Robust Direction-of-Arrival Estimation using improved Coprime Array for Wireless Communication Applications

K. S. Shashidhara
Department of Electronics and Communication Engineering, Nitte Meenakshi Institute of Technology, Bangalore, India
sks.nmit@gmail.com

K. N. Venu
Department of Electronics and Telecommunication Engineering, M S Ramaiah Institute of Technology, Bangalore, India
venu1.kn@msrit.edu

I. G. Saritha
Department of Electronics and Telecommunication Engineering, BMS Institute of Technology & Management, Bangalore, India
saritha.i.g@bmsit.in

Raghu Jayaramu
Department of Electronics and Communication Engineering, National Institute of Engineering, Mysuru, India
raghuj@nie.ac.in

Veerendra Dakulagi
Department of CSE (Data Science), Guru Nanak Dev Engineering College, Bidar, India
veerendra.gndec@gmail.com (corresponding author)

Received: 19 September 2024 | Revised: 7 October 2024 | Accepted: 29 November 2024

ABSTRACT

In wireless communication systems, robust and accurate Direction-of-Arrival (DOA) estimation is essential for tasks such as beamforming and interference suppression. This research presents advancements in the Multiple Signal Classification (MUSIC) algorithm leveraging enhanced coprime sensor arrays for DOA estimation. Coprime arrays, characterized by their non-uniform spacing derived from coprime integers, offer superior angular resolution compared to traditional uniform arrays. By exploiting this unique array geometry, the proposed method enhances the spatial localization capabilities of the MUSIC algorithm, thereby improving signal detection and mitigation of interference. Experimental validation demonstrates the efficacy of the approach in various signal environments, highlighting its potential to enhance the performance and reliability of wireless communication systems.

Keywords-improved MUSIC algorithm; coprime sensor arrays; direction-of-arrival estimation; wireless communication; beamforming; interference suppression; spatial signal processing; antenna array design; signal localization

I. INTRODUCTION

Wireless communication systems have evolved rapidly, driven by the increasing demand for high-speed data transmission, reliable connectivity, and efficient spectrum utilization. Central to the optimization of these systems is the ability to accurately estimate the Direction-of-Arrival (DOA) of incoming signals [1-3]. DOA estimation enables adaptive beamforming, spatial multiplexing, and interference cancellation, thereby enhancing the overall performance and reliability of wireless networks. Traditional DOA estimation techniques, such as the Multiple Signal Classification (MUSIC) algorithm, typically rely on Uniform Linear Arrays (ULAs) of equally spaced sensors [4]. While effective in many scenarios, ULAs have inherent limitations in spatial resolution, particularly in environments with closely spaced signals or strong multipath propagation. These limitations can lead to inaccuracies in signal localization and reduced performance of adaptive antenna arrays. In recent years, coprime sensor arrays have emerged as a promising alternative to ULAs for DOA estimation. Coprime arrays utilize non-uniform sensor spacing based on coprime integer pairs (M , N), where M and N are coprime integers. This unique configuration offers multiple baselines with distinct inter-element spacing, effectively increasing the array aperture and enhancing angular resolution without significantly increasing the number of elements. As a result, coprime arrays mitigate spatial aliasing and improve the discrimination of closely spaced signals, making them well-suited for applications requiring high-precision spatial localization. The motivation behind this research lies in addressing the limitations of traditional DOA estimation techniques and harnessing the advantages offered by coprime sensor arrays for enhanced performance in wireless communication applications. The primary motivations can be summarized as follows.

The increasing complexity of modern communication systems and radar applications necessitates advanced techniques for efficient and accurate signal processing [2]. Beamforming, a critical component in these systems, has traditionally relied on either blind or non-blind algorithms, each with its own set of advantages and limitations [3, 4]. Blind algorithms, like the Least Square Constant Modulus Algorithm (LS-CMA), offer the benefit of not requiring a reference signal, thereby simplifying the initial setup and enhancing robustness. On the other hand, non-blind algorithms, such as the Least Mean Square (LMS) method, excel in refining beamforming weights by minimizing the mean square error, but depend on the availability of a reference signal. Combining the strengths of these two approaches presents an opportunity to overcome their individual limitations, leading to improved performance in terms of convergence speed, robustness, and signal quality. Furthermore, the utilization of Co-Prime Sensor Arrays (CPSA) promises significant advancements in spatial resolution and sensor efficiency.

