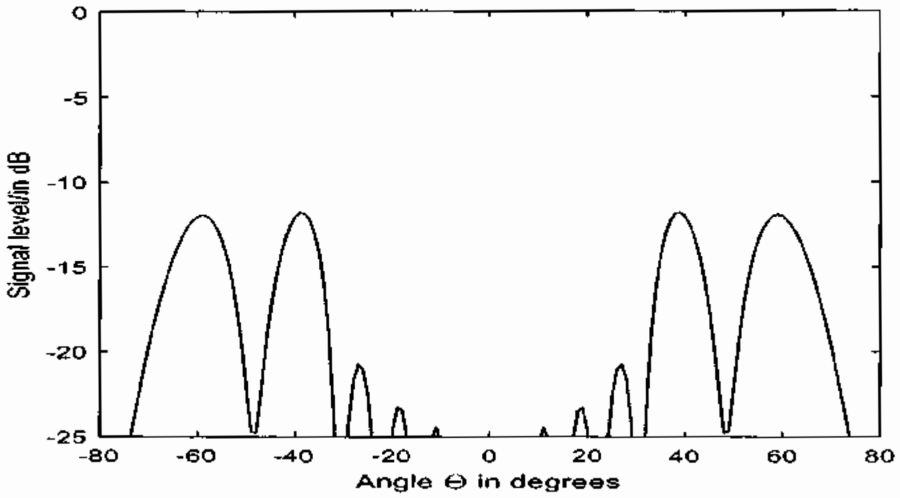


Figure 5-5 Beampattern in radar rest mode

5.5 Communication Throughput per PRI

We consider a radar operating in active mode for tracking purposes. In our scenario, the radar and communications have the same waveform. During one PRI, the communication transmission has two achievable rates: one rate in active mode denoted by q_w and another rate in rest mode represented by q_r, where $q_w \leq q_r$ .The ratio of the transmitted communication to the pulse repetition interval is known as the throughput Q. The throughput in active mode can be formulated as

$$= \frac{t_w}{T_t} \qquad 5.32$$

where T_t is the total time of one pulse repetition interval. In the literature, the throughput for communication has been taken in active mode only. To increase the communication throughput, we propose a technique that transmits the communication and inhibits the radar transmission during the radar rest mode duration τ_r. The increase in the throughput in radar rest mode for the communication can be written as

$$Q_{increased} = \frac{\tau_r}{T_t} \qquad 5.33$$

- The total throughput for a communication link during one pulse repetition interval is

$$Q_{max} = Q_w + Q_{increased} = \frac{t_w}{T_t} + \frac{\tau_r}{T_t} \qquad 5.34$$

The increase in the throughput is given as

$$\left({}^{Q_{max}}/_{Q_w} \right) = \frac{t_w + \tau_r}{t_w} = 1 + {}^{\tau_r}/_{t_w} \qquad 5.35$$

In addition, we assume L sidelobe levels transmitting information to *R* receivers located in the sidelobe region. According to our optimization problem, $\log_2 L$ bits of information can be transmitted to every communication receiver. In this case, the maximum bits transmitted during every PRI can be written ($RK\log_2 L$ in active mode + $RK \log_2 L$ in radar rest mode), where K is the radar waveform. In contrast, for the same setup, the authors in [18] transmitted only $RK\log_2 L$ in active mode. The difference between our proposed scheme and all existing methods is that the proposed technique has a higher throughput because the communication transmission is conducted during both modes of the radar, the active and rest modes. Furthermore, for the same transmitted beam, each sidelobe has its own distinct power level. To validate this claim, we investigate the transmission of the same beampattern towards different sidelobe directions with different power levels, as shown in the simulation section. Table II shows a comparative summary of the data rates achieved for the previous existing techniques and the corresponding enhancement proposed in this chapter with the (*GSC-DFRC*) method. The abbreviations in this table are as follows: W is the weight vector, L is the number of sidelobe levels, B is the bits per pulse, K is the radar waveform, R is the communication constraints towards each communication receiver, and P is the distinct phase of every communication receiver. These parameters are used in the literature for problem optimizations such as in Eq. (5)

TABLE II. A COMPARATIVE SUMMARY OF THE DATA RATES ACHIEVED FOR THE PREVIOUS EXISTING TECHNIQUES

Signaling strategy	***Domain***	***Parameters Exploited***	***Existing maximum data rate=*** $Q_w = Q_{during\ active\ mode}$	***Proposed maximum data rate=*** Q_{max} ***(Eq. (34); if applied to any existing DFRC)***
Sidelobe AM [69]	*Spatial*	$W = L \geq 2$, $R=1, B=1$ *per pulse*, $K=1$	$Q_w = \log_2 L$	$Q_w + \mathrm{Q}_{increased} = (\log_2 L)_w + (\log_2 L)_{increased}$
Sidelobe-based multiwaveform ASK [112]	*Spatial*	($W_1=W_{low}$ *for* $B=1$, $W_2=W_{high}$ *for* $B=0$) *during each* K. $K(\leq k)$ *is fixed, where* k *is the possible* K *to be transmitted.*	$Q_w = K \log_2 L$	$Q_w + \mathrm{Q}_{increased} = (K \log_2 L)_w + (K \log_2 L)_{increased}$
Multiwaveform single-level ASK [101]	*Spatial*	$W_1=W_{high}$ *is related to the highest* L. (K and R *vary*). For all zeros, K=1. $B_{1,k}$=1 else: $B_{1,1}$=0, $\mathrm{B}_{1,k}$=0 or 1, $\sum_{k=1}^{K} B_{1,k} = K$	$Q_w = K \leq k$, *where* k *is the possible* K *reached for* R.	$Q_w + \mathrm{Q}_{increased} = (K \leq k)_w + (K \leq k)_{increased}$
Multiuser ASK [87]	*Spatial*	$W = L^R$ *and* L *vary for distinct SLL.* K *and* B *vary.*	$Q_w = RK \log_2 L$	$Q_w + \mathrm{Q}_{increased} = (RK\log_2 L)_w + (RK\log_2 L)_{increased}$

