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MUSIC-Aided Two-Stage Adaptive Beamforming Using Distributed Array Radar Systems

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Abstract: Distributed Array Radar (DAR) systems provide enhanced spatial diversity and interference suppression capabilities compared with conventional phased-array radars. However, the presence of simultaneous mainlobe and sidelobe jammers significantly degrades target detection performance, particularly when the directions of arrival (DOAs) of interference sources are unknown. Existing two-stage adaptive beamforming approaches effectively suppress multiple jammers but generally assume prior knowledge of jammer directions, limiting their practical applicability [5]. This paper presents a MUSIC-aided two-stage adaptive beamforming framework for distributed array radar systems operating in multiple mainlobe and sidelobe jamming environments. The proposed method integrates the Multiple Signal Classification (MUSIC) algorithm to estimate the DOAs of the desired target and interference sources directly from the received array data. The estimated DOAs are subsequently employed for Stage-1 Linearly Constrained Minimum Variance (LCMV) beamforming to suppress sidelobe jammers while preserving the mainlobe response at each distributed radar node. The beamformed outputs are then transmitted to a fusion center, where Stage-2 Minimum Mean Square Error (MMSE) beamforming performs centralized mainlobe jammer suppression. MATLAB simulations demonstrate that the proposed framework accurately estimates signal directions, effectively suppresses both sidelobe and mainlobe jammers, preserves the desired target response, and improves output SINR under severe interference conditions. The proposed approach provides a practical extension to existing two-stage adaptive beamforming techniques for distributed radar systems operating in realistic electronic warfare environments.
Keywords: Distributed Array Radar, Adaptive Beamforming, MUSIC, Direction of Arrival Estimation, LCMV, MMSE, Mainlobe Jamming, Sidelobe Jamming.

I. INTRODUCTION

Distributed Array Radar (DAR) has emerged as a promising architecture for next-generation radar systems due to its capability to exploit spatial diversity through multiple geographically distributed radar nodes. By coherently combining observations from several arrays, DAR systems provide improved angular resolution, enhanced target detection capability, and increased robustness against interference compared with conventional single-array radar systems. These advantages make distributed radar particularly suitable for surveillance and electronic warfare applications operating in complex electromagnetic environments[5].

Adaptive beamforming is widely employed in radar systems to suppress interference while maintaining a high gain toward the desired target. Classical beamforming algorithms such as the Minimum Variance Distortionless Response (MVDR)[6,7] and Linearly Constrained Minimum Variance (LCMV)[6] beamformers effectively mitigate sidelobe interference by adaptively placing nulls in the directions of interfering sources. However, when strong jammers are located within or close to the mainlobe, conventional adaptive beamforming often introduces significant mainlobe distortion, resulting in reduced target detection performance[2,3].

To overcome this limitation, Chen et al. proposed a two-stage adaptive beamforming framework[5] for distributed array radar systems in which Stage-1 performs Multiple Sidelobe Cancellation with Mainlobe Maintenance (MSLC) using LCMV beamforming at each radar node, while Stage-2 performs centralized Multiple Mainlobe Cancellation (MMLC) using MMSE beamforming at the fusion center[5]. This hierarchical processing strategy effectively suppresses both sidelobe and mainlobe jammers while preserving the desired target response. However, the framework assumes that the directions of arrival (DOAs) of the target and jammer signals are known a priori, which is rarely achievable in practical radar systems.In realistic electronic warfare scenarios, the DOAs of interference sources are unknown and must be estimated directly from the received array measurements before adaptive beamforming can be performed. Inaccurate DOA information leads to steering vector mismatch, reducing interference suppression capability and degrading beamformer performance. Therefore, integrating reliable DOA estimation with two-stage adaptive beamforming is essential for practical distributed radar applications[2,5].

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This paper proposes a MUSIC-aided two-stage adaptive beamforming framework that extends the conventional distributed radar architecture by incorporating Multiple Signal Classification (MUSIC)-based DOA estimation prior to adaptive beamforming. The estimated DOAs are utilized to construct accurate steering vectors for Stage-1 LCMV beamforming at each radar node and Stage-2 MMSE beamforming at the fusion center. The proposed framework enables practical implementation without assuming prior knowledge of jammer locations while maintaining effective suppression of simultaneous mainlobe and sidelobe jammers.