II. RELATED WORK

Author in [1] provides a comprehensive overview of smart antenna systems, emphasizing their role in modern wireless communications. The book discusses core concepts such as adaptive beamforming, spatial signal processing, and interference suppression, laying a strong foundation for subsequent research in antenna technology. Authors in [2] investigate the integration of massive Multiple Input Multiple Output (MIMO) systems with Reflected Intelligent Surfaces (RIS) to meet the capacity demands of future 6G networks. Their research highlights how RIS can effectively manipulate wireless propagation, improving signal quality and expanding system capabilities in dynamic environments. Authors in [3] propose a novel time-domain strategy for designing smart antennas that enhances system performance by focusing on efficient signal processing techniques. This method improves the adaptability of antenna systems, particularly in scenarios that require rapid adaptation to changing requirements. Author in [4] introduces the MUSIC algorithm, a groundbreaking contribution to the field of array signal processing. This high-resolution method for DOA estimation provides accurate localization of multiple emitters, which is becoming a widely adopted technique in wireless communications. Authors in [5] develop an Estimating Signal Parameter via Rotational Invariance Techniques (ESPRIT) algorithm that leverages the Nyström method for computational efficiency in DOA estimation. Their approach balances accuracy and processing speed, making it suitable for real-time applications in environments with limited computing resources. Authors in [6] explore the application of evolutionary optimization methods and the Coherently Radiating Periodic Structures (CORPS) technique to design advanced beamforming networks. Their work demonstrates how optimized antenna configurations can improve communication efficiency while reducing interference. Authors in [7] present an innovative approach to electronic beam steering in time-modulated antenna arrays. By employing a pulse-shifted switching sequence, their method achieves precise beam control and effective harmonic suppression, enabling efficient multibeam operations.

Authors in [8] extend the traditional MUSIC algorithm using the Nyström approximation to address computational challenges in DOA estimation. This enhancement retains the accuracy of the original algorithm while reducing its computational complexity, making it practical for complex scenarios. Authors in [9] propose a time-modulated multibeam steered antenna array that uses optimized switching sequences to improve beamforming efficiency. This design is particularly effective in dynamic environments requiring simultaneous multibeam operations with minimal interference. Authors in [10] provide a comprehensive review of adaptive DOA estimation methods based on time-frequency analysis. Their work focuses on resolving overlapping signal issues and achieving high-resolution parameter estimation, making these methods applicable in diverse signal processing scenarios.

Authors in [11] explore coprime sampling techniques and their application to the MUSIC algorithm, highlighting the benefits of non-uniform sensor configurations in improving spatial resolution and DOA estimation accuracy. Authors in [12] conduct a performance analysis of beam-scan, MIN-NORM, MUSIC, and Minimum Variance Distortionless Response (MVDR) DOA estimation algorithms, comparing their efficacy in differentiating closely spaced signals and mitigating noise and interference. Their study provides insight into the strengths and limitations of existing DOA estimation techniques, highlighting opportunities for improvement through algorithmic enhancements and sensor array configurations. Author in [13] introduce the lasso method for regression shrinkage and selection, offering a statistical approach to feature selection and model regularization in signal processing applications. Authors in [14] explored sparse signal recovery techniques using sparse Bayesian learning, focusing on the reconstruction of temporally correlated source vectors in noisy environments. Their research contributes to the theoretical foundations of sparse signal processing, offering insights into improving signal detection and estimation accuracy in complex wireless communication scenarios. Authors in [15] reviewed the design and optimization of self-deployable damage-tolerant composite structures, highlighting strategies for enhancing structural integrity and reliability in aerospace applications. Their work emphasizes the importance of advanced material science and Structural Health Monitoring (SHM) techniques in ensuring the longevity and performance of composite materials under varying operational conditions. Authors in [16] conducted a comprehensive review of SHM techniques for investigating damage characteristics in composite components of the aviation industry, emphasizing the integration of sensor networks and data analytics for proactive maintenance and safety assurance.

