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Circular Array with Central Element for Smart Antenna

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Abstract Numerous studies of smart antennas have already been conducted using linear or planar arrays, not as much effort has been devoted to other configurations. The performance of smart antennas with circular array and circular array with central element are examined and simulated in C-band (4–8 GHz). In this paper, the first module presents the design of circular antenna array with central element suitable for beamforming technique in wireless applications. A circular arrangement of eight circular sector microstrip antennas is proposed, a central element was added to array to increase steering capability of proposed array. The second module suggests a MUSIC (MUltiple SIgnal Classification) to accurately estimate the DOA (Direction Of Arrival) of the signal of interest, and LMS algorithm for beamforming technique to concentrate the power in the desired direction and nullify the power in the interferer direction. The modelling and simulation of antenna array is computed using HFSS. The beamforming algorithm is designed in Matlab.

Keywords Smart Antenna, Circular Antenna Array, Array Factor, MUSIC, DOA, LMS

1. Introduction

Since the beginning of the twentieth century, antenna designers have investigated different antenna architectures to meet the requirements of communication systems. A large variety of antennas have been developed to date; they range from simple structures such as monopoles and dipoles to complex structures such as phased arrays. A detailed study of circular sector patch antenna is presented in[1]. This antenna has interesting dimension, so it can be integrated easily in antenna array.

Recently , Smart antenna[2-3] have received increasing interest for improving the performance of wireless radio systems, their application has been suggested for mobile-communications systems, to overcome the problem of limited channel bandwidth, satisfying a growing demand for a large number of mobiles on communications channels. However Conventional Antenna systems, which employ a single antenna, radiate and receive information equally in all directions. This unidirectional radiation leads to the distribution of energy in all directions.

This Wasted power becomes a potential source of interference for other users or for other base stations in other cells. On The other hand, smart antennas consist of an antenna array, combined with signal processing in both space and time, they are capable of automatically changing the directionality of their radiation patterns in the response to their signal environment so they basically attempt to enhance the desired signal power and suppress the interferers by beamforming toward the DOA (direction of arrival) of the desired signal and null steering in the case of the interferences. The smart antenna systems can be divided into two categories. These are: switched beam system, and adaptive arrays. In this paper adaptive arrays are investigated and used for smart antenna model.

MUSIC[4-5] algorithm is high resolution and accurate method which is widely used in the design of smart antennas. MUSIC is based on exploiting the eigenstructure of input covariance matrix.

Our smart antenna will be designed using a circular sector microstrip antenna. This antenna was studied in [1]. A circular arrangement of eight circular sector microstrip antennas is proposed, then we added a central element to array to increase steering.

This paper is organized as follow: Design and simulate of circular sector patch elements and arrays are presented in section II. In section III, DOA estimation algorithm is developed. Then, the DOA algorithm supplies this information to the beamformer to orient the maximum of the radiation pattern toward the SOI (Signal Of Interest) and to reject the interference by placing nulls toward their direction, followed by the conclusion.

2. Antenna Design

2.1. Single Element Design

Figure 1 shows the architecture of the proposed antenna. It is a circular sector antenna fed by microstrip line. The

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used substrate is RO3200 (εr = 10.2), thickness h=0.127 cm.The angle and radius of circular sector patch are respectively α = 90° and a=1cm.

In many applications it is necessary to design antennas with very directive characteristics to meet the demands of long distance communication. This can be achieved by forming an assembly of radiating elements in electrical and geometrical configuration, which is referred to as an array.

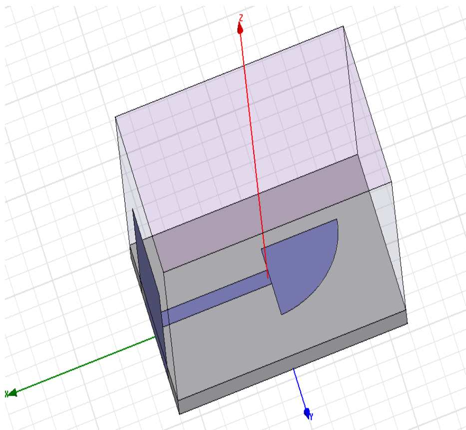


Figure 1. Circular sector patch antenna designed in HFSS fed by microstrip line

2.2. Array Design

2.2.1. Circular Array

The planar arrangements can be sub-divided into three other categories; circular, rectangular, and square. Among these three categories, the circular arrays do not have edge elements. Without edge constraints, the beam pattern of a circular array can be electronically rotated. Besides, the circular arrays also have the capability to compensate the effect of mutual coupling by breaking down the array excitation into a series of symmetrical spatial components[6,7]. Figure 2 presents the geometry of circular array antenna:

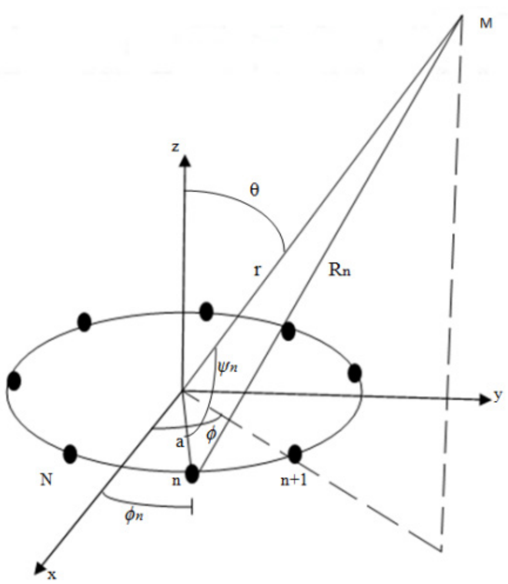


Figure 2. Circular antenna array[8]

The array factor at far-field point AF(θ,ϕ) is given by (1)

$$AF(\theta,\phi) = \sum_{n=1}^{N} I_n \, e^{j\,(ka\sin\theta\ \cos(\phi_n-\phi_0)+\alpha_0)} \quad (1)$$

Φn: The angular position of element n

αn: The phase of excitation of element n

In: The amplitude of excitation of element n

N: Number of element array

From (1), the AF is a function of the geometry of the array and the excitation phase, by varying the separation and/or the phase between the elements, the characteristics of the total field of the array can be controlled.