The main contributions of this work are summarized as follows:

A MUSIC-based DOA estimation stage is integrated into a two-stage adaptive beamforming framework for distributed array radar systems.

The proposed method eliminates the requirement for prior knowledge of jammer directions by estimating target and interference DOAs directly from the received array data.

A complete MATLAB implementation of the distributed radar signal processing chain, including MUSIC estimation, Stage-1 LCMV beamforming, Stage-2 MMSE beamforming, and performance evaluation, is developed.

The proposed framework is validated under simultaneous mainlobe and sidelobe jamming scenarios using beam pattern analysis and output SINR performance.

II. SYSTEM MODEL

A. Distributed Array Radar Configuration

The proposed distributed array radar (DAR) system consists of $\boldsymbol{N}$ spatially separated radar nodes, each equipped with a Uniform Linear Array (ULA) of $\boldsymbol{M}$ antenna elements with an inter-element spacing of $\boldsymbol{d = \lambda/2}$, where $\boldsymbol{\lambda}$ is the carrier wavelength. Each radar node independently receives the target echo, mainlobe jamming (MLJ), sidelobe jamming (SLJ), and additive white Gaussian noise (AWGN). Local preprocessing is performed at every radar node using MUSIC-based direction-of-arrival (DOA) estimation followed by Stage-1 Linearly Constrained Minimum Variance (LCMV) beamforming. The beamformed outputs are transmitted to a fusion center, where Stage-2 Minimum Mean Square Error (MMSE) beamforming is applied to suppress the remaining mainlobe interference and generate the final beamformed Signal. [5]

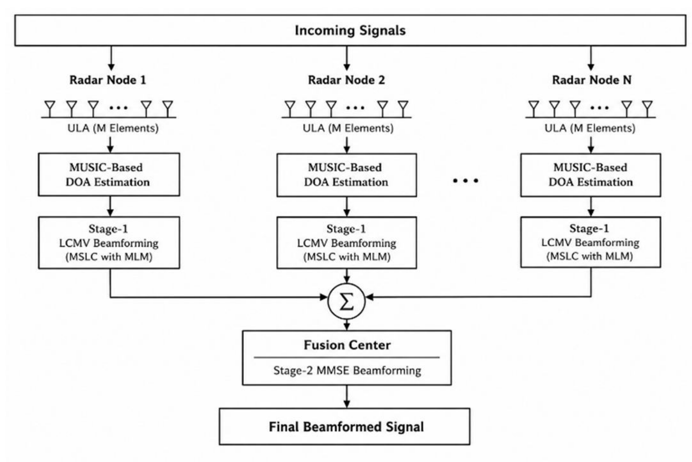

Figure. 1: System architecture of the proposed MUSIC-aided two-stage adaptive beamforming framework for distributed array radar.

B. Received Signal Model

Consider a distributed radar system observing one desired target and K interference sources. The received signal vector at the radar node is expressed as follows, based on the standard array signal model **[1,7]**:

$$\mathbf{x}(t) = \mathbf{a}(\theta_0)s(t) + \sum_{k=1}^{K} \mathbf{a}(\theta_k)j_k(t) + \mathbf{n}(t) \qquad (1)$$

where $\mathbf{x}(t)$ is the received signal vector, $s(t)$ denotes the desired target signal, $j_k(t)$ represents the k^{th} jammer signal, $\mathbf{a}(\theta)$ is the steering vector corresponding to direction θ, $\mathbf{n}(t)$ denotes additive white Gaussian noise.

For Ltemporal snapshots, the received data matrix is

$$\mathrm{X} = [\mathrm{x}(1), \mathrm{x}(2), \ldots, \mathrm{x}(L)] \qquad (2)$$

The sample covariance matrix is estimated as [1]

$$\mathrm{R} = \frac{1}{L}\mathrm{X}\mathrm{X}^{H} \qquad (3)$$

where $(\cdot)^H$denotes the Hermitian transpose. The covariance matrix serves as the input for both the MUSIC DOA estimation stage and the subsequent adaptive beamforming algorithms.

C. Steering Vector Formulation

For an M-element ULA with inter-element spacing $d = \lambda/2$, the steering vector corresponding to an incident signal arriving from angle $\theta$is given in equation 4 [1], [6]:

$$\mathbf{a}(\theta) = [1 \quad e^{-j\pi \sin\theta} \quad \ldots \quad e^{-j(M-1)\pi \sin\theta}]^T \qquad (4)$$

The estimated steering vectors obtained from the MUSIC algorithm[1] are employed in Stage-1 LCMV beamforming for sidelobe jammer suppression and subsequently in Stage-2 MMSE beamforming for centralized mainlobe jammer cancellation.