Sidelobe-based QAM, *Ref.* [104]	*Spatial*	$W=(LP)^R$, L, P, R, and K vary.	$Q_w = RK\log_2 LP$	$Q_w + Q_{increased} = (RK\log_2 LP)_w + (RK\log_2 LP)_{increased}$
Sidelobe-based GSC (proposed) *Ref.* [107]	*Spatiotemporal*	*Two weight vectors are transmitted during different radar modes to multiple communication receivers.* $W=2$, $K=2$, $R=4$, ($B=1$ *or* 0; *Eq.(13)).*	$Q_w + Q_{increased} = (RK\log_2 L)_w + (RK\log_2 L)_{increased}$	

Table 5-2 . A COMPARATIVE SUMMARY OF THE DATA RATES ACHIEVED FOR THE PREVIOUS EXISTING TECHNIQUES

5.6 Simulation Results

In this section, we investigate the proposed system under different scenarios to prove that the communication transmission during the radar rest mode increased the throughput and does not have any influence on the radar operation during the radar active mode time. Fir this setup, we used a ULA having 16 elements for transmission. The distance between these elements is considered to be d with have wavelength. The next examples discuss and simulate the found results.

Example 1: GSCs Behavior during the PRI

In this example, we simulated the proposed idea of using two GSCs as shown in. Fig.5.6 . From the simulation result in this figure, GSC_1 operation takes place during radar active mode and its line represented by red line. The GSC_1 in this mode , transmits a radar function in main lobe towards a specific target to performs a target surveillances or tracking towards $\theta_t = 0°$, while it performs a communication transmission via sideloe transmission towards $\theta_{c1} = -60°$, $\theta_{c2} = -40°$, $\theta_{c3} = 40°$ and $\theta_{c4} = 60°$. In contrast to the above discussion, the communication occurred by subtracting both GSCs (GSC_2 - GSC_1) to remove the main lobe of both GSCs and keep the difference in power between them. This difference in power between the two GSCs is equal to the power available in side lobe region as in active mode. Therefore, the communication in rest mode is identical to the communication transmitted in active mode. One more point to be mentioned here is that, both beam patterns transmitted during active and rest mode are having the same position. is represented by the blue dashed line and functions in rest mode. The communication transmission that occurs in the sidelobe in active mode keeps the radiation towards their receivers in rest mode. The communication signal in rest mode is identical to the level transmitted towards four communication users. To increase the number of sidelobe levels for the same beampattern, we propose another scenario to allow each communication user in each sidelobe to have its own power level to be transmitted towards its intended communication receiver. This can be achieved by using Eq._5(a-c), as shown in Fig. 5.8. The first beampattern has four sidelobe levels (from left to right): SLL_1=-6 dB, SLL_2= -7 dB, SLL_3=-10 dB and SLL_4= -5 dB. Similarly, the corresponding second beampattern has the sidelobe levels: SLL_1=-11 dB, SLL_2= -9 dB SLL_3=-8 dB and SLL_4= -12 dB. Note that the behavior of these independent sidelobe levels in different communication directions enables multiuser access. In both scenarios, we consider the case of a narrow beam, and we find that the radar operation in the mainlobe is not affected by the secondary function (communication in this scenario). The SLL differences are clearly separated from each other, which definitely leads to better detection at the communication receiver ends.

Example 3: Communication Transmission in Radar Rest Mode: With the same setup in example 2, the radar function is out of active mode, so the main beam radiation at angle $\theta_t = 0°$–_towards the target goes to the deep null after every pulse width transmission. As a result, the mainlobe will not function in rest mode, while the four communication signals in the sidelobe region will keep the four communication transmission processes towards their intended receivers located at $\theta_{c1} = -60°$, $\theta_{c2} = -40°$,$\theta_{c3} = 40°$ and $\theta_{c4} = 60°$. We consider two beampatterns: each radiated beam represents either "1" or "0" using the same information embedding scheme as explained in example 2. The sidelobe levels associated with the beam patterns are constrained at SLL=-10 dB and SLL=-14 dB, as shown in Fig. 5.9. Similar to Fig. 5.7, the proposed scenario maintains the transmission in radar rest mode to allow each communication user in each sidelobe to have its own power level to be transmitted towards its intended communication receiver, as shown in Fig.5.10. The first beampattern has four sidelobe levels (from left to right): SLL_1=-6 dB, SLL_2= -7 dB SLL_3=-10 dB and SLL_4= -5 dB. Similarly, the corresponding second beampattern has the sidelobe levels: SLL_1=-11 dB, SLL_2= -9 dB, SLL_3=-8 dB and SLL_4= -12 dB. This mechanism/approach of using rest mode for the transmission allows the communication transmission to continue and exploit the full time of the PRI. This leads to a higher throughput and enhances the signal-to-noise ratio, as explained in this chapter.

