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PERFORMANCE EVALUATION OF ENHANCED MUSIC-BASED MULTI-USER DOA ESTIMATION USING EMBEDDED RADIATION PATTERNS FOR MILLIMETER-WAVE COMMUNICATION SYSTEMS

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ABSTRACT

Integrating radiation patterns into the multiple signal classification (MUSIC) algorithm is a critical advancement for enhancing Direction of Arrival (DoA) estimation. DoA estimation accuracy is essential in modern 5G/6G Base Stations to enable precision beamforming, spatial multiplexing, and high-accuracy localization. Traditional MUSIC algorithms ignore the antenna elements' radiation patterns and mutual coupling. The contribution of this paper is the replacement of the conventional steering vectors (CSV) with the rigorous steering vector for millimeter wave systems. Enhancing MUSIC-based DoA estimation algorithm using embedded radiation elements pattern (ERP) for multiple users is achieved by designing a microstrip antenna array, which operates in millimeter wave at $\mathbf{28\ GHz}$ using Rogers RT/Duroid 5880 substrate material, using Ansys electronic desktop. The simulated results evaluate the DoA performance in terms of root mean square error (RMSE) across the range of signal-to-noise ratios $\boldsymbol{SNR} \in [-\mathbf{20\ dB}, \mathbf{10\ dB}]$ and different numbers of users, under the assumption of 100 snapshots. Both conventional and rigorous methods for presenting steering vectors achieve competitive DoA estimation for the single-user case. The ERP steering vector (ERPSV) method performs better than CSV for multi-user in noisy environments, with a low SNR value. ERPSV achieves zero RMSE for 9 users simultaneously at the SNR value $\mathbf{10\ dB}$, while CSV fails to distinguish 2 users at the SNR less than $\mathbf{5\ dB}$. The results achieved are presented in more detail in the simulated results section.

KEYWORDS: CSV, Direction of arrival DoA, enhanced MUSIC, ERPSV.

INTRODUCTION

Modern wireless systems require more accurate localization, better communication efficiency, and stronger interference management, driving research into 3D beamforming and Direction of Arrival (DoA) prediction. Anomalies capable of precisely determining the direction of receiving signals and steering beams in three-dimensional space are essential for applications such as 5G/6G communications, radar systems, satellite communications, indoor positioning, and vehicle-to-element communications. Designing an antenna array opens up valuable opportunities to estimate the angular DoA (elevation and azimuth) of incoming signals by indicating the spatial locations of the electromagnetic waves that reach the antenna array [1], [2], [3].

DoA estimation has surfaced as a viable solution to address the recent advancements in autonomous driving and localization. Traditional DoA estimation algorithms assume element isotropy and electromagnetic isolation, and use CSV. [4] computed the efficiency and accuracy of DoA estimation across various noise scenarios. It compared two different DoA algorithms, which are MUSIC and ESPRIT, applied using a 2D antenna array in varying signal-to-noise ratio (SNR). The ESPRIT algorithm is more complex than MUSIC, but it achieves higher accuracy and shorter excitation time. [5] proposed an efficient model with practical antenna configurations to estimate the angle of arrival (AoA) on mobile phones. This proposed model consists of two stages: offline and online. In the offline stage, a lookup table is generated from antenna responses at every angle, while in the online stage, the AoAs are estimated using the lookup table to synthesize a steering vector. The experimental results of this model are close to the simulated results with a realistic antenna array using Wireless InSite software.

They sometimes neglect the involved electromagnetic effects of the antenna array itself. However, [6] proposed an Embedded Radiation Pattern (ERP) approach that accounts for mutual coupling and gain-loss effects to improve beamforming approaches while [7] used to improve the reliability of the DoA estimation compared to CSV for Bluetooth Low Energy (BLE) at $2.4\,GHz$. Simulation results demonstrated that this approach achieved lower Mean Absolute Error under both line-of-sight and multipath conditions, and its performance improved with an increased number of snapshots.