Table I. Simulation Configuration Parameters

Parameter	Value
Number of radar nodes (N)	8
Elements per array (M)	30
Carrier frequency	10 GHz
Inter-element spacing	$\lambda/2$
Number of snapshots	12000
Target DOA	0°
Mainlobe jammer DOAs	−1°, 1.4°
Sidelobe jammer DOAs	−40°, -15°, 29°, 37°
SNR	0 dB
JNR	30 dB

III. PROPOSED MUSIC-AIDED TWO-STAGE ADAPTIVE BEAMFORMING

To enable practical implementation of distributed array radar systems under unknown interference conditions, the proposed framework integrates MUSIC-based direction-of-arrival (DOA) estimation with a two-stage adaptive beamforming architecture. Unlike conventional two-stage beamforming methods that assume prior knowledge of target and jammer directions, the proposed approach estimates the DOAs directly from the received array measurements and subsequently utilizes the estimated steering vectors for adaptive beamforming. The overall processing framework consists of three sequential stages: (i) MUSIC-based DOA estimation, (ii) Stage-1 LCMV beamforming for sidelobe jammer suppression, and (iii) Stage-2 MMSE beamforming for centralized mainlobe jammer suppression.

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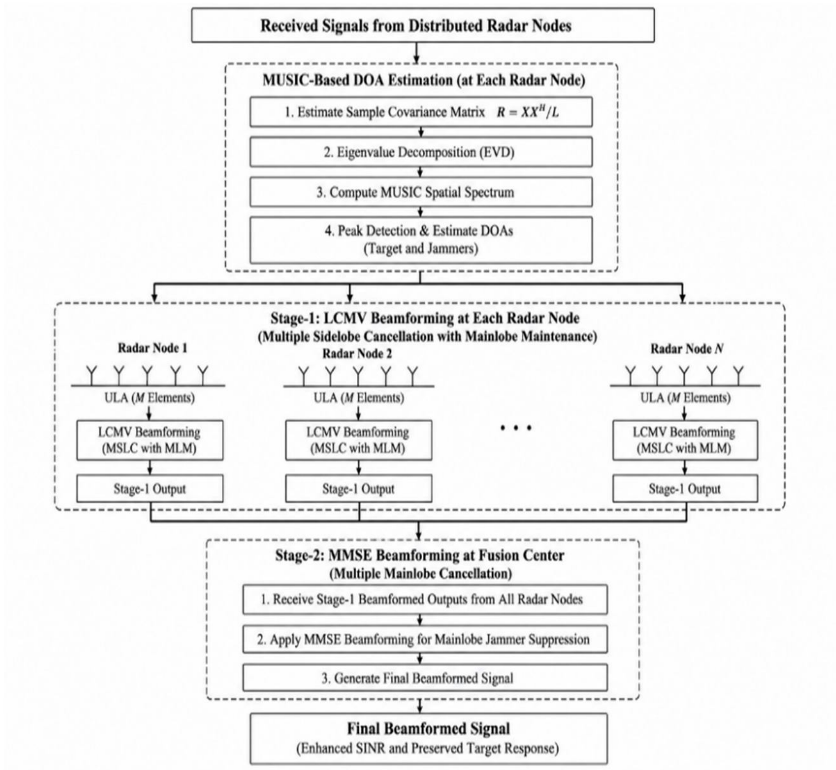

Figure. 2 : Two-Stage Beamforming Processing Framework

A. *MUSIC-Based DOA Estimation*

The MUSIC algorithm is employed to estimate the directions of arrival of the desired target and multiple jammer signals prior to adaptive beamforming[1]. The sample covariance matrix obtained from (3) is first decomposed using eigenvalue decomposition (EVD) [1] as

$$\mathrm{R} = \mathrm{E}\Lambda\mathrm{E}^{H} \qquad (5)$$

where Λ is the diagonal matrix of eigenvalues and E contains the corresponding eigenvectors. The eigenvectors associated with the smallest eigenvalues constitute the noise subspace

$$\mathrm{E}_{n} = [\mathrm{e}_{K+1}, \mathrm{e}_{K+2}, \dots, \mathrm{e}_{M}] \qquad (6)$$

where K denotes the total number of impinging signals. [1]

The MUSIC spatial spectrum [1] is evaluated as

$$P_{\mathrm{MUSIC}}(\theta) = \frac{1}{\mathrm{a}^{H}(\theta)\mathrm{E}_{n}\mathrm{E}_{n}^{H}\mathrm{a}(\theta)} \qquad (7)$$

The dominant peaks of the spatial spectrum correspond to the estimated DOAs of the target and jammer signals. These estimated directions are used to construct the steering vectors required for the subsequent beamforming stages.

