Performance Enhancement of Array Configurations with DF Algorithms Based for RDF

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***Abstract*— Now adays, there are requirements for keeping communication in a perfect state. These requirements need to prevent disabilities that limit communication systems by monitoring spectrum, processing the interference, removing jammers and illegal radio frequency sources. Direction of arrival (DOA) estimation is one of the localization techniques that used antenna array and signal processing to localize the direction of RF sources in the field of Radio Direction Finding (RDF). In this paper, we implement the comparison of DOAs performance together with their different antenna array configurations such as Uniform Linear Arrays (ULAs), Uniform Circular Arrays (UCAs), and Uniform Rectangular Arrays (URAs). From this analysis, different criteria such as high frequency, correlated signal, closely spaced sources, and noise are considered, and the results show the graph of the power of the signals against the scanned angles in 2D and 3D dimensions. Therefore, it is concluded that (ULA) and (UCA) were proved a good performance according to the cases discussed in this article, and MUSIC confirms suitable performance with all simulation cases.**

Keywords*— *ULA, URA, UCA, RDF, DOA.

I. Introduction

Radio direction finding (RDF) is known as one of the most effective systems used to estimate the direction of a received signal from where it was transmitted. It indicates forms of radio or wireless communication that achieve many communication goals. It combines the received signals' direction information by using multiple antennas or smart antennas and digital beamforming to identify the angle of the coming signal [1],[2]. As known, the smart antenna is a system of multiple non-intelligence antennas that have digital processing algorithms responsible for the intelligent appearance of this system. Therefore, one of the most important specifications of smart antennas has the direction of arrival (DOA) algorithms which are represented the basic formation of the RDF system to estimate the direction of the signal by calculating the beamforming vectors. DOA algorithms are responsible for knowing the direction of emitters that provided the ability for locating and tracking the desired signal [3]. Direction of Arrival (DOA) estimation with different array geometry has wide applications in many communications fields, such as mobile communication, Electronic Surveillance Measure (ESM), radar, sonar, etc. The principle of these systems has been studied in this paper, which aims to obtain the best or the high-resolution DOA estimation of an emitter is of the utmost significance in many fields [5]. In recent years, many types of research and approaches and different DOA estimation methods, and various array geometries have been made. Subsequently, to achieve the best-desired requirements of these systems, one must consider an important matter: the selected array geometry with the DOA estimation method, responsible for the RDF system's overall performance. Clarification on this, each DOA algorithm gives a different performance when used with various arrays geometries. In another meaning, a certain array shape with the position of the elements in the array obliges conditions on the other DOA algorithms performance and proves different results of the RDF systems [5],[7]. From the DOA algorithm side, the algorithm is selected according to different limitations as the estimation accuracy has immunity or less affected to noise, multipath interference, and channel interference. Therefore, many DOA estimation algorithms such as MUSIC, Root-MUSIC, and WSF are considered super-resolution algorithms. Each one can operate with specific antennas arrays shapes. The DF algorithm selection along with array geometry comes to determine the best performance of DF estimation and to overcome ambiguities problems that concern employing a random array geometry for suppression the noise and interference, which is one of the most impeding factors to select the DF techniques [5],[8]. However, many stable DF algorithms can operate with various array geometries. It is worth mentioning that the super-resolution DOA estimation methods prove more complicated to the DF systems than other DOA methods. Moreover, the DF algorithm efficiency can be evaluated by measuring the necessary performances with a specific array geometry, which are a very important matter to super-resolution techniques [9].

For array geometries side. There are DOA algorithms that have been tested with a single array geometry or more geometries, and evaluation comes through noting many standards for the array geometry performance. Many performance comparisons have been implemented on arrays design parameters: the number of elements, the element spacing, the number of incoming signals, and the number of snapshots for several array geometries [5],[11]. Moreover, the studies sometimes cover the types of elements. The obtained results are compared with other types applicable to the real-world situation where the amplitude and phase specifications of each element influence the overall system's performance. Some researchers compare the array antenna's geometries and impose element type with its phase and amplitude characteristics on the arrays. Various high-resolution DOA algorithms are possible impacts with various antennas element types. However, a smart antenna comes to gain the resolution of DOA applications [11],[12].