In this paper, the contribution is to replace the theoretical steering vectors with rigorous ERPSV steering vectors for millimeter-wave systems at 28 GHz in 5G base stations. This study enhances the MUSIC algorithm to mitigate the mm-wave mismatch at the physical layer to improve the accuracy of the multi-user DoA estimation. First, 64 microstrip elements are arranged in a square antenna array to operate at 28 GHz and then placed as a base station, using Ansys Electronics Desktop. ERPSVs are extracted for post-processing in MATLAB to enhance MUSIC-based DoA estimation across different SNR value and multi-user.

The rest of this paper is organized as follows. Section II presents the methodology and mathematical expressions for Enhanced MUSIC-based DoA estimation. The co-simulated results of MATLAB with Ansys are shown and discussed in Section III, while Section IV summarizes the results and discussion of this paper.

ENHANCED MUSIC-BASED DOA ESTIMATION

The effectiveness of subspace-based MUSIC DoA estimation is essentially dependent on the mathematical orthogonality between the signal subspace and the noise subspace. Orthogonality is achieved only when the array manifold, comprising all possible steering vectors, precisely aligns with the hardware's actual physical response. Traditional DoA estimation algorithms use CSV as stated in (1)[8].

$$\boldsymbol{a}(\theta,\varphi) = \begin{bmatrix} \exp\left(j\beta\overrightarrow{r_1}\cdot\vec{p}(\theta,\varphi)\right), \exp\left(j\beta\overrightarrow{r_2}\cdot\vec{p}(\theta,\varphi)\right), \dots, \\ \exp\left(j\beta\overrightarrow{r_M}\cdot\vec{p}(\theta,\varphi)\right) \end{bmatrix}^T \in \mathbb{C}^{M\times N} \quad (1)$$

Where $\beta = 2\pi/\lambda$ is the propagation phase constant, $\overrightarrow{r_1}$ is the position vector of the mth array element, $\vec{p}$ is the direction unit vector at $\overrightarrow{x_0}$, $\overrightarrow{y_0}$, and $\overrightarrow{z_0}$ on the x, y, and z axes, respectively, as (2), and M and N is the total number of the antenna elements and all (θ,φ) possible states, respectively.

$$\vec{p}(\theta,\varphi) = \cos\varphi\sin\theta\,\overrightarrow{x_0} + \sin\varphi\sin\theta\,\overrightarrow{y_0} + \cos\theta\,\overrightarrow{z_0} \quad (2)$$

$\boldsymbol{a}(\theta,\varphi)$ indicates CSV under two assumptions: element isotropy and electromagnetic isolations, ignoring mutual coupling between adjacent elements. MUSIC spatial spectrum ($\boldsymbol{P}$) can be computed as (3) to estimate DoA (θ,φ), which is the peak location when the denominator approximates to zero at the orthogonality [9].

$$\boldsymbol{P}(\theta,\varphi) = \frac{1}{\boldsymbol{a}^H(\theta,\varphi)\,\boldsymbol{E_n}\boldsymbol{E_n}^H\boldsymbol{a}(\theta,\varphi)}$$

Where $\boldsymbol{E_n}$ is the noise subspace of the covariance matrix of the received multiple incoming signals.

The ERP accounts for both co-polarization and cross-polarization, mutual coupling among antenna array elements, finite element spacing, and array geometry. This can be achieved by replacing CSV with the ERPSV of the actual design antenna array as stated in (4).

$$\boldsymbol{B}(\theta,\varphi) = [\boldsymbol{b_1}(\theta,\varphi), \boldsymbol{b_2}(\theta,\varphi), \dots, \boldsymbol{b_M}(\theta,\varphi)]^T \in \mathbb{C}^{M\times N} \quad (4)$$

Where $\boldsymbol{B}(\theta,\varphi)$ is the complex radiation pattern matrix, and $\boldsymbol{b_1}(\theta,\varphi)$ is the ERP of the first element for N all (θ,φ) possible states in the 3D radiation of the Ansys project. Therefore, (5) expresses the enhanced MUSIC spatial spectrum.

$$\boldsymbol{P}(\theta,\varphi) = \frac{1}{\boldsymbol{B}^H(\theta,\varphi)\,\boldsymbol{E_n}\boldsymbol{E_n}^H\,\boldsymbol{B}(\theta,\varphi)}$$

Using ERPs, the Enhanced MUSIC algorithm effectively calibrates the physical reality of the 28 GHz environment, eliminating the systematic error caused by system mismatch and enabling high-accuracy DoA estimation. The enhanced MUSIC-based ERPSV method is detailed in Algorithm 1.

