

# INTEGRATED RADAR-COMMUNICATION SYSTEMS: A UNIFIED MIMO PLATFORM APPROACH

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## Abstract

This research presents a comprehensive study of a unified MIMO-based radar-communication (RadCom) platform that utilizes Orthogonal Frequency Division Multiplexing (OFDM), aimed at addressing the growing need for multifunctional systems that can simultaneously detect, track, and communicate information using shared hardware and spectral resources. Frequency Shift Keying (FSK) is employed to embed communication data into radar emissions, preserving the radar's mainlobe integrity while utilizing sidelobe regions for communication. This method is designed to counteract jamming and ensure reliable data delivery even in contested environments. Additionally, a time-domain strategy is introduced using radar rest mode for continuous communication transmission. Performance evaluation is conducted through comprehensive simulations using metrics such as Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), Cramer-Rao Lower Bound (CRLB), and communication throughput per Pulse Repetition Interval (PRI). The results demonstrate that the proposed dual-mode transmission strategy significantly improves data throughput and system resilience, with minimal impact on radar accuracy and resolution. Furthermore, the system enables multi-user connectivity through independently modulated sidelobes and adaptive beam pattern control.

## INTRODUCTION

The ever-increasing demand for spectrum resources in modern wireless communication and sensing systems has led to growing interest in the integration of radar and communication functionalities into a unified platform. Radar systems are traditionally employed for detecting, tracking, and estimating the parameters of targets using reflected electromagnetic signals, whereas communication systems are designed to reliably transfer information over a known or estimated channel. Although their operational goals differ, both systems share similar hardware, spectral bands, and signal processing techniques, creating opportunities for convergence [1][2].

Integrated radar-communication (RadCom) systems aim to consolidate these two functionalities into a single platform to improve spectral efficiency, reduce hardware costs, and enable multifunctional capabilities. Such

integration holds promising applications in areas like intelligent transportation, autonomous vehicles, spectrum-sharing environments, and defense systems. However, the realization of these systems remains technically challenging, as radar demands high accuracy, real-time responsiveness, and robustness to interference, while communication requires high throughput, low latency, and secure transmission [3].

This study presents a novel framework for a dual-function radar-communication (DFRC) system that operates over a MIMO platform using Orthogonal Frequency Division Multiplexing (OFDM). The proposed system introduces a spatiotemporal approach in which both radar and communication functionalities are realized through advanced beamforming techniques. Specifically, Generalized Sidelobe Cancellers (GSCs) are used to separate radar and communication tasks across spatial and temporal

domains. During the radar's active mode, communication signals are transmitted through modulated sidelobes, while the radar mainlobe focuses on target detection. In radar rest mode—typically unused in conventional systems—a second GSC enables continued sidelobe-based communication by canceling the mainlobe, thereby maintaining uninterrupted data transmission throughout the pulse repetition interval (PRI).

### Problem Statement

The integration of radar and communication systems into a single operational platform offers numerous advantages, including spectrum efficiency, hardware reuse, and functional versatility. However, designing a system that can simultaneously meet the performance demands of both radar and communication domains remains a significant challenge. Radar systems require high-resolution target detection, real-time responsiveness, and robustness against interference, while communication systems demand high data rates, low latency, and resilience to jamming and signal distortion. Most existing studies in the field of joint radar-communication (RadCom) systems focus either on spectrum sharing or basic coexistence without fully exploiting the temporal and spatial resources of modern radar architectures. Conventional systems often use radar's sidelobe regions for low-rate communication, but these methods are limited to radar's active transmission windows, leaving the rest mode periods underutilized. Moreover, ensuring reliable multi-user communication through sidelobes without degrading the radar's mainlobe performance presents additional challenges in beamforming design and power control.

Another limitation is the lack of integrated solutions that can extend communication transmission into the radar's rest periods while maintaining mainlobe integrity and overall system stability. Current RadCom models do not sufficiently address how to leverage the idle time within pulse repetition intervals (PRI) to boost Strengthening the communication and radar system integration procedure to satisfy demands

on a single platform. Although several publications have addressed integration strategies for radar-communication systems, additional attention is required for practical implementation.

### Aim and Objectives

The purpose of this research project is to address the following potential problems: -

The primary aim of this research is to design, implement, and evaluate a unified MIMO-OFDM-based dual-function radar-communication (DFRC) system that enables simultaneous sensing and data transmission. The proposed system seeks to enhance spectral efficiency, ensure reliable target detection, and maintain continuous communication by leveraging spatial and temporal domain techniques, including the use of Generalized Sidelobe Cancellers (GSCs) during both radar active and rest modes. To achieve this aim, the research is guided by the following specific objectives:

- To analyze the theoretical foundations of integrated radar and communication systems, highlighting the trade-offs and design challenges associated with simultaneous operation.
- To investigate and evaluate existing RadCom frameworks, including coexistence, cooperative, and co-design models, with a focus on their limitations in exploiting radar rest modes and sidelobe regions.
- To develop a dual-mode transmission strategy that utilizes Generalized Sidelobe Cancellation (GSC) configurations for embedding communication signals into the radar sidelobes during both active and idle periods.
- To simulate and assess system performance using metrics such as Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), Cramer-Rao Lower Bound (CRLB), and communication throughput across varying operating conditions.

### Literature Review

Researchers, businesses, and agencies like the FCC are paying close attention to the congestion of the radio frequency (RF) spectrum caused by the growing demand for wireless communication. The goal is to leverage common waveforms or

unified structures to create a multipurpose radio frequency spectrum [4-9]. Coexistence of radar and communications has become a viable way to address issues with RF spectrum. One significant advancement in this area is dual-function radar-communications (DFRC) systems, which enable communication signals to support main radar operations as a secondary function. By effectively using radar resources, these systems alleviate spectrum congestion and combine communication and radar capabilities into a single, shared architecture. Radar emissions may communicate thanks to information embedding techniques including waveform diversity, time-modulated arrays, and sidelobe control. These methods make advantage of temporal, geographical, and signal-sharing strategies. It is crucial to look at radar and communication systems separately, analyzing their development, distinctions, and similarities before diving into the combination radar-communication system and studying the body of current research.

Derived from "radio detection and ranging," radar is a device that can determine the size, shape, trajectory, speed, direction, and range of a target. Radar was created during World War II and has advanced significantly since then. Modern radars can identify a target's precise location, trajectory, ambiguity function [10-11] Doppler shift, and accomplish low probability of interception and identification (LPI and LPID). Radar usually sends out a known waveform that bounces off objects and comes back to the receiver for examination. Radars are extensively used for target information extraction and environmental sensing in both military and commercial applications [7].

Although both radar and communication systems rely on the propagation of electromagnetic waves, their goals and methods of operation are very different. Information transmission from a sender to a recipient is the main goal of communication systems, and controlling the channel is a bothersome aspect. Radar systems, on the other hand, use reflected signals to identify and estimate the characteristics of targets; crucial information is included in the channel itself. radars send known waveforms and evaluate

the unknown surroundings, but communication signals are frequently unknown and need decoding. Furthermore, unlike conventional communication systems, radar takes into consideration two-way propagation loss and necessitates high-gain antennas. [12]. Spectral congestion in RF technologies is pushing radar band users to explore coexistence, cooperation, or co-design with wireless communication systems. Rather than operating independently with high power consumption, researchers, firms, and governments are developing a unified platform to integrate both functions efficiently. This approach aims to optimize spectrum use, reduce interference, and enhance performance, fostering collaboration between legacy radar and modern wireless communication technologies for improved resource management and operational synergy.

