Subspace-Based Jamming Suppression for ISAC Systems via Covariance Matrix Reconstruction with Limited Prior Knowledge

Simplice Intungane*, Celine Nerima Wafula†, and Soo Young Shin‡
Department of IT Convergence Engineering,
Kumoh National Institute of Technology, Gumi, South Korea
Email: {*simplice21, †nerimace, ‡wdragon}@kumoh.ac.kr

***Abstract*—This paper proposes a novel data-driven anti-jamming beamforming for Integrated Sensing and Communication (ISAC) receivers under spatial interference with limited prior knowledge. Using Minimum Description Length (MDL) criterion and MUSIC,the method estimate dominant sources Angle of Arrivals (AoAs). Candidate vectors are generated from estimated AoAs and reconstructed interference covariance matrices based on signal hypotheses. An optimal vector minimizing Kullback-Liebler (KL) divergence of the output Power Spectral Density (PSD) is selected, avoiding explicit classification. This directs nulls at jammer AoAs, enhancing ISAC signal quality for communication and sensing. The method provides robust interference suppression with limited environmental data.**

***Index Terms*—AoA Estimation, Anti-jamming, Beamforming, Covariance Matrix Reconstruction, ISAC, MUSIC.**

I. Introduction

The evolution towards sixth-generation (6G) wireless systems is ushering in the paradigm of Integrated Sensing and Communication (ISAC), poised to revolutionize a multitude of applications ranging from intelligent traffic monitoring and autonomous driving to enhanced urban safety [1]. Concurrently, satellite communication, particularly leveraging Low Earth Orbit (LEO) constellations, is increasingly viewed as a crucial extension of terrestrial networks. LEO satellites offer compelling advantages such as extended coverage, lower propagation attenuation, and potentially decreased deployment costs, facilitating ubiquitous connectivity, especially in remote or under-served areas [2]. However, the inherent openness of wireless networks renders them highly vulnerable to various forms of inter- ference, including intentional and malicious jamming [3].

Spatial beamforming, like Capon's method (MVDR), suppresses interference but requires accurate steering vectors and the interference-plus-noise covariance matrix (INCM), which is often unavailable. Methods like [4] reconstruct INCM by integrating Capon spectrum over predefined angular sectors, but depend on correct sector choices. Others use projection-based techniques to calibrate steering vectors [5], still needing a nominal vector.

This paper proposes a novel anti-jamming beamforming,termed Adaptive Subspace Covariance matrix reconstruction (AS-CMR), for ISAC receivers with limited prior knowledge. First, dominant signal sources are estimated through MDL and then AoAs from array data, removing reliance on additional prior information. A performance-based selection mechanism then chooses the optimal beamformer using a signal-quality metric. Finally, the AS-CMR is validated by simulations showing significant gains over conventional baselines.

II. System Model

Consider as depicted in Fig. 1(a) a downlink in which an ISAC-enabled satellite transmits a dual-purpose baseband signal, $s_s(k)$ towards a Base Station (BS) receiver equipped with an M element Uniform Linear Array. This signal is targeted by J ground-based jammers, each emitting an interfering signal $s_j(k)$, for $j = 1, \ldots, J$. The received baseband signal at the BS array at discrete time instant k is $\mathbf{x}(k) \in \mathbb{C}^{M\times 1}$ is:

$$\mathbf{x}(k) = \alpha_s \mathbf{a}(\theta_s) s_s(k) + \sum_{j=1}^{J} \alpha_j \mathbf{a}(\theta_j) s_j(k) + \mathbf{n}(k).$$

where α_s, α_j are complex path gains from the satellite and the j-th jammer, respectively; θ_s and θ_j are their respective AoAs; $\mathbf{a}(\theta) \in \mathbb{C}^{M\times 1}$ is the array steering vector for angle θ and $\mathbf{n}(k)$ is AWGN with covariance $\sigma_n^2 \mathbf{I}_M$. For a ULA, $\mathbf{a}(\theta) = [1, e^{-j\pi \sin(\theta)}, \ldots, e^{-j(M-1)\pi \sin(\theta)}]^T$.

