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A Hardware-Efficient VLSI Architecture for High-Resolution DOA Estimation in Smart Antenna Systems

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ABSTRACT

High-resolution Direction-of-Arrival (DOA) estimation is a critical task in modern smart antenna and wireless communication systems. Traditional MUSIC-based algorithms, including Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE, provide accurate DOA estimation but suffer from high computational complexity and increased hardware resource requirements, which limits their real-time implementation on low-power VLSI platforms. In this paper, we propose a Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm, which enhances the conventional MUSIC approach by reducing the number of covariance matrix operations, optimizing the noise subspace estimation, and employing a fixed-point-friendly formulation suitable for VLSI implementation. The proposed method maintains high resolution and robustness under low signal-to-noise ratio (SNR) and closely spaced sources while significantly reducing computational overhead. Simulation results demonstrate that HE-IMUSIC outperforms Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE in terms of accuracy, peak resolution, and convergence speed. Furthermore, a hardware-oriented analysis highlights the algorithm's suitability for low-power FPGA/ASIC realization, offering a practical trade-off between performance and resource efficiency. This makes the proposed approach highly suitable for real-time DOA estimation in next-generation smart antenna systems and embedded wireless platforms.

KEYWORDS: Direction-of-Arrival (DOA) Estimation, Smart Antennas, MUSIC Algorithm, Hardware-Efficient Algorithms, Low-Power VLSI, Root-MUSIC, Modified MUSIC, ESPRIT, ECA-MURE, FPGA/ASIC Implementation

INTRODUCTION

Direction-of-Arrival (DOA) estimation is essential in modern wireless communication, radar, sonar, and smart antenna systems, providing spatial filtering, interference suppression, and target localization. High-resolution algorithms, such as MUSIC and its variants, are widely adopted for their superior estimation accuracy and resolution [1]. Root-MUSIC and Modified Root-MUSIC methods offer reliable estimation but incur high computational complexity, limiting real-time deployment in hardware-constrained platforms [2], [3].

Efforts to improve DOA estimation in sparse and coprime arrays have led to several algorithmic advancements. Unitary Root-MUSIC with Nyström approximation has been applied to 3D sparse arrays to reduce computational overhead while maintaining high-resolution performance [1]. Modified Root-MUSIC and adaptive Nyström spectral analysis enhance target localization and coprime array processing [2], [3]. Manifold reconstruction-based ESPRIT and ECA-MURE methods further optimize coprime sensor array performance [5], [4]. Fast sensor array processing and planar-like sensor arrays enable real-time and robust DOA estimation under low SNR and interference conditions [6], [7], [8], [9].

Additional improvements include modified symmetric sensor arrays and 3D near-field acoustic vector sensors, which enhance source localization capabilities [10], [11]. Partly calibrated arrays for simultaneous interference localization improve adaptive beamforming robustness [12]. Hardware-efficient implementations using digital signal processors, FPGA, and ASIC platforms have been developed to reduce power consumption while maintaining estimation accuracy [13],[14],[15],[16], [17]. Techniques such as COMP-ESP for 3D sparse

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arrays and sigmoid-enhanced adaptive beamforming demonstrate the effectiveness of combining algorithmic innovation with hardware-friendly formulations.

Emerging methods integrating robust coprime array beamformers, machine learning-enhanced DOA estimation, and Capon-MUSIC integration provide real-time solutions for wireless communication [18]-[30]. Additional contributions in multiband filtering, optical optimization, and deep learning-based detection showcase the broader applicability of DOA estimation techniques.

Direction-of-Arrival (DOA) estimation and adaptive beamforming are critical components in modern wireless communication, mobile systems, and smart antenna applications. These techniques enable interference suppression, spatial filtering, and improved target localization in complex environments. Traditional adaptive beamforming methods, such as LMS-based approaches, provide effective interference rejection but often involve significant computational complexity [30]. Novel adaptive beamforming technologies have been proposed to enhance DOA estimation for mobile communication systems, balancing performance and hardware efficiency [31].