The coexistence approach describes the spectral coexistence of communication and radar systems, in which neither system shares information to reduce the other's interference. Rather, the degree of freedom is limited and system resources are used to estimate interference [13]. By using approaches like temporal, spatial, or spatiotemporal changes, this approach enables interference reduction by enabling radar and communication systems to recognize and adapt to each other's presence. These cohabitation strategies are depicted in Figure 1, emphasizing the compromises between system adaptability and interference minimization. Coexistence techniques have been the subject of several research, including [8], [14-19], which will be examined in the section on state-of-the-art. Although coexistence allows for simultaneous operation, its efficiency and flexibility in shared spectrum situations are limited by its reliance on resource-intensive interference abatement. While coexistence allows for simultaneous operation, its efficiency and flexibility in shared spectrum situations are limited by its reliance on resource-intensive interference abatement.

Radar and communication systems exchange information as part of the collaboration method to reduce interference without affecting their primary functions. According to research [13],

[20], this approach improves interference mitigation through data interchange, increasing system efficiency while preserving the essential functioning of both systems.

### System Methodology and Operational Design

Multifunction Radio Frequency (RF) systems are becoming more and more common. Despite having commonalities within the RF spectrum and sometimes utilizing different frequency bands, radar and communication systems have historically functioned as distinct entities. The creation of unified systems, which combine many RF functionalities, such as radar and communications, into a single piece of hardware, is being fueled by the growing need for effective RF spectrum management. The goal of these systems is to decrease functional gaps and improve information exchange. Coexistence, collaboration, and co-design strategies are the main focuses of contemporary design methodologies in order to facilitate smooth integration and enhanced performance. This change addresses the growing demand for spectrum optimization and multifunctional capabilities and is a major step toward more effective and adaptable RF systems. When two systems share the same spectral resources, the coexistence technique sees them as separate entities that naturally interfere with one another. Each system functions independently inside this framework, and the unified platform enables them to continually explore and use the available spectrum while using the same bandwidth simultaneously or sequentially. On the other hand, by allowing both systems to exchange relevant data and dynamically modify their operating settings, the cooperative approach seeks to reduce reciprocal interference. This strategy ensures that each system can operate efficiently within the common spectrum by concentrating on information sharing to minimize interference and maximize performance rather than drastically changing their functionalities.

Co-design methods integrate radar and communication functions from the ground up to enhance the spectral efficiency of a unified platform. This approach involves jointly

designing both systems so that they operate seamlessly within the same hardware and spectrum, as discussed in [23]. An alternative co-design strategy embeds communication information directly into radar emissions. In these techniques, information bits or symbols are encoded into the radar waveform on a pulse-by-pulse basis, allowing the radar signal to carry both sensing and communication data. A critical aspect of these methods is managing the interplay between radar capabilities and data transmission performance throughputs, all while maintaining a constant waveform envelope with high power spectral efficiency.

Another technique explored the use of a time modulated array (TMA) for integrated radar-communication systems. In this approach, radar operates using its main lobe for sensing while communication symbols are embedded in the sidelobe region. Two separate methods are put forward by the authors: one employs a sparse time modulated array (STMA) technique where selected antenna components are cycled between active and inactive states to induce sidelobe variations, and the other uses phase-only synthesis to adjust the transmit array's phases for sidelobe modulation. This innovative method demonstrates a promising pathway toward more efficient, cost-effective, and versatile RF system integration by reducing installation requirements, lowering hardware costs, and optimizing spectrum utilization. The main lobe is usually designated as the primary radar function and the sidelobe as a secondary channel for communications in dual-function radar-communications (DFRC) unified platforms, which necessitate careful prioritization of radar and communication functions based on directivity and power allocation. A new technique that uses FSK modulation to embed information has been developed for dual-function radar-communications systems. With this method, each radar pulse's sidelobe transmits orthogonal waveforms, while the radar's primary detecting function in the main lobe remains unhindered. This method allows communication transmission and radar operation to be done simultaneously, efficiently separating the two jobs inside a single

pulse and improving overall spectrum efficiency without sacrificing radar performance.

- The method investigates independent null steering in a DFRC system that is accomplished by decoupling the weight vectors. This technique protects the communication system against jamming interference without sacrificing radar performance by selectively adjusting the sidelobe null, which targets the jammer, while maintaining the radar's main lobe capability.
- For the proposed DFRC system, a communication receiver was created that allows communication signals to be sent to one or more receivers. In order to ensure that many communication receivers can consistently receive signals while the radar maintains its primary job in the main lobe, this design makes use of the sidelobe area for communication.
- Analyze the receiver end's computed radar range.

The suggested technique was evaluated against jammer movement in Dual-Function Radar-Communication (DFRC) systems' sidelobe area. To keep the null constant at the jammer's angle of arrival, weight vectors were maintained in the first scenario, which used a static jammer. Second, to follow the movement of a moving jammer without interfering with sidelobe communications or radar operations, the null was constantly modified. In comparison to conventional DFRC systems, the results showed that relocating the null to counteract the jammer greatly enhanced communication performance by lowering the Bit Error Rate (BER). This method preserves radar capabilities while improving secure communication delivery. The structure of this methodology as follows:

### Overview of the Proposed System

The primary objective is to enable simultaneous target detection and data transmission using shared spectrum and hardware. By leveraging the flexibility of MIMO-OFDM technology and the beam-shaping capabilities of Generalized Sidelobe Cancellers (GSCs), the system is designed to efficiently allocate resources across both spatial

and temporal domains. The approach utilizes two distinct operational modes: radar active mode and radar rest mode. During the active mode, radar pulses are transmitted through the mainlobe while communication symbols are embedded in the sidelobes. In the rest mode, where the radar is typically silent, communication continues by exploiting sidelobe radiation without compromising target detection performance. A dual-GSC strategy is employed, where GSC1 operates during the active mode and GSC2 takes over during the rest mode. These two configurations are carefully designed to maintain radar performance and ensure uninterrupted communication throughout the pulse repetition interval (PRI).

### Beamforming Strategy and GSC Framework

Beamforming plays a pivotal role in balancing the requirements of radar sensing and communication transmission. In the proposed system, a constrained optimization method is applied to construct directional beampatterns using MIMO arrays. GSC1 ensures that radar energy is focused in the mainlobe direction for target detection, while sidelobe levels are modulated to deliver binary communication data to predefined users.

The sidelobe modulation technique is designed to maintain orthogonality between communication paths and the radar's mainlobe. This minimizes interference and ensures that radar detection remains accurate. During the radar rest mode, GSC2 becomes active. It mirrors the mainlobe energy of GSC1 but increases the sidelobe amplitude. Subtracting the output of GSC1 from GSC2 during the rest period effectively nullifies the mainlobe while preserving communication signals. This subtraction mechanism forms the core of the dual-mode operation and significantly enhances spectrum utilization without compromising sensing accuracy.

