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Comparison of Conformal Array and Uniform Rectangular Array with 2-D MUSIC Algorithm for Estimation of Direction of Arrival

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Abstract: *The RADAR system needs to figure out the direction of arrival (DoA) of objects, especially when they are very close to each other. This is a challenging task for any ranging and detection system. Array antenna technology, which uses multiple antennas, has advanced to the point where they can achieve high angular resolution. The proposed approach improves the accuracy of DoA estimation by keeping higher number of sensors with smaller inter-sensor spacing and higher SNR. This paper investigates how conformal arrays can be better for high-speed aircraft radar systems to achieve improved angular resolution. To achieve higher resolution in DoA estimation, a subspace- based algorithm called Multiple Signal Classification (MUSIC) is used with conformal arrays. The paper focuses on comparing conformal arrays and Uniform Rectangular arrays (URA) for DoA estimation. The results show that conformal array receivers can resolve two closely spaced objects with 25 % improvement in azimuth angle and 68 % improvement in elevation angle compared to URA receivers. As the number of array elements increases in conformal arrays, more accuracy in DoA estimation with reduced grating lobes can be achieved. This is particularly useful in applications such as radar, communication, and medical imaging, where accurate DOA estimation is critical for optimal system performance.*

Keywords: Conformal array, Rectangular array, DoA estimation, 2-D MUSIC algorithm

I. INTRODUCTION

Detecting the direction of arrival for two closely spaced targets is difficult. Sometimes, these targets might appear as one for detection systems, which can cause accidentsin situations like autonomous driving or air force systems. To improve the detection ability, proper direction of arrival estimation is important. Multiple antenna arrays can achieve high resolution during this estimation. This study compares two types of receivers: planar array (URA) and non-planar array (conformal). There are three main types of planar array namely, a uniformlinear array(ULA), a uniform rectangular array, and a uniformcircular array (UCA). The planar arrays are easy to fabricate. URA is the simplest array to fabricate that gives maximum gain [1].But conformal arrays can remove the heavy instrument equipped on the top of existing airborne air crafts. The comparison between easy-to-manufacture URA is done witha conformal array which is a type of non-planar array. This study was limited to the hemispherical conformal array. A typical conformal array forms a smooth array of elements in a convex manner [2]. For the proposed work conformal array is considered. This work focuses on comparing the performance of planar URA with hemispherical Conformal array for DoA estimation. The depiction of two distinct antenna array setups is presented in Figure 1[3]. The configurations showcased are a) a Uniform Rectangular array and b) a Hemisphere Conformal array arrangement, both with antenna elements. To ensure an equitable comparison, the number of elements inthe array and the spacing between the arrays are maintained constant.

In this literature review, the MUSIC (Multiple Signal Classification) algorithms, which employs a high-resolution approach to determine the direction of arrival (DOA), is explored[4]. The method is based on a covariance matrix of the sensor array data and is a subspace decomposition-type algorithm that overcomes issues encountered with conventional beam-forming. By performing an eigenspace decomposition of the sensor co-variance matrix, the MUSIC algorithm allowsfor observation space between the signal and noise. Eigen vectors with large eigenvalues are considered signals, while noise has low eigenvalues. Furthermore, the MUSIC algorithmensures that the arriving vector is orthogonal to the

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noise, resulting in a considerable noise reduction. As the search angle approaches the arrival angle, the noise approaches zero, making it possible to detect closely spaced objects [5]. The MUSIC algorithm has inspired a new extension that utilizes an invariance principle present naturally for discrete sequences, resulting in the ESPRIT (Estimation of Signal Parameters via Rational Invariance Techniques) algorithm. Precise estimation of the data covariance matrix via ESPRIT is required, whichis covariance-based and necessitates a significant number of data snapshots [6].