In contrast to the existing literature, this research aims to integrate the MUSIC algorithm with enhanced coprime sensor arrays to achieve robust and accurate DOA estimation in complex wireless communication environments. While previous studies have explored various aspects of adaptive signal processing, antenna array optimization, and structural health monitoring techniques, the proposed approach uniquely leverages coprime sensor arrays to enhance spatial resolution, mitigate spatial aliasing effects, and improve signal detection and interference suppression capabilities. By bridging the gap between advanced signal processing techniques and innovative antenna array designs, this research seeks to significantly advance the field of wireless communication systems and structural health monitoring, with potential applications in 5G networks, radar systems, satellite communications, aerospace engineering, and civil infrastructure monitoring.

III. SIGNAL MODEL FOR DOA ESTIMATION USING COPRIME SENSOR ARRAYS

Coprime sensor arrays offer a unique approach to enhance spatial resolution in DOA estimation. This section details the signal model used in conjunction with coprime sensor arrays. Coprime sensor arrays are made up of two sparsely spaced uniform linear sub-arrays using the coprime numbers M and N. Figure 1 illustrates that $2M$ sensors are arranged in one subarray, separated by Nd, whereas N sensors are arranged in another subarray, separated by Md [17].

The sensor spacing d is typically set to $\lambda/2$, where λ represents the signal wavelength [18]. The extended coprime array consists of $|\mathbf{S}| = 2M + N - 1$ sensors positioned according to the set $\mathbf{S}$:

$$\mathbf{S} = \{M_n \mid 0 \le n \le N-1\} \cup \{N_m \mid 0 \le m \le 2M-1\} \quad (1)$$

Consider K uncorrelated narrowband sources arriving at the array with directions $\theta = [\theta_1, \theta_2, ..., \theta_K]^T$. The array records T snapshots, represented as [19-20]:

$$\mathbf{x}(t) = \sum_{K=1}^{K} \mathbf{a}_k \mathbf{s}_k(t) + \mathbf{n}(t),\ t = 1, 2, ..., T \quad (2)$$

where $\mathbf{x}(t)$ is the received signal vector at time t, $\mathbf{a}_k$ is the steering vector for source k, $\mathbf{s}_k(t)$ is the source signal at time t, and $\mathbf{n}(t)$ represents i.i.d. zero-mean Gaussian noise.

The matrix $\mathbf{A} = [\mathbf{a}_1, \mathbf{a}_2, ..., \mathbf{a}_k]$ represents the steering matrix of the coprime sensor array, where each column $\mathbf{a}_k$ corresponds to the steering vector for source k. The covariance matrix $\mathbf{R}_S$ of the array output $\mathbf{x}(t)$ is given by [21-22]:

$$\mathbf{R}_S = E\left[x(t)x^H(t)\right] = \sum_{K=1}^{K} p_k \mathbf{a}_k \mathbf{a}_K^H + \sigma_n^2 \mathbf{I} \quad (3)$$

where p_k denotes the power of source k, and $\sigma_n^2 \mathbf{I}$ accounts for noise in the covariance matrix.

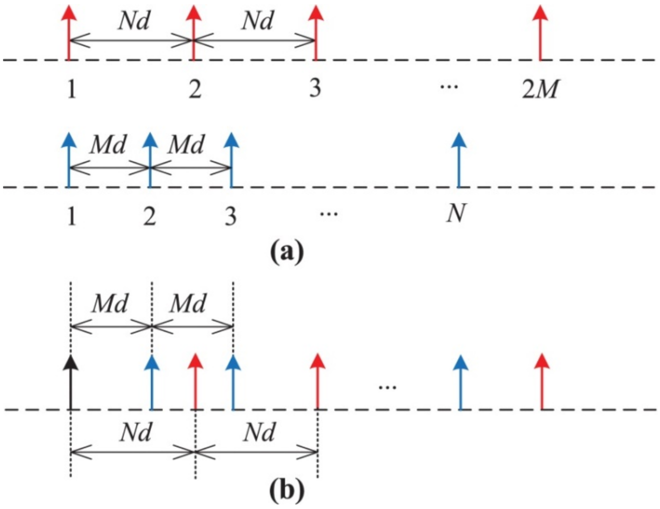

Fig. 1. Illustration of coprime sensor array structure.