Example 4: Radar performance of the main beam

Suppose that two targets are closely located 3° and 5°. We assume that the coefficients in every radar pulse are fixed. These coefficients differ from pulse to pulse. We note that the radar performance for the proposed method of dual-function radar communications outperforms the schemes [69] and [112] in terms of the root mean square error shown in Fig. 5.11 and the probability of resolution shown in Fig 5.12. The method in [69] used a single waveform in every pulse, while [112] used two waveforms, one associated with the high sidelobe beampattern and the other associated with the lower sidelobe. In our proposed method, we use two orthogonal waveforms that are transmitted with every radar pulse, which leads to better performance in terms of the direction of arrival (DOA) compared to the existing methods, to show that the system performance is identical to the result investigated in [112]. It is worth mentioning that when we increase the number of waveforms, we obtain a better result.

Example 5: Bit Error Rate for throughput analysis:

In this example, we transmit two beamforming and compare their bit error rate with that of the existing techniques mentioned above. The performance of the information embedding is computed 10^5 times. The radar mainlobe is at 0°. We transmit 2 bits in each communication beampattern to each communication receiver. The total number of bits transmitted is 8 bits for the four communication users. We design two weight vectors with two sidelobe levels varying from -10 dB for a higher sidelobe level to -14 for a low sidelobe level towards the intended communication users. For the case of multiwaveform ASK [112], the throughput in active mode is (2 $\log_2 L$). In our case, the throughput in active mode is the same, plus the throughput in radar rest mode. The total throughput will then be written as $2 \log_2 L + 2 \log_2 L = 4 \log_2 L$. Similarly, if we use any DRFC existing technique, our proposed will double the achievable throughput rate by using the same resources. We produce a higher throughput by utilizing radar rest mode as the temporal transmission domain for the sidelobe continuation transmission as calculated in section IV. We compare our results with the existing method mentioned and find that our proposed method outperforms these methods, as shown in Fig. 5.13.

communication signal that occurs in the sidelobe in radar active mode. It is assumed that, both radiation patterns have the same null position for both GSCs for the main and sidelobe regions. The sidelobe levels of both beams have equal power levels.

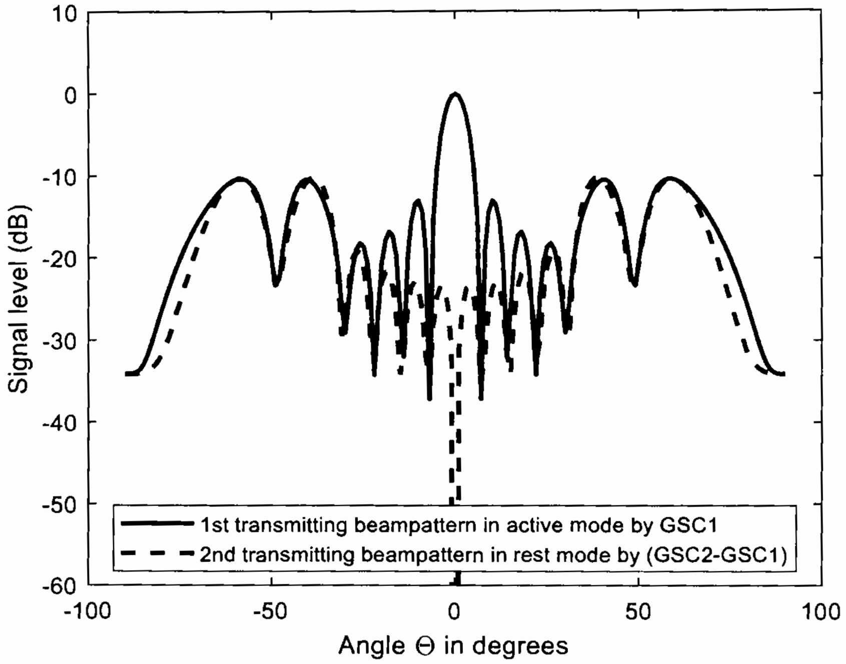
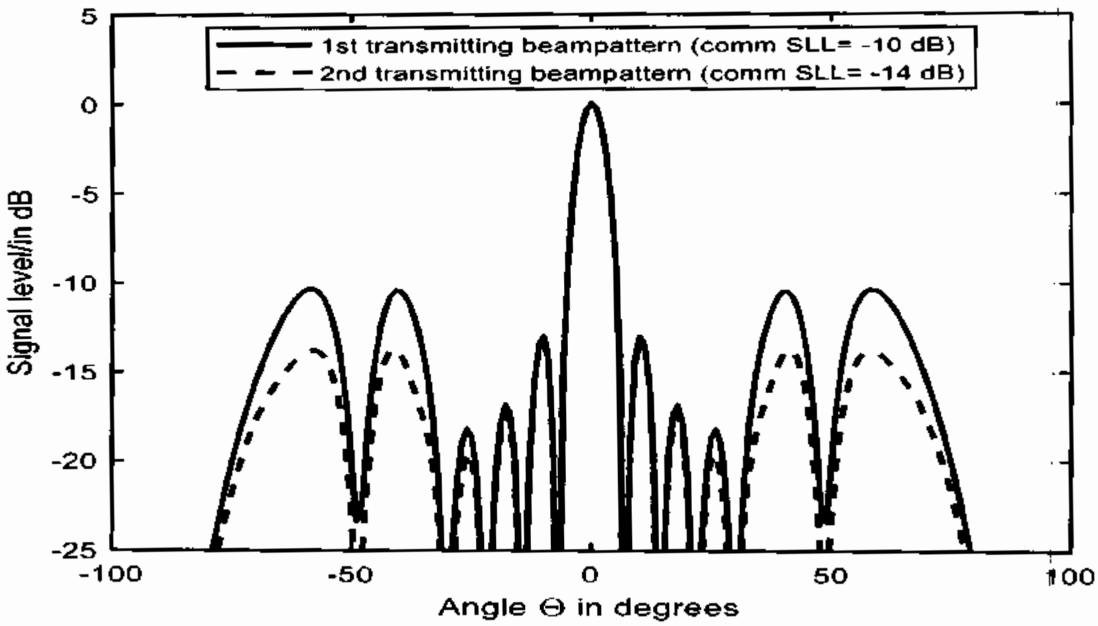