B. *Stage-1 LCMV Beamforming*

After estimating the signal directions, each distributed radar node independently performs Stage-1 adaptive beamforming using the Linearly Constrained Minimum Variance (LCMV) criterion. The objective is to suppress sidelobe jammers while preserving the desired mainlobe response. The optimization problem is formulated as [6]:

$$\min_{\mathrm{w}} \mathrm{w}^{H}\mathrm{R}\mathrm{w} \text{ subject to} \mathrm{C}^{H}\mathrm{w} = \mathrm{f} \qquad (8)$$

where $\mathbf{C}$ represents the constraint matrix constructed from the estimated steering vectors and $\mathbf{f}$ specifies the desired response. The optimal weight vector is obtained as [6]:

$$\mathrm{w}_{\mathrm{LCMV}} = \mathrm{R}^{-1}\mathrm{C}(\mathrm{C}^{H}\mathrm{R}^{-1}\mathrm{C})^{-1}\mathrm{f} \qquad (9)$$

The beamformed output at each radar node is then computed by

$$y_n(t) = \mathrm{w}_{\mathrm{LCMV}}^H \mathrm{x}_n(t) \qquad (10)$$

where $y_n(t)$ denotes the Stage-1 output of the n^{th} radar node. The resulting beam preserves the desired target while effectively suppressing sidelobe interference.

C. Stage-2 MMSE Beamforming

The Stage-1 beamformed outputs from all radar nodes are transmitted to the fusion center, where centralized beamforming is performed to suppress the remaining mainlobe jammers [5]. The beamformed signals are first combined into

$$\mathrm{y} = [y_1, y_2, \dots, y_N]^T \qquad (11)$$

The MMSE weight vector is determined by[7]

$$\mathrm{w}_{\mathrm{MMSE}} = \mathrm{R}_y^{-1} \mathrm{r}_{yd} \qquad (12)$$

where R_y is the covariance matrix of the Stage-1 outputs and $\mathbf{r}_{yd}$ is the cross- correlation vector between the received data and the desired signal.

The final beamformed signal is obtained as

$$y_{\mathrm{out}} = \mathrm{w}_{\mathrm{MMSE}}^H \mathrm{y} \qquad (13)$$

This centralized processing exploits the spatial diversity of the distributed radar network to generate narrow adaptive nulls toward the mainlobe jammers while maintaining a distortionless response in the target direction.

D. Computational Flow

The proposed framework operates sequentially by estimating the DOAs using the MUSIC algorithm, constructing steering vectors from the estimated directions, performing local Stage-1 LCMV beamforming at each radar node, and finally applying centralized Stage-2 MMSE beamforming at the fusion center. Compared with conventional two-stage beamforming approaches [5], the proposed framework removes the requirement for prior knowledge of jammer directions while preserving effective suppression of simultaneous mainlobe and sidelobe interference.

IV. SIMULATION RESULTS AND ANALYSIS

The proposed MUSIC-aided two-stage adaptive beamforming framework was implemented in MATLAB R2025b to evaluate its performance in suppressing simultaneous mainlobe and sidelobe jammers in a distributed array radar environment. The simulation considers eight distributed radar nodes, each employing a 30-element Uniform Linear Array (ULA) with an inter-element spacing of $\lambda/2$. The desired target is located at 0°, while two mainlobe jammers are positioned at -1° and 1.4°, and four sidelobe jammers are located at -40°, -15°, 29°, and 37°. The carrier frequency, SNR, and JNR are set to 10 GHz, 0 dB, and 30 dB, respectively. The principal simulation parameters are summarized in Table I.

