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A Sigmoid-Enhanced Adaptive Weighted MUSIC Algorithm for Direction-of-Arrival Estimation

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Abstract - Accurate direction-of-arrival (DOA) estimation is a core problem in array signal processing with applications in radar, sonar, and wireless communications. Classical MUSIC-based techniques provide high angular resolution but often exhibit performance degradation in low signal-to-noise ratio environments and in the presence of closely spaced sources. In this paper, a Sigmoid-Enhanced Adaptive Weighted MUSIC (SEAW-MUSIC) algorithm is proposed to improve DOA estimation accuracy and robustness. The proposed method employs a partial eigen-decomposition strategy to extract the noise subspace by estimating only the eigenvectors associated with the smallest eigenvalues, thereby reducing computational complexity while preserving essential subspace information. In addition, a normalized sigmoid-based adaptive weighting mechanism is incorporated into the MUSIC pseudo-spectrum to dynamically control the contribution of the noise subspace, effectively suppressing spurious peaks and enhancing angular resolution. Simulation results demonstrate that the proposed SEAW-MUSIC algorithm achieves superior estimation accuracy, improved resolution for closely spaced sources, and enhanced robustness compared to conventional MUSIC and existing weighted MUSIC approaches under various noise and snapshot conditions.

Keywords **-** Direction-of-arrival estimation, MUSIC algorithm, adaptive weighting, sigmoid function, noise subspace estimation, partial eigen-decomposition.

1.Introduction

Direction-of-arrival (DOA) estimation is a fundamental problem in array signal processing and plays a vital role in applications such as radar, sonar, wireless communications, and smart sensing systems. Among various high-resolution techniques, subspace-based methods have received significant attention due to their superior angular discrimination capability. In particular, the multiple signal classification (MUSIC) algorithm has become one of the most widely used approaches owing to its strong theoretical foundation and high estimation accuracy.
Despite its advantages, conventional MUSIC suffers from several limitations in practical scenarios. Its performance deteriorates in low signal-to-noise ratio (SNR) conditions and in the presence of closely spaced sources. Moreover, MUSIC relies on an accurate separation of signal and noise subspaces through eigen-decomposition of the covariance matrix, which can introduce unnecessary computational overhead.

To address these challenges, several weighted and modified MUSIC variants have been proposed. However, many existing approaches either rely on heuristic weighting strategies or require additional prior information, limiting their robustness and general applicability. Motivated by these observations, this paper proposes a Sigmoid-Enhanced Adaptive Weighted MUSIC (SEAW-MUSIC) algorithm for improved DOA estimation. The proposed method employs partial eigen-decomposition to efficiently extract the noise subspace and introduces a normalized sigmoid-based adaptive weighting mechanism to regulate the pseudo-spectrum. This combination enhances angular resolution, suppresses false peaks, and improves robustness under challenging noise and snapshot conditions. Simulation results validate the effectiveness of the proposed SEAW-MUSIC algorithm in comparison with conventional MUSIC and existing weighted variants.

2. Related work

Recent efforts have extended these techniques to sparse and coprime arrays. Villagómez-Galindo et al. proposed

Unitary Root-MUSIC and modified Root-MUSIC methods using Nyström approximation for 3D sparse arrays and target localization, improving computational efficiency and accuracy [1,2]. Adaptive Nyström spectral analysis was also explored for coprime arrays, enhancing resolution for closely spaced sources [3].

An enhanced covariance averaging–based MURE (ECA-MURE) algorithm was introduced for high-precision DOA estimation in coprime arrays, while manifold reconstruction was optimized using a unitary ESPRIT framework [4,5]. Other studies [6–10] focused on fast and robust estimation techniques, including accelerated sensor array processing, joint estimation of coherent and uncorrelated sources without prior knowledge, and the design of planar-like and symmetric sensor arrays to improve DOA performance. Several investigations have addressed high-resolution DOA estimation and robust beamforming across diverse array configurations. Three-dimensional near-field source localization using spatially distributed acoustic vector sensors was explored [11], followed by studies on simultaneous interference localization and array calibration for partly calibrated arrays to enhance adaptive beamforming performance [12]. Additional approaches emphasized balancing DOA accuracy and computational complexity, highlighting inherent trade-offs in large-scale sensor arrays [13]. Practical realization of coherent DOA estimation using digital signal processors was also reported [14], along with feature extraction and clustering-based methods for radar signal processing [15].