2.2.2. Circular Array with Central Element

The circular array can be designed with an element at the center as shown in figure 3:

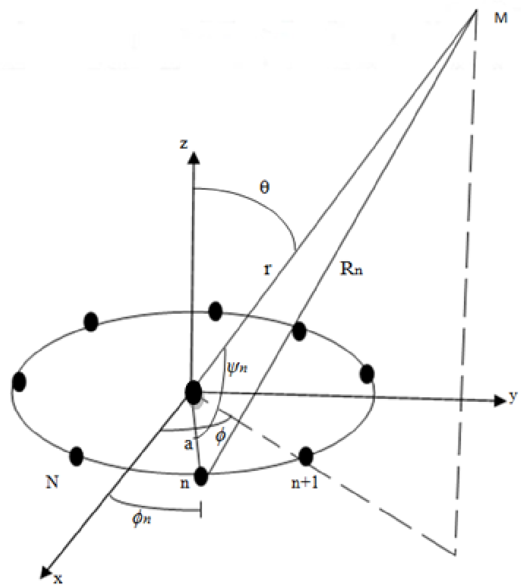


Figure 3. Circular antenna array with central element

Given that the modified array shown in Figure 3 has one antenna element at the centre and the radius for this element is 0, the displacement phase factor on the array factor becomes $e^{j\beta_x}$ where βx is the phase excitation of the element at the centre. The total field of the array is determined by the addition of the fields radiated by the individual elements. Thus, the resulting array factor for the modified array is the sum of the array factor of the standard circular array plus the antenna element at the centre:

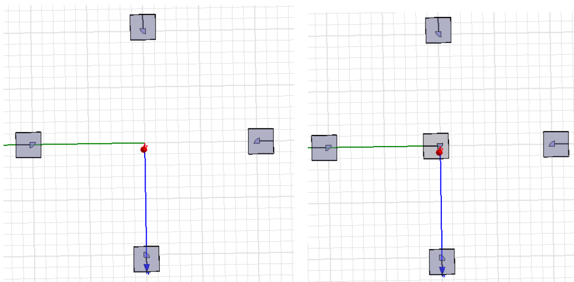
$$AF(\theta,\phi) = e^{j\beta_x} + \sum_{n=1}^{N} I_n e^{j[ka\ \sin\theta\ \cos(\phi-\phi_n)+\beta_n]} \quad (2)$$

This array factor represents the modified circular antenna array shown in Figure 3. To check the impact of central element, many arrays will be designed in the following section.

We presented in this section the basic notions of antenna arrays. These notions are used to predict the elements to be taken into consideration for the design of an array antenna to have desired characteristics. But the calculation of the radiation characteristic of an antenna array is very complex, even for the simplest array, which justifies the use of HFSS simulator method for the synthesis antenna.

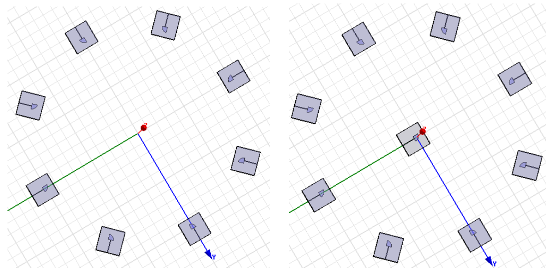
2.2.3. Proposed Design

Studied arrays will be designed using HFSS. The software enables to compute antenna array radiation patterns and antenna parameters. HFSS models the array radiation pattern by applying an "array factor" to the single element's pattern[9]. Figure 4 present studied Arrays. The radius of circular array is chosen to get an inter-element distance of 0.6λ. The numbers of elements for proposed arrays are 4 and 8. For arrays with central element, will be noted: 4+1 and 8+1.



(a) (b)

Four circular sector microstrip antenna in circular array:
(a) without central element (b) with central element



(c) (d)

Eight element circular sector microstrip antenna in circular array:
(c) without central element (d) with central element

Figure 4. Proposed antenna arrays

2.3. Simulation of Single and Antenna Arrays

2.3.1. Return Loss

Figure 5 shows the return loss simulated for proposed circular sector microstrip antenna.

This antenna resonates at three frequencies: 4.48 GHz, 5.27GHz and 7.8 GHz with return loss between -12dB and -14dB. So we can say that proposed antenna exploit well the C-band.

For all arrays, we got the same curve of single element. So changing number of element didn't impact return loss of antenna.