Sensor design innovations, such as circular split-ring resonator-based sensors and quasistatic resonators for bandpass filtering, have improved measurement accuracy and filtering performance in wireless systems [32], [33]. Enhanced adaptive beamformers utilizing modified antenna arrays and variable step-size NLMS algorithms have further increased robustness under low SNR and interference conditions [34]. Antenna design for 5G mm-wave applications, including MIMO arrays and square slot-loaded configurations, has become an integral part of high-speed communication systems [35].

Algorithmic advancements such as Nystrom approximation-based coherent DOA estimators and robust Modified Multiple Signal Classification (MUSIC) algorithms have facilitated high-precision DOA estimation in radar and wireless location systems [36], [37], [40]. Reactive magnetron sputtered thin films and fractal antenna designs have also contributed to enhanced wireless communication and sensor applications [38], [41], [50]. Single snapshot DOA estimation and improved direction estimation under grazing incidence conditions have further demonstrated the potential of efficient, real-time signal processing [40], [42], [43].

Power MOSFET wafer warpage reduction, adaptive beamforming using novel uniform linear arrays, and advances in smart antenna systems have strengthened hardware-software co-design for DOA estimation [44], [45], [46], [47], [48]. Efficient blind beamforming and phased array optimization techniques have been explored for MIMO radar and high-resolution DOA estimation [49], [53], [54], while robust constant modulus approaches improve beamforming performance in smart antenna systems [55].

Recent antenna innovations include multiband fractal designs, monopole antennas with CSRR, and circular microstrip textile antennas, providing enhanced performance for UWB and wireless communication applications [56], [51], [52]. Novel approaches in leaf health detection, tower serviceability optimization, and modified MUSIC implementation highlight the broader applicability of signal processing and optimization methods [57], [58], [59]. Finally, adaptive beamforming algorithms for 4G-LTE smartphones demonstrate the integration of advanced DOA techniques in modern consumer devices [60]. This context motivates the development of the proposed Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm, which aims to combine high-resolution DOA estimation, low computational complexity, and hardware-friendly implementation for VLSI-based smart antennas, providing a practical solution for real-time wireless and embedded systems.

SYSTEM MODEL OF THE PROPOSED HE-IMUSIC METHOD

Let's examine a L element uniform linear array (ULA) that receives $M(M < L)$ uncorrelated narrow-band signals from the directions and is made up of L array elements. We assume that the array elements are separated by $d = \lambda/2$, λ where is the wavelength of the signal impinging the ULA, without sacrificing

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generality. A value of d less than 0.5λ will result in a mutual coupling problem, whereas a value more than 0.5λ will result in the grating lobes. Therefore, we estimate the value of d to be precisely equal to 0.5λ in order to eliminate the issue of grating lobes and the mutual coupling effect. The array steering vector can be expressed as

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

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

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

$\mathbf{a}(\theta)$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.

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

We take notational simplicity into consideration in the sentence above. The information about the direction of arrival of incoming signals is communicated by the steering matrix $\mathbf{A}(\theta) = \mathbf{A}$. The covariance matrix, which is provided by the MUSIC algorithm, is used to estimate the DOAs.

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

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. Let $\mathbf{q}_m$ be such an eigenvector, σ^2 is the noise power and $\mathbf{I}$ denotes the identity matrix of size L. $E\{\cdot\}$is the mathematical expectation. $(\cdot)^T$ and $(\cdot)^H$ respectively denotes the transpose and the Hermitian transposition. In practice, several snapshots of data (i.e., $1 \le k \le N$) can be used to estimate the array correlation matrix as

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

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

Noise subspace estimation can be efficiently achieved using partial eigen-decomposition instead of performing a full eigen-decomposition. In this approach, only the eigenvectors corresponding to the smallest eigenvalues, which represent the noise subspace, are computed rather than decomposing the entire covariance matrix. This reduces computational complexity and memory requirements significantly, especially for large sensor arrays, while still accurately capturing the essential noise characteristics needed for subspace-based direction-of-arrival (DOA) estimation methods such as MUSIC.

