A Robust, 3-Element Triangular, Reflector-less, Single Beam Adaptive Array Antenna for Cognitive Radio Network: Inter-element Distance Dependent Beam

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***Abstract*— Cognitive Radio is a promising technique that allows the use of underused television spectrum to reach to remote, rural communication network users. In order to develop non-interfering, broad band communication link scattered users, there is a need for robust, narrow beam antennas with minimum of side lobes. In this paper we report the flexibility of a three element array antenna that produces single main beam with minimum negligibly small side lobes, without the use of any additional structures such as reflectors. The paper explores the geometrical arrangement and inter-element distances of such an antenna where single, rotatable beams are electronically produced towards pre-determined user clusters. The paper demonstrates the single beam, as opposed to multiple beams, that the antenna generates in different directions in the 360º of the horizontal plane, as well as the flexibility in changing the antenna size (that is the inter element distance), to successfully achieve the single beam antenna without resorting to the conventional reflectors that are used to flip the mirror beam that appears in linear array antennas. The analytical solution, as opposed to iteratively calculated solution using such techniques as least mean square (LMS) method, makes the digital beam steered reported herein light on memory and fast in solution to give the desired beam.**

***Index Terms*— Smart Antenna; Adaptive Array; Cognitive Radio; Single-Beam Array.**

I. Introduction

Cognitive Radio system belongs to the broader category of wireless communication systems which are required to operate in multipath, multi-mobile user, complex (e.g. underground) environment [1-7]. It often requires adaptive signal processing and localization of the user geographical cluster [8-11]. Cognitive Radio systems have entered into the mainline communications systems as an attractive technique to efficiently use the frequency spectrum, especially the unused spectrum of the band allocated for television broadcast [13-14]. The use of smart antennas to focus on a geographically clustered set of users, who may or may not be mobile, enables the service provider to direct the base station wireless antenna beam towards the users in a manner not to interfere with who may be registered to use the band or in the case when the band is completely vacant and unused. Smart antennas make use of stationary, mounted antennas on a transmission tower where the elements of the array antenna radiate signals in a manner where they strengthen each other in the direction where the antenna beam should be focused, while cancelling the radiation or reception in other directions where when transmitting the antenna should not interfere with other users making use of the same spectrum band, or in reception not to receive signals from certain known directions.

In most antenna arrangements, when the array elements are placed in a straight line, a reflect needs to be sued to direct the rotatable main beam (single beam) of the smart antenna to an azimuth angle that varies from 0^o to 180^o. Thus the unavoidable mirror image of the rotatable main beam that generated from 180^o to 360^o at the same time can be redirected in the direction of the main beam. Therefore, we need two sets of arrays placed side by side along with reflectors to have the single beam coverage of the entire azimuth angle from 0o to 360^o. In this paper we present a three element single beam reflector-less array antenna by placing the three elements at the vertices of a triangle with optimized current component to rotate the main beam (single beam) from 0^o to 360^o while retaining a narrow beam width and low levels of side lobes.

By placing array elements in unconventional manner [15] and appropriately adjusting the current component of every element as per the requirement of the main beam direction by using Least Mean Square (LMS) optimization, we are able to rotate the single beam electronically any direction through 0^0-360^0. The LMS based adaptive solver matches the beam generated to any desired beam. It is also shown that the beam width and the strength of the beam may be altered by changing the distance between each adaptive antenna element. With a single rotating beam the systems can cover an area of 360^0 while nullifying all other beams outside the look angle with the minimum 3 elements.

II. The Three-Element Adaptive Array

Analytically we can show that set of dipoles in a straight line produce the radiation pattern symmetrical on both side of the line of axis where the dipoles are placed. As a result it is not possible to direct the single beam in all directions by placing any number of dipoles in a straight line. However, our objective is to steer a single beam through 0^0-360^0. Therefore it is required minimum 3 dipole elements to be placed not in a straight line. Accordingly, we model a general setup as shown in Figure 1 where dipoles are not placed in a straight line, but in a triangular form.

