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A variable length linear array for smart antenna systems

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Adaptive Arrays have been used extensively in wireless communications applications to reduce interference between desired users and interfering signals. In particular a large concentration of research has been directed to the Uniform Linear Array (ULA). However in most situations presented the authors utilise a fixed array length. In a mobile environment this has the disadvantage of producing a fixed beamwidth due to the fixed array length. This paper proposes an algorithm which can be used to determine the required beamwidth for a number of incoming signals by altering the length a specified number of elements present in an antenna array. This is achieved by the difference in the arrival angle of the desired user and a range incoming interferers known having a varied angle spread. The Least Mean Square (LMS) algorithm is incorporated into the algorithm for optimisation of the radiation pattern.

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A Variable Length Linear Array for Smart Antenna Systems

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Abstract

Adaptive Arrays have been used extensively in wireless communications applications to reduce interference between desired users and interfering signals. In particular a large concentration of research has been directed to the Uniform Linear Array (ULA). However in most situations presented the authors utilise a fixed array length. In a mobile environment this has the disadvantage of producing a fixed beamwidth due to the fixed array length. This paper proposes an algorithm which can be used to determine the required beamwidth for a number of incoming signals by altering the length a specified number of elements present in an antenna array. This is achieved by the difference in the arrival angle of the desired user and a range incoming interferers known having a varied angle spread. The Least Mean Square (LMS) algorithm is incorporated into the algorithm for optimisation of the radiation pattern.

Keywords – Adaptive Antenna, LMS, Linear Array.

1. INTRODUCTION

Adaptive Antenna systems are comprised of two components this includes the antenna array which is used for transmission and reception purposes and the adaptive algorithm which is used to determine the weight coefficients for optimisation of the array. The antenna array can be designed so that the radiation pattern formed contains a main lobe with a specific beamwidth. If the number of elements in the array is increased then the beamwidth is reduced hence having a more concentrated radiation beam. The adaptive algorithm is used to ensure that the array maintains directivity to a desired user and steers clear of interfering signals. The adaptive algorithm will use information such Angle of Arrival (AOA) and angle spread or angle difference as a means of determining the optimal solution for different situations.

Angle spread is range of arrival angles which are received at the antenna array. The adaptive algorithm will use information such as angle spread to ensure that interference from unwanted users is rejected and a concentration on desired signals is maintained. For example Wang [1] discusses the effect of the angle spread for a uniform linear array. In this situation it is stated that a large angle spread directly degrades the inter-element correlation giving rise to the inaccuracy of AOA estimation. Rao and Jones [2] state that antenna diversity rely on the assumption that the received signals that arrive at the receiver are uncorrelated and propose an efficient multi-sensor detection algorithm in the presence of angular spreading. In this instance the use of the Discrete Fourier transform is employed which serves as an efficient optimal spatial combiner for uniform linear arrays in multipath channels. Jami et al [3] utilises angle spread information to develop a handset tracking algorithm using the Kalman Filter Algorithm. In this instance the angle spread information is used to tune the filter coefficients which in turn significantly reduce the error in the position estimation of the handset.

This paper proposes a new method of controlling the beamwidth of uniform linear array by utilising the basis of the difference in the angle of arrival (AOAs) for incoming signals. In this instance the algorithm will determine the most appropriate number of elements to activate to obtain an optimal solution for multiple signals that have close AOAs. This method is advantageous as it allows the antenna system to vary the beamwidth as the interfering signal AOA encroaches upon the location of the desired user. This ensures that the main power of the radiation pattern avoids signals that are deemed as interferers. Furthermore the behaviour of a uniformly excited linear array regarding an increase in the number of elements is presented as well as an accurate method of measuring the First Null Beam Width (FNBW) beamwidth for a specified number of elements.

2. THEORY

The Linear Array

Linear arrays consist of radiating elements that are spaced in a straight line [4]. With this configuration the linear array provides one dimension of control, whereby the ability of sweeping in either the azimuth (φ) plane or the adjustment in the elevation (θ) plane is available but sweeping in both directions simultaneously is not. The radiation pattern of the array is a weighted sum of radiating element patterns and its directivity is achieved by changing the weight coefficients that are calculated using an adaptive algorithm.