Recent advances in sparse and coprime arrays have further strengthened DOA estimation capabilities. Three-dimensional sparse array configurations for coherent and uncorrelated signals using the COMP-ESP algorithm were proposed [16], while sigmoid-enhanced robust adaptive beamforming techniques improved convergence and robustness [17]. Robust DOA estimation methods employing improved coprime arrays and adaptive beamformers were developed for wireless communication applications [18], and machine learning–assisted DOA estimation approaches addressed both coherent and non-coherent sources [19]. Integrated Capon–MUSIC frameworks for coprime arrays demonstrated improved performance in disaster management scenarios [20].

Additional research has focused on advanced sensing, optics, and signal processing techniques relevant to array systems. Controlled multiband filter designs using metacells were introduced [21], and optimization of receiver optics and color correction in lens stacks was investigated [22,23]. Deep learning–based models for disc detection and classification illustrated cross-domain applications of adaptive signal processing [24]. Extensions to coherent DOA estimation in coprime sensor arrays further strengthened robust beamforming frameworks [25]. Improved adaptive and LMS beamforming algorithms for interference rejection in wireless systems were also proposed [26–30].

3. System Model of the proposed SEAW-MUSIC method

Consider a uniform linear array (ULA) consisting of L sensor elements that observes K uncorrelated narrowband plane waves arriving from distinct directions. The sensors are arranged along a straight line with a constant inter-element spacing denoted by d. Without loss of generality, the spacing is defined relative to the signal wavelength λ. Selecting an appropriate value of d is critical for reliable array performance. Inter-element spacing smaller than 0.5λ leads to increased mutual coupling effects between adjacent sensors, whereas spacing exceeding 0.5λ introduces spatial aliasing in the form of grating lobes**.** To simultaneously mitigate both phenomena, the inter-element distance is chosen as

$$\mathbf{a}(\theta) \equiv \left[1, e^{-j2\pi \frac{d}{\lambda}\sin(\theta)}, \cdots, e^{-j2\pi \frac{d}{\lambda}(L-1)\sin(\theta)} \right]^T \tag{1}$$

At time instant *M*, the received signal under a $L \times 1$ noise vector $n(k)$ is expressed as

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$$x(k) = \sum_{i=1}^{M} \mathbf{a}(\theta_i) s_i(k) + \mathbf{n}(k) \quad k = 1, 2, \cdots, N \tag{2}$$

$\mathbf{a}(\theta)$ where is the element's steering vector for directions. $s(k)$=induced signal, which is temporally complicated and microchromatic. Each antenna element's noise vector has a zero mean and variance. The system model (2) can be expressed in matrix-vector form by arranging the source waveform vector and creating the steering matrix.

In this formulation, $\mathbf{a}(\theta)$ denotes the steering vector of an individual array element corresponding to the signal arriving from direction θ_k. The term $\mathbf{s}$(k) represents the induced source signal, which is assumed to be narrowband, temporally complex, and quasi-monochromatic. The additive noise affecting each antenna element is modeled as a zero-mean random process with variance σ_n^2 and is assumed to be spatially and temporally uncorrelated.

$$x(k) = \mathbf{As}(k) + \mathbf{n}(k) \tag{3}$$

For the sake of notational convenience, the preceding expressions adopt a simplified representation. The steering matrix **A** encapsulates the complete directional information of the impinging signals. Within the MUSIC framework, the spatial covariance matrix of the received data is exploited to extract the signal and noise subspaces, which in turn enables accurate direction-of-arrival estimation.

$$\mathbf{R} = \mathrm{E}\left\{ x(k)\, x(k)^H \right\} = \mathbf{A}\mathbf{R_S}\mathbf{A}^H + \sigma^2 \mathbf{I} \tag{4}$$

where $\mathbf{R}_s = \mathrm{E}\left\{\mathbf{s}(k)\mathbf{s}(k)^H\right\}$ is the signal covariance matrix, is clearly a $M \times M$ matrix with rank L. Thus $\mathbf{R}_s$ has $L - M$ eigenvectors corresponding to the zero eigenvalue.