### Spatiotemporal Signal Allocation

The integration of radar and communication tasks is facilitated through intelligent spatiotemporal signal allocation. Spatially, the mainlobe of the radar is dedicated to target detection, while sidelobes are allocated to communication. Temporally, the system leverages both radar active and rest modes to transmit information, thereby utilizing the entire pulse repetition interval (PRI) for communication.

Communication signals are embedded in sidelobes using varying amplitude levels to represent binary data. This allows multiple users to be addressed in different angular directions with distinct power allocations. The use of OFDM ensures that multiple subcarriers can be modulated independently, offering flexibility in allocating bandwidth and optimizing spectral efficiency. The modulation design also supports multi-user scenarios where each sidelobe beam is uniquely assigned to a specific receiver, ensuring directed and secure data transmission.

### Communication-Radar Task Separation

A key challenge in unified DFRC systems is the effective separation of radar and communication functions without the need for additional spectrum or hardware. In the proposed design, this is achieved through a combination of null steering, constrained beamforming, and adaptive sidelobe management. Steering vectors are used to define target and communication directions, while blocking matrices ensure that power is confined away from unintended angles.

The dual-GSC framework further enhances this separation by isolating radar and communication signals across different time segments. GSC1 operates when radar pulses are active, while GSC2 dominates during idle intervals. By carefully designing the gain vectors and weight matrices, the system ensures that mainlobe radar tasks and sidelobe communication streams coexist without interference.

### Methodological Workflow

The proposed methodology involves several coordinated steps that enable the integration of radar and communication tasks:

1. Design a MIMO-OFDM waveform with capabilities for both target detection and data transmission.
2. Construct GSC1 to handle radar mainlobe operations and sidelobe communication during active mode.
3. Develop GSC2 to maintain sidelobe communication in the radar rest mode and suppress mainlobe emissions.
4. Utilize beamforming and null steering algorithms to ensure angular separation between radar and communication targets.
5. Evaluate system performance through simulations measuring SNR, BER, CRLB, and throughput across pulse intervals.

in our structured workflow the system allows to achieve continuous, multi-user communication while maintaining radar precision. It addresses key challenges such as interference management, resource allocation, and spectral coexistence, making the solution viable for real-world DFRC applications.

### Problem Formulation and System Model

During the radar's active mode, sidelobe activity limits the CDR utilizing sidelobe-based information embedding, which stays constant. A novel method that allows communication transfer in both active and rest phases of the radar is offered to increase throughput. This method increases total data capacity without sacrificing radar functionality by having GSC1 monitor the radar signal through the mainlobe while also facilitating communication during active mode signal via the sidelobe as shown in Figure 1.

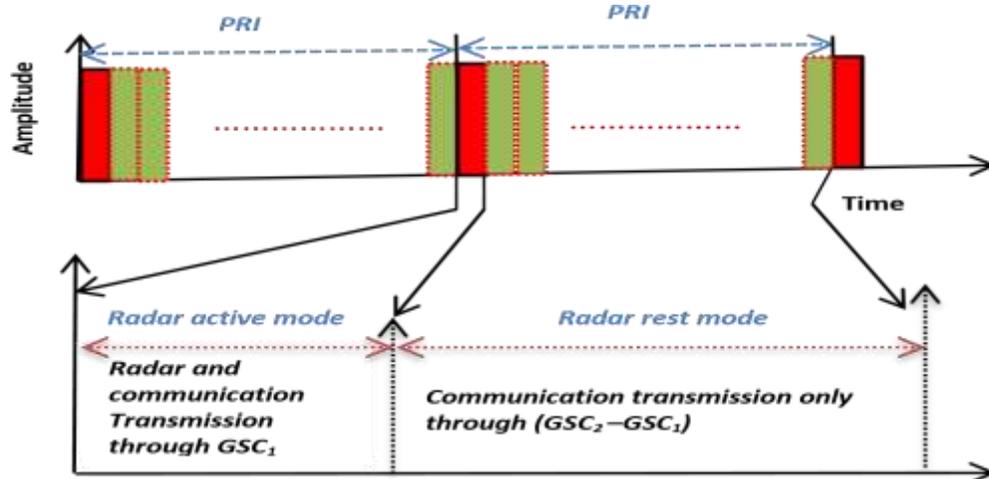


Figure 1: Visual depiction of the transmission signaling structure for the proposed PRI.

The duration of processing during active mode in the suggested system is represented by the notation  $t_w$ . Two parts, GSC1 and GSC2, work together while the radar is in rest mode. They purposefully produce variances in the sidelobe areas while maintaining the same amplitude powers in the mainlobe. A unique signal is produced and sent during the rest mode time by deducting the sidelobe powers of GSC1 and GSC2. This method ensures effective utilization of both active and idle times while preserving radar detection integrity by permitting extra communication transfer without interfering with primary radar operations. Through the use of the ordinarily inactive rest state, the technique increases communication capacity and provides an innovative method for dual-function radar and communication systems where performance balancing is crucial.

An M-element uniform linear transmit antenna array, separated by  $d$ , is used in this study. In the active mode of the radar, the antennas

$$\min_{\mathbf{w}_1} \max_{\theta} |\mathbf{w}_1^H \mathbf{a}_1(\theta)| \quad (1)$$

$$\text{s.t. } \mathbf{w}_1^H \mathbf{a}_1(\theta_t) = 1, \quad \theta_t \in \Theta \quad (2)$$

$$\mathbf{w}_1^H \mathbf{a}(\theta_{ci}) = \Delta_{1,i} e^{j\Omega_i} \text{ for } 1 \leq i \leq k - 1 \quad (3)$$

In the aforementioned mathematical expressions,  $\mathbf{w}_1$  is an M-by-1 weight vector,  $(\cdot)^H$  represent the Hermitian operator,  $\mathbf{a}_1(\theta_t)$  is an M-by-1 steering vector directed at the target located at  $\theta_t$  in radar spatial sector  $\Theta$ ,  $\mathbf{a}_1(\theta_{ci})$  is an M-by-1 steering vector towards a predefined  $i^{\text{th}}$  communication receiver located at

concurrently emit the radar signal and the communication signal, and in the rest mode, when there is no radar transmission, the antennas are only used for communication, which maximizes the use of transmission time for both functions. It also focuses on the case of a single target scenario, which simplifies the analysis and allows for a more straightforward assessment of the performance of the proposed dual-function radar-communication system.

### DFRC in Radar Active Mode

The enhancement task is to simultaneously broadcast a communication waveform passed through the sidelobe area as a secondary function and a desired radar waveform through the mainlobe as the primary function. Maintaining radar performance while permitting interference-free transmission is the aim. The following formulas offer a mathematical explanation of this dual-function transmission technique that balances communication and radar goals.

angle ( $\theta_{ci}$ ) and  $\Delta_{1,i} e^{\Omega_i}$  represents the intended communication signal strength within the corresponding sidelobe region.

As shown in Figure 2, a generalized sidelobe canceller (GSC1) is used for transmission while the radar is in active mode in order to solve the optimization problem. In order to facilitate the optimization process and guarantee efficient simultaneous radar and communication operation, the pertinent parameters for the suggested GSC1 configuration are presented.