The respective complex current phasors of the dipoles are taken as I_1, I_2, and I_n. Hence the electric field (far-field) at the observation point P could be given as:

$$E = A_0 I_1 e^{-j\beta r_1} + A_0 I_2 e^{-j\beta r_2} + \ldots + A_0 I_n e^{-j\beta r_n} \qquad (1)$$

where A_0 and β are a constant and the phase constant, respectively.

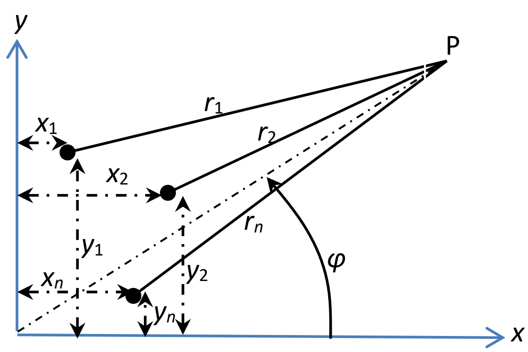


Figure 1: Schematic diagram of dipole placement

Substituting for r_1, r_2, and r_n in terms of the distance from origin, we can simplify equation (1) as the following:

$$E = w_1 e^{j\beta(x_1\cos\varphi + y_1\sin\varphi)} + w_2 e^{j\beta(x_2\cos\varphi + y_2\sin\varphi)} + \ldots + w_n e^{j\beta(x_n\cos\varphi + y_n\sin\varphi)} \qquad (2)$$

where w_1, w_2, and w_n are the complex weights and proportional to the complex current phasors I_1, I_2, and I_n. Since we are interested on resultant single beam, we need to optimize the value of the complex weights w_1, w_2, and w_n such that the resultant field must be matched with our desired single beam function $f(\varphi)$. Thus Equation (2) can be written as:

$$w_1 e^{j\beta(x_1\cos\varphi + y_1\sin\varphi)} + w_2 e^{j\beta(x_2\cos\varphi + y_2\sin\varphi)} + \ldots + w_n e^{j\beta(x_n\cos\varphi + y_n\sin\varphi)} = f(\varphi) \qquad (3)$$

The optimization of complex weights w_1, w_2, and w_n can be done either by analytical methods or iterative methods [12]. Since we wish to confine the number of dipole elements as few as possible, an analytical optimization method is more appropriate.

III. Weights for Forming the Beam

We have implemented the analytical method to optimize the complex weights w_1, w_2, and w_n. In equation (3), by multiplying complex conjugate of the first term $e^{-j\beta(x_1\cos\varphi + y_1\sin\varphi)}$ and integrate by angle φ over the limit from 0 to 2π, we get:

$$\begin{aligned} & w_1 \int_0^{2\pi} d\varphi + w_2 \int_0^{2\pi} e^{j\beta[(x_2\cos\varphi + y_2\sin\varphi)-(x_1\cos\varphi + y_1\sin\varphi)]} d\varphi \\ & + \ldots + w_n \int_0^{2\pi} e^{j\beta[(x_n\cos\varphi + y_n\sin\varphi)-(x_1\cos\varphi + y_1\sin\varphi)]} d\varphi \\ & = \int_0^{2\pi} f(\varphi) e^{-j\beta(x_1\cos\varphi + y_1\sin\varphi)} d\varphi \end{aligned} \qquad (4)$$

We can obtain n number of equations similar to (4) by multiplying with respective conjugates, if we consider n number of dipole elements. Hence the above n such equations can be written into a matrix form as:

$$\begin{bmatrix} A_{11} & A_{12} & \ldots & A_{1n} \\ A_{21} & A_{22} & \ldots & A_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ A_{n1} & A_{n2} & \ldots & A_{nn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \ldots \\ w_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \ldots \\ b_n \end{bmatrix} \qquad (5)$$

Where $A_{ij} = \int_0^{2\pi} e^{j\beta[(x_j\cos\varphi + y_j\sin\varphi)-(x_i\cos\varphi + y_i\sin\varphi)]} d\varphi$

$$b_i = \int_0^{2\pi} f(\varphi) e^{-j\beta(x_i\cos\varphi + y_i\sin\varphi)} d\varphi .$$

Thus the optimized coefficients can be obtained by:

$$\begin{bmatrix} w_1 \\ w_2 \\ \ldots \\ w_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \ldots & A_{1n} \\ A_{21} & A_{22} & \ldots & A_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ A_{n1} & A_{n2} & \ldots & A_{nn} \end{bmatrix}^{-1} \begin{bmatrix} b_1 \\ b_2 \\ \ldots \\ b_n \end{bmatrix} \qquad (6)$$

where the matrix elements A_{ij} and b_i are numerically calculated.