This paper study the impact of various array geometries with different DF estimation considering super-resolution DOA algorithms. It can be considered a unique approach for evaluating the effect of arrays geometries types on a super-resolution DF performance through mixing certain rules. The performance of each geometry is compared to several DOA estimations to achieve an accuracy criterion. We also select the best geometry for every DF algorithm. According to our knowledge, this proposed approach has not been studied completely to consider the standard to evaluate array geometries. We take different types of array geometry, ULA, URA, UCA geometries, to be used as equipment for RDF applications. Array geometries are of eclectic interest by their uniform performance over the different angles and simple concept geometry. It can easily be developed to get a new geometry by changing spacing elements or inserting new elements to the structure, or varying the geometry to obtain a better array performance in response to DOA estimation algorithms.

The residue of this paper is organized to present sections as follows. Section II introduces the antenna arrays geometries system for ULA, URA, and UCA and application scenarios as well as it discusses the brief description of the DOA estimation algorithms. Section III presents simulations' results with the comparative evaluation of each array geometry with the DOA estimation algorithm. Finally, Section IV confers the conclusions of this paper.

II. RESEARCH METHOD

A. *Overview of Antenna Array Geometry*

Scientists, including those interested in wireless communication, were working hard themselves as objectively exploring the multiple antenna field to achieve the best performance and reach the smart antenna concept. Smart antenna systems are swiftly appearing as important technologies to provide an optimal function to develop the overall DF system performance.

Besides the researchs in DOA algorithms, which allow the optimal performance of existing array geometries, it can be discovered array geometries with the best specifications [5],[11]. Multiple antennas are suitable for the RDF systems since they provide the DOA estimation of numerous almost impossible signals with a single antenna. By utilizing the digital signal processing techniques, a smart antenna can estimate accurate DOA, greater immunity to noise and interference, enhance the DF system behavior, and minimize overall infrastructure costs [8],[9].

This paper introduces the most common antenna array geometries that are also known as antenna array configurations. It demonstrates the arrangement of elements through different parameters such as with a number of elements and spacing of inter-element, which depends on the wavelength of the signal, as well as deals with the analysis of the specifications of array geometries such as radiation pattern and the time delay between elements that are considered as major impact the DOA performance. In smart antennas investigation that is suitable for RDF systems.

It has the most basic common types of antennas arrays geometries are uniform linear arrays (ULA), uniform circular arrays (UCA), and uniform rectangular arrays (URA), which are comprehensively studied. Various algorithms have been proposed to estimate the (DOAs) of signals arriving at the antenna array.

B. *Uniform Linear Array (ULA)*

Uniform Linear Array (ULA) is a set of antenna elements configured as a straight line placed on the axis. Each sub-element has a specific sub-spacing according to the frequency of the received signal. The first sub-element is placed at the origin position and becomes a reference position to the other sub-element arranged beside it [11],[13]. ULA is a conventional type of antenna array geometry that is considered the antenna arrays' base configuration. Furthermore, it is a very important matter to study the impact of ULA on the performance of DOA algorithm estimation because of its simple structure and widely used. Recently, some super-resolution DOA estimation algorithms are operated only with ULA.

However, it has many drawbacks: it can estimate angles only in the range from 0 ° to 180 ° and receive information with one-dimensional angular only [13]. As shown in Fig. 1 and Fig. 2, the array elements are arranged in the x-axis so that the signal is received in each of the antenna from the reference element to the last element [4]. ULA accumulates the incoming signals from a direction of angle related to the broadside of the array.