IV. PROPOSED IMPROVED MUSIC ALGORITHM WITH COPRIME SENSOR ARRAYS

A popular technique for estimating Direction-of-Arrival (DOA) is the MUSIC algorithm, which makes advantage of the covariance matrix's eigenstructure when processing received signals. Our goal in this section is to obtain increased resolution and accuracy in DOA estimation by presenting an improved version of the MUSIC algorithm specifically designed for coprime sensor arrays.

Consider K uncorrelated narrowband sources that arrive at a coprime sensor array in the directions $\theta = [\theta_1, \theta_2, ..., \theta_K]^T$. $|\mathbf{S}| = 2M + N - 1$ sensors make up the array, where M and N are coprime integers. Every sensor spacing d equals $\lambda/2$, where the signal wavelength is denoted by λ. At time t over T snapshots, the received signal vector is given by (2) and the covariance matrix $\mathbf{R}_S$ of the array output $\mathbf{x}(t)$ is given by (3). The proposed algorithm is as follows:

1. Let us construct the augmented array covariance matrix: Define an augmented array covariance matrix $\mathbf{R}_{aug}$ combining the covariance matrices of two coprime subarrays:

$$\mathbf{R}_{aug} = \begin{bmatrix} \mathbf{R}_{sub1} & 0 \\ 0 & \mathbf{R}_{sub2} \end{bmatrix} \quad (4)$$

   where $\mathbf{R}_{sub1}$ and $\mathbf{R}_{sub2}$ are the covariance matrices of the two coprime subarrays.

2. Eigenvalue Decomposition: Perform eigenvalue decomposition on $\mathbf{R}_{aug}$ to obtain its eigenvalues λ_i and corresponding eigenvectors $\mathbf{e}_i$.

3. Let us compute the MUSIC Spectrum: Calculate the MUSIC spectrum $\mathbf{P}_{MUSIC}(\theta)$ for direction θ:

$$\mathbf{P}_{MUSIC}(\theta) = \frac{1}{\mathbf{e}_i^H \mathbf{V}_N \mathbf{e}_i} \quad (5)$$

   where $\mathbf{V}_N$ is the noise subspace spanned by eigenvectors corresponding to the N smallest eigenvalues of $\mathbf{R}_{aug}$.

4. DOA estimation: the peaks in $\mathbf{P}_{MUSIC}(\theta)$ are the estimated directions of arrival $\hat{\theta}_k = \left[\hat{\theta}_1, \hat{\theta}_2, ..., \hat{\theta}_k\right]^T$.

V. RESULTS AND DISCUSSION

We compare the performance of the suggested enhanced MUSIC algorithm for DOA estimation in various scenarios with several well-known algorithms, such as Capon, classic MUSIC [4], ESPRIT [5], and the more recent Modified MUSIC (MMUSIC) [8], in this section. The Root Mean Square Error (RMSE) [23-25] statistic is generally used to analyze the performance under various angular separation, snapshot, and Signal-to-Noise Ratio (SNR) situations.

The simulation setup utilizes a coprime sensor array with parameters M and N, as outlined in earlier sections. The sensor spacing is $d = \lambda/2$, where λ represents the signal wavelength. In this analysis, K uncorrelated narrowband sources are simulated with varying SNR, snapshots, and angular separation. Key simulation parameters include:

- Array geometry: Coprime array with $M = 4$, $N = 5$.
- SNR range: -10 dB to 20 dB.
- Snapshots: 100 and 500.
- DOA angles: Randomly generated between $[-60^o, 60^o]$.
- Noise model: Additive White Gaussian Noise (AWGN) with variance σ^2.