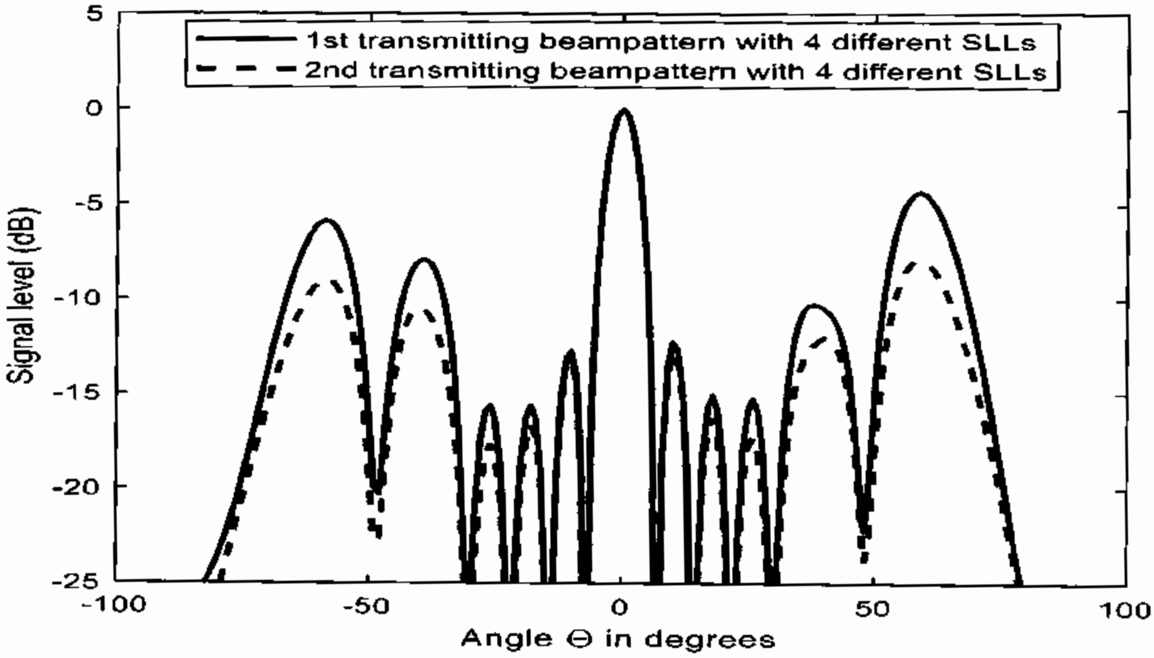
Figure 5-6 First beampattern through GSC1 in radar active mode (red line) and the second beampattern through (GSC2-GSC1) in radar rest mode (blue dashed line) (Example 1).