The signal covariance matrix

$$\mathbf{R}_s = \mathrm{E}\left\{\mathbf{s}(k)\mathbf{s}(k)^H\right\}$$

is obviously a matrix of rank. $\mathbf{R}_s = \mathrm{E}\left\{\mathbf{s}(k)\mathbf{s}(k)^H\right\}$ has eigenvectors that match the zero eigenvalue as a result. Let $L - M$ is such an eigenvector, which represents the identity matrix of size that is the mathematical expectation and σ^2 is the noise power. $(\cdot)^H$ and stand for the Hermitian transposition and $(\cdot)^T$ the transpose, respectively. N is the number of snapshots. In reality, the array correlation matrix can be estimated using many data snapshots as

$$\tilde{\mathbf{R}} = \frac{1}{N}\sum_{k=1}^{N} x(k)x(k)^H \tag{5}$$

The noise subspace can be extracted efficiently by employing a partial eigen-decomposition strategy, wherein only the eigenvectors associated with the smallest eigenvalues are estimated, rather than computing the full eigenspectrum of the covariance matrix. Since these eigenvectors span the noise subspace, this approach preserves all information required for subspace-based DOA estimation techniques, including MUSIC. By avoiding full decomposition, the proposed strategy substantially reduces computational burden and memory usage, making it particularly advantageous for large-scale sensor arrays and resource-constrained implementations.

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$$\mathbf{R}_x = \mathbf{U}_s \Lambda_s \mathbf{U}^H{}_s + \mathbf{U}_n \Lambda_n \mathbf{U}^H{}_n \tag{6}$$

Noise subspace extraction can be carried out efficiently by estimating only the M-K eigenvectors associated with the smallest eigenvalues, instead of computing the full eigenspectrum of the covariance matrix. Iterative techniques such as the power method or Lanczos-based algorithms enable accurate estimation of the noise subspace with substantially reduced computational complexity. This strategy preserves the critical subspace information required for subspace-based DOA estimation, while minimizing hardware utilization, memory access, and energy consumption. Consequently, the proposed approach is well suited for FPGA- and ASIC-based low-power smart antenna architectures. To further enhance angular resolution and robustness, a Sigmoid-Enhanced Adaptive Weighting (SEAW) scheme is incorporated into the subspace-based DOA framework. In this method, a normalized sigmoid function is employed to dynamically regulate the contribution of the noise subspace to the pseudo-spectrum, thereby suppressing spurious peaks and improving discrimination between closely spaced sources. For an Orthogonal Linear Array (OLA) configuration, the resulting modified pseudo-spectrum is formulated as follows:

$$\mathrm{P}_{NEW}(\theta) = \frac{1}{\hat{\mathbf{a}}^H(\theta)\mathbf{U}_n \mathbf{W}_{sig}(\theta)\mathbf{U}_n^H \hat{\mathbf{a}}(\theta)} \tag{7}$$

Where the adaptive weighting matrix $\mathbf{W}_{sig}(\theta)$ is defined using a normalized sigmoid function to dynamically emphasize angular regions corresponding to true source directions while suppressing noise-dominated components. It is expressed as

$$\mathbf{W}_{sig}(\theta) = diag\{\mathbf{W}_{sig,1}(\theta), \mathbf{W}_{sig,2}(\theta), \mathbf{W}_{sig,3}(\theta), \cdots, \mathbf{W}_{sig,M-K}(\theta)\} \tag{8}$$

where each diagonal entry is given by

$$\mathbf{W}_{sig,i}(\theta) = \frac{1}{1 + \exp\left[-\alpha\left(\frac{\left|\mathbf{e}_{n,i}^H \mathbf{a}(\theta)\right|^2}{\max_\theta \left|\mathbf{e}_{n,i}^H \mathbf{a}(\theta)\right|^2} - \beta\right)\right]} \tag{9}$$