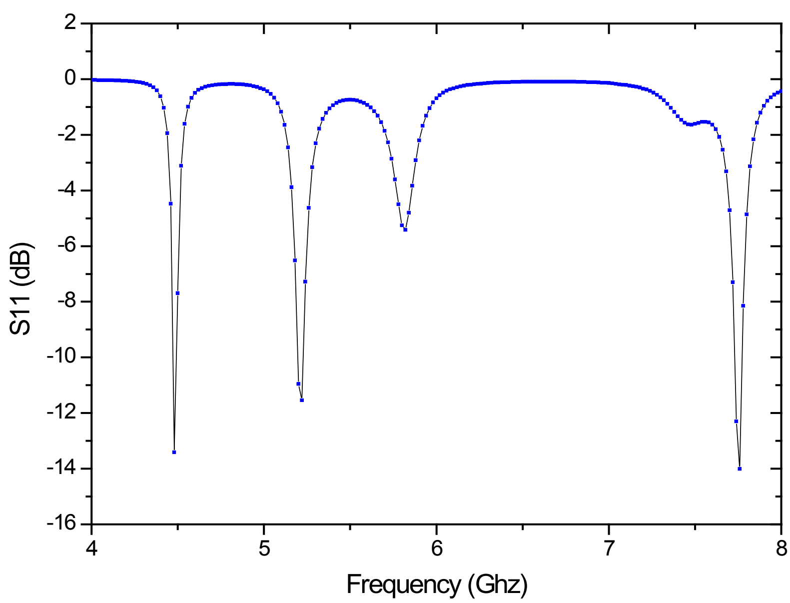


Figure 5. Return loss of rectangular and circular sector microstrip antenna in C-band

2.3.2. Radiation Pattern

The radiation pattern of an antenna is important in determining most of the characteristics which include beamdwidth, beam shape, directivity and radiated power. Radiation pattern is computed using HFSS. So in this section, we trace radiation pattern for single element, array of 4, 4+1, 8 and 8+1 elements.

In figure 6, we traced radiation pattern in E-plan of circular sector antenna. Main lobe is directive and there is no secondary lobe.

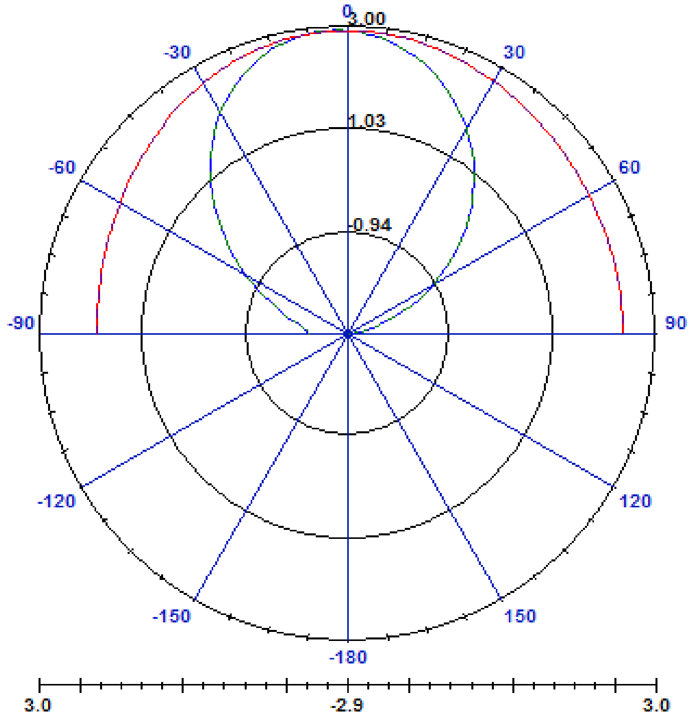


Figure 6. Radiation pattern of circular sector antenna at 4.48 Ghz

Figure 7, show radiation pattern of 4 and 4+1 array element. The main lobe is more directive than single element pattern, but there is more secondary lobe.