The conformal array, which is designed to follow a prescribed shape, is planar or flat. A flat curving antenna mountedon an umbrella shape is an example of a conformal array. Traditional antennas are always planar, while conformal antennas are usually mounted on a curved surface. Although conformal arrays consist of multiple individual antennas, they act as a single antenna. Initially developed for military useon the curving skin of a military aircraft, conformal antennas are now utilized in ships, passenger aircraft, and even land vehicles. After 3G, conformal antennas have also been used in mobile base stations. These antennas are an extension of phased array antennas, with most transmitters connected through phase shifters that allow for phase control in the feed current, thereby enabling beamforming in the desired direction. Typically, conformal arrays are of varying lengths and small sizes relative to their footprints [7].

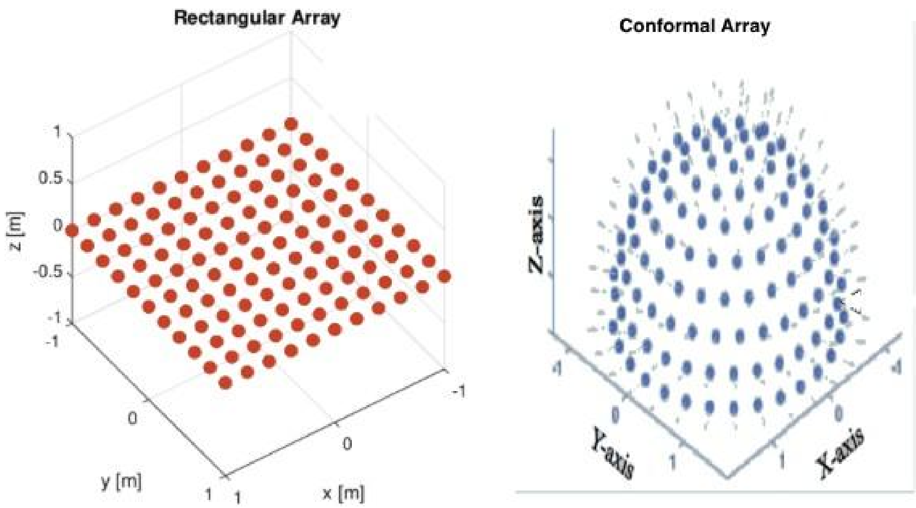

Fig. 1. a) Uniform Rectangular array b) Conformal array

Several high-resolution algorithms have been invented for DOA estimation, such as 2D-Multiple Signal Classification (MUSIC) [8] using Uniform Linear Array (ULA), Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) with ULA [5], Propagator Method (PM) [9], a tensor algorithm with ULA [10, 11], and others. Many techniques have been described in the literature for estimating DOA angles in antenna arrays. The majority of these techniques rely onthe uniform array structure and the array covariance matrix's eigen structure. The iterative method of DOA estimation isconsidered using ULA and Uniform Circular Array (UCA) geometries [12], while DOA estimation with a single snapshotis studied for UCA geometry [13]. Conformal arrays, which include spherical, conical, and cylindrical conformal arrays, are arrays whose components are mounted on smoothly curvedcarrier surfaces [7]. The optimization of element weights ofthe conical phased array antenna using a genetic algorithm has been proposed for the conical structure of a conformal array antenna [14]. With the advent of conformal antenna arrays, a unique DOA estimate algorithm that integrates geometric algebra and the MUSIC algorithm was suggested for cylindrical conformal arrays.[15] Several papers have proposed techniques for DOA estimation using compressed sensing and joint sparsity. Elbir et al. used the joint sparsity of the compressed sensing technique to jointly estimate the DOAs and mutual coupling coefficient with single and multiple snapshots based on the mutual coupling effect [16] Cheng et al. proposed an improved angle performance in bistatic MIMO radar using a multi-SVD-based subspace estimation approach, which showed improved angle estimation performance, especially when only a small number of pulses were available [17] However, all of the aforementioned techniques perform much worse when the targets are spatially close to one another. Therefore, for

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increasing the angular resolution ofclosely spaced targets, URA with 2D-MUSIC and Conformal Array with 2D-MUSIC are simulated with the calculation of DOA.