A. MUSIC DOA Estimation

The MUSIC algorithm was first applied to estimate the directions of arrival of the desired target and interference signals from the received array measurements. Figure 4 presents the MUSIC spatial spectrum after covariance estimation, forward-backward averaging, and spatial smoothing. Six dominant peaks were detected, corresponding to the jammer directions of **−40°, −15°, −1°, 1.4°, 29°, and 37°**, which exactly match the predefined source locations. The accurate estimation of these directions confirms the effectiveness of the proposed preprocessing stage and provides reliable steering vectors for the subsequent adaptive beamforming process.

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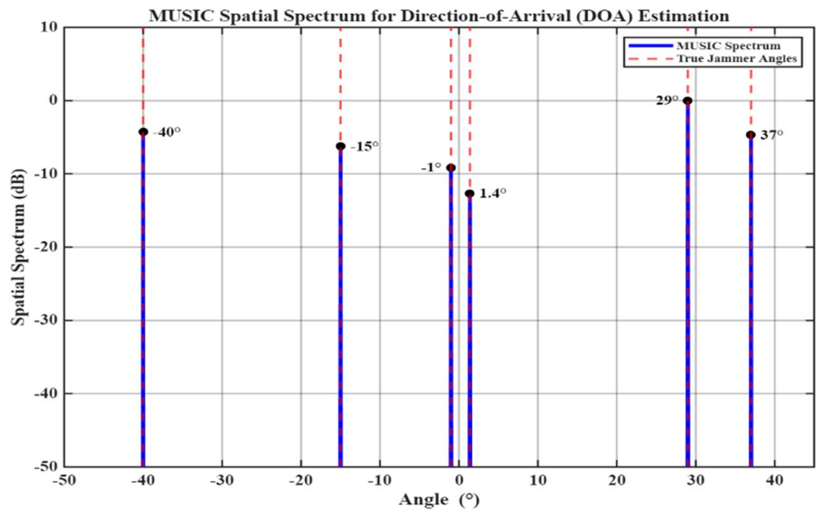

Figure. 4 :MUSIC Spectrum for Direction-of-Arrival Estimation

B. *Stage-1 LCMV Beamforming Performance*

Using the MUSIC-estimated sidelobe jammer directions, Stage-1 LCMV beamforming was independently performed at each radar node. The resulting beam pattern is illustrated in Fig. 5. Deep adaptive nulls were formed at all sidelobe jammer directions while maintaining the desired beam around the target direction. The measured null depths were −117.76 dB at −40°, −118.21 dB at −15°, −117.28 dB at 29°, and −129.91 dB at 37°, demonstrating excellent sidelobe interference suppression. The output SINR after Stage-1 was −31.55 dB, which is nearly identical to the conventional beamformer (−31.56 dB). This behavior is expected because Stage-1 is primarily designed to eliminate sidelobe interference while preserving the mainlobe response rather than improving the overall SINR.

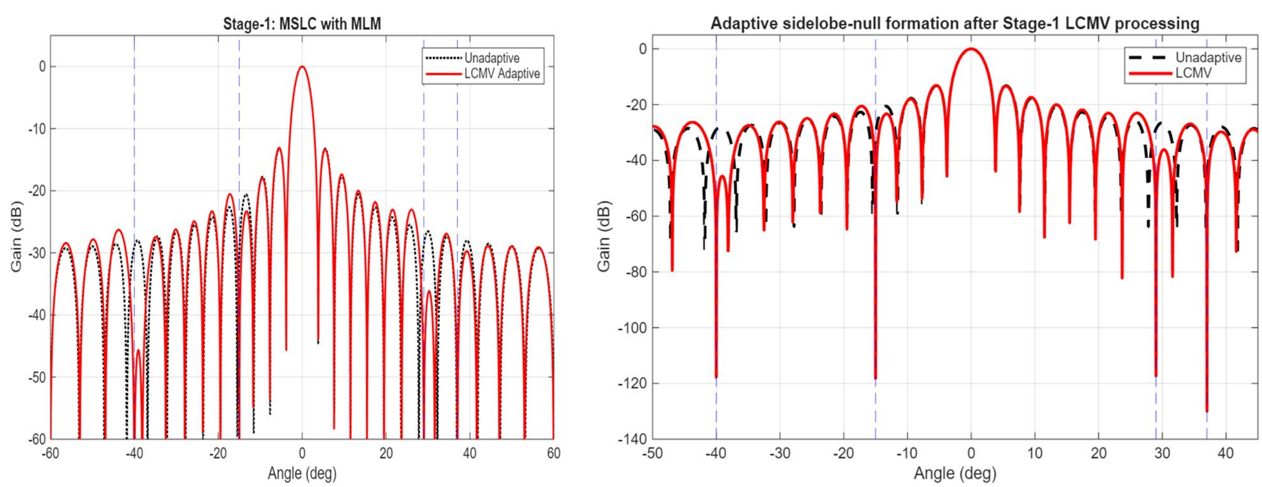

Figure. 5: stage-1 Adaptive Beam Pattern (MSLC with MLM)