The constraint matrix is:

$$C_1 = [\bar{a}(\theta_t) \quad \bar{a}(\theta_{c1}) \quad \bar{a}(\theta_{c2}) \dots \quad \bar{a}(\theta_{k-1})] \tag{4}$$

The blocking matrix is:

$$B_1 = \text{null}[C_1^H] \tag{5}$$

The gain vector is:

$$C_1^H w_1 = f_1 \tag{6}$$

The quiescent weight vector is:

$$w_{q1} = C_1(C_1^H C_1)^{-1} f_1 \tag{7}$$

The adjustable weight vector is:

$$w_{a1} = (B_1^H R_x B_1)^{-1} B_1 R w_{q1} \tag{8}$$

with  $k$  representing the number of columns in  $C_1$ , In this context,  $k-1$  represents the number of distinct communication channels. The matrix  $C$  is an  $M \times k$  times the constraint matrix containing steering vectors, while  $B$  is an  $M \times (M-k)$  times blocking matrix orthogonal to the space formed by  $C$ . The inverse operator is used for matrix operations.  $g$  is the gain vector associated with the  $k$  constraints, with  $k=5k$  in this scenario, and  $R$  represent correlation matrix. These parameters allow for the generic expression of the transmitted steering vector in a specific direction.

$$\bar{a}(\theta_i) = [1 \quad e^{-j(\frac{2\pi \sin \theta_i}{c})} \dots \dots \dots e^{-j(\frac{2\pi(M-1)\sin \theta_i}{c})}]^T \tag{9}$$

where,  $^T$  represent transpose operator. The proposed approach derives the optimal weight vector by minimizing the beamformer output's mean square error while meeting many linear restrictions, which is represented as:

$$f_1 = C^H w_1 = \begin{bmatrix} \chi \\ \Delta_{1,1} e^{\Omega_1} \\ \Delta_{1,2} e^{\Omega_2} \\ \Delta_{1,3} e^{\Omega_3} \\ \Delta_{1,4} e^{\Omega_4} \end{bmatrix} \tag{10}$$

where

$$e^{\Omega_i} = \begin{cases} e^0, & \text{for } \Omega = 0 \\ e^1, & \text{for } \Omega = 1 \end{cases} \tag{11}$$

Here,  $\chi = 1$  Indicates a unit gain in the direction of  $\theta_t$  Directed radar signal power at the target.  $\Delta_{1,i} e^{\Omega_i}$  Represents the intended communication signal, whereas the symbol  $\Delta$  values within column indicate the communication power allocated to the SL region and  $\Omega \in [0,1]$  Indicates binary information bits mapped to each sidelobe level; a higher sidelobe level in the received beam pattern corresponds to a transmitted bit of one, otherwise zero.

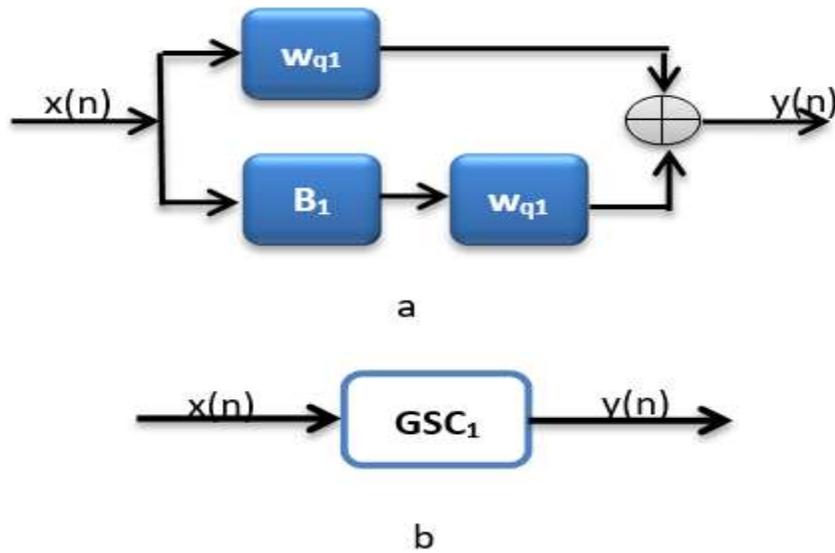


Figure 2: Schematic pertaining to the generalized sidelobe canceller (GSC). Diagram (b) represents an equivalent form of (a)

The blocking matrix is obtained by expressing the orthogonal complement as

$$C_1^H B_1 = 0 \tag{12}$$

In the above equation 0 represents the null matrix. Accordingly, the gain vector can be reformulated as

$$C^H(w_{q1}) = \begin{bmatrix} \Delta_{1,1} e^{j\Omega_1} \\ \Delta_{1,2} e^{j\Omega_2} \\ \Delta_{1,3} e^{j\Omega_3} \\ \Delta_{1,4} e^{j\Omega_4} \end{bmatrix} \tag{13}$$

where  $w_{q1}$  serves as the baseline beamformer ensuring signal transmission toward the intended direction.  $w_{q1}$  is fixed and remains unaffected by the lower branch of  $GSC_1$ . In the case of an optimization problem without constraints, where the weight vector in the bottom branch is the sole needs to be adjusted, i.e.,  $w_{a1}$ . Taking into account the output signal of the first  $GSC_1$  given as:

$$w_{q1}^H x(n) - w_{a1}^H B_1^H x(n) = y_1(n) \tag{14}$$

the resulting output power is given by

$$E|y_1(n)|^2 = (w_{q1} - B_1 w_{a1})^H E[x^*(n)x(n)](w_{q1} - B_1 w_{a1}) \tag{15}$$

$$E|y_1(n)|^2 = (w_{q1} - B_1 w_{a1})^H R_x (w_{q1} - B_1 w_{a1}) = P_{GSC_1} \tag{16}$$

The five-constraint correlation matrix  $R_x$  for five constraints is given by

$$R_x = R_t + R_{c1} + R_{c2} + R_{c3} + R_{c4} \tag{17}$$

where  $R_t$  is the radar correlation matrix, and  $(R_{c1} + R_{c2} + R_{c3} + R_{c4})$  are the correlation matrices for. For these signals, the correlation matrix is expressed as

$$R_x = \begin{bmatrix} \sigma_1^2 & \dots & \mathbf{0} \\ \vdots & \sigma_2^2 & \vdots \\ \mathbf{0} & \dots & \sigma_i^2 \end{bmatrix} \quad (18)$$

$\{\sigma_i^2\}_i^M$  represents the transmitted signal's power.  $R_x = \sigma^2 \mathbf{I}$  for scenario the case of white noise only, where  $\mathbf{I}$  is the M-by-M identity matrix and  $\sigma^2$  is the noise variance. Therefore, Eq. (18) can be reformulated as

$$w_{a1} = (\mathbf{B}_1^H \mathbf{B}_1)^{-1} \mathbf{B}_1 w_{q1} \quad (19)$$

The Figure 4 shows the pattern of the beam of a multi-input, multi-output dual-function radar-communication (MIMO-DFRC) system working in its characteristic mode. The normalised power in terms of decibels is represented in the vertical axis whereas the horizontal axis is the azimuth angle in degrees. The zero-degree reference is denoted by a red vertical line (radar target) and the receivers of communication are denoted by the green and yellow dashed lines (at -40, 20 and 40 degrees). The figure shows the ability of the system to support radar and communication capabilities at the same time where difference in power is measured as a variation throughout the angular spectrum. Strong peaks in the diagram testify to the skill of the algorithm of beam forming, and troughs are areas of reduced strength, which can be explained by lowered sensitivity.