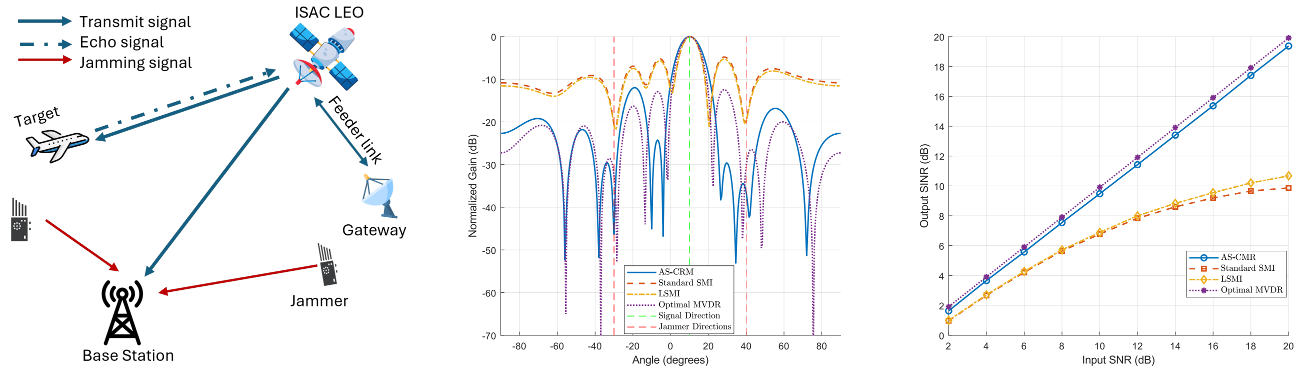
III. Proposed Robust Beamformer

The conventional MVDR beamformer's reliance on exact prior knowledge of the INCM ($\mathbf{R}_{i+n}$) and desired signal steering vector ($\mathbf{a}(\theta_s)$) limits its practical use. The AS-CRM method proposed in this study estimates these adaptively.

From K received baseband snapshots $\mathbf{x}(k) \in \mathbb{C}^M$, the Sample Covariance Matrix (SCM) is computed: $\hat{\mathbf{R}} = \frac{1}{K}\sum_{k=1}^{K} \mathbf{x}(k)\mathbf{x}^H(k)$. Eigenvalue Decomposition (EVD) of $\hat{\mathbf{R}} = \mathbf{E}\boldsymbol{\Lambda}\mathbf{E}^H$ yields eigenvalues $\boldsymbol{\Lambda}$ and eigenvectors $\mathbf{E}$. The number of dominant signal sources, $\hat{D}$, is estimated via the MDL criterion applied to the eigenvalues:

$$MDL(d) = -\log\left(\frac{\prod_{i=d+1}^{M} \hat{\lambda}_i^{1/(M-d)}}{\frac{1}{M-d}\sum_{i=d+1}^{M} \hat{\lambda}_i}\right)^{(M-d)K} + \frac{d(2M-d)\log K}{2},$$

where $\hat{D} = \arg\min_d MDL(d)$ and d = 0, …, M-1.



(a) (b) (c)

Figure 1: Simulation results. (a)Proposed system (b)Proposed beam pattern vs Baselines. (c) Output SINR vs Transmit SNR.

Noise power $\hat{\sigma}_n^2$ is the mean of the $M - \hat{D}$ smallest eigenvalues. Eigenvectors corresponding to these form the noise subspace $\hat{\mathbf{E}}_n$.

Angles of Arrival (AoAs) $\{\hat{\theta}_1, \ldots, \hat{\theta}_{\hat{D}}\}$ are found from peaks in the MUSIC pseudospectrum:

$$P_{\text{MUSIC}}(\theta) = (\mathbf{a}^H(\theta)\hat{\mathbf{E}}_n\hat{\mathbf{E}}_n^H\mathbf{a}(\theta))^{-1}.$$

The power $\hat{P}_i$ for each $\hat{\theta}_i$ is estimated from the noise-whitened SCM, $\hat{\mathbf{R}}_s = \hat{\mathbf{R}} - \hat{\sigma}_n^2\mathbf{I}_M$.