The performance of each algorithm is quantified using the RMSE of DOA estimates, computed as follows [26-28]:

$$RMSE = \sqrt{\frac{1}{K}\sum_{k=1}^{K}\left(\hat{\theta}_k - \theta_k\right)^2} \quad (6)$$

where $\hat{\theta}_k$ denotes the estimated DOA and θ_k represents the true DOA of the k source.

Figure 2 shows the RMSE performance of the proposed improved MUSIC algorithm compared to Capon, traditional MUSIC, ESPRIT, and MMUSIC, with 100 snapshots and SNR values ranging from -20 dB to 20 dB. As evident from the results, the proposed method significantly outperforms the other algorithms, particularly in low-SNR conditions (SNR < 0 dB). The ability of the improved MUSIC algorithm to reduce noise interference and enhance spatial resolution allows it to achieve a much lower RMSE.

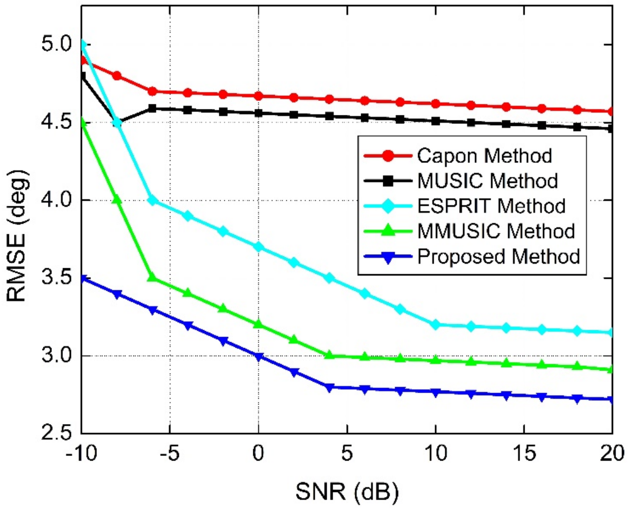

Fig. 2. RMSE versus SNR for 100 snapshots.

Figure 3 illustrates the RMSE performance with the number of snapshots increased to 300. Similar to the 100-snapshot case, the proposed improved MUSIC algorithm continues to show superior performance over Capon, traditional MUSIC, ESPRIT, and MMUSIC. The RMSE decreases with increasing SNR, and the proposed method maintains the lowest error rate across all tested SNR values. The larger number of snapshots contributes to more accurate DOA estimation, further improving the algorithm's performance.

To analyze the impact of the number of snapshots on performance, we compared the RMSE versus the number of snapshots in Figure 4. As expected, increasing the number of snapshots significantly reduces the RMSE for all algorithms. However, the proposed improved MUSIC method consistently outperforms the other techniques, demonstrating robust performance even with a smaller number of snapshots. This makes the method especially suitable for scenarios where data are limited.

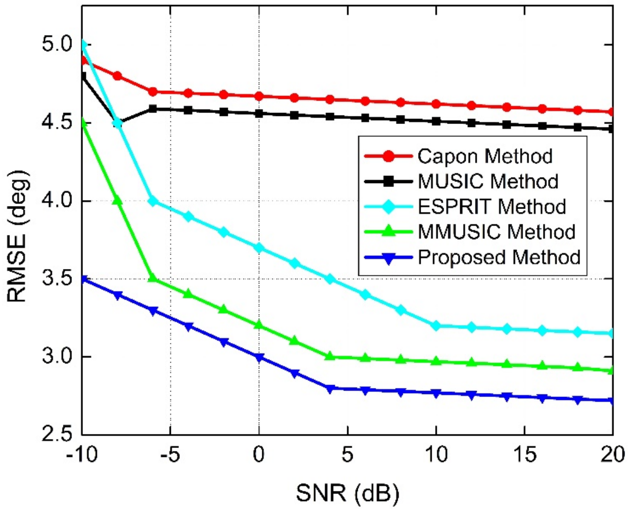

Fig. 3. RMSE versus SNR for 300 snapshots.