The architecture shown in Figure 5 is a generalised Sidelobe Canceller (GSC) architecture, which is a ubiquitous architecture used in adaptive filtering and beamforming

paradigms. The system is divided into two main modules which are denoted as GSC1 and GSC2, each of them contains a group of subcomponents. The input signal  $x(n)$  is split into two parallel branches and different weight vectors of the signal are applied to the signals in the branches viz,  $w_{q1}$ ,  $w_{a1}$ ,  $w_{q2}$  and  $w_{a2}$ . With suitable tuning of these coefficients, the GSC tries to cancel the undesirable sidelobe responses but at the same time retain the desirable mainlobe fidelity; the results of the combination of the output of the two signal sources are added as the inputs of the two signals, and they are  $y_1(n)$  and  $y_2(n)$  to add to this cancellation policy.

This cancellation method depends on an adaptive filtering infrastructure that allows the dynamic cancellation of interference or noise components and amplification of the desired signal at the same time. This type of methodology employs signal integrity in a range of applications such as radar system and telecommunications infrastructure among others.

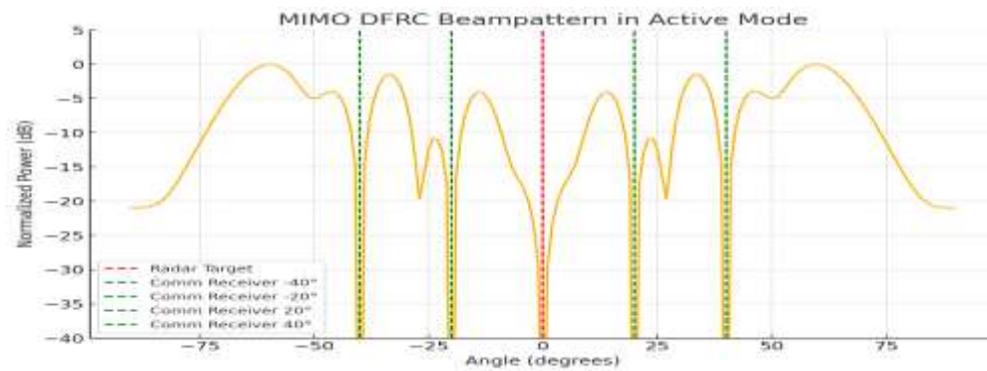


Figure 03: MIMO DFRC Beampattern in active mode for different angles

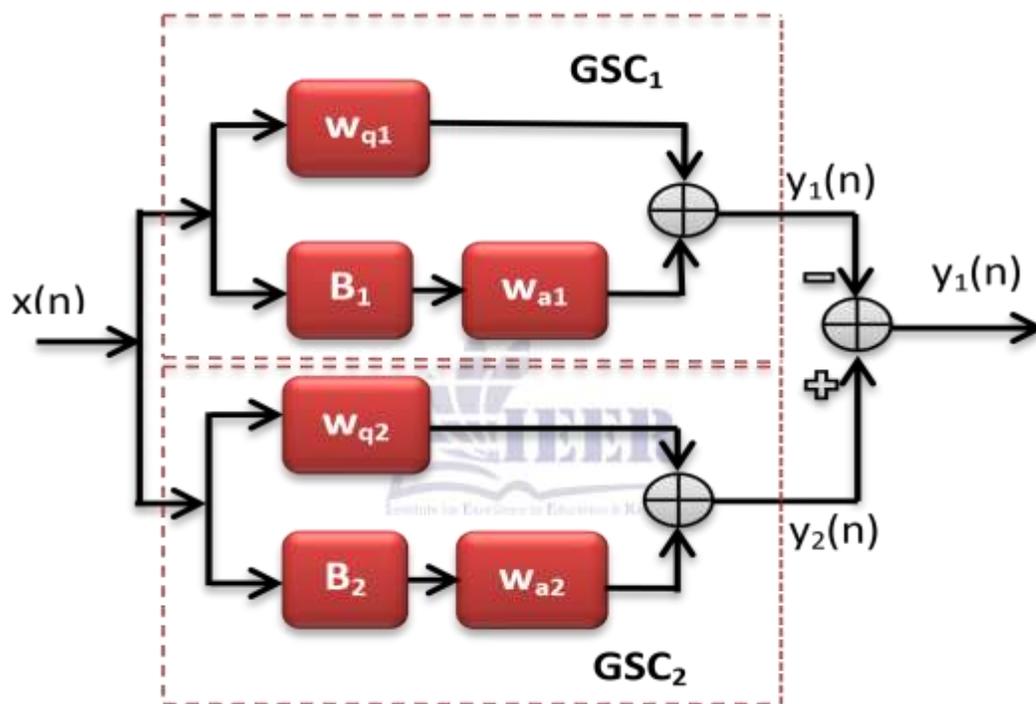


Figure 5: Novel approach for a unified transmitter system.

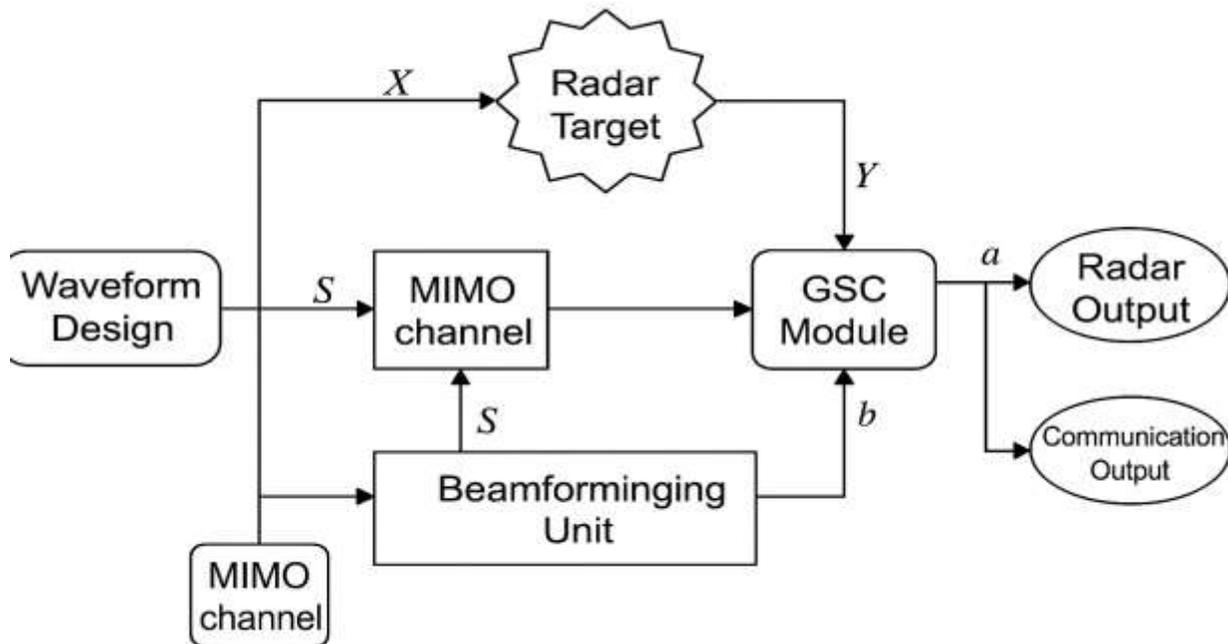


Figure 4: Operational structure of a Dual-Function Radar-Communication (DFRC)