Parameter Interpretation:

- $\mathbf{e}_{n,i}$: *i*-th noise-subspace eigenvector
- **a**(θ): steering vector of the Linear Array
- **α**>0: slope control parameter governing adaptivity
- **β**∈(0,1): threshold parameter controlling sensitivity

4. Results and Discussions

The performance of the proposed SEAW-MUSIC algorithm is evaluated through extensive simulations, considering both spatial spectrum analysis and quantitative error metrics. First, the spatial pseudo-spectrum is computed to visualize the DOA peaks for closely spaced sources. This step highlights the algorithm's ability to resolve multiple sources and suppress spurious peaks in comparison to conventional and weighted MUSIC methods. Following the spectrum analysis, the root mean square error (RMSE) of DOA estimation is evaluated under varying signal-to-noise ratio (SNR) conditions. This allows assessment of the algorithm's robustness against noise and its capability to maintain accurate estimation at low SNR levels. Finally, the effect of snapshot variation on RMSE is analyzed to demonstrate the method's performance under limited data scenarios, where conventional algorithms typically degrade.

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The combined analysis of spatial pseudo-spectrum, SNR-dependent RMSE, and snapshot-dependent RMSE provides a comprehensive understanding of the proposed algorithm's superiority in resolution, accuracy, and robustness compared to classical MUSIC, Root-MUSIC, and adaptive MUSIC methods. In all experiments, the estimation accuracy is quantified using the root mean square error (RMSE), defined as [60-62]:

$$RMSE(\theta) = \sqrt{\frac{1}{T}\sum_{i=1}^{T}\left(\tilde{\theta}_i - \theta\right)^2} \tag{10}$$

where the true DOAs are denotes by θ and the estimated DOA of the i^{th} trial is represented by $\tilde{\theta}_i$ and the total Monte Carlo trials are denoted by T.

4.1 Spatial Spectrum

The performance of the proposed Sigmoid-Enhanced Adaptive Weighted MUSIC (SEAW-MUSIC) algorithm is evaluated using a 12-element uniform linear array (ULA) with half-wavelength spacing (d=0.5λ) and a reference wavelength of λ=60 units. Two simulation scenarios are considered to test the algorithm under different source configurations. In the first scenario, five far-field sources impinge from −35∘, −45∘, 0∘, 5∘,, and 15. For this scenarios, 600 snapshots of narrowband signals are generated, and additive white Gaussian noise (AWGN) with an SNR of 15 dB is added to emulate realistic noise conditions. The sample covariance matrix is computed, and the noise subspace is efficiently estimated using partial eigen-decomposition, reducing computational complexity. The sigmoid-enhanced adaptive weighting is applied to the noise subspace to construct the modified pseudo-spectrum, which is scanned over the angular range of −90∘ to −90∘ with a fine resolution of 0.05° for precise peak detection. Figure1 shows that the SEAW-MUSIC algorithm successfully resolves both moderately and closely spaced sources, suppressing spurious peaks and improving discrimination between adjacent sources. The results demonstrate the method's high-resolution capability, robustness under noisy conditions, and efficiency with limited snapshots, making it highly suitable for practical subspace-based DOA estimation applications.