Algorithm 1: Enhanced MUSIC-based ERPSV method
1. Simulate a full-wave electromagnetic field of a 64-element array at 28 GHz.
2. Extract a 64 ERPSV of the antenna array.
3. Generate a multi-user randomly located at (θ,φ) with 100 snapshots
4. Add an additive white Gaussian distribution to get the noisy received signals.
5. Compute the covariance matrix of the received matrix. Then, compute the noise subspace using eigenvector-decomposition.
6. Scan the enhanced MUSIC spatial spectrum using ERPSVs.
7. Estimate the DoA (θ,φ) for multi-user simultaneously.

RESULTS AND DISCUSSION

This section presents the performance of the enhanced MUSIC-based Multi-user DoA estimation, and compares it with the traditional MUSIC algorithm. The ERPSVs are extracted from the square antenna array using 2024/R1 Ansys software. A (8×8) uniform square microstrip antenna array operates at 28 GHz, which is placed parallel to the yz plane with dx=$dy = \lambda/2$ element spaces along x and y, respectively, above the ground $15m$, and tilted 20° as shown in Figure 1. The microstrip elements are rectangular microstrip patch antennas. They are constructed on Rogers RT/Duroid 5880 substrate material which has a thickness $h = 0.244\,mm$ and an electric permittivity $\epsilon_r = 2.2$ [10]. Square antenna array with length $5.35\,cm$ results in an input impedance $\sim 50\ \Omega$ and the return loss $s_{i,i} = -35\,dB$ at $f = 28\,GHz$ with bandwidth $\sim 1\,GHz$. The realized gain of each element in the antenna array ranges from $5.95\,dBi$ to $4.8\,dBi$ using full-wave analysis of the antenna array when exciting the corresponding element with 1 $watts$ and remaining elements with zero watts to produce 64 ERPSVs. The main beam realized gain of the antenna array is $23.07dBi$ as shown in Fig. 1.

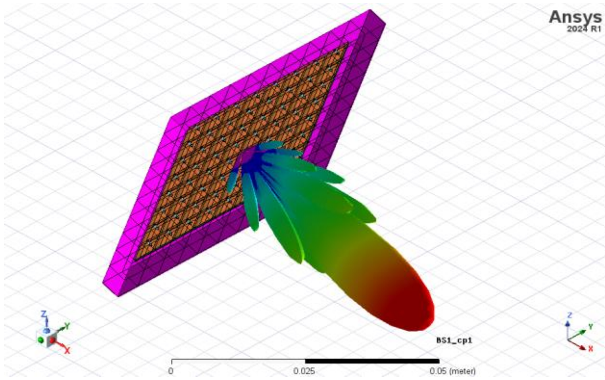
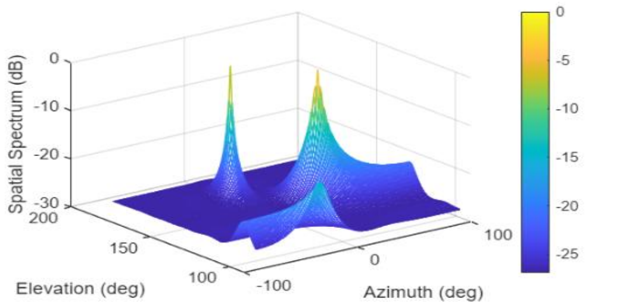
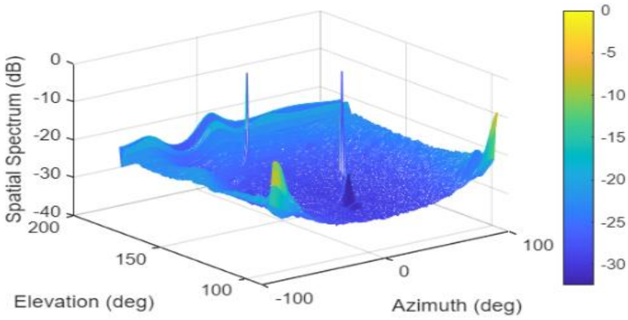


Fig. 1: Realistic microstrip antenna array.