The Figure 6 presents the operational structure of a Dual-Function Radar-Communication (DFRC) system employing a MIMO antenna array in conjunction with a pair of Generalized Sidelobe Cancellers (GSCs), reflecting the novel transmission architecture proposed in the referenced study. This architecture enables simultaneous radar and communication operations by carefully managing spatial beamforming and temporal resource allocation within the pulse repetition interval (PRI). During radar active mode, the first GSC (GSC1) forms a high-gain mainlobe towards the radar target, while modulated sidelobe levels convey binary communication data toward predefined user directions. The optimal weights for this configuration are derived through constrained minimization of output power, satisfying linear constraints for radar and multiple sidelobe-based communication receivers. In the radar rest mode—typically underutilized in conventional DFRC frameworks—the second GSC (GSC2) operates in parallel with GSC1, maintaining identical mainlobe power and doubling the sidelobe power. Subtraction of their outputs

effectively nullifies the radar beam while preserving the sidelobe communication transmission at active-mode levels. This enables communication to persist throughout the entire PRI, thereby substantially increasing throughput. The beam patterns generated by both GSCs maintain orthogonality in mainlobe and sidelobe power domains, as mathematically formulated using steering vectors, blocking matrices, and quiescent beamformer weights. The figure thus captures the essence of the spatial-temporal optimization strategy that allows continuous and interference-resilient multiuser communication without degrading radar target detection performance—a significant enhancement over conventional single-GSC or active-mode-only DFRC approaches.

#### Simulation Results

The simulation considers a uniform linear array comprising 16 transmit antenna elements, each spaced at half a wavelength ( $d = \lambda/2$ ). It is demonstrated that communication transmissions occurring in the sidelobe region do not interfere with radar functionality during its active phase.

Additionally, throughput over time was analyzed. The outcomes of the simulation are illustrated through the following scenarios:

**GSCs Behavior During the PRI**

We verify that concept of employing two GSCs in this example. The red line in Figure 7 indicates that GSC1 is operating in active mode. Four communication signals with identical waveforms directed to their targeted communication receivers plus radar signal directed in the direction of the target make up the GSC1 radiation pattern. The radiation pattern sends a signal for communication in the sidelobe area towards,, and, and a radar signal to track via the

mainlobe in the direction of  $\theta_{c1} = -60^\circ$ ,  $\theta_{c2} = -40^\circ$ ,  $\theta_{c3} = 40^\circ$  and  $\theta_{c4} = 60^\circ$ . The blue dashed line shows the resultant subtraction of both GSCs and operates in rest mode. In rest mode, the radiation is directed towards their receivers by the communication transmission that takes place in the sidelobe during active mode. In radar active mode, the communication signal that takes place in the sidelobe is the same as the rest mode of the communication signal. The null point for both GSCs for the main and sidelobe areas is considered to be the same for both radiation patterns. Both beams' sidelobe levels have power levels that are equivalent.

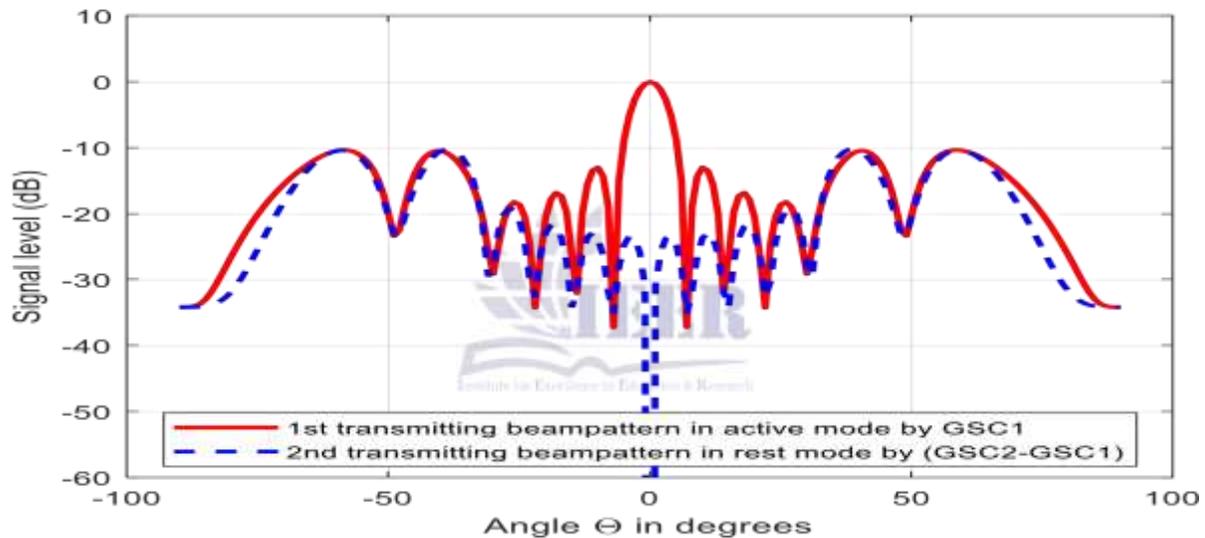


Figure 7: Transmitting beampattern in active and rest mode.