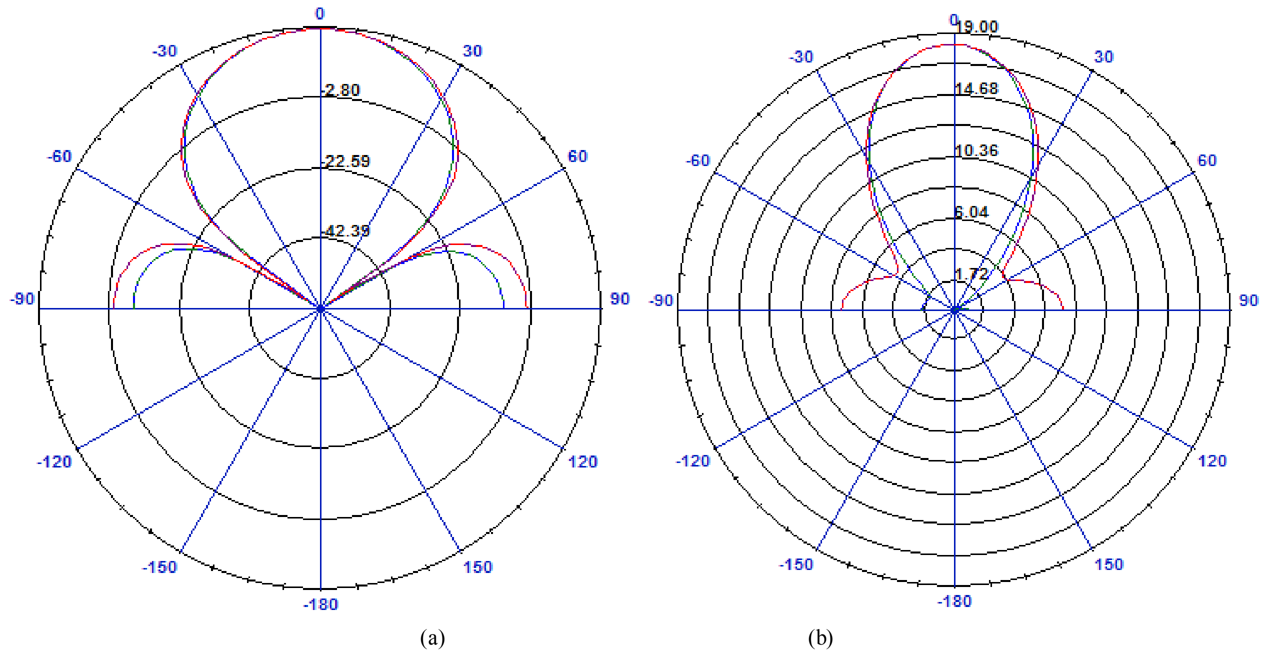
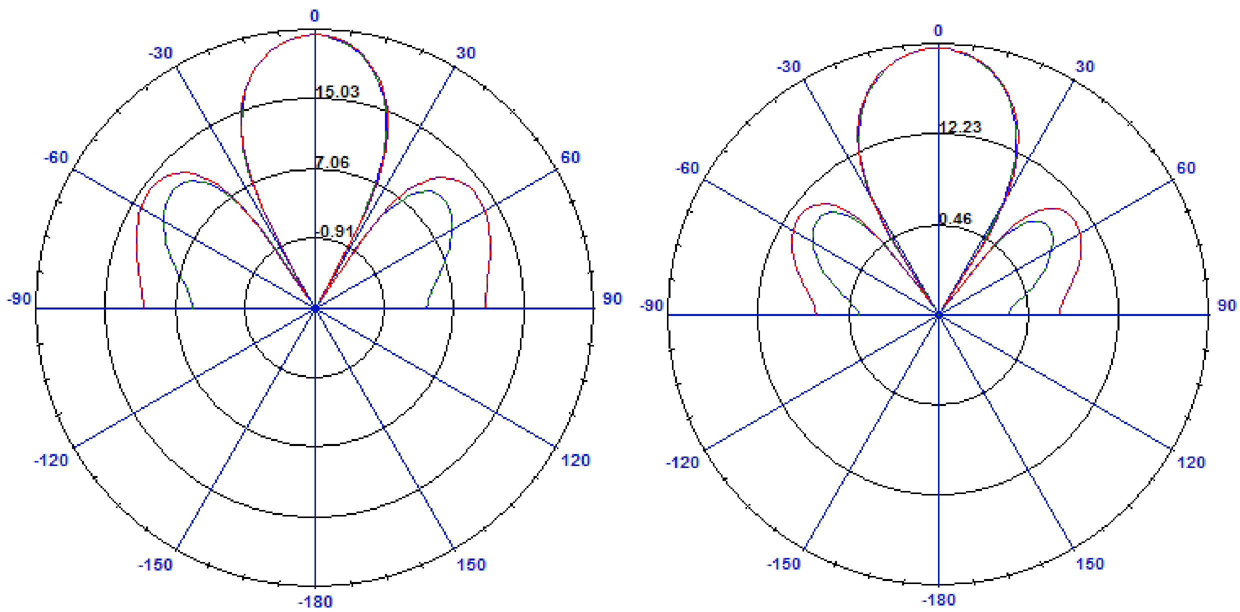


Figure 7. Radiation pattern of 4 element circular array (a) without central element (b) with central element

Then we trace radiation pattern of 8 and 8+1 element array:



(c) (d)

Figure 8. Radiation pattern of 8 element circular array (a) without central element (b) with central element

From Figure 6,7 and 8, it can be observed clearly that the beam widths of all major lobes became narrow and the number of side lobes increases, when the number of element increases.

A planar arrangement with an element at the centre increases array steering capability as well as reducing the side lobe levels.

2.3.3. Directivity and Gain

The directivity is a measure of the directional properties of an antenna compared to the isotropic antenna. The gain of the antenna directly depends on the radiation efficiency and the directivity of the antenna[10].

The table 1 show generated gain and directivity for circular sector antenna array for different number of elements (M = 1; 4; 4+1; 8; 8+1).

Table 1. Gain and directivity for circular sector microstrip antenna array for M = 1; 4; 4+1; 8; 8+1

Number of elements	Gain (dB)	Directivity (dB)
1	5	5.13
4	10.70	10.80
4+1	11.67	11.77
8	13.71	13.81
8+1	14.22	14.32

For array with larger the number of elements, the total gain and directivity increase. But we cannot increase number of element to infinite number, it's important to take in consideration the dimension of array.

3. Smart Antenna

A smart antenna is an antenna array system aided by some smart algorithm designed to adapt to different signal environments. A smart antenna is an antenna system that can modify its beam pattern or other parameters, by means of internal feedback control while the antenna system is operating.

The basic idea behind smart antennas is that multiple antennas processed simultaneously allow static or dynamical spatial processing with fixed antenna topology. The pattern of the antenna in its totality is now depending partly on its geometry but even more on the processing of the signals of the antennas individually. Several algorithms have been developed based on different criteria to compute the complex weights[11-12].