Conformal arrays are antenna arrays that can be custom- designed to fit onto non-planar surfaces, such as the curved fuselage of an aircraft or the surface of a ship. One of the key benefits of using conformal arrays is their ability to enhance the resolution of an antenna system, enabling it to detect and distinguish closely spaced objects. This is achieved by allowing non-uniform spacing between the antennas in tearray, which facilitates more accurate spatial sampling of incoming signals.

II. METHODOLOGY

Mathematical model

The reference system used for the mathematical model ofa conformal Uniform Rectangular Array (URA) is typically a Cartesian coordinate system. The Cartesian coordinate system is a three-dimensional coordinate system that uses three perpendicular axes, usually labeled x, y, and z, to define the position of an object in space. In the context of antenna arrays,the x and y axes are typically used to define the positions of the individual antenna elements in the URA, while the z axis used to define the distance between the antenna elements and the target object. The origin of the Cartesian coordinate system is usually located at the center of the URA as shown infig.2. In this system, we measure the angle θ from the z-axis, while we measure the angle ϕ from the x-axis. Specifically, θ represents the azimuth angle, ϕ represents the elevation angle,and r denotes the vector to the observation location.

The mathematical model of a conformal array can be described using various parameters, such as the spacing between the antenna elements, the size of the array, and the direction of the incoming signal. By using the Cartesian coordinate system as a reference system, the mathematical model can accurately describe the physical properties and behavior of the conformal array in various applications, such as radar systems and communication systems. Let us assume that there are two narrow-band signals received on either a Uniform Rectangular Array (URA) or a Conformal array from two closely spaced objects arriving from two unknown directions. First, we will consider the URA case. For the conformal array, the URA is projected onto a hemisphere shape. However, in a conformal array, the antenna element's broadside directions are typically oriented in multiple different directions.

$$(\theta, \phi) = (\theta_1, \phi_1), (\theta_2, \phi_2), ... (\theta_k, \phi_k) \quad (1)$$

The angle θ in this study is defined as the angle between thewave direction and the z-axis. The elevation angle ϕ is defined as the angle between the x-axis and the projection of the wave direction onto the X-Y plane. It is important to note that forthe hemispherical coordinate system used in this study, θ is in the range of [0, Π/2] and ϕ is in the range of [0, 2Π].The practical covariance matrix of array output (CMAO) is given by Equation 5:

$$x(t) = As(t) + n(t) \quad (2)$$

where $A = \{(\theta 1, \phi 1), (\theta 2, \phi 2),.... (\theta k, \phi k)\}$

As shown in equation 2, x (t) depends upon s(t) and n(t).

Where s (t) = Kx1 vector of source waveform

n(t) = Mx1vector of white noise

Now to calculate each individual element in' A', we use equation7.

$$a(\theta,\phi)=(1, e\, j(2\Pi/kc) dx \sin\theta\cos\phi + dy \sin\theta\sin\phi \;\ldots\ldots,\; e\, j\,(2\Pi/kc)\,(Mx-1)\, dx \sin c\cos\phi + (My-1)\, dy\, y \sin\theta\sin\phi\,) \quad (3)$$

Equation 3 is used to calculate each individual element in the array factor matrix 'A' for a conformal array in spherical coordinates, where is the elevation angle and is the azimuth angle. We assume that M_{xx} and M_{yy} denote the number of elements in the x and y directions, respectively, with corresponding element spacing denoted as dx_x and dy_y, respectively and k is the wave number. The exponential term in the equation represents the phase shift of the signal as it travels from each element to the receiving antenna.