Weight coefficients are updated using the adaptive algorithm. For the given weights the radiation pattern is formed based on the following formula [5].

$$z(t) = As(t)\sum_{m=0}^{M-1} w_m e^{-j\beta\Delta x\cos\phi\sin\theta} = As(t)f(\theta,\phi) \quad (1)$$

where $f(\theta, \varphi)$ is the array factor and represents the ratio of the received signal available at the array output, $z(t)$ to the signal $As(t)$, w_m are the weight coefficients for a particular antenna element: i=1,..., M, $\beta=2\pi/\lambda$ is the phase propagation factor and a pair (φ, θ) denotes the desired angle of arrival.

The beamwidth of an antenna array is the measured angle that the main lobe of the radiation pattern induces. Generally it is measured at the 3dB point where the radiated power is 0.707 of the maximum power radiated and the First Null beamwidth (FNBW) which is the first location where the radiated power is close to zero. It can be shown that for a uniformly excited linear array the beamwidth will decrease in size as the number of elements is increased. For example, the 3dB beamwidth for a uniformly excited linear array for a large number of M is given as [6]:

$$\phi_3 \approx \frac{0.8858\lambda}{Md\cos\phi_0} \quad (2)$$

Where d represents the elements spacing and λ is the wavelength. If the number of elements is increased such that:

$$\lim_{M\to\infty} \frac{0.8858\lambda}{Md\cos\phi_0} \quad (3)$$

It can be observed that the beamwidth of the array will become smaller as the number of elements is increased, this can be seen in Figure 1.

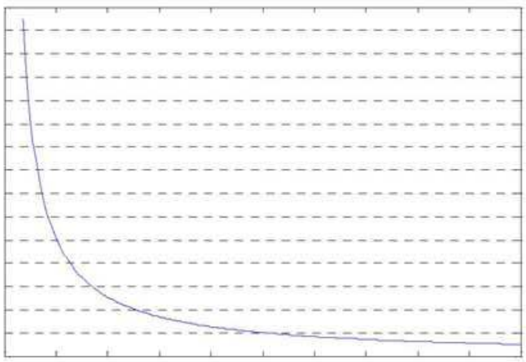

Figure 1: 3dB Beamwidth for Increasing Number of Elements.

Therefore when designing the array, consideration must be given to the number of elements with regards to the beamwidth generated. Equation 2 represents the beamwidth for a uniformly excited linear array; however this equation does not take into consideration of obtaining an accurate first null beamwidth measurement for an optimised, equally spaced linear array. Having an approach which calculates the first null beamwidth is advantageous as it allows the accurate measurement of the performance of the array radiation pattern. The FNBW can be obtained by finding the first minimum of the curve this can be calculated though the following process;

$$\frac{\partial z(t)}{\partial \phi} f(\theta,\phi) \quad (3)$$

$$\frac{\partial z(t)}{\partial \phi} = j\beta m\Delta x \sin\phi_0 \sin\theta e^{-j\beta m\Delta x\cos\phi_0\sin\theta} \quad (4)$$

And can be proven by ensuring that $f`(\theta, \varphi)>0$. The process in which the FNBW is obtained is based on Figure 2. This in turn can be represented through the following:

$$FNBW = 2[f(\theta,\phi_0) - f(\theta,\phi_2)] \quad (5)$$

$$FNBW = 2(\phi_0 - \phi_2) \quad (6)$$

Equation 5 represents the FNBW which was used for an optimised linear array for an AOA of φ_0. From the Figure it can be seen that a range of values for the linear array is calculated, in this

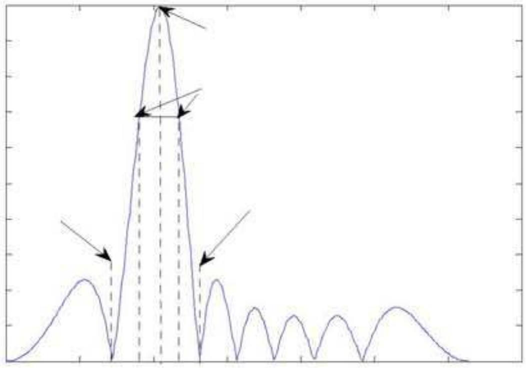

Figure 2: Calculating the FNBW.