Example 2: DFRC Transmission in Active Mode

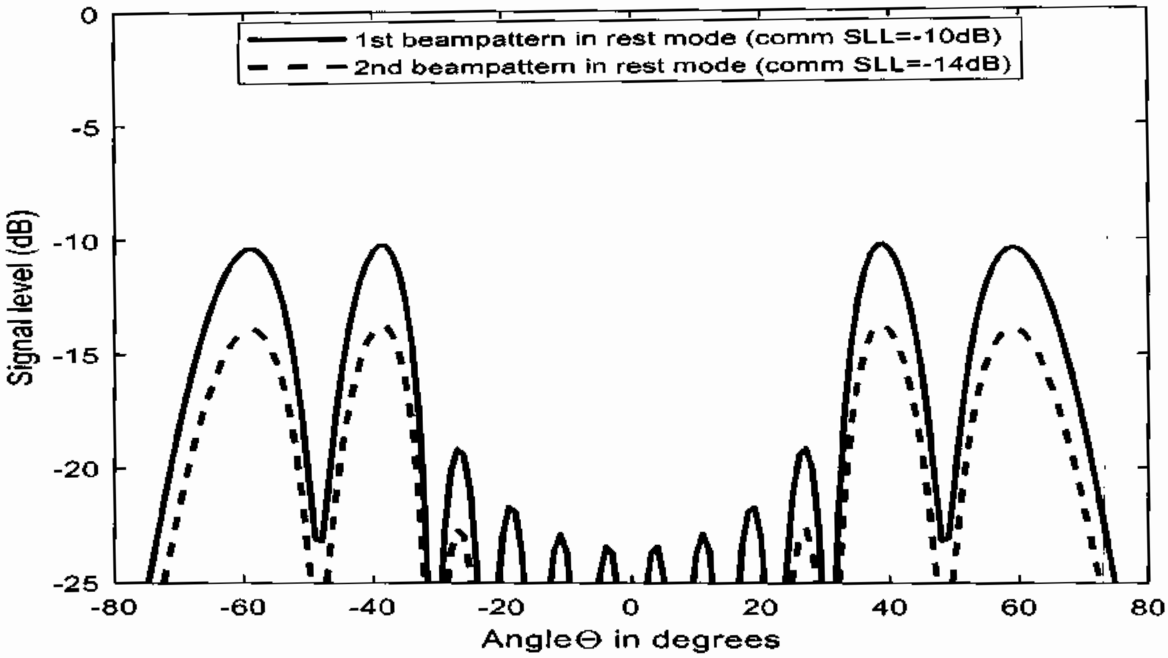
During the active radar mode time, we design two beampatterns with the same power in the mainlobe towards a radar target, and in the same time, we allow variable sidelobe levels of the two beampatterns to represent the communication information transmitted towards the four communication directions. In Fig.5.7, the communication sidelobe level associated with the higher beampattern (red line) is constrained at (-10 dB) and represents the transmitted bit "1". The communication sidelobe level associated with the lower beampattern (blue dashed line) is constrained at (-14 dB) and represents the transmitted bit "0". Note that, each beampattern has one sidelobe



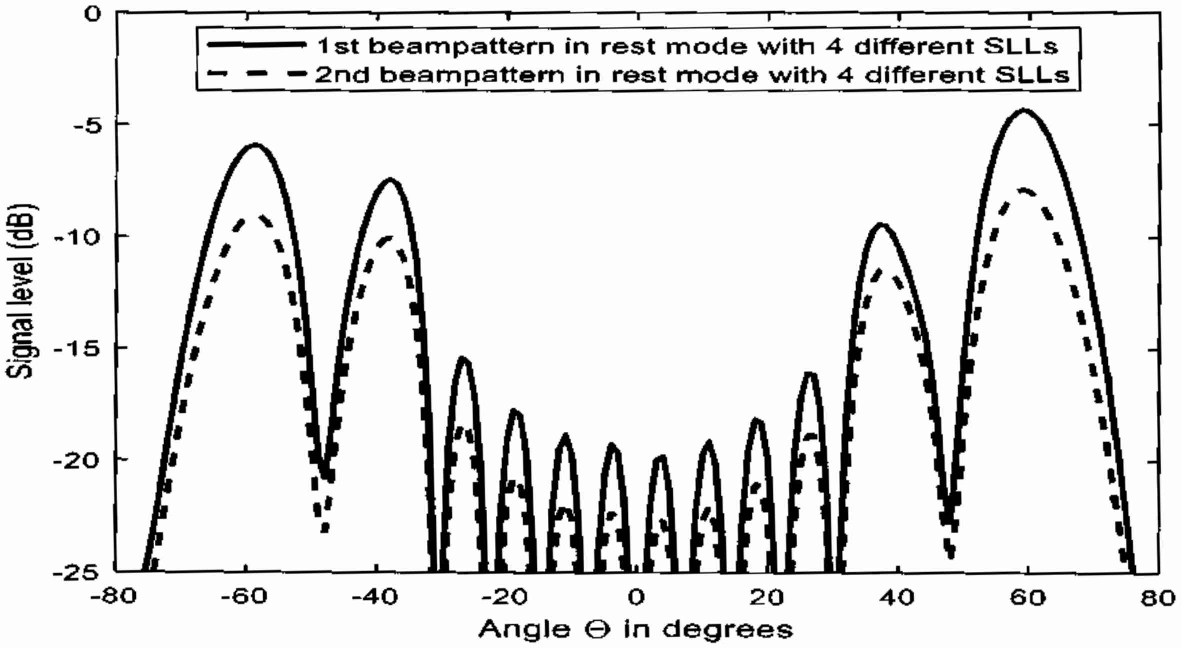
5-7 First beampattern DFRC carrying the target and four communications in radar active mode with bit "1".. The second beampattern carrying the communication with bit "0" (Example 2).