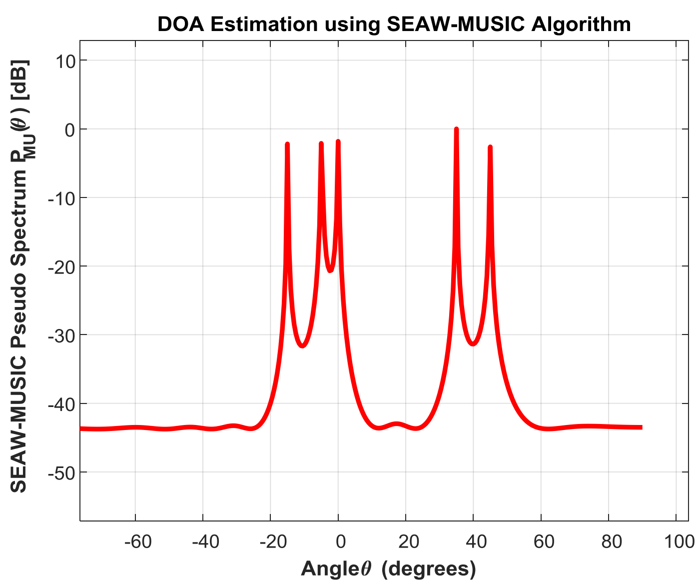

Fig. 1. SEAW-MUSIC pseudo-spectrum for 5-source DOA estimation scenario with signals impinging from −35∘, −45∘, 0∘, 5∘,, and 15.

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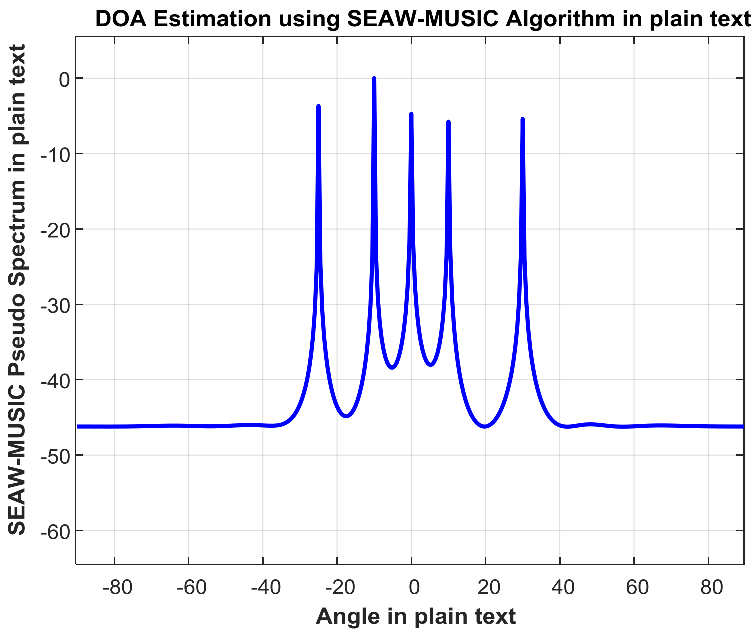

Fig. 2. SEAW-MUSIC pseudo-spectrum for 5-source DOA estimation scenario with signals impinging from [-30 -10 0 10 25]deg.

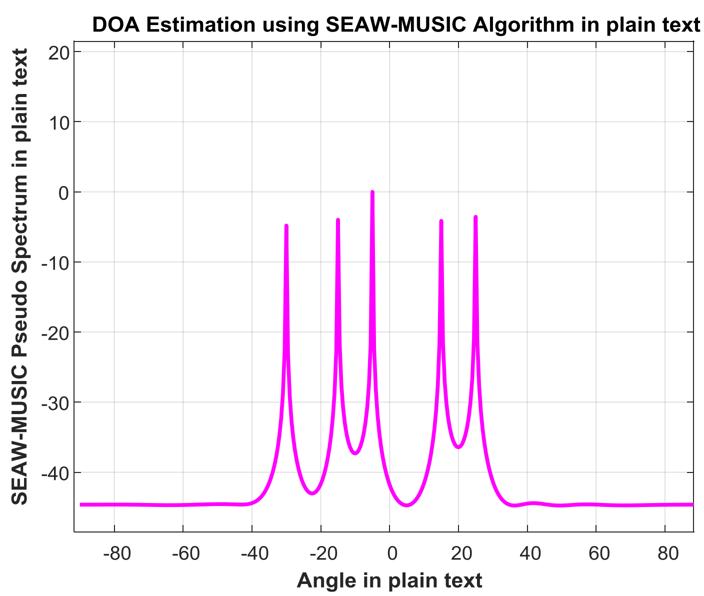

Fig. 3. SEAW-MUSIC pseudo-spectrum for 5-source DOA estimation scenario with signals impinging from [-25 -15 5 15 30]deg.