The spatial spectrum outputs of MUSIC-based CSV and ERPSV are shown in Fig. 2 for scenarios involving two sources, which may be mobile devices and/or vehicles. We randomly set the azimuth and elevation of the incoming signals, assuming 100 snapshots. Both methods can perform relatively accurate DoA estimation at $SNR = 10\ dB$ in terms of azimuth and elevation RMSE in degrees. However, the spatial spectrum of the enhanced MUSIC-based ERPSV yields narrower outputs, significantly outperforming the other in terms of positioning performance as compared with existing [11].



(a) CSV: $(\theta,\varphi) = \{(135^{\circ}, 27^{\circ}), (160^{\circ}, -15^{\circ})\}$



(b) ERPSV: $(\theta,\varphi) = \{(135^{\circ}, 27^{\circ}), (160^{\circ}, -15^{\circ})\}$

Fig. 2: Spatial spectrum of MUSIC-based 2-user DoA estimation.

The comparison between the CSV and ERPSV methods is shown in Fig. 3 for a single-user (K=1) and a 2-user (K=2) case across different SNR values. Both methods achieve competitive DoA estimation for the single-user case. However, the ERPSV method performs better for 2-user in noisy environments, with a low SNR value, and the CSV method fails to distinguish 2-user at the SNR less than 5 dB as shown in figures 3 and 4. Moreover, RMSE of the MUSIC-based ERPSV method performs zero degrees of RMSE when the received power equals the noise power.

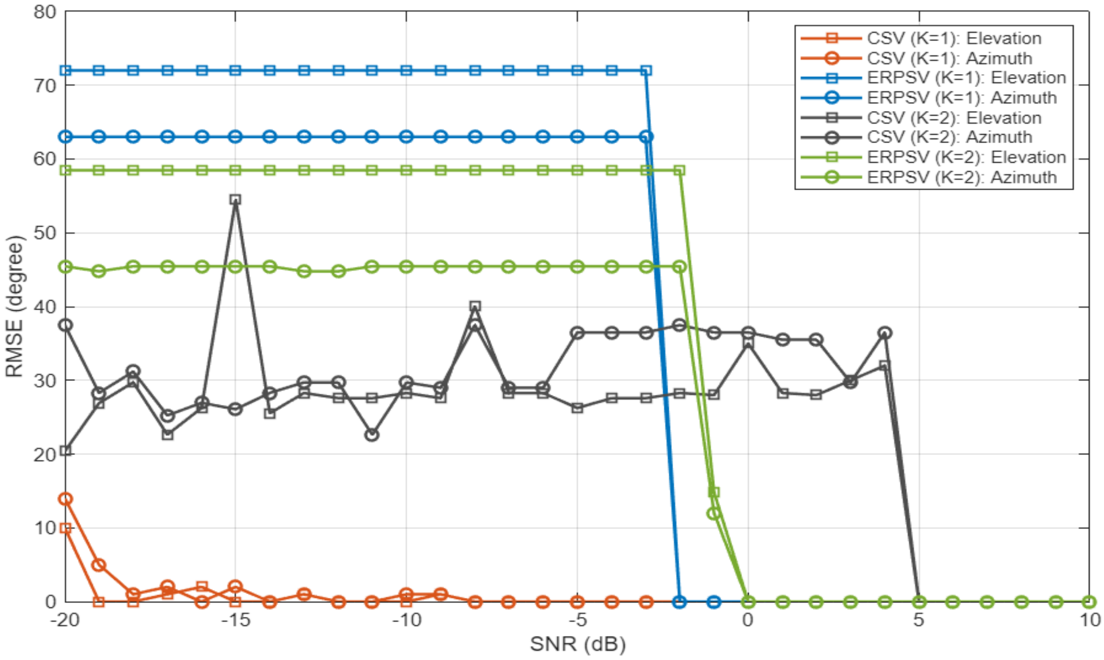


Fig. 3: MUSIC-based DoA performance under different SNR values.