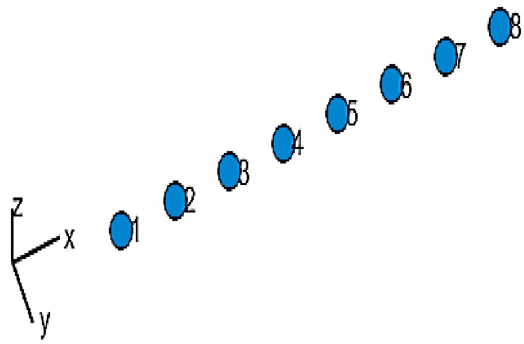

Fig. 1. ULA geometry with eight elements

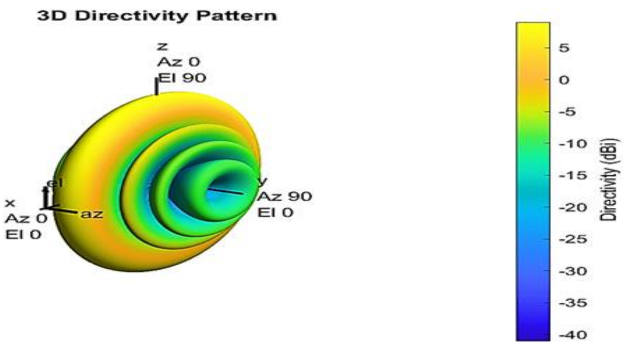

Fig. 2. (3D)- Directivity pattern of ULA

C. *Uniform Rectangular Array (URA)*

Uniform Rectangular Array is a set of antenna elements configured from two or more uniform linear sub-arrays put from the x-axes in the x-y plane. Each sub-element is equally spaced according to the wavelength of the incoming signal. The first element is placed at a specific point, known as a reference point, and other elements are arranged in a rectangular form [11]. URA configuration needs a large number of elements to work properly.

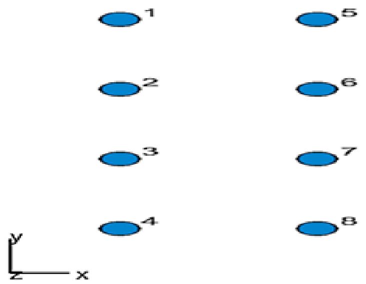

Fig. 3. URA geometry with eight elements

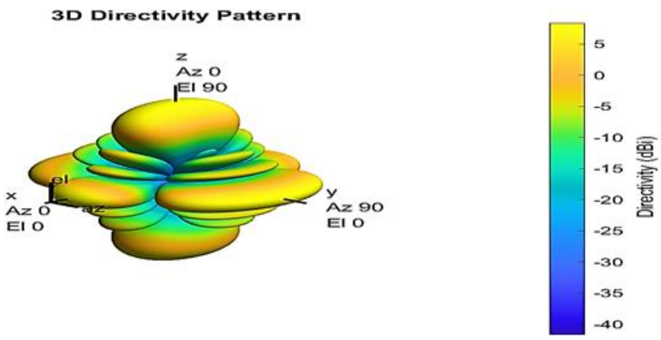

Fig. 4. (3D)- Directivity pattern of URA

However, in this paper, it is taken a minimum number of elements. It will also evaluate URA performance with the DOA algorithm estimation and other array geometries [5],[11]. In Fig. 3 and Fig. 4, the antenna array's rectangular configuration has a set of two ULAs located in parallel to the x–y plane [4]. URA is a widely used array geometry because it is a concentrated displacement type with many array elements placed in small plane space. Similarly, the smart antenna's performance can be enhanced by increasing the number of elements through a limited space.

D. *Uniform Circular Array (UCA)*

Uniform Circle Array (UCA) is a set of antenna elements configured as a circle form placed on the y-x axis. Each sub-element has a specific sub-spacing according to the frequency of the received signal. The first sub-element is placed at a distance from the original position, representing a radius and becoming a reference position to the other sub-elements arranged beside it [11],[13].