C. *Stage-2 MMSE Beamforming Performance*

The Stage-1 beamformed outputs from all distributed radar nodes were coherently combined at the fusion center for centralized MMSE beamforming. Figure 6 shows the Stage-2 beam pattern, where narrow adaptive nulls are introduced at the estimated mainlobe jammer directions. Compared with Stage-1, the beam gain at **−1°** decreased from approximately **−1.00 dB** to **−60.87 dB**, while the gain at **1.4°** decreased from **−2.01 dB** to **−65.78 dB**. These results demonstrate that the proposed Stage-2 processing effectively suppresses the remaining mainlobe jammers while maintaining the desired target response. The corresponding output SINR increased to **22.68 dB**, indicating substantial improvement in interference rejection.

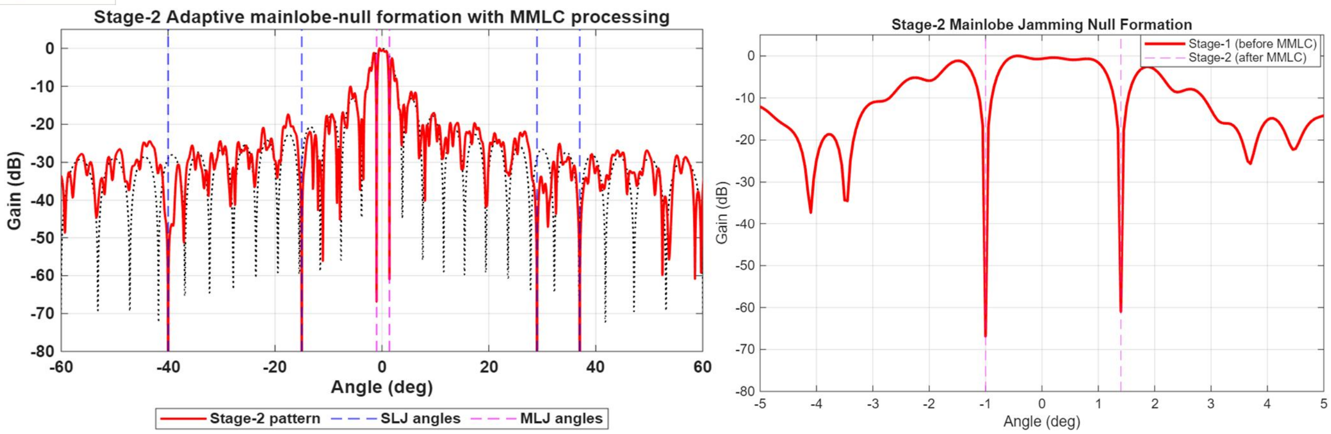

Figure. 6 : Stage-2 Adaptive mainlobe-null formation with MMLC processing

D. Overall Beamforming Performance

Figure 7 compares the conventional beamformer, Stage-1 LCMV beamformer, and the proposed Stage-2 MMSE beamformer. The conventional beamformer exhibits limited interference suppression capability, whereas Stage-1 introduces deep nulls only toward the sidelobe jammers. After centralized Stage-2 processing, additional nulls are generated at the mainlobe jammer directions without degrading the target beam. This sequential processing enables simultaneous suppression of both sidelobe and mainlobe interference, thereby improving the overall beamforming performance of the distributed radar system.