As illustrated in the figure 9, the smart antenna consists of N antenna elements separated from each other by a known distance d, and receives M signals. Let's define the array signal vector by:

$$X(t) = (X_1(t) X_2(t) \dots X_n(t) \dots X_N(t))^T \quad (3)$$

The incoming signal vector by

$$S(t) = (S_1(t) S_2(t) \dots S_m(t) \dots S_M(t))^T \quad (4)$$

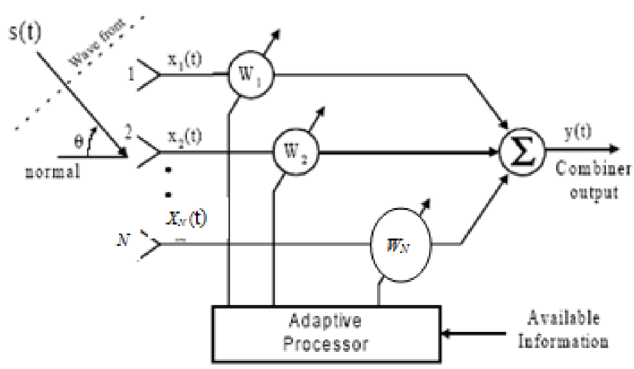


Figure 9. Smart antenna architecture

The noise vector by

$$n(t) = (n_1(t) n_2(t) \dots n_n(t) \dots n_N(t))^T \quad (5)$$

Where n(t) is a with a zero mean Gaussian white noise.

$a(\phi_i)$ is the steering vector of the array expressing its complex response to a planar wavefront arriving from direction $\phi_i = (\theta_i, \varphi_i)$. The array response vector $a(\phi_i)$ for circular array is given by:

$$a(\phi_i) = \begin{bmatrix} a_1(\phi_i) \\ \vdots \\ a_{N-1}(\phi_i) \\ a_N(\phi_i) \end{bmatrix} = \begin{bmatrix} e^{j\beta_x} \\ e^{j[ka\sin(\theta_i)\cos(\varphi_i - \varphi_1)]} \\ \vdots \\ e^{j[ka\sin(\theta_i)\cos(\varphi_i - \varphi_N)]} \end{bmatrix} \quad (6)$$

Now if we consider all sources simultaneously, the signal at the nth element will be:

$$X_n(t) = \sum_{i=1}^{M} a_n(\phi_i)\, S_i(t) + n_n(t) \quad (7)$$

And array factor

$$A = (a(\emptyset_1) a(\emptyset_2) \dots a(\emptyset_n) \dots a(\emptyset_N))^T \quad (8)$$

We can now write in matrix notation:

$$X(t) = AS(t) + n(t) \quad (9)$$

Let's denote the weights of the beamformer as:

$$W = (W_1(t) W_2(t) \dots W_n(t) \dots W_N(t))^T \quad (10)$$

Where W is called the array weight vector. The total array output will be:

$$y(t) = \sum_{m=1}^{M} W_m^* X_m(t) + n(t) = W^H X(t) + n(t) \quad (11)$$

Where superscripts T and H, respectively, denote the transpose and complex conjugate transpose of a vector or matrix.

3.1. DOA Estimation

In this paper, we use MUSIC to determinate DOA of signals impinging on smart antenna.

The received signal covariance matrix Rxx can be represented by

$$R_{xx} = AR_{ss}A^H + \sigma^2 I = U\Lambda U^H \quad (12)$$

U represents the unitary matrix (analogous to an orthonormal matrix if Rxx is real) and Λ is a diagonal matrix of real eigenvalues ordered in a descending order (first eigenvalue is largest)

$$\Lambda = diag(\lambda_1, \lambda_2, \dots, \lambda_M) \quad (13)$$

Any vector orthogonal to A is an eigenvector of Rxx with value $\sigma 2$ and there exist M-N such vectors. The remaining eigenvalues are larger than $\sigma 2$, which enable one to separate two distinct eigenvectors-eigenvalues pairs, the signal pairs and the noise pairs.

The signal pairs are governed by the signal eigenvalues-eigenvectors pairs corresponding to the eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_N \geq \sigma^2$, and the noise pairs are governed by the noise eigenvalues eigenvectors pairs corresponding to the eigenvalues $\lambda_{N+1} = \dots \lambda_M = \sigma^2$.

One can further express the received signal covariance matrix as

$$R_{xx} = U_s \Lambda_s U_s^H + U_n \Lambda_n U_n^H \quad (14)$$

Where Us and Un are the signal and noise subspace unitary matrices.

The key issue in estimating the direction of arrival consists of observing that all the noise eigenvectors are orthogonal to A, the columns of Us span the range space of A and the columns of Un span the orthogonal complement of A. By definition the projection operator onto the noise subspaces is:

$$P_n = U_n U_n^H \quad (15)$$

Assuming A is full rank (the signals are linearly independent), and since the eigenvectors in UnH are orthogonal to A, it is clear that

$$U_n^H A = 0, \quad \phi \in (\phi_1, \dots, \phi_N) \quad (16)$$

The estimated signal covariance matrix (from measurements) will produce an estimated orthogonal projection onto the noise subspace Pn. The MUSIC spatial "pseudo-spectrum" is defined as

$$P_{MUSIC}(\phi) = \frac{1}{a^H(\phi) P_n a(\phi)} \quad (17)$$

If ϕ is equal to DOA one of the signals, so the denominator is identically zero. Music, therefore, identifies as the directions of arrival, the peaks of the function PMUSIC (ϕ).