The covariance matrix of array output (CMAO) in theory can be represented as a (M x M) matrix R and is given by equation 4,

$$R = E\,X(t).X^H(t) = ARsA^H + \sigma^2 I \quad (4)$$

where *Rs* is the K x K signal covariance matrix, I is the M x M identity matrix, σ^2 is the noise variance, and E(.) represents mathematical expectation. The superscript {H} denotes matrix Hermitian transpose.
The practical covariance matrix of array output (CMAO) is given by Equation 5;

$$R = 1/N \sum_{t=1}^{N} X(t) X^H(t) \quad (5)$$

In a conformal array, the mathematical modeling of the steering vector for arbitrary geometry can be represented as:

$$a_k = [\, g_1 e^{-jk0p1ui},\ g_2 e^{-jk0p2ui} \dots\dots\dots\dots g_n\, e^{-jk0pmui}]^T \text{ ....where (k=1, 2…n) (6)}$$

Here, k 0= $2\pi/\lambda$ and λ is the wavelength. The vector *pi* (i=1,2,.....m) denotes the coordinate vector for each element and *ui* represents the unit vector in the ith direction for the i[th]signal. Similarly, *gi* ....(i=0,1,.....m) is the pattern of each element and *pi* (i=0,1,......m) is the unit vector made up by element and origin of the whole coordinate system. The position vector of the n[th] array element is represented as p*n*, which is given by:

$$\overrightarrow{P_n} = x_n x\hat{} + y_n y\hat{} + z_n z\hat{} \quad (7)$$

Furthermore, let $u\hat{}$ be a unit vector in the direction of a plane wave incident on the array, which is given by:

$$u\hat{} = (-\sin\theta\cos\emptyset)\, x\hat{} + (-\sin\theta\sin\emptyset)\ y\hat{} + (-\cos\theta)\ z\hat{} \ (8)$$

Standard 2D MUSIC

The Eigen Value Decomposition (EVD) of theoretical CMAO and practical CMAO can be defined in a standard way as given by equation 9,

$$R = Z_s \pi_s Z_s^H + Z_n \pi_n Z_n^H \quad (9)$$

Where $Z_s = [Z_1, Z_2 \dots\dots Z_k]$, $Z_n = [Z_{k+1}, Z_{k+2} \dots\dots Z_M]$, $\pi_s = diag[\pi_1, \pi_2 \dots\dots \pi_k]$, $\pi_n = diag[\pi_{k+1}, \pi_2 \dots\dots \pi_{M,}]$ with the subscript s and n are standing for signal and noise subspace. Based on orthogonally between span (Vs) and span of V(n). The conventional 2D MUSIC algorithm suggests searching the following,

$$P_{2D}\_MUSIC = P_{2D-MUSIC}(\theta, \phi) = 1/a^H(\theta, \phi) Z_n Z^H\, a(\theta, \phi) \quad (10)$$

over the total 2D angular field of view $[0, \pi/2]$ ans $[0,\ 2\pi]$ with a fine grid. K peaks of P_MUSIC(θ) indicate source DOAs.

Proposed method

In this study, we have chosen two different antenna structures, namely URA and conformal array. To better understand the effect of array size on the performance variation in the direction of arrival, we have examined two different array structures, namely conformal array and rectangular array. To simplify the calculations, we placed the scanning element at (0,0,0) in the spherical coordinate system. The distance between the object and the scanning element was normalized. We selected two frequencies that strike the receiver from two closely spaced objects: 1.6KHz and 1.8KHz. The direction of arrival for the first object was set to 16^o azimuth and 0^o elevation, while the second object was placed in the simulation at 17^o azimuth and 20^o elevation. We set the speed of light constant to 2.99792458 X 10^8, while the array operating frequency (f_c) was set to 3 X 10^8. We computed the wavelength (λ) using Equation 11.

$$\lambda = c/f_c \, (11)$$

where
c = speed of light
f_c = array operating frequency

The sampling rate was varied over four different values, namely 10, 100, 1000, and 10,000 Hz. A conformal array was designed with isotropic elements based on a uniformrectangular array (URA). The array size was varied in stepsof 4 from 4 X 4 to 8 X 8. The element spacing was constant and set to (λ / 2). The size of the inscribed disc for the conformal array was set to 8.5 X (λ / 2). The position ofeach element in the URA was updated based on this radius. A phased conformal array was created with a conformal elementfrequency range varying from 50MHz to 600MHz. Random noise

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with a maximum magnitude of 10% and phase shifts up to (360^o) were added to both signals before they were transmitted towards the conformal array. The total simulation time was set to 1.5 seconds.