For each $\hat{\theta}_i$ hypothesized as the desired signal, an INCM $\hat{\mathbf{R}}_{i+n}^{(i)}$ is reconstructed using other estimated sources $\{\hat{\theta}_j\}_{j\neq i}$ and their powers $\hat{P}_j$, plus $\hat{\sigma}_n^2\mathbf{I}_M$:

$$\hat{\mathbf{R}}_{i+n}^{(i)} = \sum_{\substack{j=1 \\ j\neq i}}^{\hat{D}} \hat{P}_j\mathbf{a}(\hat{\theta}_j)\mathbf{a}^H(\hat{\theta}_j) + \hat{\sigma}_n^2\mathbf{I}_M.$$

The i-th candidate MVDR vector is:

$$\mathbf{w}_i = \frac{(\hat{\mathbf{R}}_{i+n}^{(i)})^{-1}\mathbf{a}(\hat{\theta}_i)}{\mathbf{a}^H(\hat{\theta}_i)(\hat{\mathbf{R}}_{i+n}^{(i)})^{-1}\mathbf{a}(\hat{\theta}_i)}.$$

The optimal beamformer $\mathbf{w}_{\text{opt}}$ is selected from $\{\mathbf{w}_i\}$ by finding which one, when applied to $\mathbf{x}(k)$, produces an output $y_i(k)$ whose Power Spectral Density (PSD) $\hat{P}_i(f)$ best matches a reference ISAC signal PSD $P_{\text{ref}}(f)$. This match is quantified by minimizing the Kullback–Leibler (KL) divergence:

$$D_{\text{KL}}(P_{\text{ref}}\|\hat{P}_i) = \sum_f P_{\text{ref}}(f)\log\left(\frac{P_{\text{ref}}(f)}{\hat{P}_i(f)}\right).$$

with $\mathbf{w}_{\text{opt}} = \arg\min_{i\in\{1,\ldots,\hat{D}\}} D_{\text{KL}}(P_{\text{ref}}\|\hat{P}_i)$. The selected $\mathbf{w}_{\text{opt}}$ is then used for interference suppression.

IV. Numerical Results

Performance is assessed with a ULA ($M = 10$ antennas, $\lambda/2$ spacing, $K = 100$ snapshots). An ISAC signal and $J = 2$ jammers (JNR=10dB) are simulated. Benchmarks: Ideal MVDR, Sample Matrix Inversion (SMI), Loaded SMI (LSMI).

Fig. 1(b) shows the AS-CMR's beam pattern mirrors the Ideal MVDR, placing deep nulls at jammer AoAs without prior knowledge, while maintaining signal of interest gain. Fig. 1(c) plots output SINR vs input SNR. The proposed method closely tracks Ideal MVDR performance, effectively suppressing interference, and significantly outperforms SMI/LSMI, which are sensitive to steering vector errors, in all scenarios considered.

V. Conclusion

This paper introduced a data-driven adaptive beamforming framework for ISAC jamming mitigation with limited prior spatial knowledge. It directly estimates sources parameters and uses a performance-based criterion for beamformer selection, removing the need for prior jammer information. Numerical results demonstrated robust anti-jamming efficacy, approaching ideal MVDR performance and substantially outperforming conventional methods. This work has offered a practical solution for enhancing ISAC reliability in contested environments.

Acknowledgment

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2025-RS-2024-00437190) supervised by the IITP(Institute for Information Communications Technology Planning Evaluation, 50%) This work was supported by Institute of Information communications Technology Planning Evaluation (IITP) grant funded by the Korea government(MSIT) (No. 2021-0-02120, Research on Integration of Federated and Transfer learning between 6G base stations exploiting Quantum Neural Networks, 50%).

References

[1] Y. Shu, C. Qi, and S. Mao, "Joint transmit waveform and receive filter design for isac system with jamming," *IEEE Transactions on Vehicular Technology*, pp. 1–6, 2025.

[2] Q. Wang, X. Chen, Q. Qi, M. Li, and W. Gerstacker, "Multiple-satellite cooperative information communication and location sensing in leo satellite constellations," *IEEE Transactions on Wireless Communications*, vol. 24, no. 4, pp. 3346–3361, 2025.

[3] Z. Wei, H. Qu, Y. Wang, X. Yuan, H. Wu, Y. Du, K. Han, N. Zhang, and Z. Feng, "Integrated sensing and communication signals toward 5g-a and 6g: A survey," *IEEE Internet of Things Journal*, vol. 10, no. 13, pp. 11 068–11 092, 2023.

[4] M. Yang, P. Chen, T. Luo, and M. Sun, "Low-complexity covariance matrix reconstruction method for wideband adaptive beamforming," *IEEE Communications Letters*, vol. 29, no. 3, pp. 502–506, 2025.

[5] J. He, T. Shu, V. Dakulagi, and L. Li, "Simultaneous interference localization and array calibration for robust adaptive beamforming with partly calibrated arrays," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 57, no. 5, pp. 2850–2863, 2021.