case $0\leq\varphi\leq\pi$, where φ_0 located at the maximum position and the first null is located at φ_1 and φ_2. The difference between the two positions is obtained and multiplied by 2 to take into consideration the symmetry of the main lobe, note that either φ_1 or φ_2 can be used to obtain the beamwidth. Furthermore the 3dB beamwidth can also be obtained by setting (1) to 0.707 and obtaining the corresponding angles. From Equation 5 the behaviour of the FNBW can be obtained as the number of elements is increased from 4 to 50, this result can be seen for numerous AOAs in Figure 3.

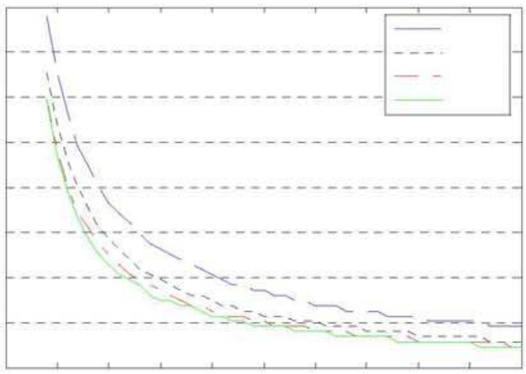

Figure 3 FNBW for different AOAs.

It can be observed that an optimised, equally spaced linear array will behave in a similar manner to that of a uniformly excited linear array when the number of elements is increased. Therefore by utilising the beamwidth of an antenna array the smart antenna system can effectively reduce the interference a desired signal will experience. This advantage can be build upon the fact that an antenna array also has *M-1* nulls which can be used to remove interferers.

B. Least Mean Square (LMS) Adaptive Algorithm

The LMS algorithm is a gradient based adaptive algorithm. The update process is obtained by estimating the gradient of the quadratic surface and then moving the weights in the negative direction of the gradient by a small amount known as the step size [7] and represented by μ. The LMS algorithm is represented by the following:

$$\varepsilon_k = d_k - X_k^T W_k \tag{7}$$

$$W_{k+1} = W_k + 2\mu\varepsilon_k X_k \tag{8}$$

In (6) ε is the error and represents the difference between the desired and the received signal. If the step size is small enough then this will lead the system to converge. The LMS algorithm has been employed on numerous occasions for the development of smart antenna systems. This is due to it low complexity and low implementation [8] [9] [10].

3. The VLA Algorithm

The Varying Linear Array (VLA) algorithm is a proposed method to control the beamwidth of a smart antenna system by varying the number of elements activated when the radiation pattern is produced. This is done in order to reject interfering signals which may affect the overall system performance of the adaptive antenna. The VLA alters the number of radiating elements depending on the determined angle difference between the desired signal and the closest interfering signal. The proposed method utilises a large fixed array and activates the required number of elements based on the calculated angle difference. This approach activates the elements sequentially. The motivation behind this approach is that by activating the elements sequentially, the antenna array will be viewed as a complete array of the activated elements with no recognition of the deactivated elements and hence system parameters such element spacing will remain the same. For example;

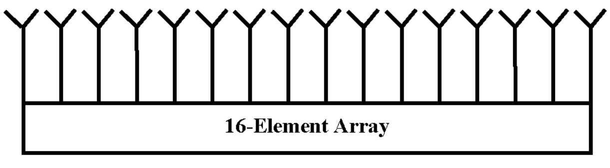

Figure 4: 16-Element Linear array with all elements fully activated.