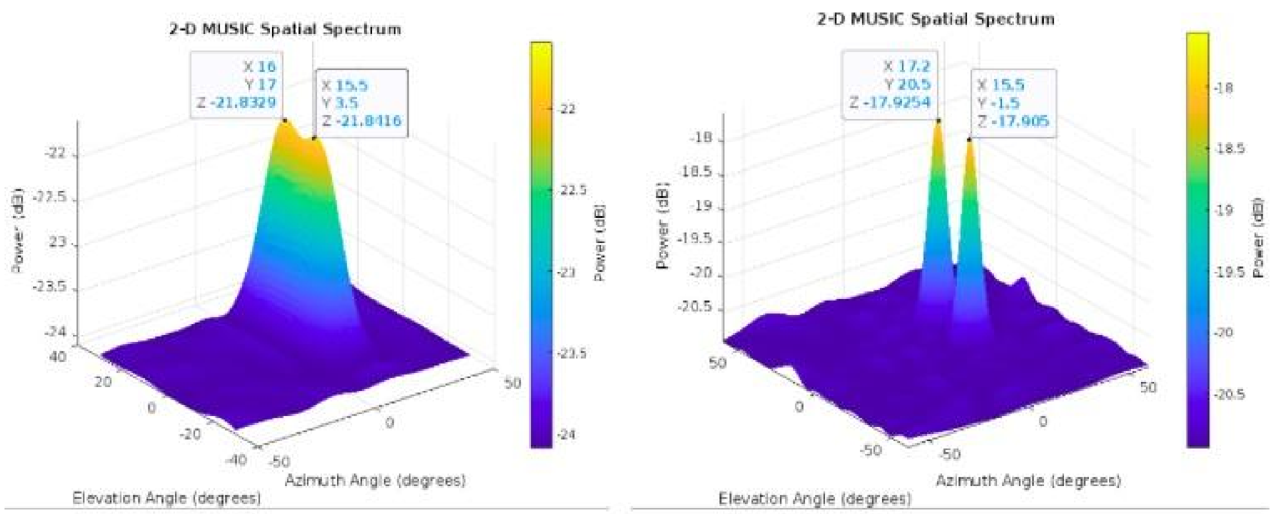
We utilized a 2D Multiple Signal Classification (MUSIC) estimator for our analysis. The estimator received information regarding the sensor array, positioning of the conformal array element, operating frequency, number of signal sources, and the output port number for the direction of arrival. The simulation varied both azimuth and elevation angles withinthe range of -60^o to +60^o, with a step size of 1^o. Finally, the output from the estimator was plotted as a 3D graph.

III. RESULTS AND DISCUSSIONS

The selection of the array type was based on its abilityto distinguish between two closely spaced targets. Figure 3 displays the separation capability of the two closely spaced objects, where Figure 3(a) shows the performance of the uniform rectangular array (URA), and Figure 3(b) shows the performance of the conformal array when varied within the range of 60^o to -50^o. We considered a 16 x 16 array in boththe URA and conformal array with a sampling frequency of 1000 samples/second. It was observed that the 2D MUSIC spatial spectrum using the URA was unable to separate the two peaks, while the conformal array was able to distinguish between the two peaks of the closely spaced arrays. However, grating lobes were more pronounced in the conformal array with an increase in sampling frequency or number of samples per second. As shown in Table 1, there is a difference in the actual azimuth and elevation angles. The use of the conformal array resulted in less error compared to the URA. Additionally,the power level of the conformal array signal was better than that of the URA for DoA estimation.