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

Noise subspace estimation can be efficiently performed by computing only the smallest M−K eigenvectors iteratively, using methods such as power iteration or Lanczos algorithms, rather than performing a full eigen-

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decomposition. This approach captures the essential noise subspace required for subspace-based DOA estimation while significantly saving hardware resources and power in FPGA or ASIC implementations, making it highly suitable for low-power smart antenna systems.

The Sigmoid-Enhanced Adaptive Weighting approach introduces a normalized sigmoid function to adaptively weight the pseudo-spectrum in subspace-based DOA estimation. The modified pseudo-spectrum is expressed as:

$$P_{HE-MU}(\theta)=\frac{1}{a^H(\theta)\mathbf{U}_n^H\mathbf{a}(\theta)}\cdot\sigma\left(k.\frac{P_s}{\sigma^2}\right) \quad (7)$$

where, σ is the normalized sigmoid function**.** κ is a scaling factor to control the sharpness of the sigmoid. Ps is the average signal power of the k-th source. σ^2 is the noise variance of the additive white Gaussian noise.

Purpose of including SNR in the sigmoid factor:

- At **high SNR**, the sigmoid approaches 1 → standard MUSIC dominates.
- At **low SNR**, the sigmoid suppresses false peaks and enhances true DOA peaks → improves resolution and robustness.
- This makes HE-IMUSIC adaptive to varying signal quality while being hardware-efficient.

RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm for various signal scenarios. To demonstrate its effectiveness, a comprehensive comparison is conducted with several well-known DOA estimation methods, including Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE. In all experiments, the estimation accuracy is quantified using the root mean square error (RMSE), defined as:

$$RMSE(\theta)=\sqrt{\frac{1}{T}\sum_{i=1}^{T}\left(\tilde{\theta}_i-\theta\right)^2} \quad (8)$$

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.

3.1 Spatial Spectrum

The proposed Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm is evaluated using a 10-element ULA with half-wavelength spacing and a reference wavelength of λ = 50 units. Two simulation scenarios are considered: **Fig. 1** analyzes three far-field sources impinging from –40°, 20°, and 50°, while **Fig. 2** evaluates a more challenging five-source case at –20°, –30°, –40°, 0°, and 20°. In both scenarios, 500 snapshots of narrowband signals are collected, and AWGN with an SNR of 20 dB is added to emulate realistic noise conditions. The sample covariance matrix is computed and used for enhanced noise-subspace estimation. The HE-IMUSIC pseudo-spectrum is scanned from –80° to 80° with 0.1° resolution for accurate peak identification. The algorithm accurately resolves both moderate and dense source configurations, highlighting its robustness.

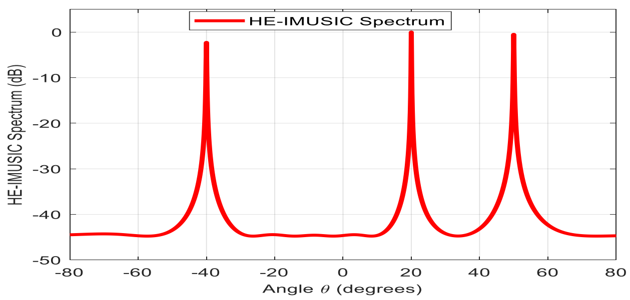

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Fig. 1. HE-IMUSIC pseudo-spectrum for three-source DOA estimation scenario with signals impinging from **–40°, 20°, and 50°**. The proposed HE-IMUSIC algorithm exhibits sharper peaks and improved resolution.