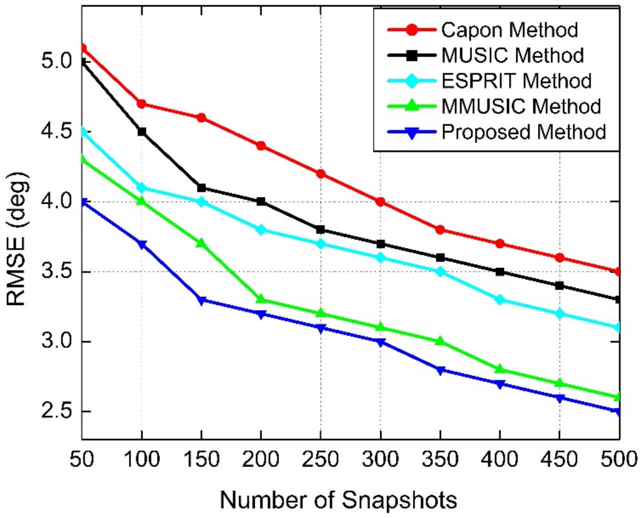

Fig. 4. RMSE versus number of snapshots.

Finally, the effect of angular separation between sources on the RMSE is examined in Figure 5. The proposed method demonstrates its ability to accurately estimate DOAs even when the angular separation between sources is small. The RMSE increases as the angular separation decreases, but the proposed improved MUSIC still outperforms other methods in cases of closely spaced sources. This advantage stems from the enhanced spatial resolution of the coprime array configuration, coupled with the refined MUSIC algorithm.

Several key observations can be made from the above results:

- SNR sensitivity: The proposed improved MUSIC algorithm achieves significantly better performance than Capon, traditional MUSIC, ESPRIT, and MMUSIC, especially at low SNR values.
- Snapshot efficiency: The algorithm performs consistently well across different snapshot sizes, with more pronounced improvements when snapshots are limited to 100.
- Angular resolution: The proposed approach exhibits superior resolution capabilities for closely spaced sources, which is crucial for accurate DOA estimation in challenging scenarios.

Hence, the proposed improved MUSIC algorithm, which exploits the unique properties of the coprime array, demonstrates notable advantages over existing methods in terms of accuracy and robustness. Its low RMSE under varying SNR, snapshot, and angular separation conditions makes it highly effective for real-world applications, particularly in environments with limited data or closely spaced signals.

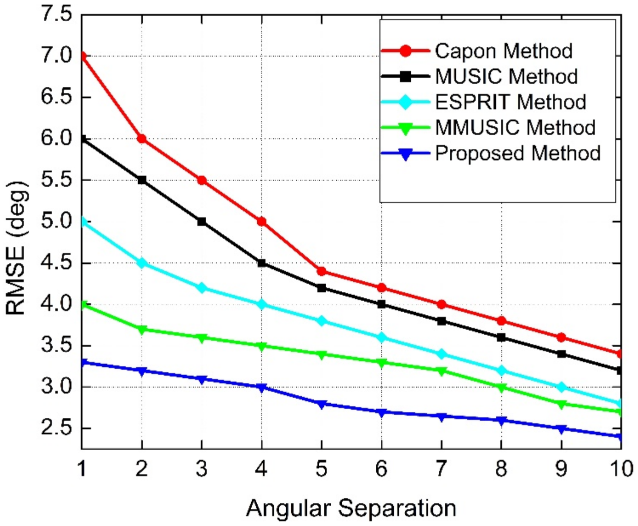

Fig. 5. RMSE versus angular separation.