3.2. Adaptive Beamforming

Using the information supplied by the DOA, the adaptive algorithm computes the appropriate complex weights to direct the maximum radiation of the antenna pattern toward the SOI and places nulls toward interferes. The adaptive beamforming algorithm chosen in this project is the LMS for its low complexity [13-15]. The LMS algorithm is an approximation of the steepest descent method using an estimator of the gradient instead of the actual value of the gradient. This simplifies considerably the calculations to perform and allows the LMS algorithm to be performed in real time. Based on the array geometry of Figure 8, the signal received by the array is given by:

$$y(n) = W^H x(n) \quad (18)$$

The error is given by:

$$e(n) = d(n) - y(n) \quad (19)$$

The expression for weight updating:

$$W(n+1) = W(n) + \mu x(n) e^*(n) \quad (19)$$

μ is a step size parameter which is related to the rate of convergence; however, convergence of the w(n) is assured by the following condition:

$$0 \leq \mu \leq \frac{2}{\lambda_{\max}} \quad (20)$$

Where λmax is the largest eigenvalue of autocorrelation matrix Rxx of received signal.

4. Results Simulations

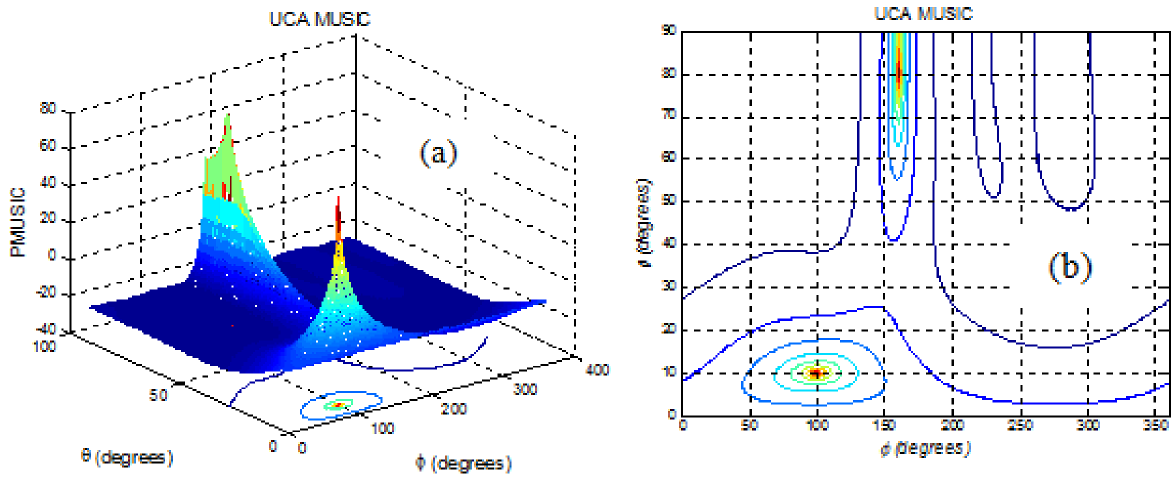


Figure 10. DOA estimations for F1 (a) 3-D spectrum MUSIC (b) 2-D spectrum MUSIC

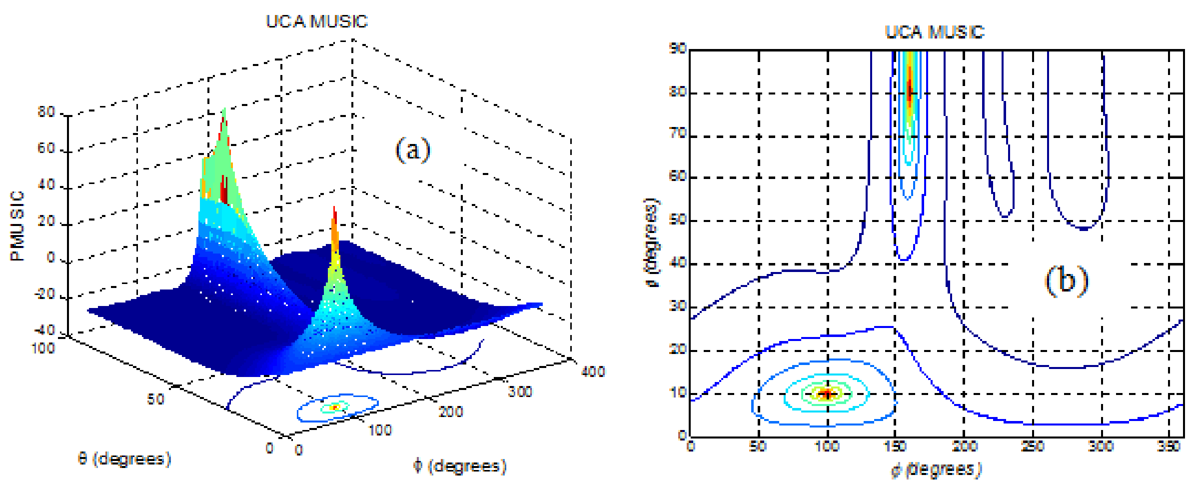


Figure 11. DOA estimations for F2 (a) 3-D MUSIC spectrum (b) 2-D MUSIC spectrum

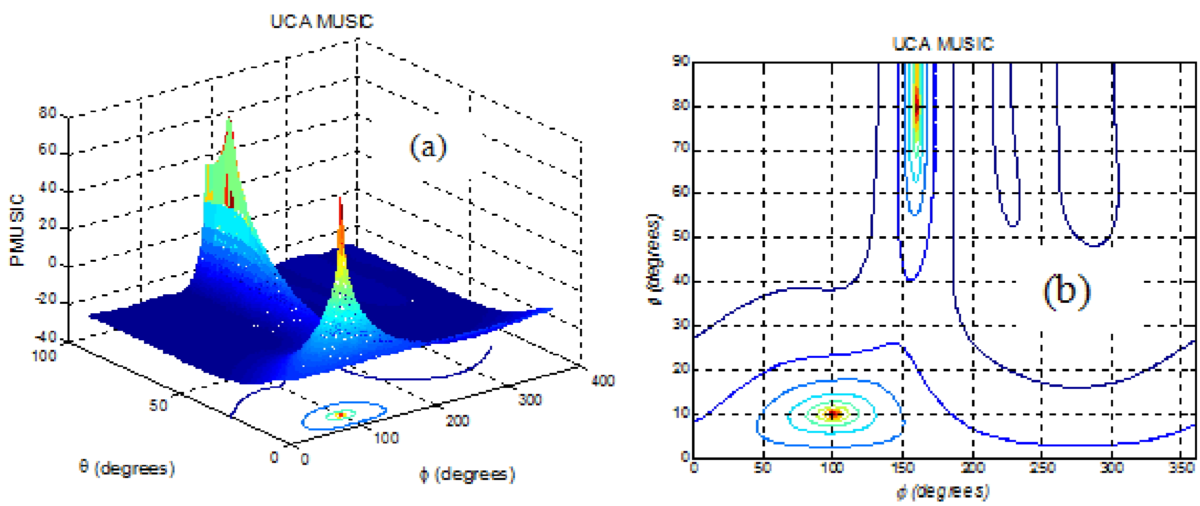


Figure 12. DOA estimations for F3 (a) 3-D MUSIC spectrum (b) 2-D MUSIC spectrum