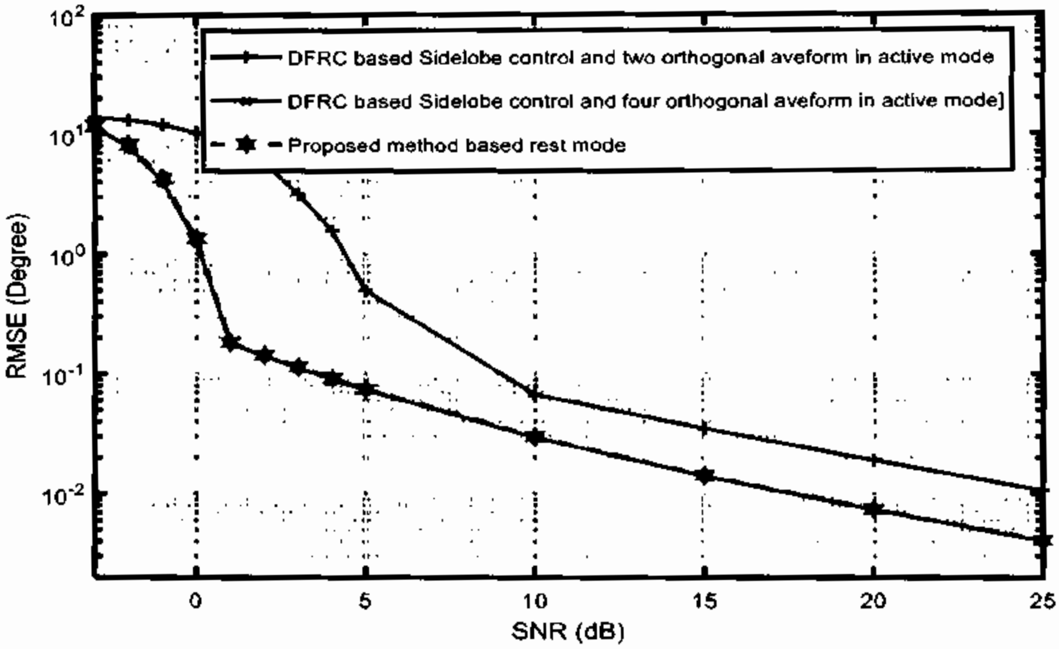
5-8 Two beampatterns with 8 sidelobe levels perform DFRC in different communication directions in radar active mode; 2nd scenario (SLL=8).



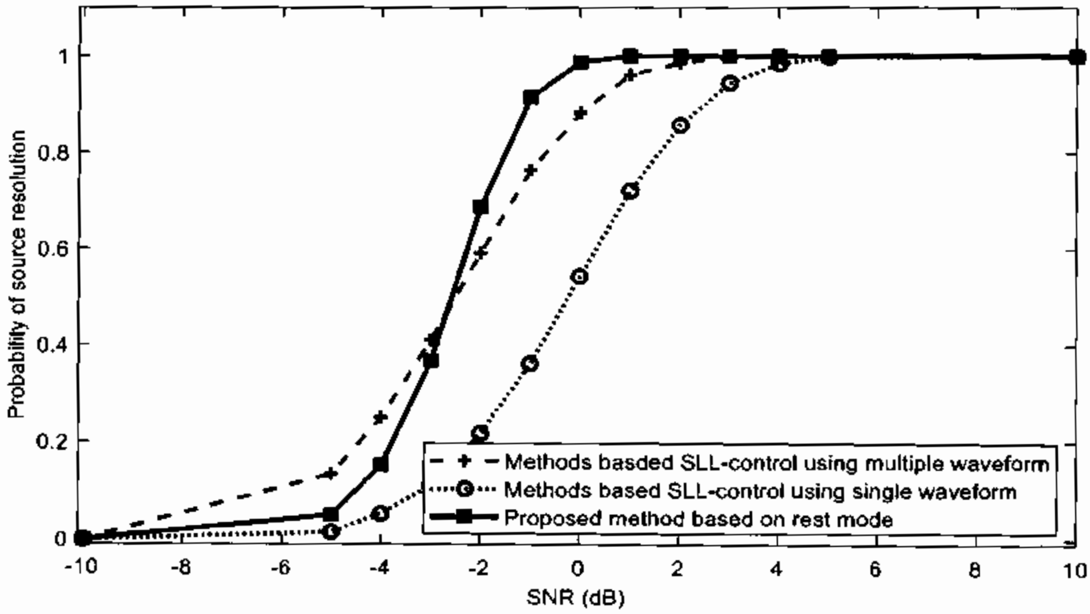
5-9 Communication transmission via GSC2-GSC1 producing the same SLLs (example 3); 1st scenario (SLL=2).



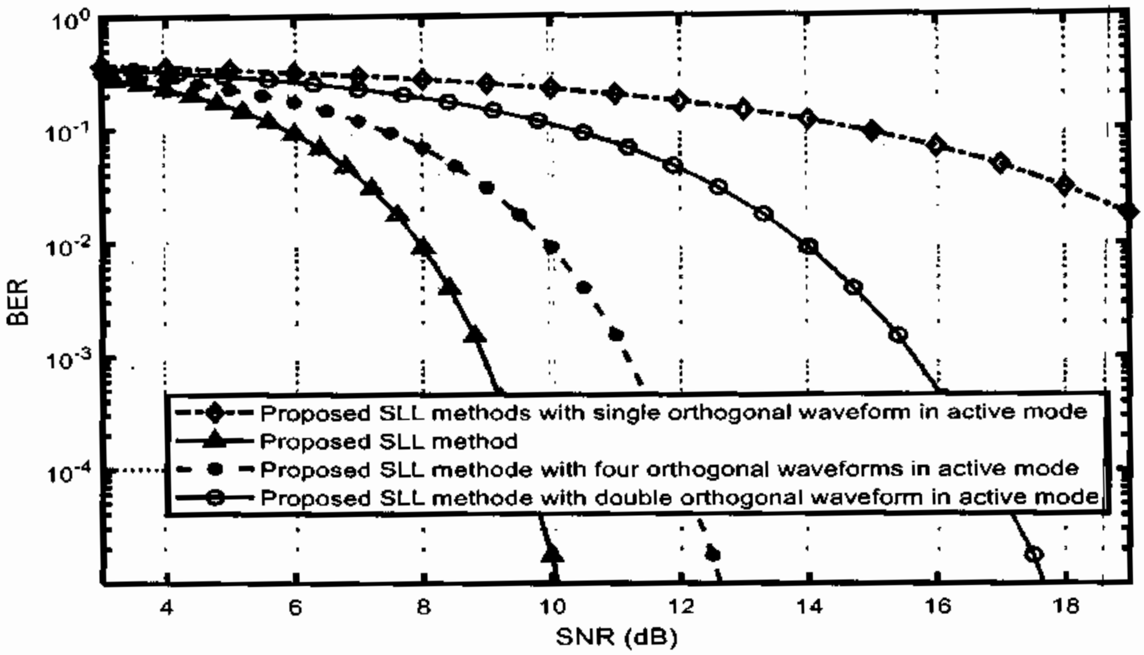
5-10 Communication transmission via GSC2-GSC1 SLLs producing different SLLs (example 3); 2nd scenario (SLL=8).