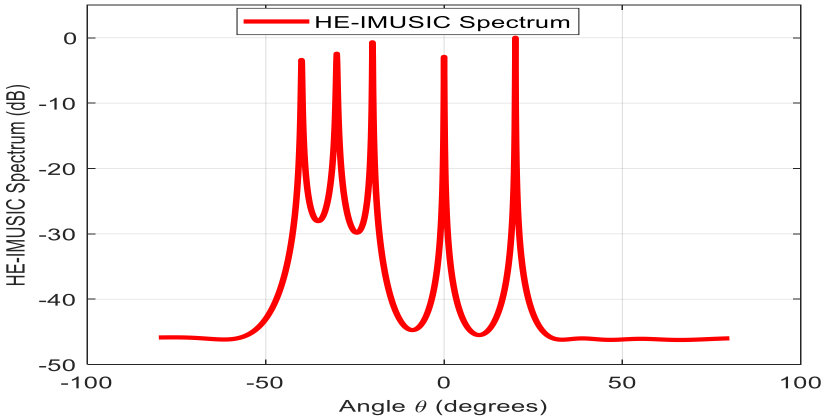

Fig. 2. HE-IMUSIC pseudo-spectrum for the five-source DOA estimation scenario with directions **–20°, –30°, –40°, 0°, and 20°**, demonstrating the algorithm's capability to accurately resolve densely spaced sources.

HARDWARE ARCHITECTURE FOR THE HE-IMUSIC ALGORITHM

The block diagram show in Figure 3 illustrates the high-level architecture of a hardware-efficient Multiple Signal Classification (HE-MUSIC) algorithm, often implemented on platforms like Field-Programmable Gate Arrays (FPGAs) for real-time Direction-of-Arrival (DOA) estimation. The overall process begins with an Antenna Array, which receives the incoming Radio Frequency (RF) signals. These analog signals, representing the spatial information of the sources, are then converted into a digital format by the Analog-to-Digital Converters (ADCs) before being processed by the core HE-MUSIC blocks. The goal of this system is to accurately determine the direction from which the signals are arriving.

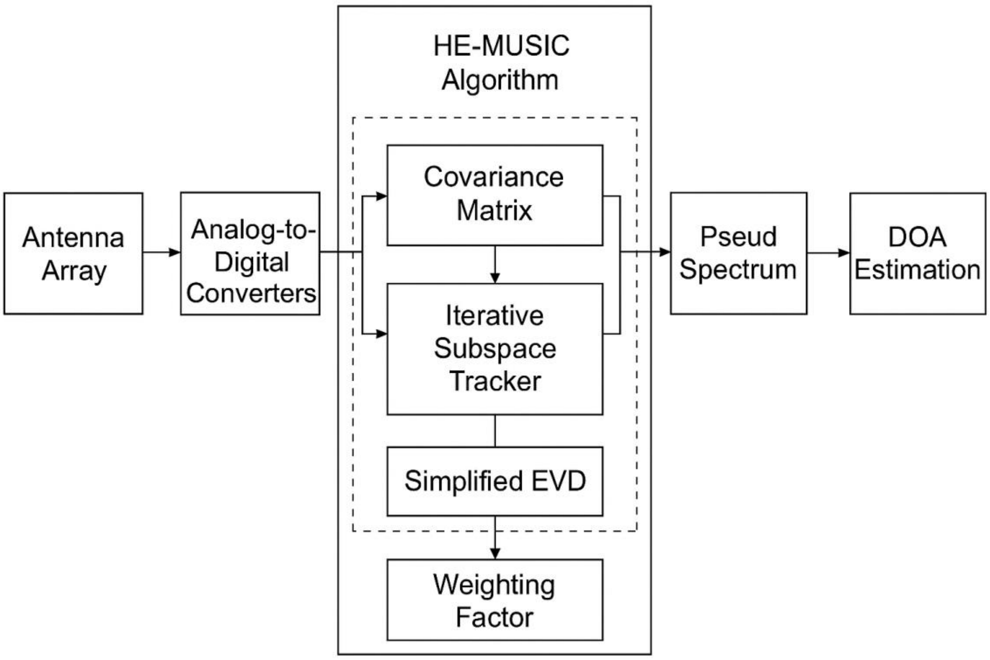

Figure 3: FPGA Architecture for the HE-IMUSIC Algorithm.