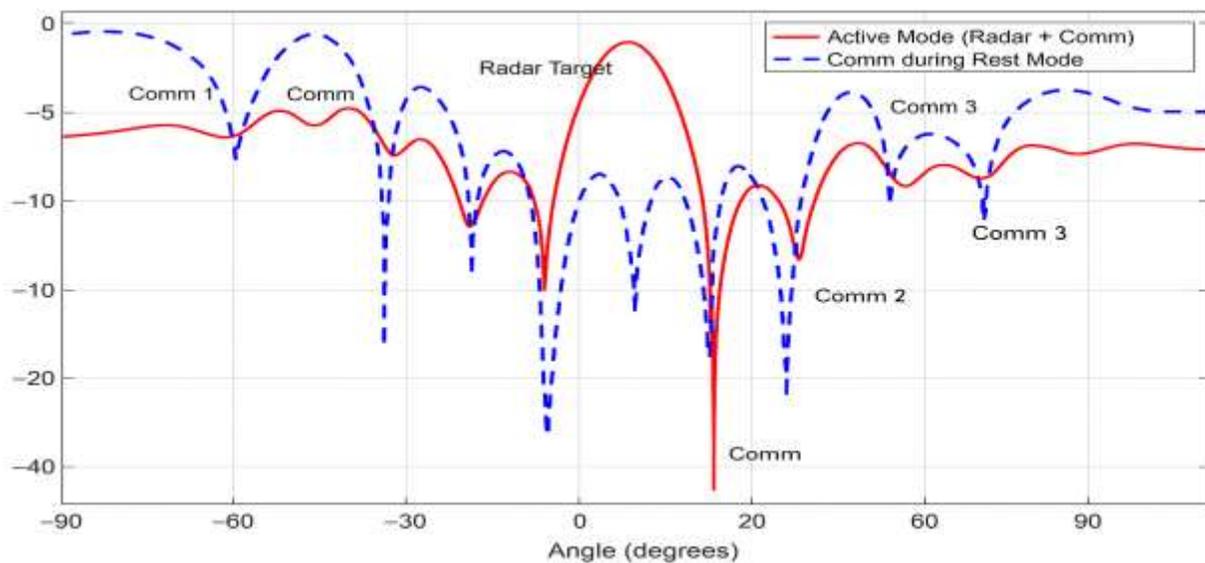


Figure 8: Radar-active and rest mode states in DFRC

Figure 8 presents the operational structure of a Dual-Function Radar-Communication system (DFRC) employing a MIMO antenna array in conjunction with a pair of Generalized Sidelobe Cancellers (GSCs), reflecting the novel transmission architecture proposed in the referenced study. This architecture enables simultaneous radar and communication operations by carefully managing spatial beamforming and temporal resource allocation within the pulse repetition interval (PRI). During radar active mode, the first GSC (GSC1) forms a high-gain mainlobe towards the radar target, while modulated sidelobe levels convey binary communication data toward predefined user directions. The optimal weights for this configuration are derived by constrained minimization of output power, subject to linear constraints for radar and multiple-sidelobe-based communication receivers. In radar rest mode—typically underutilized in conventional DFRC frameworks—the second GSC (GSC2) operates in parallel with GSC1, maintaining identical mainlobe power while doubling sidelobe power. Subtracting their outputs effectively nullifies the radar beam while preserving sidelobe communication transmission at active-mode levels. Hence, enables communication to persist throughout the entire PRI, thereby substantially

increasing throughput. The beam patterns generated by both GSCs maintain orthogonality in mainlobe and sidelobe power domains, as mathematically formulated using steering vectors, blocking matrices, and quiescent beamformer weights. The figure thus captures the essence of the spatial-temporal optimization strategy that enables continuous, interference-resilient multiuser communication without degrading radar target-detection performance—a significant enhancement over conventional single-GSC or active-mode-only DFRC approaches.

#### DFRC Signal Emission Under Active Radar mode

In a Multiple-Input Multiple-Output (MIMO) radar-communication (RadCom) system, two distinct transmit beampatterns are synthesized, each maintaining equal power in the mainlobe directed toward the radar target. Simultaneously, the sidelobe levels of these beampatterns are modulated to embed communication signals intended for multiple users. For instance, in Figure 9, the first beampattern (depicted by the red line) constrains its sidelobe levels to -10 dB, representing the transmission of bit '1'. Conversely, the second beampattern (illustrated by the blue dashed line) sets its sidelobe levels at -14 dB, corresponding to the transmission of bit

'0'. Each beam pattern transmits uniform sidelobe levels toward all communication users.

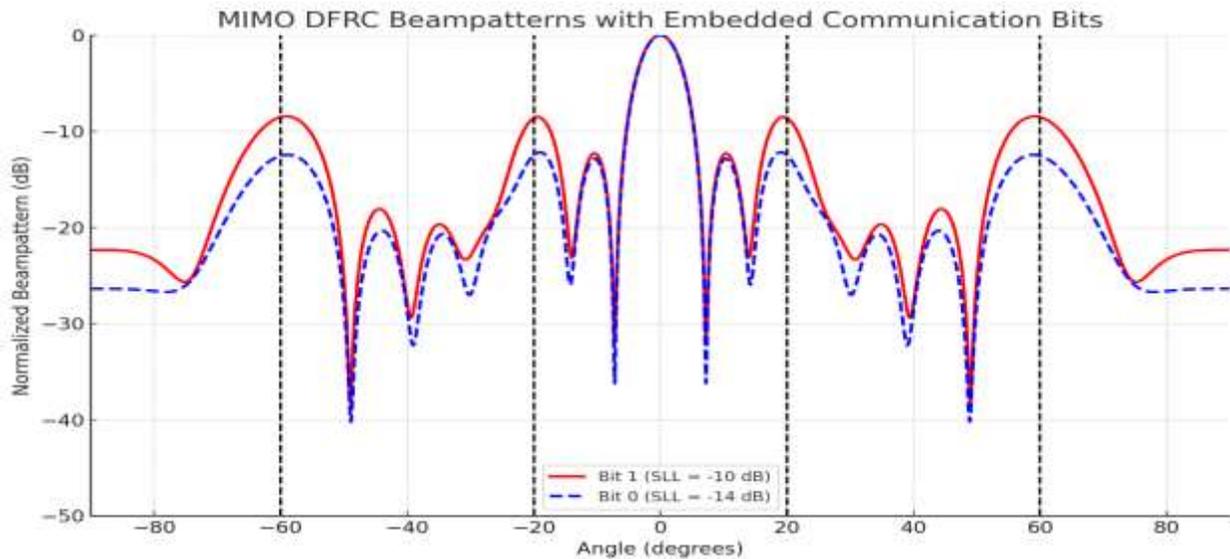


Figure 9: MIMO DFRC Beampatterns with embedded communication bits.

Figure 10 compares the efficiency of three methodologies in terms of Root Mean Square Error (RMSE) and Signal-to-Noise Ratio (SNR). The red line represents sidelobe control used in Method 1, and the purple line represents sidelobe control used in Method 2, both of which are obtained via a reference [19]. The blue stars indicate the proposed method, which shows

higher performance with lower RMSE across various SNR values. As SNR increases, RMSE decreases for all methods, but the proposed method consistently outperforms the others, indicating it is more efficient at reducing error at high SNR. Hence, the proposed approach is better as a sidelobe control mechanism than the existing mechanisms.

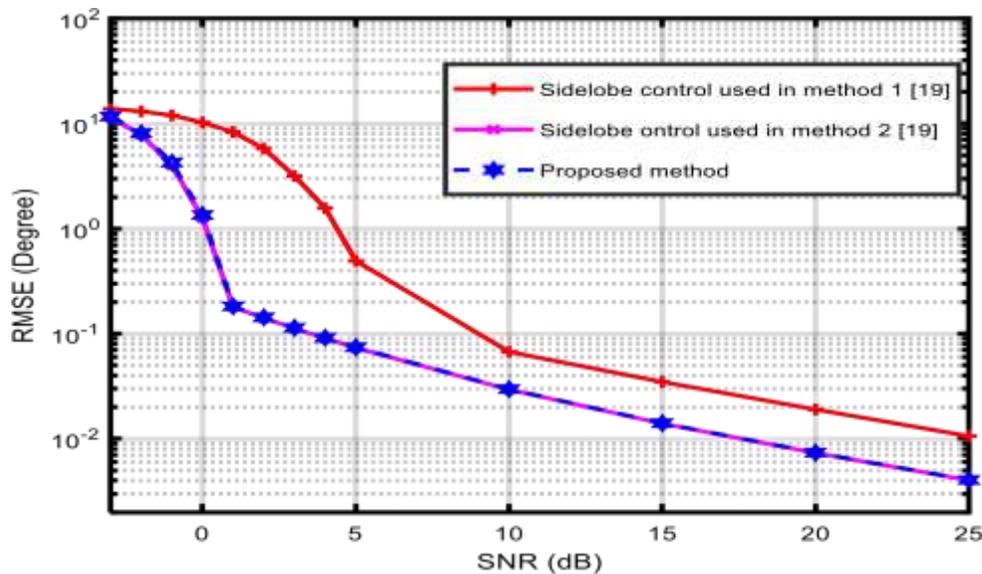


Figure 10: RMSEs of the DOA estimation vs the SNR

Figure 11 presents the likelihood of resolution versus the signal-to-noise ratio (SNR) for three different methods. The red dashed line depicts SLL -control Method 1, and the blue dashed line depicts SLL -control Method 2. The black line at the bottom marks down the procedure that is suggested. With increasing SNR, the probability