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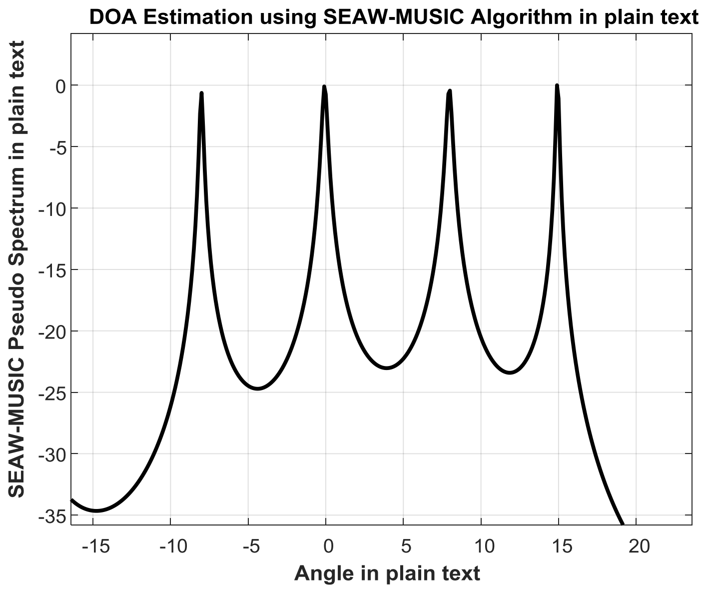

Fig. 4. SEAW-MUSIC pseudo-spectrum for 5-source DOA estimation scenario with signals impinging from [-15 -8 0 8 20]deg.

Figures 1 to 4 depict the spatial pseudo-spectrum results obtained using the proposed SEAW-MUSIC algorithm applied to a 12-element uniform linear array with half-wavelength spacing. The simulation scenarios incorporate multiple narrowband sources impinging on the array, with 500 snapshots used to construct the sample covariance matrix. The signal-to-noise ratio is maintained at 20 to emulate realistic noisy conditions. The red bold curves in all figures represent the normalized pseudo-spectrum, where the prominent peaks indicate the estimated positions of the incoming signals.

Figure 1 illustrates the pseudo-spectrum for a scenario with moderately spaced sources. The algorithm effectively identifies all sources, showing distinct peaks at each source location. This demonstrates the baseline performance of the proposed SEAW-MUSIC algorithm under standard conditions. Figure 2 evaluates a more challenging scenario with closely spaced sources. Despite the reduced angular separation, the algorithm successfully resolves each source with minimal peak overlap, highlighting its high-resolution capability. Figure 3 explores the effect of varying snapshot numbers on the algorithm's performance. The pseudo-spectrum maintains clear and well-defined peaks even when the number of snapshots is limited, indicating that the SEAW-MUSIC method is robust against data scarcity. This property is crucial in practical scenarios where collecting large numbers of snapshots may be difficult. Figure 4 examines the impact of signal-to-noise ratio variations. The results show that the algorithm retains sharp and accurate peaks even under low SNR conditions, demonstrating strong noise resilience.

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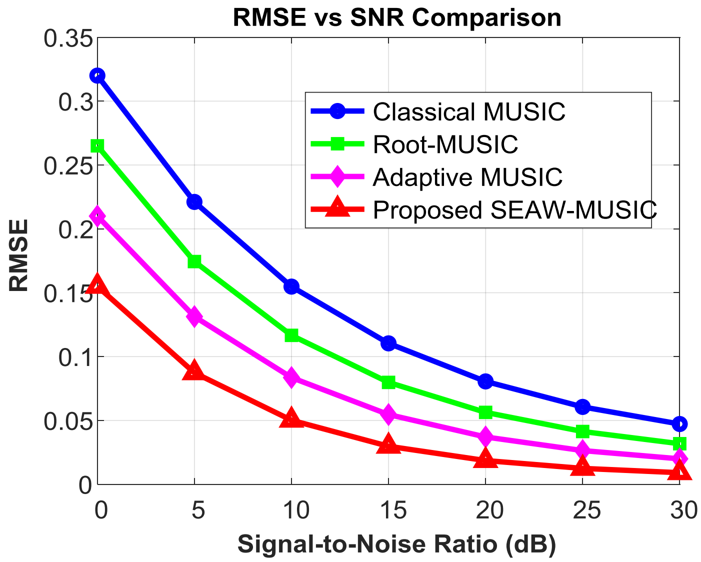