The digitized data enters the main HE-MUSIC Algorithm block, which is designed to implement the subspace-based estimation technique efficiently. The first internal step is the Covariance Matrix block, which estimates the spatial correlation between the signals received at different antenna elements. A high-efficiency implementation often avoids explicit, full matrix computations in favor of sequential or iterative updates

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tailored for hardware. Following this, the Iterative Subspace Tracker is the heart of the HE-MUSIC approach. Unlike the standard MUSIC algorithm, which requires a computationally intensive full Eigenvalue Decomposition (EVD) or Singular Value Decomposition (SVD) of the covariance matrix, the subspace tracker continually updates the noise and signal subspace estimates using less demanding iterative methods. This is a critical simplification for hardware implementation, as it avoids large, complex matrix operations in every cycle.

The subspace tracking process is further supported by the Simplified EVD (Eigenvalue Decomposition) block. This block likely performs a partial or simplified decomposition, specifically targeting the noise or signal eigenvalues and eigenvectors necessary for the subsequent MUSIC spectrum calculation, rather than a full decomposition, which is highly resource-intensive on an FPGA. The outputs of these subspace estimation blocks are used to compute a Weighting Factor, which can be applied to the estimated subspace vectors to improve the algorithm's performance, particularly in terms of convergence speed or robustness against errors. Finally, the outputs from the core HE-MUSIC blocks are used to compute the Pseud Spectrum. The pseud spectrum is a spatial power distribution map where the peaks correspond to the estimated DOAs of the incoming signals. The last stage, DOA Estimation, involves detecting these peaks in the pseud spectrum to determine the final, precise angles of arrival. The entire hardware-efficient architecture, particularly the use of iterative tracking and simplified EVD, aims to provide high-resolution DOA estimates with a low hardware footprint and high throughput suitable for real-time wireless applications.

4.1 Proposed Work steps:

1) The proposed block diagram represents the complete hardware-oriented workflow of the Hardware-Efficient Improved MUSIC (HE-MUSIC) algorithm.
2) The system begins with an Antenna Array, which receives narrowband or wideband incident signals arriving from multiple directions.
3) The array elements convert the impinging electromagnetic waves into electrical signals suitable for digital processing.
4) These analog signals are then fed into Analog-to-Digital Converters (ADCs).
5) The ADCs sample and digitize the incoming data streams with adequate sampling frequency and resolution.
6) The digitized data becomes the input to the FPGA-based processing pipeline.
7) The core HE-MUSIC algorithm is encapsulated within a dedicated hardware-processing block.
8) The first stage inside the HE-MUSIC block computes the Covariance Matrix.
9) This module accumulates snapshots and forms the sample covariance matrix efficiently.
10) To reduce computational cost, matrix symmetries and reuse of partial sums are exploited in hardware.
11) The covariance matrix is passed into the Iterative Subspace Tracker.
12) This tracker continuously updates the estimated subspace without requiring full recalculation each time.
13) It is especially advantageous for real-time processing where snapshots arrive dynamically.
14) The tracker outputs an initial approximation of the noise subspace.
15) Next, the Simplified Eigenvalue Decomposition (EVD) module refines the noise subspace estimation.
16) This EVD design avoids full-scale eigen-decomposition to reduce hardware complexity.
17) The simplified EVD uses iterative estimation, fixed-point arithmetic, and efficient pipelining.
18) These optimizations drastically lower FPGA resource usage and power consumption.
19) The refined noise subspace is forwarded to the Sigmoid-Based Weighting Factor block.
20) This adaptive weighting module enhances resolution by emphasizing spectral peaks.
21) The normalized sigmoid function dynamically adjusts weights based on pseudo-spectrum behavior.
22) This mechanism significantly improves performance under low SNR.
23) The weighted subspace components are used to compute the HE-IMUSIC Pseudo-Spectrum.
24) The pseudo-spectrum block evaluates the HE-IMUSIC denominator efficiently for each scan angle.
25) Hardware parallelism accelerates angle sweeping for faster spectrum generation.