of resolution increases, and the recommended technique attains the highest resolution probability across the entire range of SNR values. As a result, the suggested approach achieves a high level of signal resolution at both low and high SNRs compared with control-based strategies.

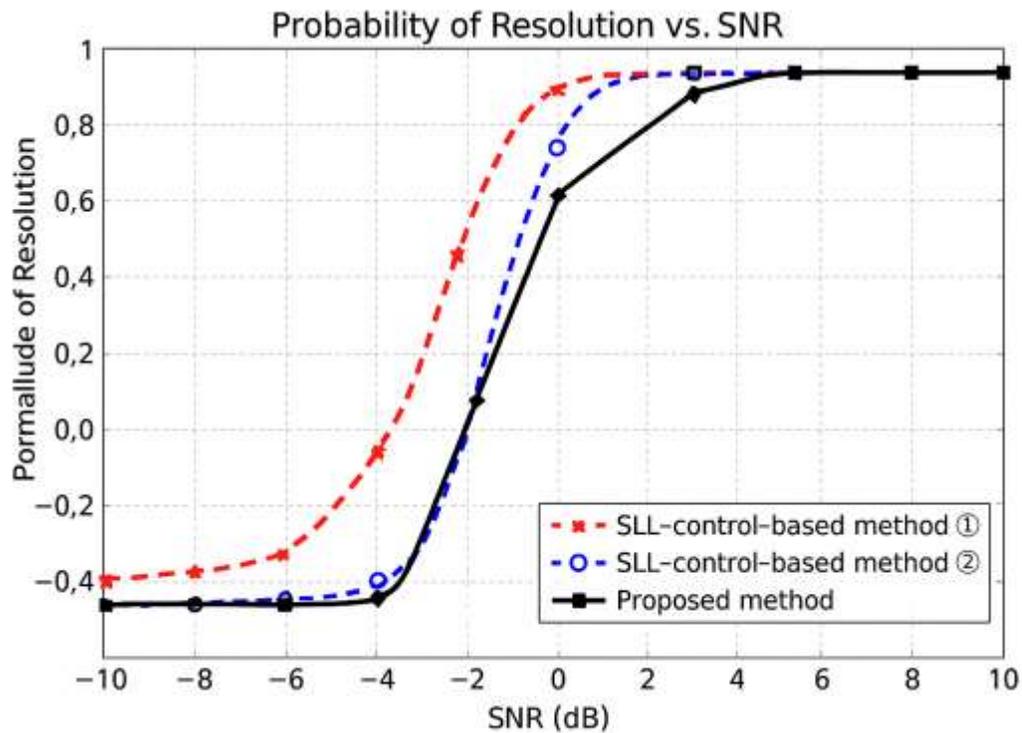


Figure 011: Probability of the resolution as a function of the SNR.

The Figure 12 illustrates the relationship between the Bit Error Rate (BER) and the Signal-to-Noise Ratio (SNR) for different Signal-to-Noise Ratio Sidelobe Level (SLL) management strategies. The horizontal axis shows SNR in decibels, and the vertical axis shows BER on a logarithmic scale. The black curve corresponds to the SLL technique, as recommended in reference [17].

The red, blue, and magenta curves correspond to the proposed SLL methods [1], [2], and [3], respectively, as presented in reference [19]. As SNR increases, BER decreases in all methods, but overall BER shows the lowest values in the methods with references, such as [17]; thus, the errors are lower than those of other SLL control methods.

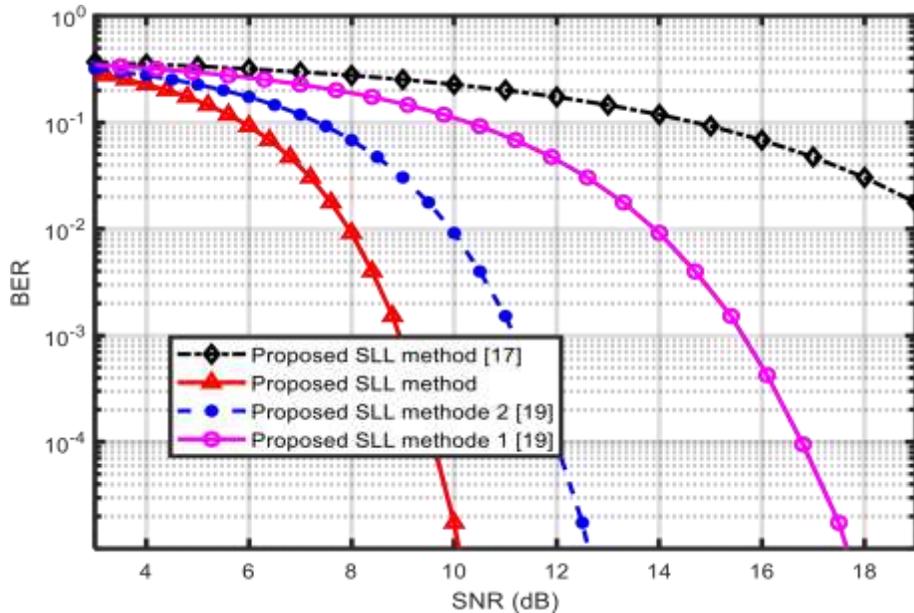


Figure 012: The BERs versus the SNR for four methods.

### Conclusion

This study presented a novel framework for realizing a dual-function radar-communication (DFRC) system by leveraging both the spatial and temporal resources available at the radar transmitter. The approach introduces two distinct operational modes that work in harmony to optimize spectral efficiency. In active mode, the radar and communication functionalities coexist: the radar uses the main lobe to detect and track targets. In contrast, communication signals are embedded in the sidelobe region, enabling simultaneous operation. The second mode, referred to as rest mode, is dedicated exclusively to communication; here, radar transmission is temporarily paused, allowing sidelobe power to be fully reallocated to enhance communication performance. A core innovation of this framework lies in its method of information embedding through modulation of the sidelobe levels across multiple angular directions, effectively enabling multi-user data transmission without compromising radar accuracy. The impact of this sidelobe-level control was further investigated through simulation figures and resolution probability plots, which demonstrated that the proposed method significantly improves communication

throughput and maintains high-resolution radar performance, especially under low SNR conditions.

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