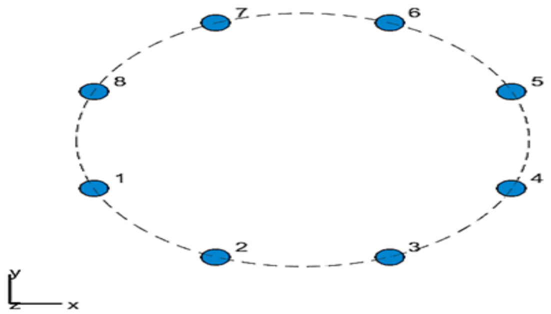

Fig. 5. UCA geometry with eight elements

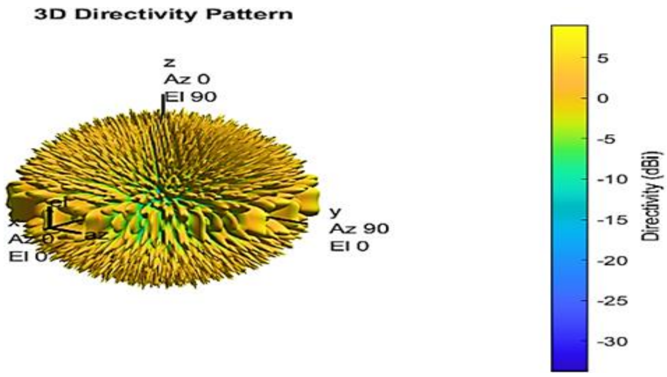

Fig. 6. (3D)- Directivity pattern of UCA

Figure 5 and Fig. 6 show UCA with eight elements forming a circle in the x-y plane and 3D directivity pattern [4]. It is profusely used because it has a good performance that can operate in two dimensions state and can prove a constant DOA estimation in the range from 0 ° to 360 ° to estimate the two-dimensional angular of RF source. In UCA, it needs more number array elements for improving performance. However, the calculation amount will be larger, and structures will become more complex [7]. Certainly, UCA is one of the most popular geometric shapes of arrays in studies because of the eclectic specifications.

Furthermore, along the z-axis, UCA is isotropic, which implies that the azimuth cannot influence DOA estimation performance. As mention previously, UCA is not a complex configuration. Therefore, there is a possibility to develop this configuration. With the insertion of two elements, upper and lower, the circle center takes another arrangement known as a spherical array [11].

E. *Overview of DOA Estimation*

The antenna array development has made DOA estimation techniques a very important part of smart antenna systems' efficient functioning. The antenna array receives various signals a collects data from all its elements after that does the combination of the spatial signals. Furthermore, it has optimally processing techniques to process the collecting data for estimating the Directions of Arrival (DOA) of the incoming signals through the high-resolution DOA algorithm's estimation. DOA algorithms are considered a vital part of the smart antenna [7],[8]. The DOA estimation techniques can be divided into two main methods, spectral-based and parametric methods. First, the spectral-based methods, which are called conventional methods, provide DOA estimates by capturing the highest peaks of the function determined with the range of interesting angles. The parametric methods provide a synchronous scan for all important parameters and with the needs of more computational complexity; these methods prove a more accurate DOA estimation [7],[8]. DOA estimation is the researchers' favorite topic in the smart antenna field, specifically high-resolution algorithms highlighted in this paper. The first proposed algorithm is the Spectral Estimation Method by Bartlett, which is Beamscan. It estimates the DOA by calculating the spatial spectrum and selecting the maximum peak [8][10]. The second proposed by J. Capon is the Minimum Variance Distortionless Response (MVDR) algorithm, which makes spectrum estimation and then applies the Maximum likelihood (ML) [13],[10]. The third proposed is MUSIC by Schmidt, which estimates through analyzing orthogonal subspaces, which are signals subspace and noise subspaces [6]. Later, MUSIC was improved by Barabell to become more accurate, called ROOT-MUSIC [6],[10]. The fourth proposed is the Root Weighted Subspace Fitting (ROOT-WSF) algorithm is an eclectic approach compared to other DOA algorithms. This paper shows the effect of using array types on different DOA algorithms, including Beamscan, MVDR, MUSIC, ROOT-MUSIC, and ROOT-WSF algorithms [4].

III. Results and Discussions

This study's results are presented in this sector to show the various array geometries' performances with different DOA algorithms. The study considered several tests by changing different affected array geometry and take the following parameter for all tests such as frequency 2.4 GHz for Wi-Fi applications, the number of incoming signals (3), the number of antennas (8), and the number of the snapshots (2000). Firstly, the three types of array geometries, ULA, URA, and UCA, are experimented with spatial spectrum DOA algorithms such as Beamscan, MVDR, and MUSIC. Secondly, all tests for five DOA algorithms show in Table I, Table II, and Table III with checking the better performance can be obtained for Wi-Fi applications. In these simulations' experiments, all arrays' geometries have been considered with the sub-antenna spacing of $\lambda/2$, where λ is the wavelength of incoming signals. The presented simulation results are implemented by MATLAB R2020a.

A. *DOA Spatial Spectrum*

In the following sector, array's geometries performance is evaluated using DOA spatial spectrum techniques. Therefore, the test results are considered based on the graphs of power against the scanned angles. The simulation results are shown for the following three types of arrays geometries. The simulation deals with a one-dimensional array and two-dimensional array, respectively.