5-11 RMSEs of the DOA estimation vs the SNR



5-12 Probability of the resolution as a function of the SNR



5-13 The BERs versus the SNR for four methods.

5.7 Conclusion

In this chapter, we used the spatio-temporal approach as a platform for transmitting radar and communication during radar active mode. Then the communication signal produced in sidelobe of the active mode will its transmission during radar rest mode. This idea has been conducted by using two GSCs. The result of this technique maintained the radar function and performance during the active mode transmission in mainlobe intact. Moreover, the communication performance is increased tremendously. Different scenarios have been conducted to prove this idea. Different future directions of this work can be extending such as using this rest mode for different modulation communication transmission techniques. Moreover, different cognitive approaches and scenarios can be used for further enhancement of this system.

CHAPTER 6

CONCLUSION AND THE FUTURE WORKS

6.1 Conclusion

In this dissertation, we have gone in deep study and investigation for radar-communication integration system and its applications. We discussed the various types of radar-communication integrations that have been found in the literature so far. Three types of radar-communication unification system have been proposed. The whole pulse repetition interval PRI in radar pulse has been exploited in order to increase the communication transmission beside the radar function without any disturb to the radar primary functions. The pulse repetition interval in every radar pulse has two modes, one is an active and the other is the listening mode. We investigate the temporal approach for dual function radar communication system in terms of active and listening modes available in every pulse repetition interval.

We first, analyze the spatial approach in this dissertation, we investigate the dual function for Radcom system based on sidelobe approaches; we have proposed new information embedding method based on frequency shift keying as a new technique introduced to Radcom systems. Beside that we eliminate the jammer disturbance available in sidelobe region by using independent null steering based on decoupling weights. Our proposed shows that our communication transmission is better than existing techniques in terms of jammer avoidance and bit error rate.

To analyze the temporal approach, we have proposed a new techniques to allow communication transmission during radar rest/listening mode. In this approach, we transmitted two beampatterns. We investigate the frequency diverse array for joint radar and communication systems. The basic idea is to use the transmitter modules of the radar system for communication purpose during sleeping mode as a secondary function. The radar will be performing its routine functions during the active mode as primary function.

A Frequency Diverse Array (FDA) at the transmitter side will be used to produce an Orthogonal Frequency Division Multiplexed (OFDM) signal, which is proposed for communication system. The directivity of radar antenna, FDA in this case, provides an additional advantage to mitigate the interferences other than the Direction of Interest

(DoI). The proposed technique allows two beam patterns to be transmitted sequentially. Due to the communication signal transmission during the main lobe of the second beampattern, the Bit Error Rate BER achieved is better than the existing techniques which used the sidelobe transmission of the existing techniques. In simulation, two transmitted beams have been considered for the proposed platform having unified FDA structure. The simulation results also indicate the novelty of idea to suppress the interferences in terms of direction of interest. Furthermore, we analyzed the signal-tointerference ratio (SINR) and Cramer-Rao lower bounds (CRLB) for angle and range estimation for the proposed technique.

To analyze the spatial-temporal approach, we have proposed new techniques to allow the communication transmission occurs in active and rest mode. We introduced a new method for radar communication integration. The methods found in the literature regarding radar and communication system unification were mostly focused only on the DFRC/RADCOM transmission during the radar active mode. These available methods limited the communication throughput transmission as it is bounded by the short time of radar pulse in active mode. To increase the throughput of communications without disturbing the radar task, we designed a new system that allows the communication transmission during the entire pulse repetition interval. This approach has been achieved by designing two generalized sidelobe cancellers (GSCs) to work together. We exploit two radar modes to transmit the DFRC system. The first mode is the active mode, the radar task is accomplished in mainlobe, and communications transmission occurred in sidelobes. During this active mode, only one GSC is working. In rest mode, both the GSCs are working. The first GSC has the mainlobe and sidelobe levels as in active mode, and the second GSC has the same mainlobe level but double the power in the sidelobes. The output of both is the difference of the two generalized sidelobe cancellers, in which the mainlobe is cancelled, while the sidelobes have the same power, as in the case of active mode. The proposed system permits the wireless communication to be transmitted during the entire pulse repetition interval. Therefore the throughput achieved has been enormously.