Figure 4 represents a 16-element linear array. In this instance the above array is fixed in length and cannot vary its size if it did not require the use of all the elements. However by utilising the VLA algorithm it is determined that for a particular wireless scenario only the first ten elements need activation to adequately support the desired user and reject the remaining interfering signals. Therefore the following outcome is obtained:

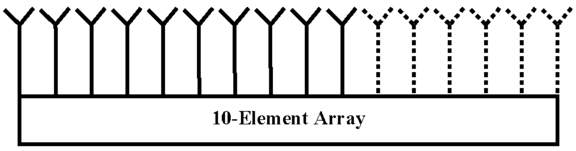

Figure 5: 10-Elements activated after using the VLA algorithm.

Figure 5 is the subsequent result when it is determined that not all the elements require activation for the desired outcome. In this sense only the first ten elements are activated and hence can be "seen" as a ten element linear array when optimisation is required. This is due to the fact that there is no signal being applied to the remaining elements. Furthermore due to the sequential activation there is no hindrance regarding the index of the array element being activated.

This approach is advantageous as it contributes to the overall reduction in the interference level by determining what the required beamwidth is to avoid other signals considered as interfering signals. Furthermore by determining the number of required elements can lead to a reduction in the amount of power needed to drive the antenna elements in comparison to a fixed antenna array. In doing so this further leads to enabling a system to become more scalable as it allows the operator to expand the array as required.

The means in which the VLA algorithm determines the number of elements to activate is by using a lookup table of predetermined values which are based on the results presented in Figure 3. To accurately obtain the beamwidth for a specific desired AOA five lookup tables are employed covering arrival angles of φ=0, 30, 45, 60, and 90°. This is to ensure that the calculated beamwidth for the desired arrival angle is as close as possible to the beamwidth that is required for the desired AOA. A sample lookup table can be seen in Table 1 based on calculations obtained from (5).

Φ=60°	No. Of Elements	3dB Beamwidth (°)	FNBW (°)
	8	13.7510	30.9397
	9	11.4592	27.5020
	10	10.3132	25.2101
	11	9.1673	22.9183
	15	6.8755	17.1887
	19	5.7296	13.7510
	21	4.5837	11.4592
	24	3.4377	10.3132
	28	3.4377	9.1673
	30	3.4377	8.0214

Table 1: Lookup table used for the VLA algorithm.

Table 1 is an example of the lookup tables used for the VLA algorithm. In this instance the table used is designed to handle AOA of desired users that arrive close to that of 60°. It can be seen that for each calculated beamwidth there is a corresponding number of elements. The VLA algorithm operates on the following assumptions:

- The arrival angles of all incoming signals have been determined and are known to the system.
- The desired incoming signal has been determined and is set as the first signal so as to become the reference signal to all other incoming arrival angles.
- The remaining signals are signal copies of the original desired signal.

The VLA algorithm operates firstly by obtaining a number of incoming AOAs;

$$\varphi_n = |\varphi_1, \varphi_2, ..., \varphi_N| \quad (9)$$

where

$n = 1, 2, 3, ..., N$ and $\varphi_1 = \varphi_{desired}$

The difference is then determined between the desired AOA and the remaining incoming signals to produce a vector of angle differences.

$$\varphi_{diff} = |\varphi_{diff\ 1}, \varphi_{diff\ 2}, ..., \varphi_{diffN}| \quad (10)$$

Equation 10 is the resultant angle differences between the desired signal and the remaining incoming signal AOA. The smallest difference in (10) is then used to select the number of elements in association with the desired AOA.

$$\underset{\phi_{smallest}}{\arg\min} = |\phi_{diff}| \quad (11)$$

$$BW_{required} = 2\varphi_{smallest} \quad (12)$$

Equation 12 multiplies the smallest difference to ensure that the both sides of the main radiation lobe are incorporated.