VI. CONCLUSION

In this paper, we proposed an improved Multiple Signal Classification (MUSIC) algorithm for Direction-of-Arrival (DOA) estimation using a coprime array configuration. Through extensive simulations, the proposed method was compared with several well-known algorithms, including Capon, traditional MUSIC, Estimating Signal Parameter via Rotational Invariance Techniques (ESPRIT), and Modified MUSIC (MMUSIC). The results demonstrated that the proposed improved MUSIC algorithm consistently outperforms these methods in terms of RMSE across various scenarios, including varying SNR, number of snapshots, and angular separation. The key strengths of the proposed method lie in its ability to maintain high accuracy in low-SNR environments and with limited snapshots, making it particularly suitable for real-world applications where data collection is constrained. Additionally, the enhanced angular resolution allows for more precise DOA estimation even when sources are closely spaced. Future work includes exploring further optimizations in coprime sensor array configurations to handle more complex and dynamic signal environments. Additionally, integrating machine learning techniques with the enhanced MUSIC algorithm could potentially improve real-time DOA estimation and interference suppression in highly congested wireless communication systems. Expanding the proposed method to accommodate 3D spatial localization is another promising direction for future work.

REFERENCES

[1] L. C. Godara, *Smart Antennas*. Boca Raton, FL, USA: CRC Press, 2004.

[2] H. B. Mahesh, G. F. A. Ahammed, and S. M. Usha, "Design and Performance Analysis of Massive MIMO Modeling with Reflected Intelligent Surface to Enhance the Capacity of 6G Networks," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12068–12073, Dec. 2023, https://doi.org/10.48084/etasr.6234.

[3] A. Chakraborty, G. Ram, and D. Mandal, "Time-Domain Approach Towards Smart Antenna Design," in *Wideband, Multiband, and Smart Antenna Systems*, M. A. Matin, Ed. Cham, Switzerland: Springer International Publishing, 2021, pp. 363–394.

[4] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 3, pp. 276-280, Mar. 1986, https://doi.org/10.1109/TAP.1986.1143830.

[5] C. Qian, L. Huang, and H. C. So, "Computationally efficient ESPRIT algorithm for direction-of-arrival estimation based on Nyström method," *Signal Processing*, vol. 94, pp. 74–80, Jan. 2014, https://doi.org/10.1016/j.sigpro.2013.05.007.

[6] M. A. Panduro and C. del Rio-Bocio, "Design of beam-forming networks using CORPS and evolutionary optimization," *AEU - International Journal of Electronics and Communications*, vol. 63, no. 5, pp. 353–365, May 2009, https://doi.org/10.1016/j.aeue.2008.02.009.

[7] A. Chakraborty, G. Ram, and D. Mandal, "Electronic Beam Steering in Timed Antenna Array by Controlling the Harmonic Patterns with Optimally Derived Pulse-Shifted Switching Sequence," in *International Conference on Innovative Computing and Communications*, Singapore, 2022, pp. 205–216, https://doi.org/10.1007/978-981-16-3071-2_18.

[8] G. Liu, H. Chen, X. Sun and R. C. Qiu, "Modified MUSIC Algorithm for DOA Estimation With Nyström Approximation," *IEEE Sensors Journal*, vol. 16, no. 12, pp. 4673-4674, Jun. 2016, https://doi.org/10.1109/JSEN.2016.2557488.

[9] A. Chakraborty, G. Ram, and D. Mandal, "Time-modulated multibeam steered antenna array synthesis with optimally designed switching sequence," *International Journal of Communication Systems*, vol. 34, no. 9, 2021, Art. no. e4828, https://doi.org/10.1002/dac.4828.

[10] P. K. Eranti and B. D. Barkana, "An Overview of Direction-of-Arrival Estimation Methods Using Adaptive Directional Time-Frequency Distributions," *Electronics*, vol. 11, no. 9, Jan. 2022, Art. no. 1321, https://doi.org/10.3390/electronics11091321.

[11] P. Pal and P. P. Vaidyanathan, "Coprime sampling and the music algorithm," in *2011 Digital Signal Processing and Signal Processing Education Meeting*, Sedona, AZ, USA, 2011, pp. 289–294, https://doi.org/10.1109/DSP-SPE.2011.5739227.

[12] Z. Jaafer, S. Goli, and A. S. Elameer, "Performance Analysis of Beam scan, MIN-NORM, Music and Mvdr DOA Estimation Algorithms," in *2018 International Conference on Engineering Technology and their Applications*, Al-Najaf, Iraq, 2018, pp. 72–76, https://doi.org/10.1109/IICETA.2018.8458076.