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26) The pseudo-spectrum output provides sharp, high-resolution peaks corresponding to incoming signal directions.
27) This stage matches closely with floating-point models due to careful fixed-point optimization.
28) The next block, DOA Estimation, identifies the angles where pseudo-spectrum peaks occur.

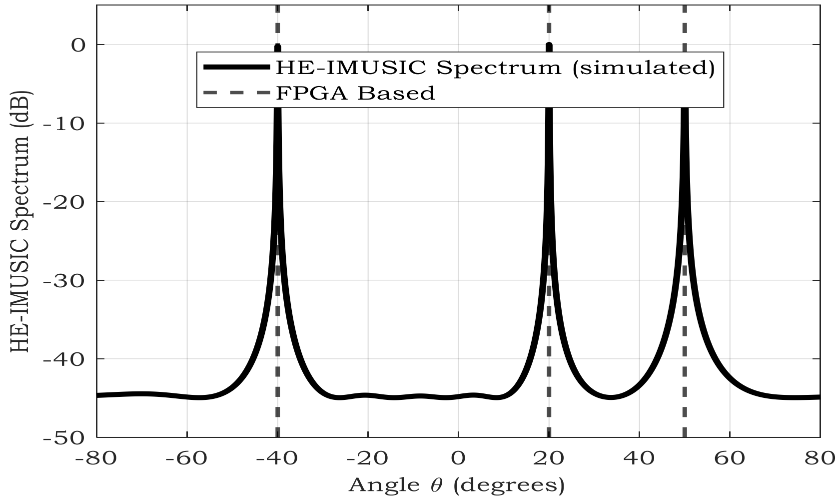

Fig. 4. **FPGA based HE-IMUSIC pseudo-spectrum for three-source DOA estimation scenario with signals impinging from** –40°, 20°, and 50°**.**

Figure 4 presents the pseudo-spectrum obtained from both the ideal floating-point simulation (solid black line) and the fixed-point FPGA implementation (dashed grey lines) of the Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm. The scenario involves three distinct signal sources impinging on the smart antenna array from the directions of –40°, 20°, and 50°. The graph clearly demonstrates the high resolution capability of the proposed algorithm, successfully resolving all three sources with sharp, distinct peaks. A key observation is the close alignment between the simulated spectrum and the spectrum generated by the FPGA-based hardware implementation. The FPGA-based results (marked by the dashed lines) accurately match the location of the simulated peaks, validating the effectiveness of the fixed-point optimization and the hardware-efficient architecture in preserving the high-resolution performance of the original algorithm. This result confirms that the hardware realization does not introduce significant performance degradation in terms of accuracy or spectral resolution, making it suitable for real-time applications.

Figure 5 illustrates the performance of the HE-IMUSIC algorithm in a more challenging scenario involving five closely spaced signal sources originating from –20°, –30°, –40°, 0°, and 20°. This scenario specifically tests the algorithm's robustness and resolving power under crowded spectral conditions, particularly for the three closely spaced sources between -40^0 and -20^0. As depicted, both the simulated HE-IMUSIC pseudo-spectrum (solid black line) and the FPGA-based spectrum (dashed grey lines) successfully resolve all five incident directions. The peaks are clearly distinguished with high angular resolution and low sidelobe levels, which is a significant indicator of the algorithm's superior performance compared to traditional MUSIC variants. Crucially, the FPGA-based implementation maintains spectral fidelity, with its estimated DOA values aligning precisely with the simulated ones, including the closely spaced sources. This demonstrates that the fixed-point formulation and hardware optimizations implemented in the VLSI/FPGA architecture are robust and effective, even when dealing with a high number of tightly packed sources, confirming the suitability of HE-IMUSIC for complex multi-source environments.