The simulated system consists of an eight circular arrangement of circular sector antenna array spaced by distance d = 0.6 λ. It is assumed that there are two signals impinging on smart antenna with θ=[10°,80°] and φ=[100°,160°], the

SNR=20 dB. After the antenna array receives all the signals from all directions, the MUSIC algorithm determines the directions of impinged signals on antenna array as shown in Figures 10-12 for three frequencies F1=4.48 GHz, F2=5.27 GHz and F3=7.8 GHz, and 100 snapshots. Then an adaptive array is simulated in MATLAB by using the LMS algorithm. The true array output y(t) is converging to the desired signal d(t). The interferers are cancelled by placing nulls in the direction of the interferers. We have chosen step size = 0.01 for our simulation. After the calculating weights we apply the normalized weights as excitations in the designed antenna array. The resulting Array factor plot for θ and φ are shown in Figures 13-14 for three frequencies F1, F2 and F3.

Figures 10-12 show the MUSIC spectrum. Peaks of this spectrum indicate DOA of signals impinging on array antenna. MUSIC can accuracy estimate DOA with SNR=20 dB for the three frequencies.

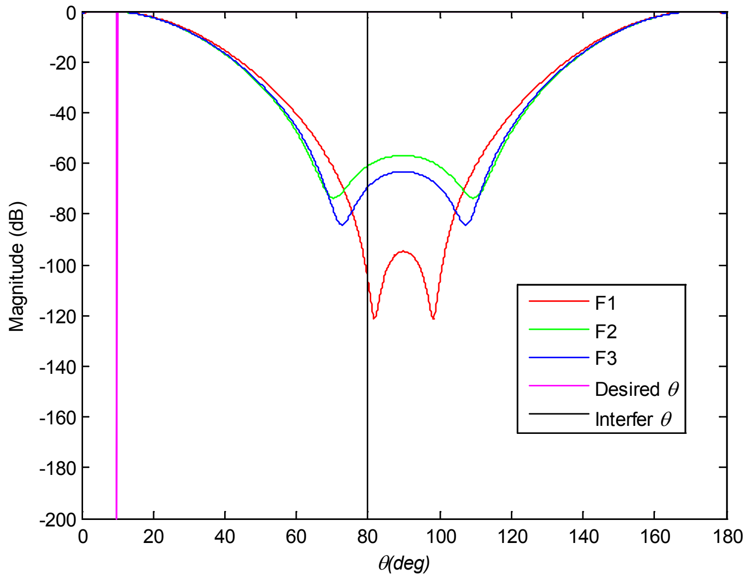


Figure 13. Array factor plot for θ

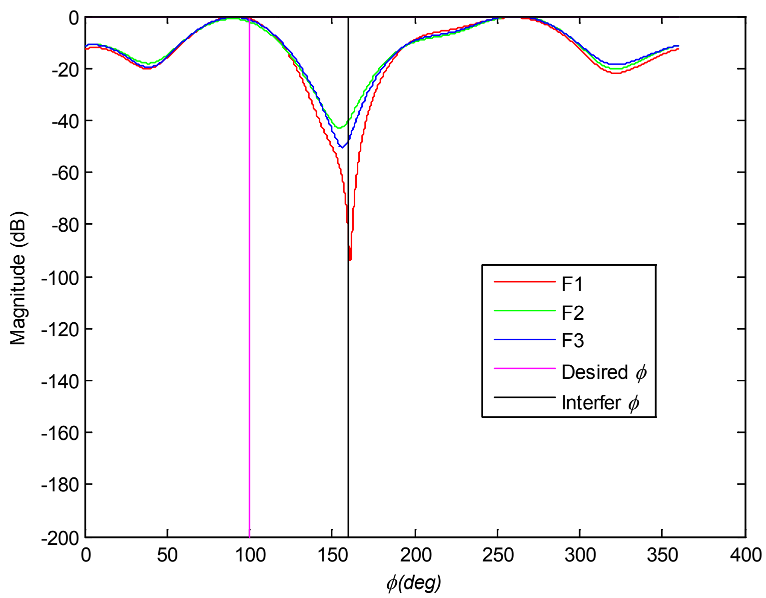


Figure 14. Array factor plot for φ

Figures 13-14 give good results for three frequencies, the main beam is centred on the direction of desired DOA θ=10° and ϕ=100° so Smart Antenna directs the main beam towards the desired signal and eliminates interferer by forming null in direction θ=80° and ϕ=160°, hence null is below -50 dB.