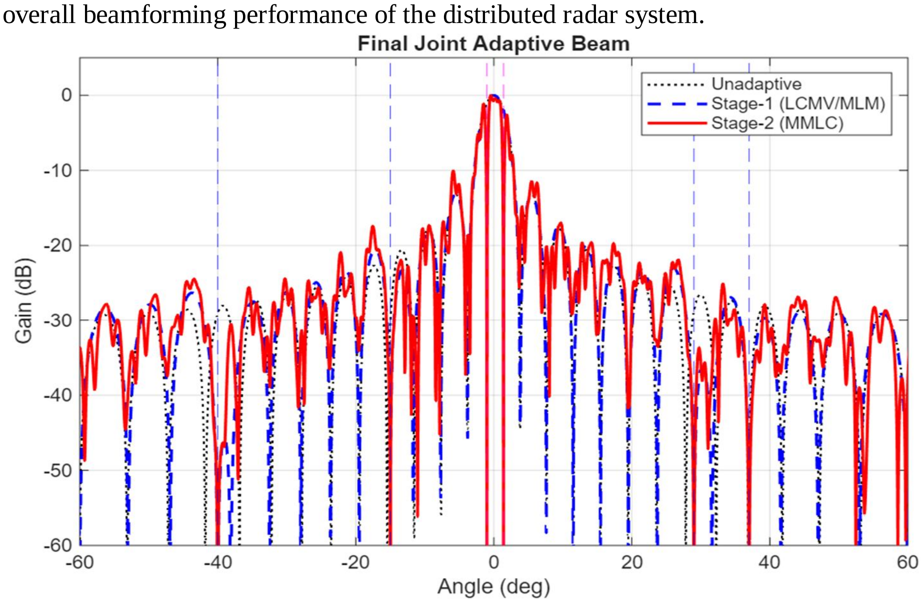

Figure. 7: Final Joint Adaptive Beam Pattern

These results demonstrate that the integration of MUSIC with the two-stage beamforming framework successfully compensates for the absence of prior jammer DOA information.

E. SINR Performance Analysis

The output SINR obtained using the conventional beamformer, Stage-1 beamformer, and the proposed Stage-2 beamformer is summarized in Fig. 8. The conventional beamformer achieved an output SINR of **−31.56 dB**, whereas Stage-1 produced **−31.55 dB**, indicating that sidelobe jammer suppression alone provides negligible SINR improvement. After centralized MMSE processing, the output SINR increased significantly to **22.68 dB**, corresponding to an overall improvement of approximately **54.24 dB** compared with the conventional beamformer. This substantial improvement confirms that integrating MUSIC-based DOA estimation with two-stage adaptive beamforming enables effective suppression of multiple mainlobe and sidelobe jammers while preserving the desired target signal.

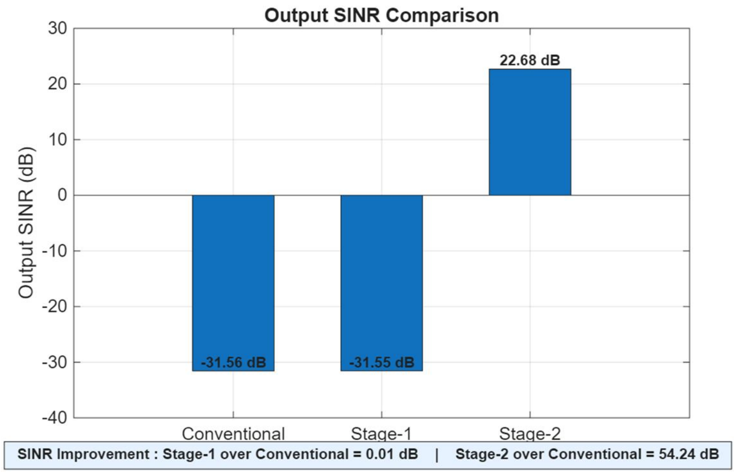

Figure. 8 : Output SINR Comparison

V. CONCLUSION

This paper presented a MUSIC-aided two-stage adaptive beamforming framework for distributed array radar systems operating under simultaneous mainlobe and sidelobe jamming conditions. Unlike conventional two-stage beamforming approaches that assume prior knowledge of jammer directions, the proposed framework integrates MUSIC-based direction-of-arrival estimation to automatically determine the spatial locations of the desired target and interference sources. The estimated steering vectors are subsequently employed for Stage-1 LCMV beamforming at individual radar nodes and Stage-2 MMSE beamforming at the fusion center.

Simulation results demonstrate that the proposed framework accurately estimates the DOAs of multiple interference sources while effectively suppressing both sidelobe and mainlobe jammers. The sequential beamforming strategy preserves the desired target response, produces narrow adaptive nulls toward jammer directions, and improves the output SINR under severe electronic interference. The proposed method enhances the practical applicability of distributed array radar systems by eliminating the requirement for prior jammer direction information while maintaining robust adaptive beamforming performance.