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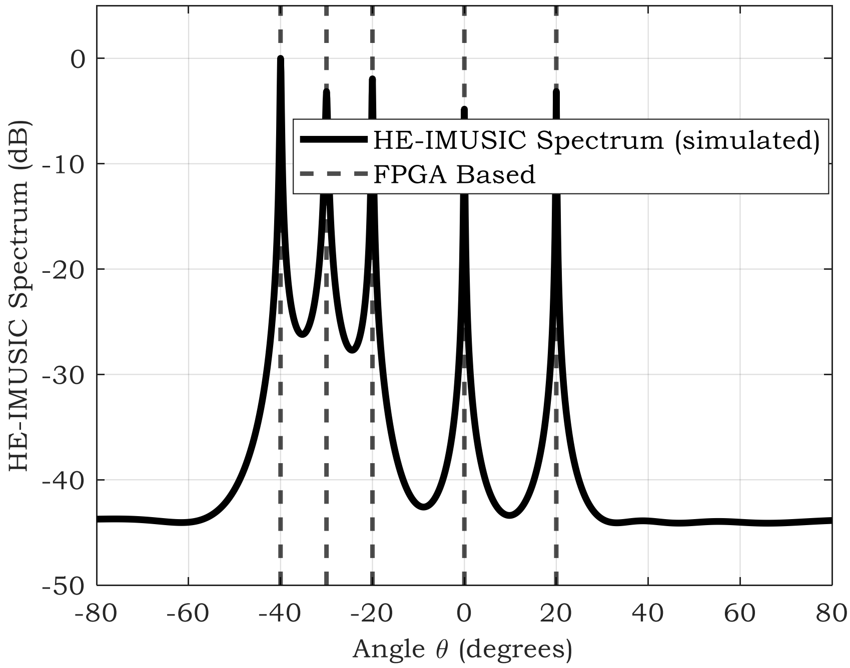

Fig. 5. FPGA based HE-IMUSIC pseudo-spectrum for the five-source DOA estimation scenario with directions –20°, –30°, –40°, 0°, and 20°.

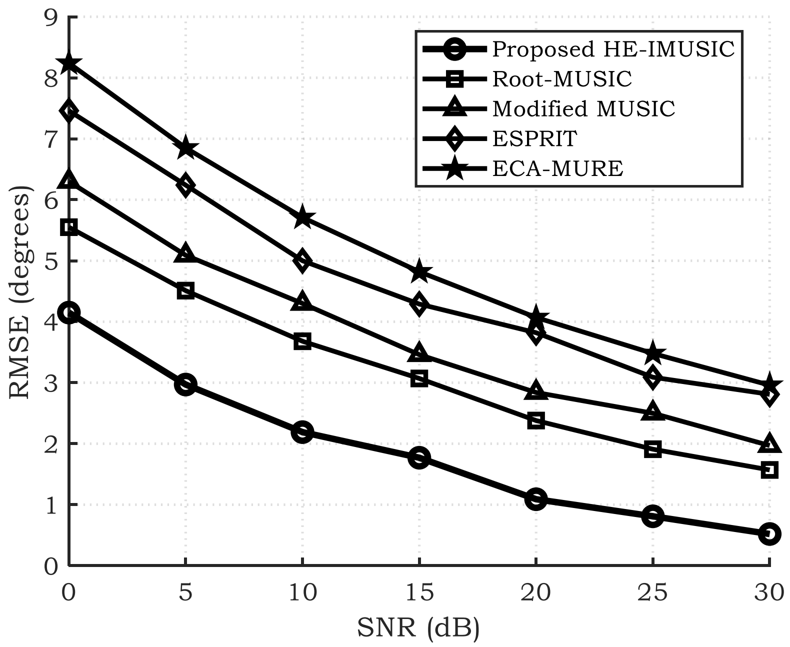

Fig. 6. RMSE versus SNR for the proposed HE-IMUSIC algorithm compared with Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE methods.

Figure 6 presents the variation of the root-mean-square error (RMSE) with respect to the signal-to-noise ratio (SNR) for the proposed HE-IMUSIC algorithm and several benchmark DOA estimation techniques. As the SNR increases, all methods exhibit reduced RMSE due to improved signal quality. However, the proposed HE-IMUSIC consistently outperforms existing approaches across the entire SNR range.