TABLE I: ESTIMATION OF AZIMUTH, ELEVATION ANGLE WITH POWER COMPARISON

Parameters	Actual Azimuth angle and elevation angle	Estimated angle with URA	Estimated angle with conformal array
Az1	17^o	16^o	17.2^o
Az2	16^o	15.5^o	15.5^o
E1	20^o	17^o	20.5^o
E2	0	3.5^o	-1.5^o
Power in (dB)	-	-21.8	-17.92^o



a) With Uniform Rectangular array b) With Conformal array

Fig. 3. Graph showing power output variation with respect to azimuth and elevation angle variation to evaluate the performance of 2D-MUSIC with (a) URA and (b) Conformal Array.

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The performance of the proposed DOA estimation system with respect to the sampling frequency is illustrated in Figure 4. Figure 4a shows that at N=10, the DOA has a clear separation of roughly 1dB between the two closely spaced objects with minimal noisy lobes. However, when URA is considered, only one peak is available at N=10, meaning that the two nearby objects cannot be resolved. Figure 4b shows that at N=1000, the spacing between the two lobes has reduced to a 0.5dB difference, and the noisy lobes at the bottom have increased in number and magnitude. As the number of samples increases, more noise enters the system from multiple antennas. Figure 4c shows that at N=1000, the difference between the two closely spaced object lobes has reduced to 0.3dB, while the noisy lobes in the periphery of the two main lobes are more in magnitude. Figure 4d shows that at N=10000, the MUSIC spatial spectrum does not significantly improve, and the difference between the two lobes is less than 0.5dB. The number of side-lobes around the main lobe is largerin magnitude, which is one drawback of using a conformal array. However, at a low number of samples, grating lobes arevery less.

The impact of MIMO transceiver array size on the detectionof direction of arrival is illustrated in Figure 5. In Figure 5a, with an array size of 4x4, small objects cannot be identified separately, and their signals are merged together to form a single large lobe in the center. Figure 5b shows the MIMO radar transceiver antenna spatial spectrum for an 8x8 array. Compared to the 4x4 array, closely spaced objects can be detected with a difference between the lobes of less than 0.2dB. Figure 5c shows the 2D MUSIC spatial spectrum response for a 16x16 array. With an almost four times larger size, the detection capability of two closely spaced objects hasincreased significantly. With the 16x16 array, the difference between the lobes can reach a magnitude of at least 3dB.The results presented in Table 1 were obtained using an 16 x 16 array size with a sampling frequency of 10. The table includes values for azimuth angle (Az), elevation angle (El), power (P), peak1 and peak2 (corresponding to the two objects),delta (variance), and valley (the minimum point between peak1and peak2 of the received waveform). The results show that the conformal array provides better resolution in both azimuthand elevation angle space compared to the uniform rectangulararray. The improvement in azimuth angle was observed to be 25%, while for elevation, it was 68%. Furthermore, the peak-to-valley ratio was found to improve by 3.36% with the conformal array. Additionally, the variance of the conformal array was smaller compared to the uniform rectangular array. Based on these results, it can be concluded that the conformal array outperforms the URA for DoA estimation of two closelyspaced objects.