Figures 15-17 show the error between the output and the reference signal over 500 iterations for three frequencies, the error decreases much faster, consequently the convergence is reached after about 50 iterations, and the final error is very low.

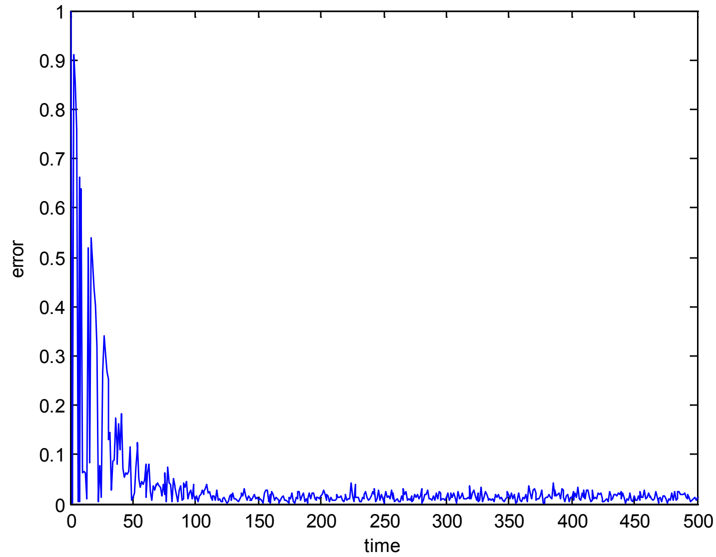


Figure 15. Error plot for LMS algorithm for F1

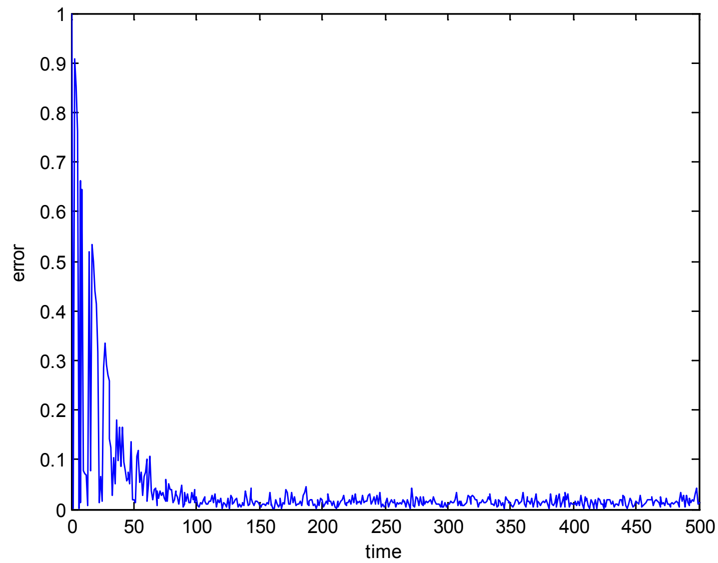


Figure 16. Error plot for LMS algorithm for F2

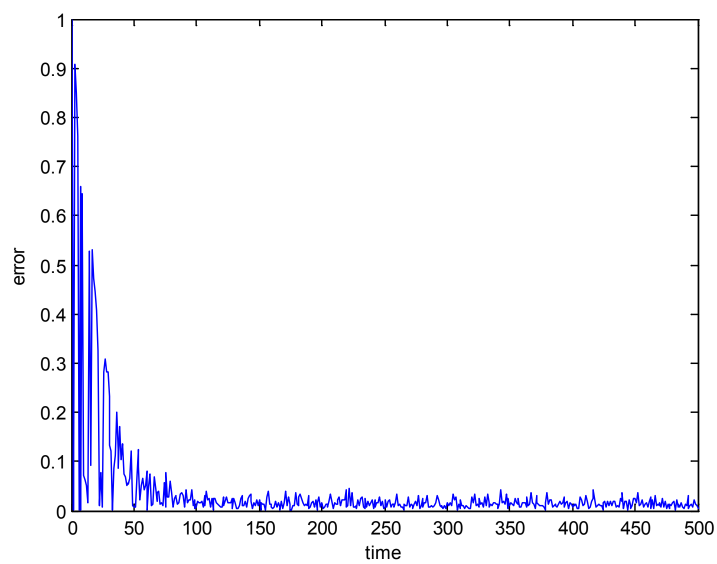


Figure 17. Error plot for LMS algorithm for F3

5. Conclusions

In this paper, we have presented an antenna array operating in C-band (4–8 GHz), which consists of eight circular sector patch elements. This antenna array has advantage to resonate at three frequencies: 4.48 GHz, 5.27 GHz and 7.8 GHz. A geometry modification to the conventional uniform circular antenna array has been proposed. This modification consists in the placement of one of the antenna elements at the centre of the array. This element modifies the overall radiation pattern in such a way that the directivity is increased whilst the half-power beamwidth angle is reduced. The result is a better capability of transmission in the desired direction and avoiding unwanted signals. It was also observed that the sidelobe levels of the radiation pattern were lower than those of the conventional circular antenna array which also helps to avoid interference.

DOA of desired and interfere signal was accurately estimated by MUSIC method. After LMS algorithm was applied to direct the main beam towards the desired signal and form null in the direction of interfere, consequently simulations demonstrate that this antenna is feasible for integration on smart antenna systems.

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