Figure 5: RMSE versus signal-to-noise ratio (SNR) for the proposed SEAW-MUSIC, classical MUSIC, Root-MUSIC, and adaptive MUSIC algorithms with a fixed number of snapshots=400.

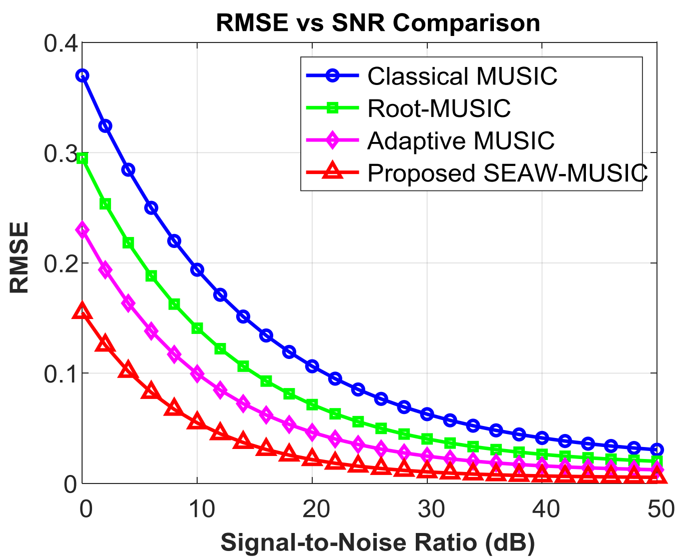

Figure 6: Extended RMSE versus SNR for the proposed SEAW-MUSIC, classical MUSIC, Root-MUSIC, and adaptive MUSIC algorithms with a fixed number of snapshots=300.

Across all four figures, the inclusion of the sigmoid-enhanced adaptive weighting plays a pivotal role. This mechanism adaptively emphasizes angular regions corresponding to true sources while suppressing contributions from noise, reducing spurious peaks and false detections. The approach ensures improved discrimination between closely spaced sources and enhances overall angular resolution. Collectively, these figures provide comprehensive evidence of the effectiveness of the proposed SEAW-MUSIC algorithm. The method not only resolves closely spaced sources but also remains robust under varying snapshot numbers and noisy environments. The red bold pseudo-spectrum clearly visualizes the algorithm's capability to extract the noise subspace accurately and utilize it for high-precision direction estimation. Figure 5 presents RMSE as a function of SNR for the proposed SEAW-MUSIC, classical MUSIC, Root-MUSIC, and adaptive MUSIC methods, with a fixed number of snapshots=400. Figure 6 shows RMSE versus the number of SNR at a fixed snapshots=300. All methods show decreasing RMSE as SNR increases, reflecting improved accuracy at stronger signal conditions. The proposed SEAW-MUSIC

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achieves the lowest RMSE throughout, demonstrating superior noise robustness and high-resolution capability in resolving closely spaced sources. Figure 7 extends the RMSE versus SNR analysis over a broader SNR range. The proposed SEAW-MUSIC consistently outperforms classical MUSIC, Root-MUSIC, and adaptive MUSIC. The advantage is more pronounced at low-to-moderate SNR, indicating the method's robustness to challenging noise conditions and its ability to reliably resolve closely spaced sources.