IV. Results for Beam-Steering and Different Inter-Element Distances

We have considered 3 element array as shown in Figure2. The desired function we have chosen is the sinc function as defined below.

$$f(\varphi) = \text{sinc}(\varphi - \varphi_0) \quad (7)$$

where φ_0 is the desired angle.

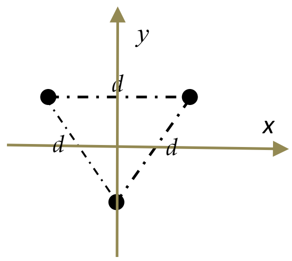
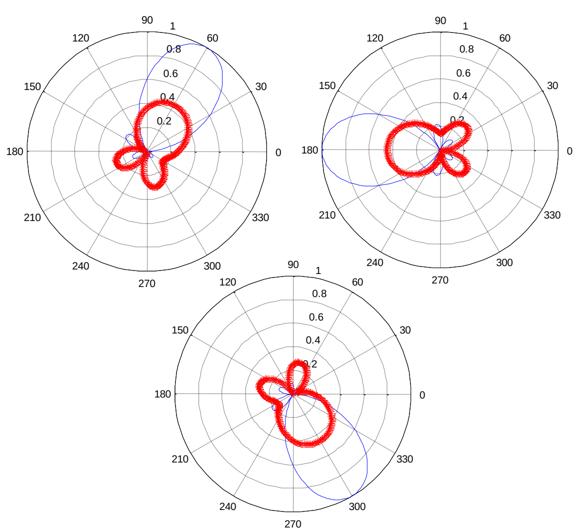


Figure 2: Schematic diagram of the Equilateral Triangular array model

With these simulation parameters, we turn to MATLAB to verify our analytical results. The radiation pattern in Figure 3 shows the results obtained from our MATLAB simulations when the distance between the dipoles is half-wavelength while the desired angles are 60^0, 180^0 and 300^0. It is seen that the optimized pattern falls in line with the desired pattern, except that the signal strength is smaller. The results shown in Figure 3 also demonstrates that when the e desired beam is rotated over the entire space, the optimized beam using the weights calculated from (6) is able to match and to steer the beam to follow the geographical cluster of users. In Cognitive Radio systems, thus the spectrum may be efficiently used for both stationary and mobile users, enabling the unused spectrum which itself may be time, and space dependent in its characteristics.

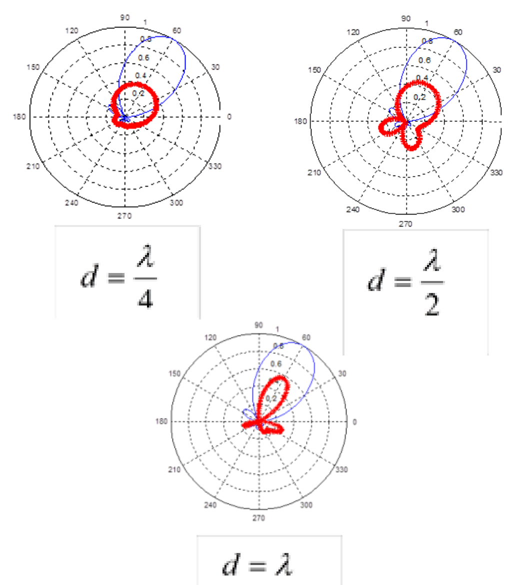


BeamDesired ****** BeamOptimized Beam

Figure 3: Beam Rotation of 3 Element Array

In order to study the beam-width and side-lobe variation with the change of the distance between dipoles, the distance between two dipoles are selected as quarter, half and full wavelengths. The comparison between the radiation patterns and the distance between two dipoles are obtained as shown in Figure 4. As we have expected, when the distance between two elements is smaller, the beam-width is larger while the number of side-lobes reduces. The inter element distance dependence is due to the delay between the two field components at the receiver point is smaller since the delay is depends on the angle of arrival and the distance between two elements. Hence it is expected that there is large angle of arrival (beam-width) between peak and null points. On the other hand, when the distance between two elements increases, the angle of arrival (beam-width) is small between the peak and null points while the number of side lobes increases. In this case, we optimized the beam using three elements. Therefore the peak direction is single but the number of side lobes increases with increasing distance between two elements.