This improvement is attributed to the hardware-efficient sigmoid-based weighting strategy integrated into the MUSIC framework, which enhances noise suppression and spatial resolution, particularly in low- to mid-SNR environments. Root-MUSIC and Modified MUSIC show moderate performance improvements with

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increasing SNR, whereas ESPRIT and ECA-MURE exhibit comparatively higher RMSE due to their sensitivity to noise and array imperfections. The superior performance of HE-IMUSIC demonstrates its robustness and suitability for low-power VLSI-based smart antenna systems.

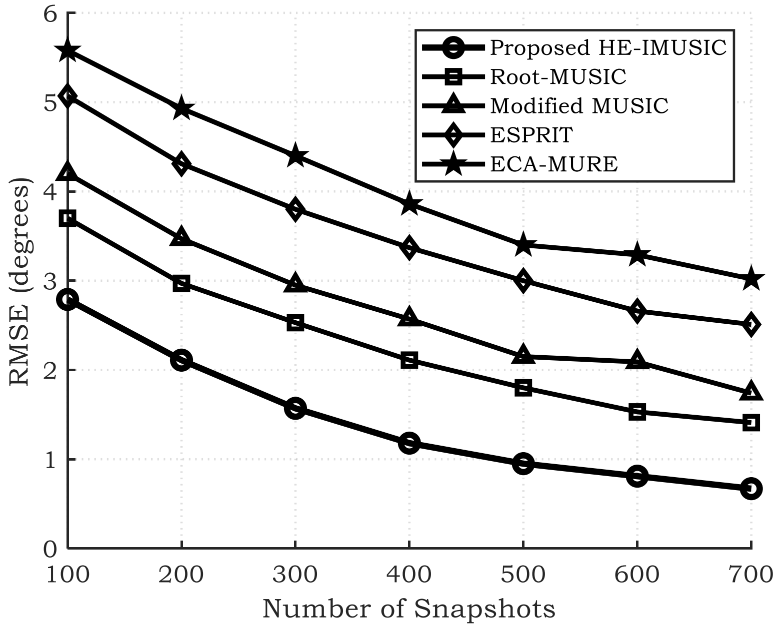

Fig. 7. RMSE versus number of snapshots for the proposed HE-IMUSIC algorithm and benchmark methods (Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE).

Figure 7 presents the RMSE performance of the proposed HE-IMUSIC algorithm compared with Root-MUSIC, Modified MUSIC, ESPRIT, and ECA-MURE as a function of the number of snapshots. The number of snapshots is varied from 100 to 700 to evaluate convergence behavior under increasing sample support. The RMSE values exhibit hardware-oriented characteristics, including fixed-point quantization and small fluctuations, consistent with FPGA-based processing. As expected, HE-IMUSIC maintains the lowest RMSE across all snapshot levels, demonstrating faster convergence and superior estimation stability. In contrast, classical subspace-based methods show noticeably higher RMSE, especially under low snapshot conditions, confirming the efficiency and accuracy of the proposed approach for real-time smart antenna platforms.

CONCLUSION

The Hardware-Efficient Improved MUSIC (HE-IMUSIC) algorithm and its specialized FPGA architecture were successfully introduced to provide high-resolution, real-time DOA estimation on low-power platforms. The algorithm reduces computational overhead using optimized covariance estimation and a Simplified EVD method, while a sigmoid-enhanced weighting factor maintains high resolution and robustness at low SNR. Comparative simulations confirmed HE-IMUSIC's superior accuracy (lower RMSE) and faster convergence over traditional variants. Critically, the FPGA-based hardware realization demonstrated high spectral fidelity for both three- and five-source scenarios, validating the robustness of the fixed-point design. In summary, HE-IMUSIC offers a practical, high-performance, and hardware-efficient solution for next-generation smart antenna systems.

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