In all the three methods used in this thesis, are introduced to enhance the performance of communication and keep the radar intact. Spatial temporal method approach can be considered as one of the most practical scenario for dual function radar communication system.

6.2 Challenges and future works

The main challenge of radar-communication integration is the need to make this technology mature and reliable for different scenarios in both civil and military applications. However, the waveform design is one solution which can guide this system to be mature in the near future, but this approach still needs more investigation. Moreover, imposing many waveforms on the same carriers is still a challenge for this technology, especially, when both functions are working on the same band. Furthermore, DFRC is less costly, more efficient, but it requires an efficient way to manage the radio resources very well. This management for radio can be done in the form of time, frequency and space managements. Moreover, this technology can be applied on 5th generation and 6th generation as well. Furthermore, this technology can be a good candidate for ultra wide band applications. Finally, list of many problems and challenges which still need to be addressed and solved for this technology such as:

- **Internet of things (IoT) challenges:** to implement this system, the design and initial work must start with less number of devices connected to each other, then the expansion will be done later on. For this approach, someone needs to design proper waveforms to be used in the scenarios of IoT by taking in account the prediction, detection techniques and plus adaptive waveform as well as the interference mitigation during the implementation of this techniques. The degree of cooperation among different services should be taken in account as well. Moreover, connecting radar to Internet of things (IoR) will lead to what can be known as Internet of Radar(IoR) [172].

- **Spectrum sharing and power allocation:** the spread spectrum approach for this technology should give more attention and deep investigation to study the spread spectrum from different aspects/views such as the resources management, allocations, interferences, location of the DFRCs transmitters and receivers , waveform design, spatial and temporal approach, cooperation and finally the function priorities among these systems. Cognitive radio-radar spectrum needs to be studied and investigated. This will lead to a robust and intelligent system.
- **Cognitive approach based on feedback:** one of our future works should is the focus on the transmitted power during active and rest mode when the feedback and environment take place in the system analysis.
- **Waveforms design:** based on the reconfiguration and adaptive mechanisms are needed to avoid the congestion of many different devices implemented on a single platform to perform the radcom applications. What constraints are further required to provide the waveform of such system to ensure robust operation for RadCom functions?
- **Innovative integrations:** in order to enhance the integration process of radar and communication systems to fulfill the requirements on a single platform, researchers in many publications focused on the integration techniques of radar-communication systems, but this system still needs to pay more attention to be able to come to the real life application.

- **Multifunction transceiver for Autonomous / Unmanned Aerial vehicles**: despite the automotive vehicles are studied since more than a decade, but up to date, there are is a lot of unexplored area and directions to be done in this field. Implementing DFRC systems for autonomous vehicles is a new horizon which requires different and innovative scenarios that allow designers to apply the fundamental concepts of DFRC systems [171]. To achieve a better multifunction transceiver for RadCom technology, we should subject the idea to real life application and make a test bed on roads for the designed vehicles.
- **RadCom based different smart radars:** In state of the arts, we found that the integration which based on the detection and estimation for conventional radars can be applicable for different classes of intelligent radars. In other words, subjecting the radar-communication integration to different types of smart radars while enhance the advancement of this system.
- **Radar performance under radar-embedded communication:** How the random digital sequence affects the radar performance and cause a misleading detection especially in intelligent transportation systems. This idea should be studied as a future problem in this field.
- For all this, innovative techniques are need to design a new waveforms for joint radar communication system.
- Radar communication integration based on MIMO radar and MIMO communications transmission during rest mode is one of the future directions of this work.

- **Mathematical analysis:** How to subject this RadCom signal to be analyzed by different mathematical analysis such Wigner Ville distribution (WVD), ambiguity function (AF) and choi wiger distribution (CWD)?
- Until now, there no simulator software for this technology, who can work on simulator, designs for RadCom system.
- Concept of spatial-temporal approach for RadCom still needs a lot of studies. Different composite waveforms and recursive implementation needs to tb designed in future work.
- Enhancement of LPI property based on different coding techniques and information theory to serve both civil and military application need to be investigated.
- **RadCom based 5th and 6th Generation:** This technology (RadCom) will play an important role in the 6th generation. The 6th generation is just introduced in some papers. 6th generation is supposed to connect all types of wireless communication together using artificial intelligence and machine learning. Internet of things IoT. The joint radar and communication system as well as combining different RF services from same or different bands are expected to play important role in this generation.
- **Artificial Intelligence and Machine Learning based RadCom:** One of the future directions in this field is an artificial intelligence and machine learning for the future 6th generation. If the compressed sensing is implemented for DFRC system at the estimation and receiver side, then ML/AI can play a vital role in solving such issues [137].

- **Security and privacy issues:** as this technology grows up day by day, the future direction of this field is the security and privacy issues. Using DFRC technology in military application needs a lot of study, because if jammer or eavesdropper look to perntarate or hack the information embedded to the radar emission and reached to this information, the jammer may decipher it . Therefore, security at physical layer or any higher layer should be implemented.
- **Graph signal processing** is a promising approach for the joint radar-communication networks.
- **Test bed Laboratory:** Finally, connecting the ideas/research with industries and/or implementing a laboratory for RadCom system in this university, will boost up the research directions and increase the reputation of this institution as one of the leading university in the world. Moreover, this is the first institution in Pakistan having an experience in RadCom technology with outcome of a PhD thesis. This only needs established RadCom Lab and fund with dedicated group of research.

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