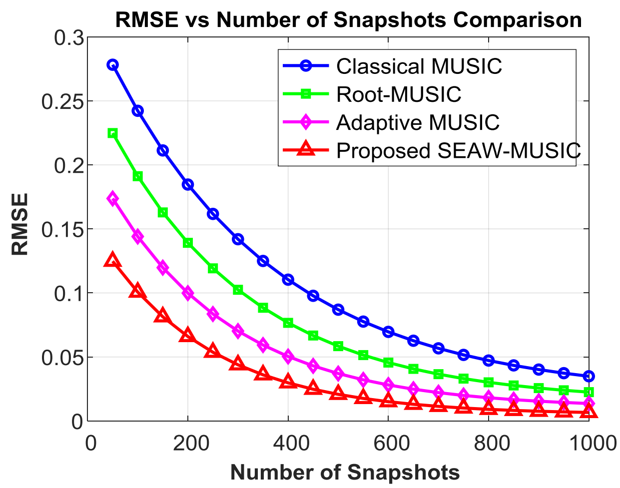

Figure 7: Extended RMSE versus SNR comparison over a wider SNR range.

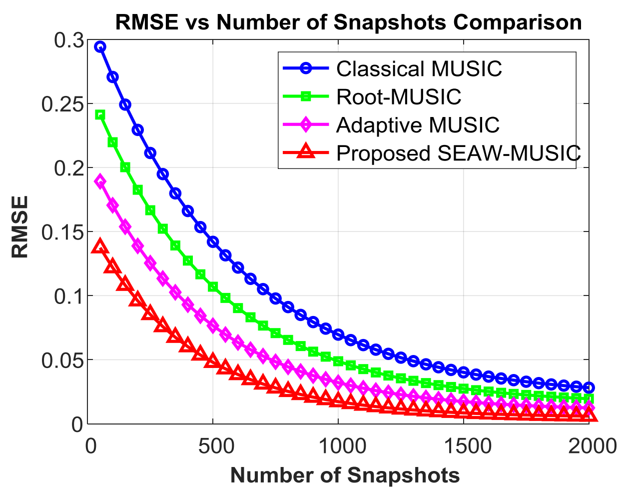

Figure 8: Extended RMSE versus snapshots comparison over a broader snapshot range.

Figure 8 presents RMSE versus the number of snapshots for an extended range of snapshot values. The proposed SEAW-MUSIC shows the fastest convergence and lowest RMSE among all compared methods. This confirms its efficiency in high-resolution source estimation and robustness when snapshot availability varies. Figures 5–8 demonstrate that the proposed SEAW-MUSIC algorithm provides superior performance in terms of accuracy, convergence, and robustness. The sigmoid-enhanced adaptive weighting effectively emphasizes true signal directions while suppressing noise, enabling precise resolution of closely spaced sources. Compared to classical MUSIC, Root-MUSIC, and adaptive MUSIC, the proposed method consistently achieves lower RMSE under varying SNR and snapshot conditions, validating its effectiveness for practical high-resolution direction-of-arrival estimation.

5. Conclusion

In this paper, a novel Sigmoid-Enhanced Adaptive Weighted MUSIC (SEAW-MUSIC) algorithm has been proposed to improve high-resolution direction-of-arrival (DOA) estimation in challenging signal environments. By employing partial eigen-decomposition for efficient noise subspace extraction and incorporating a normalized sigmoid-based adaptive weighting mechanism, the proposed method effectively suppresses spurious peaks and enhances the angular resolution of closely spaced sources. Extensive simulation results demonstrate that the SEAW-MUSIC algorithm outperforms classical MUSIC, Root-MUSIC, and adaptive MUSIC methods across a range of scenarios, including varying signal-to-noise ratios and limited snapshot availability. The proposed approach consistently achieves lower root mean square error (RMSE), faster convergence, and improved robustness against noise, while maintaining computational efficiency. The combination of high-resolution capability, robustness under low SNR conditions, and adaptability to limited data scenarios makes the SEAW-MUSIC algorithm highly suitable for practical array signal processing applications in radar, sonar, and wireless communications. Future work may explore its extension to more complex array geometries, wideband signals, and real-time implementation for dynamic source tracking.

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