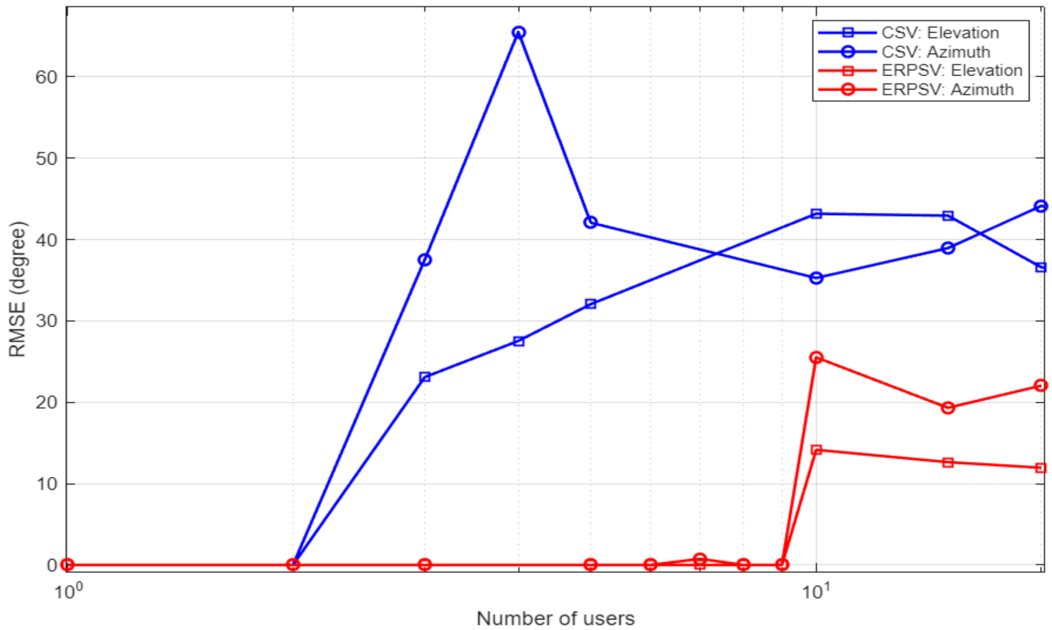


Fig. 4: MUSIC-based DoA performance under different multi-user scenarios.

Fig. 4 shows the performance of both methods under the assumption of 10 dB SNR value. It's evident that the enhanced MUSIC-based multi-user DoA algorithm using ERPSVs outperforms the one using CSVs, which improves estimation robustness and higher capacity under multiuser conditions, as it accounts for antenna-element radiation and mutual coupling and calibrates the system for the 28 GHz environment. Moreover, the enhanced MUSIC-based ERPSV method is evaluated across multiple-user scenarios at varying SNR values, as shown in Fig. 5.