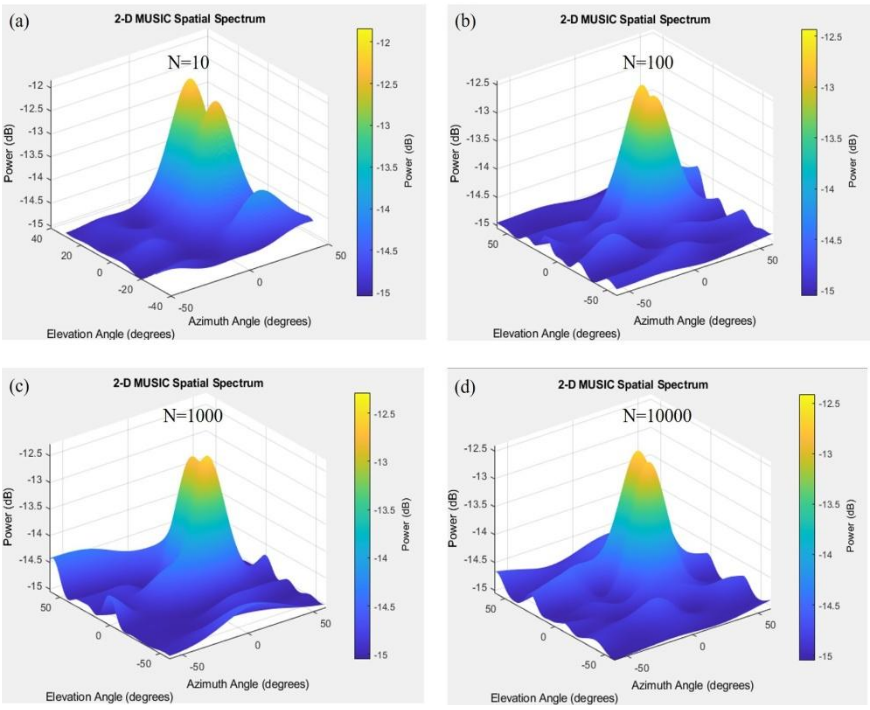

Fig. 4. Effect of sampling frequency on the performance of proposed DOA estimation system. a) at N=10 b)at N=100 c) at N=1000 d) At N=10000

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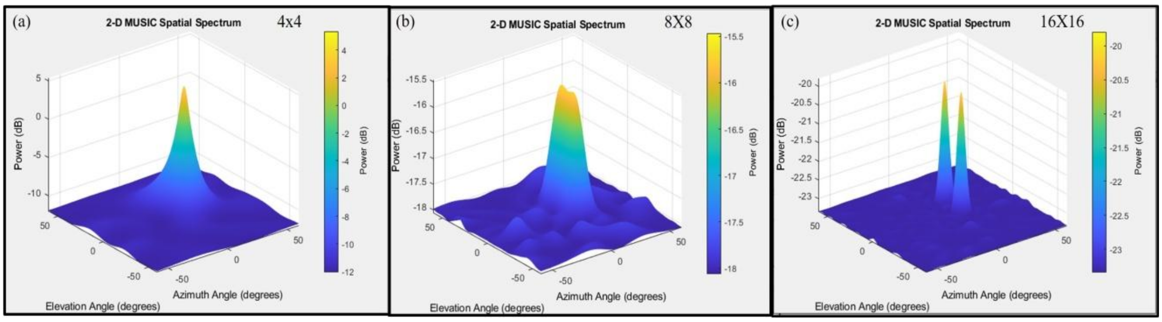

Fig. 5. Effect of transceiver array size on the detection ability of direction of arrival. a) Array size of 4x4. b) Array size 8x8 array.c) Array size 16x16 array

TABLE II: ESTIMATION OF AZIMUTH AND ELEVATION ANGLE WITH 16 X 16 CONFORMAL ARRAYS AND URA

Parameters	Estimated Angle with URA	Estimated Angle with Conformal Array
Az1	17°	16.8 °
Az2	15.5°	15.6 °
Delta(Az)	1.5 °	1.2 °
E1	15.5 °	17.2 °
E2	0	8 °
Delta(El)	15.5 °	9.2 °
P_{peak1} (dB)	-12.7 °	-12.22 °
P_{peak2} (dB)	-12.73 °	-12.62 °
P_{Valley} (dB)	-12.77 °	12.84 °

IV. CONCLUSION

In this study, we investigated the use of the 2-D Multiple Signal Classification (MUSIC) algorithm in DoA estimation with uniform rectangular and conformal arrays. The MUSIC algorithm was shown to reduce noise and improve output resolution. Our research revealed that conformal arrays do not have grating lobes, and with low sampling frequency, they caneffectively resolve two closely spaced objects, outperforming rectangular arrays. The ability to accurately detect and locate objects is critical in applications such as radar and sonar. Conformal arrays offer improved resolution and are suitable for air defense systems, where it is challenging to differentiate between two closely spaced objects with similar direction of arrival. In military applications, conformal arrays can distin- guish between closely spaced targets in the presence of strong interference and noise. Medical imaging can also benefit from conformal arrays, where they can enhance the resolution of ultrasound imaging for more precise detection and diagnosisof medical conditions.