1) *ULA - DOA Spatial Spectrum:* This part analyzes the performance of ULA with three DOA estimation algorithms, where the simulation was implemented with Beamscan, MVDR, and MUSIC algorithms. By using ULA, the DOA algorithms scan all the angles defined in the simulation. As shown in Fig. 7, it is the graph of power against the scanned angles. It has three curves for three DOA estimations to show the peak graph of DOAs mentioned above and configure a general idea of the chart, which can be used for data analysis and estimate the correct angle. In 1D-ULA-DOA estimation, the graph peaks are shown in Fig. 7, where the incident angles are 25, 40, and 55 degrees. There are three power peaks against incident angles distinguished easily in the MUSIC graph because peaks are near 0 dB to lower than -30dB. However, incident angles are not easy to differentiate from Beamscan and MVDR the curve because all power values are relatively close to the peak. Therefore, Fig. 7 shows the best result obtained from the MUSIC algorithm in using ULA.

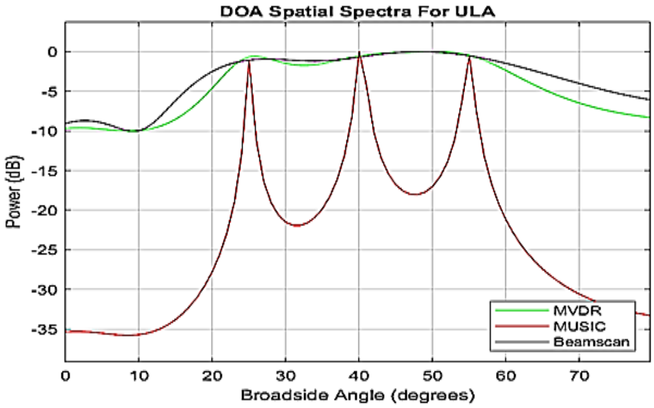

Fig. 7. Beamscan, MVDR, and MUSIC spatial spectrum For ULA

2) *URA -DOA Spatial Spectrum:* This part analyzes the performance of URA for three DOA estimation algorithms: Beamscan, MVDR, and MUSIC algorithms. By using URA, the DOA algorithms scan the angles in two-dimensional azimuth and elevation angle. Fig. 8, Fig. 9, Fig. 10, and Fig. 11 show that all charts are the graph of power against the scanned angles. Fig. 8 has three curves for the DOA estimation to show data analysis and estimate the correct angle. In 2D-URA- DOA estimation, the peak graph of two dimensions and three dimensions is shown in figures mentioned above, where the incident angles are 25, 40, and 55 degrees. There are three power peaks against incident angles, which can be organized only in MUSIC curve.