The process of how the lookup table is selected is based on the following approach; firstly the lookup table index is defined with each index having a fixed location in the vector. Each value in the vector represents a particular lookup table.

$$\varphi_{lookUpIndex} = |0, 30, 45, 60, 90| \quad (13)$$

By utilising the desired AOA and equation 13 a process of obtaining the closest lookup table is carried out. This is done in the following manner;

$$|\varphi_{lookUpDiff}| = \varphi_{desired} - \varphi_{lookUpIndex} \quad (14)$$

$$\underset{\phi_{\min\ diff}}{\arg\min} |\varphi_{lookUpDiff}| \quad (15)$$

Equation 14 produces a vector of differences between the desired AOA and the lookup index vector. The minimum value is obtained and the lookup table to select is determined by:

$$\varphi_{\min\ diff} == \varphi_{lookUpDiff} \quad (16)$$

In (16) the lookup table is determined by searching $\varphi_{lookUpDiff}$ and comparing $\varphi_{mindiff}$ when the value is obtained the location of the value is associated to the required lookup table as defined in (13). Once the appropriate lookup is determined and the required beamwidth is obtained a search is carried out to determine the number of elements required. When this value is obtained the number of elements and the desired AOA is used to produce the radiation pattern by optimising the number of elements using the LMS algorithm described in (7).

4. RESULTS

The VLA algorithm was applied to a system containing a minimum of eight elements and a maximum of thirty. It was determined that the maximum of thirty be used based on the Figure 5. It can be seen that after thirty elements the change in beamwidth in comparison to the change in the number of elements is minimal and hence not cost effective when physically designing the array. The system was run for a desired AOA of 60° and an incoming interfering signal initially of 28° and then 56°, the resultant radiation pattern can be seen in Figures 6 and 7 respectively.

It can be observed that in the first case the encroaching signal is distant with regards to angle difference and hence the VLA algorithm is not required to operate. In this instance the beamwidth of the minimum number of elements is deemed as adequate to deal with that particular scenario. However when the undesired signal has moved close to the location of the desired signal it can be observed that the VLA algorithm has determined that an increase in the number of elements be applied to avoid the interfering signal.

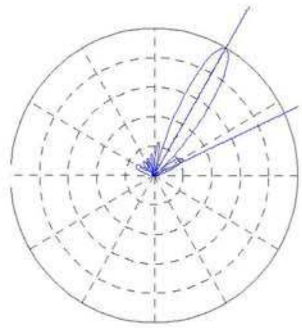

Figure 6: Radiation Pattern using the VLA algorithm for two signals, desired AOA=60°, undesired AOA=28°.

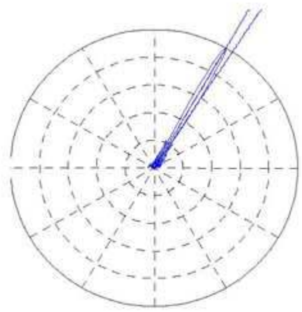

Figure 7: Radiation Pattern using the VLA algorithm for two signals, desired AOA=60°, undesired AOA=56°.

This can be seen in Figure 7. In this instance it was determined from the lookup tables the number of elements to deal with this particular scenario was 29 elements.

From this algorithm the situation arises regarding the physical limitations of such an algorithm. Hence a measurement scheme was generated to test its limitations regarding the proximity in which an interfering signal can approach based on the system described in this section. It should be noted that the nature of the incoming interfering signal is assumed to be highly directional as in the case of BWA systems. The results can be observed in the following table:

Desired AOA (^{o})	**Closest Allowed Angle (^{o})**
30	± 6.5
45	± 5
60	± 4
90	± 4

Table 2: Closest Angles allowed utilising the VLA algorithm.

Table 2 represents different desired AOAs with the corresponding limits in which the VLA can handle. In this instance it can be observed that with the described system the VLA algorithm allows for interfering signals to approach very closely to the position of the desired signal. This would be advantageous for systems where the desired signal is stationary such as Broadband Wireless Access (BWA) system and both the base station and subscriber station signals are highly directional.

5. CONCLUSIONS

This paper presented an algorithm that is a proposed method to control the beamwidth of a smart antenna system by varying the number of elements activated when the radiation pattern is produced. This method is advantageous as it gives the antenna array a greater ability to avoid interfering signals. It was also observed that as the interfering signal approached the desired user location the VLA algorithm ensured that the beamwidth was small enough to avoid the interferer. Furthermore the behaviour of a uniformly excited linear array and an optimised linear array were presented and studied. It can be seen that the both arrays and operate in similar fashion when the number of elements is increased.

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