REFERENCES

[1]. J. Xie, Q. Wang, Y. Wang, and X. Yang, "Efficienttwo-dimensional direction finding algorithm for rectilin- ear sources under unknown mutual coupling," *Sensors*, vol. 20, no. 7, p. 1914, 2020.

[2]. P. Persson, "Calculating geodesics on doubly curved surfaces: The case of a general paraboloid of revolution," 2000.

[3]. W. Bouwmeester, "Conformal phased array for disturb," 2020.

[4]. R. Schmidt, "Multiple emitter location and signal pa- rameter estimation," *IEEE transactions on antennas and propagation*, vol. 34, no. 3, pp. 276–280, 1986.

[5]. H. Krim and M. Viberg, "Two decades of array signal processing research: the parametric approach," *IEEE Signal Processing Magazine*, vol. 13, no. 4, pp. 67–94, 1996.

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International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
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[6]. C. Duofang, C. Baixiao, and Q. Guodong, "Angle esti- mation using esprit in mimo radar," *Electronics Letters*, vol. 44, no. 12, pp. 770–771, 2008.

[7]. L. Josefsson and P. Persson, *Conformal array antenna theory and design*. John wiley & sons, 2006.

[8]. X. Zhang, L. Xu, L. Xu, and D. Xu, "Direction of departure (dod) and direction of arrival (doa) estimation in mimo radar with reduced-dimension music," *IEEE Communications Letters*, vol. 14, no. 12, pp. 1161–1163, 2010.

[9]. M. Zhou, X. Zhang, X. Qiu, and C. Wang, "Two- dimensional doa estimation for uniform rectangular array using reduced-dimension propagator method," *Interna- tional Journal of Antennas and Propagation*, vol. 2015, p. 1–10, 2015.

[10]. F. Wen, J. Shi, and Z. Zhang, "Joint 2d-dod, 2d-doa, and polarization angles estimation for bistatic emvs-mimo radar via parafac analysis," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 1626–1638, 2019.

[11]. F. Wen, C. Mao, and G. Zhang, "Direction finding in mimo radar with large antenna arrays and nonorthogonal waveforms," *Digital Signal Processing*, vol. 94, pp. 75– 83, 2019.

[12]. B. Friedlander and A. Weiss, "Direction finding in the presence of mutual coupling," *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 3, pp. 273–284, 1991.

[13]. A. M. Elbir and T. E. Tuncer, "Far-field doa estimation and near-field localization for multipath signals," *Radio Science*, vol. 49, no. 9, pp. 765–776, 2014.

[14]. K. Aboul-Seoud, A.-D. S. Hafez, A. M. Hamed, and M. Abd-El-Latif, "A conformal conical phased array antenna for modern radars," in *2014 IEEE Aerospace Conference*. IEEE, 2014, pp. 1–7.

[15]. X. Lan, L. Wang, Y. Wang, C. Choi, and D. Choi, "Tensor 2-d doa estimation for a cylindrical conformal antenna array in a massive mimo system under unknown mutual coupling," *IEEE Access*, vol. 6, pp. 7864–7871, 2018.

[16]. A. M. Elbir and T. E. Tuncer, "2-d doa and mutualcoupling coefficient estimation for arbitrary array struc- tures with single and multiple snapshots," *Digital Signal Processing*, vol. 54, pp. 75–86, 2016.

[17]. Y. Cheng, R. Yu, H. Gu, and W. Su, "Multi-svd based subspace estimation to improve angle estimation accu- racy in bistatic mimo radar," *Signal processing*, vol. 93, no. 7, pp. 2003–2009, 2013.