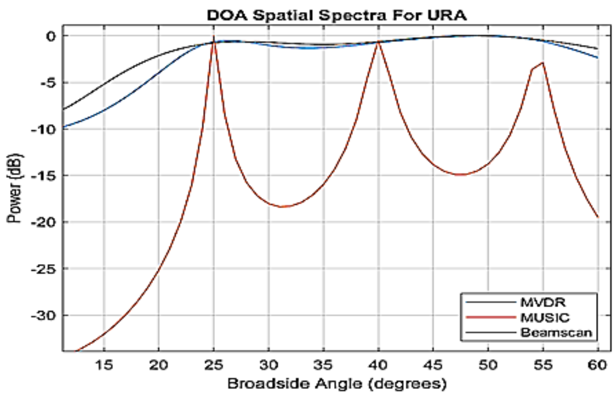

Fig. 8. DOAs spatial spectrum For URA

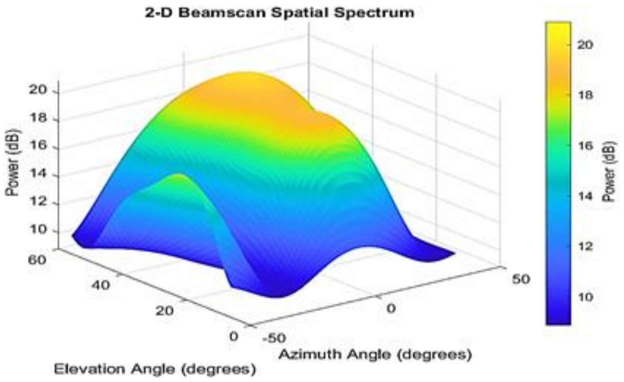

Fig. 9. Beamscan spatial spectrum For URA

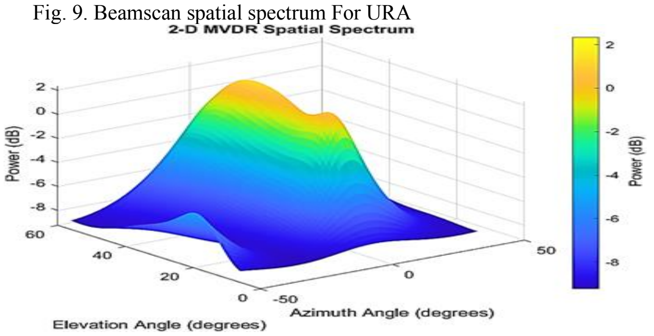

Fig. 10. MVDR spatial spectrum For URA

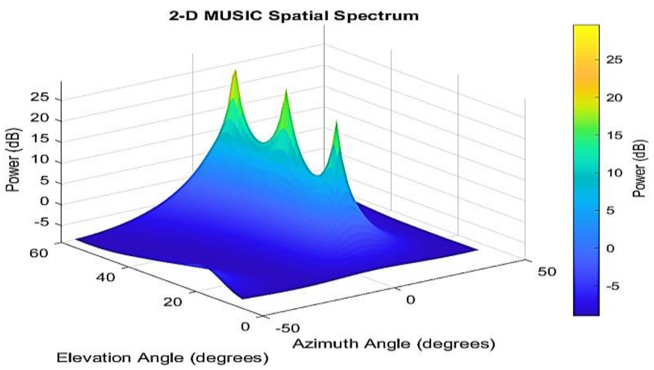

Fig. 11. MUSIC spatial spectrum For URA

3) *UCA DOA spatial spectrum:* This part analyzes the performance of UCA for three DOA estimation algorithms: Beamscan, MVDR, and MUSIC algorithms. Using UCA, the DOA algorithms scan the angles in two-dimensional azimuth and elevation angle., all charts are the graph of power against the scanned angles. Fig. 12, Fig. 13, Fig. 14, and Fig. 15 have three curves each for DOA estimation to show data analysis and estimate the correct angle. In 2D-UCA- DOA estimation, the peak graph of two dimensions and three dimensions is shown in figures mentioned above, where the incident angles are 25, 40, and 55 degrees. There are three power peaks against incident angles, which can be organized directly in the DOA curve. It is noted that Beamscan peaks are near 0dB to lower than -5 dB, MVDR peaks are near 0dB to lower than -8 dB, and MUSIC peaks are near 0dB to drop than -35dB. Therefore, the three DOA algorithms mentioned above proved a good estimation resolution with URA. However, Beamscan and MVDR curves are more difficult for distinguishing the incoming signals' angles than MUSIC.