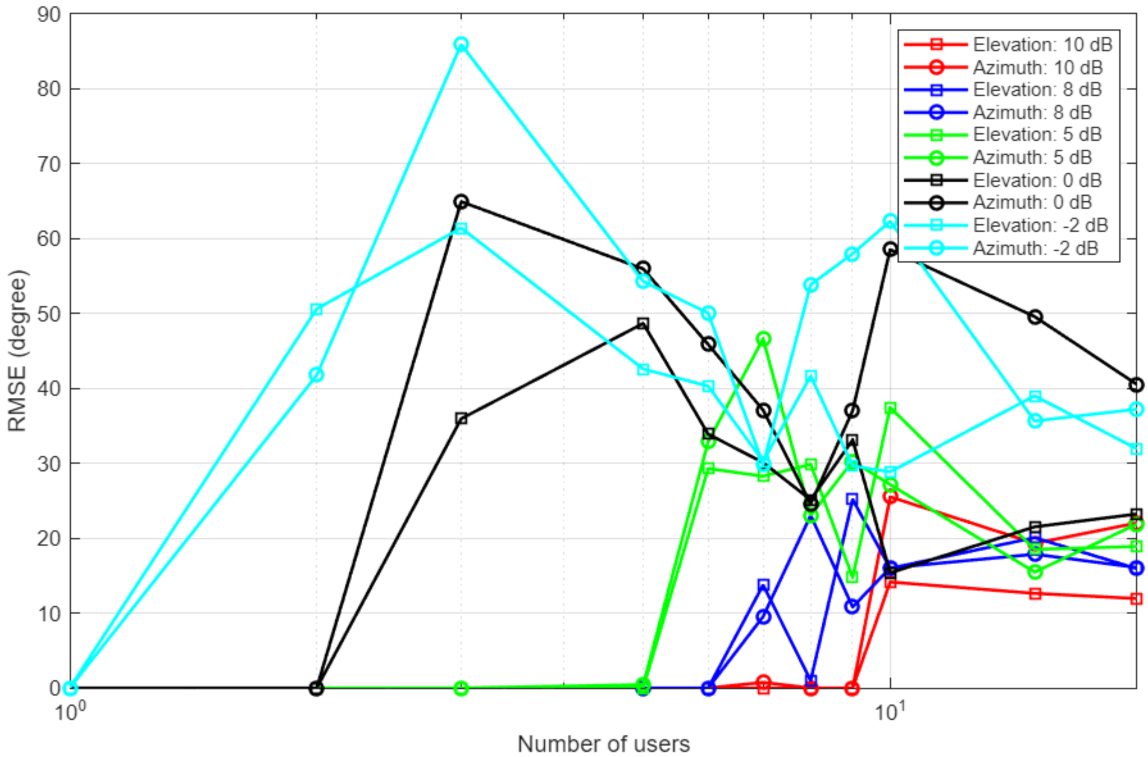


Fig. 5: Enhanced MUSIC-based ERPSV performance under different multi-user scenarios with different SNR.

The system utilizing ERPSVs can achieve zero RMSE for up to 9 users simultaneously at the SNR 10 dB value due to dependency on a clean separation between signal and noise subspaces. When the number of sources increases, the smallest signal eigenvalues get closer to the noise floor, and the pseudo-spectrum peaks become less stable. It outperforms the use of CSVs at the SNR 0 dB value. Both methods achieve almost the same performance at SNR 10 dB for CSVs, and at 0 dB for ERPSVs. It can be concluded that utilizing ERPSVs improves the performance of high-accuracy multi-user DoA estimation by approximately 10 dB.

CONCLUSIONS

This paper considers the critical influence of Embedded Radiation Patterns (ERPs) on the performance of MUSIC-based multi-user DoA estimation for 28 GHz 5G Base Stations. While traditional MUSIC algorithms rely on the idealized assumption of isolated antenna elements and ignore mutual coupling. Our research demonstrates the superiority of steering-vector-based ERPs, extracted from Ansys Electronic Desktop, for antenna-array design at mm-Wave frequencies. MUSIC-based both CSV and ERPSV can perform relatively accurate DoA at SNR 10 dB value. However, the enhanced MUSIC-based ERPSV DoA algorithm outperforms the one using CSV in terms of RMSE at a low SNR value and a high number of multiple users. ERPSV is able to achieve zero RMSE for 9 users simultaneously at the SNR value 10 dB, but CSV is unable to distinguish 2 users at the SNR less than 5 dB. The simulation results confirm that the enhanced MUSIC-based ERPSV algorithm outperforms the CSV-based algorithm for a multi-user mm-wave system, while the other fails. This advancement is essential for the reliability of future 6G and V2X (Vehicle-to-Everything) networks. Future work will explore the application of this ERP-based Deep Learning-based DoA estimation to further reduce the computational overhead in real-time tracking scenarios.

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