[13] R. Tibshirani, "Regression Shrinkage and Selection via the Lasso," *Journal of the Royal Statistical Society. Series B (Methodological)*, vol. 58, no. 1, pp. 267–288, 1996.

[14] Z. Zhang and B. D. Rao, "Sparse Signal Recovery with Temporally Correlated Source Vectors using Sparse Bayesian Learning," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 5, pp. 912–926, Sep. 2011, https://doi.org/10.1109/JSTSP.2011.2159773.

[15] P. Fernandes, R. Pinto, and N. Correia, "Design and optimization of self-deployable damage tolerant composite structures: A review," *Composites Part B: Engineering*, vol. 221, Sep. 2021, Art. no. 109029, https://doi.org/10.1016/j.compositesb.2021.109029.

[16] S. Abbas, F. Li, and J. Qiu, "A Review on SHM Techniques and Current Challenges for Characteristic Investigation of Damage in Composite Material Components of Aviation Industry," *Materials Performance and Characterization*, vol. 7, no. 1, pp. 224–258, Jun. 2018, https://doi.org/10.1520/MPC20170167.

[17] X. Qing, W. Li, Y. Wang, and H. Sun, "Piezoelectric Transducer-Based Structural Health Monitoring for Aircraft Applications," *Sensors*, vol. 19, no. 3, Jan. 2019, Art. no. 545, https://doi.org/10.3390/s19030545.

[18] L. Yu and Z. Tian, "Guided wave phased array beamforming and imaging in composite plates," *Ultrasonics*, vol. 68, pp. 43–53, May 2016, https://doi.org/10.1016/j.ultras.2016.02.001.

[19] S. Yuan, Y. Zhong, L. Qiu, and Z. Wang, "Two-dimensional near-field multiple signal classification algorithm–based impact localization," *Journal of Intelligent Material Systems and Structures*, vol. 26, no. 4, pp. 400–413, Mar. 2015, https://doi.org/10.1177/1045389X14529026.

[20] H. Zuo, Z. Yang, C. Xu, S. Tian, and X. Chen, "Damage identification for plate-like structures using ultrasonic guided wave based on improved MUSIC method," *Composite Structures*, vol. 203, pp. 164–171, Nov. 2018, https://doi.org/10.1016/j.compstruct.2018.06.100.

[21] Q. Bao, S. Yuan, F. Guo, and L. Qiu, "Transmitter beamforming and weighted image fusion–based multiple signal classification algorithm for corrosion monitoring," *Structural Health Monitoring*, vol. 18, no. 2, pp. 621–634, Mar. 2019, https://doi.org/10.1177/1475921718764848.

[22] Q. Wang, M. Hong, and Z. Su, "An In-Situ Structural Health Diagnosis Technique and its Realization via a Modularized System," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 4, pp. 873–887, Apr. 2015, https://doi.org/10.1109/TIM.2014.2362417.

[23] M. V. Galindo *et al.*, "Advanced Direction-of-Arrival Estimation in Coprime Arrays via Adaptive Nyström Spectral Analysis," *IEEE Sensors Letters*, vol. 8, no. 2, pp. 1–4, Feb. 2024, https://doi.org/10.1109/LSENS.2024.3349651.

[24] D. Veerendra *et al.*, "ECA-MURE Algorithm and CRB Analysis for High-Precision DOA Estimation in Coprime Sensor Arrays," *IEEE Sensors Letters*, vol. 7, no. 12, pp. 1–4, Dec. 2023, https://doi.org/10.1109/LSENS.2023.3332673.

[25] D. Veerendra, K. S. Balamurugan, M. Villagómez-Galindo, A. Khandare, M. Patil, and A. Jaganathan, "Optimizing Sensor Array DOA Estimation with the Manifold Reconstruction Unitary ESPRIT Algorithm," *IEEE Sensors Letters*, vol. 7, no. 12, pp. 1–4, Dec. 2023, https://doi.org/10.1109/LSENS.2023.3327568.