The proposed framework assumes narrowband signals and static jammer locations; future work will consider wideband signals and dynamic electronic warfare environments.

Future work will investigate the extension of the proposed framework to dynamic multi-target environments with moving jammers, wideband signal models, and experimental validation using real distributed radar platforms.

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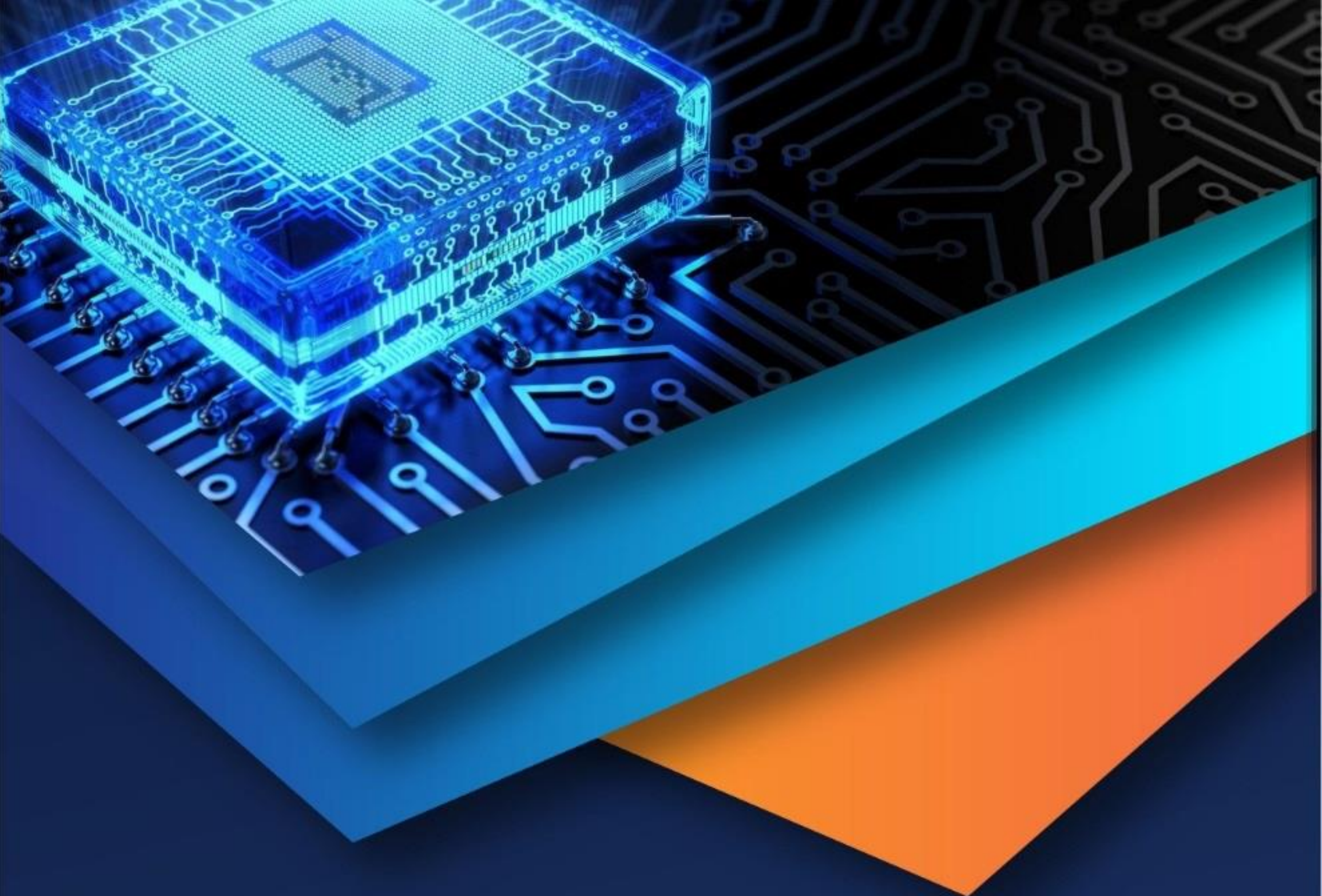

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