Finally, by using half-wave dipole elements, the three dimensional radiation patterns were obtained and shown in Figure 5. The three dimensional beam patterns are shown for different observation directions. In case, the radiation pattern of the beam needs to be changed in the vertical plane, different type of dipole elements is to be selected. The entire beam characteristics in the three dimensional space depend on the type of dipole and the distance between two adjacent dipole elements. The overall results obtained ensure that a single rotatable beam is possible with three dipole elements placed not in straight line, but at the vertices of an equilateral triangle.



Desired Beam ****** Optimized Beam

Figure 4: Beamwidth and side lobes with varying distance between antenna elements

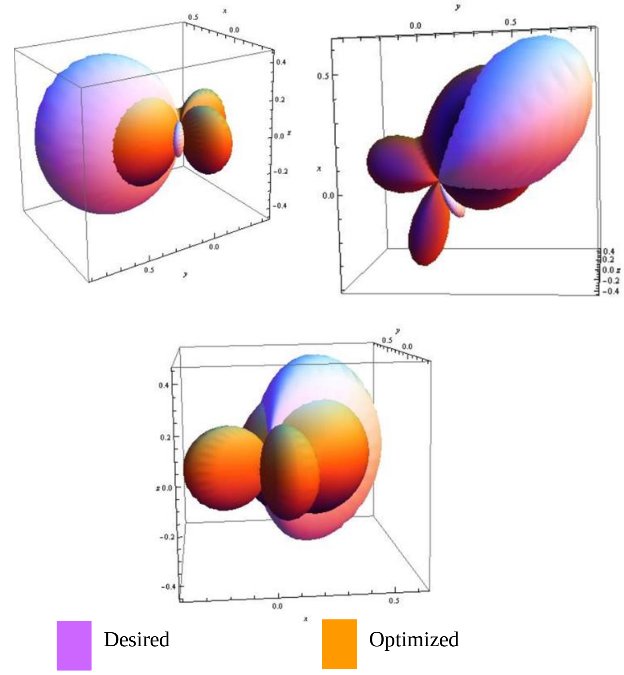


Figure 5: Three dimensional radiation patterns from different view point when half-wave dipoles placed in half-wavelength distance of an equilateral triangle.

V. Discussion of Results

The objective of this paper was to design, analyse and explore the use of a three element array antenna that would be sufficient for cognitive radio communications by steering a single beam to any desired direction. The analytical solution based three element array with the elements placed at the vertices of an equilateral triangle was shown to yield the desired beam pattern and yields to good match with the desired beam whatever the direction towards which the main beam should be pointing. Figure3. shows that it is possible to generate a single beam with no image in the desired direction. Moreover, we have shown that the beam-width of the single beam could be controllable by adjusting the distance between antenna elements. Further, the vertical plane beam could be controlled by selecting different types of dipoles that match for the requirement.

VI. Conclusions

In this paper an equilateral triangle array antenna is developed for use especially in single directional communication where the spectrum should be efficiently used as in Cognitive radio systems seeking to use the unused spectrum which may change in time and geographical location around the base station. It was shown that with the triangular three element antenna it is possible to direct a single beam to transmit or receive from only one desired location. It was also shown that the beam-width could be controlled by changing the distance between two adjacent elements. Although, increasing distance reduces the beam-width, the number of side-lobes also increases. Therefore the better option to reduce the beamwidth is to increase the number of elements to more than three. Finally, the results confirm that the single beam is capable of rotating to any direction while minimizing interference from other directions provided that the side-lobes kept small compare to the main-lobe.

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