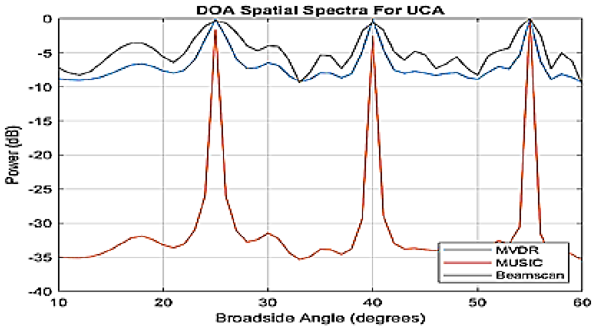

Fig. 12. DOAs spatial spectrum For UCA

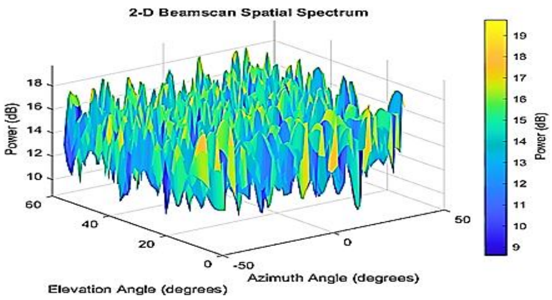

Fig. 13. Beamscan spatial spectrum For UCA

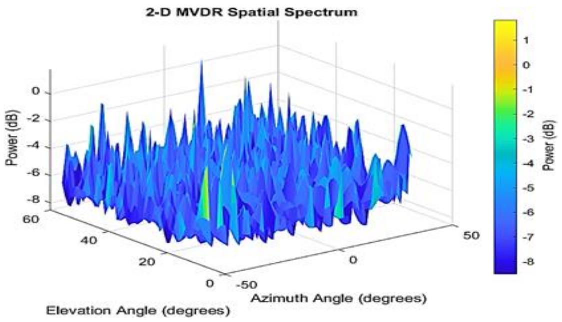

Fig. 14. MVDR spatial spectrum For UCA

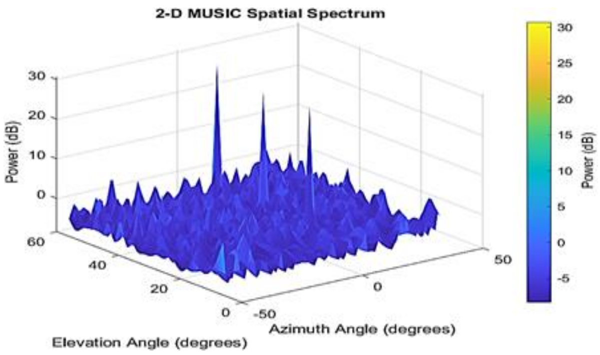

Fig. 15. MUSIC spatial spectrum For UCA

B. *Evaluation of Array Geometries with DOAs*

This section shows the effect of array antenna geometries on DOA estimation techniques. The simulation parameters considered are frequency (2.4GHz), the number of snapshots (2000), and the number of elements (8). It thought that three signals are incoming. Three angles must be estimated. The obtained results are shown in Table I,

Table II, and Table III that are considered with three incoming signals with angles 25, 40, and 55 degrees must be estimated with each DOA technique. Table I, MUSIC, ROOT-MUSIC, and ROOT-WSF proved a correct estimation compared with Beamscan and MVDR, which fail in estimation. In Table II, MUSIC demonstrated a good estimation resolution compared with Beamscan and MVDR, which fail in the estimation. ROOT-MUSIC and ROOT-WSF don't work with URA configuration. In Table III, MVDR and MUSIC give a correct estimation compared with Beamscan and ROOT-MUSIC, which have an incorrect estimation. Therefore, MUSIC provides a suitable performance and has a very high accuracy estimation with all array antenna geometries.

TABLE I. DOAS VS ULA

	Array Configuration	ULA		
	True Angle	***25***	***40***	***55***
1	Beamscan	27	3	48
2	MVDR	26	-51	51
3	MUSIC	25	40	55
4	ROOT-MUSIC	24.75	39.82	53.77
5	ROOT-WSF	24.89	40	54.92

TABLE II. DOAS VS URA

	Array Configuration	URA		
	True Angle	***25***	***40***	***55***
1	Beamscan	28	-	48
2	MVDR	26	-	49
3	MUSIC	25	40	55
4	ROOT-MUSIC	-	-	-
5	ROOT-WSF	-	-	-

TABLE III. DOAS VS UCA

	Array Configuration	UCA		
	True Angle	***25***	***40***	***55***
1	Beamscan	12	32	55
2	MVDR	25	40	55
3	MUSIC	25	40	55
4	ROOT-MUSIC	25.69	175	52.62
5	ROOT-WSF	-	-	-

IV. CONCLUSION

This paper presented a detailed analysis of array geometries performance effected on DOA algorithms estimation. It considers each case of same parameters for Wi-Fi applications, such as the number of array elements, incoming signals, and snapshots. Furthermore, according to array configuration, it is sure that the direction of incident angle is affected by signal detection. ULA operates in one dimension state such the incident angle comes close to 0 degree or 180 degree, the ability of ULA detection will decrease greatly.

However, URA and UCA can operate in two dimensions state. They can prove a constant DOA estimation in the range from 0 ° to 360 ° to estimate the RF source of two-dimensional angular. Therefore, from the analysis are made above, It is concluded that ULA had a good performance in the aspects of both accuracy and detection ability with MUSIC, ROOT-MUSIC, and ROOT-WSF over the various affected which is taken in this study and failed with Beamcans and MVDR methods. However, URA has relatively poor property in almost simulation and gives correct estimation only with MUSIC method. UCA proved a good estimation resolution with MVDR and MUSIC methods. It can be declared that ULA and UCA provide a better performance as compared with URA, which needs more elements for correct estimation. As well, MUSIC DOA estimation shows suitable performance in all simulation cases with all array geometries types. Therefore, this analysis will be desirable in future studies.

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