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Beamforming Techniques for Smart Antenna using Rectangular Array Structure

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ABSTRACT

In this paper, array theory in general has been discussed. A basic fundamental of smart antenna and beamforming techniques using rectangular array theory is discussed. Two techniques, Matrix inversion and IDFT method, for their pros and cons were described which were used for beamforming.Both the techniques found to be useful as their areas of application differs on hardware background.The design of a fully spatial signal processor using rectangular array configuration is presented in this paper. It has wideband properties and, hence eliminates the requirement of different antenna spacing. Furthermore, frequency selectivity and rejecting unwanted signals gives the satisfactory performance for practical implementation.

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1. INTRODUCTION

The growth in demand of wideband wireless services has evoked the tremendous need to increase the capacity and data-rate transmission of wireless communications systems. Since, the available spectrum to provide capacity and high data transmission rate to all the subscribed users is limited, the need and attention of latest research has moved to find a technique which will be able to fulfill these requirements. Smart antenna systems, found to be the best solution, due to the use of spatial filtering [1], which makes the signals sensitive to coming from specific directions and provides attenuation to other directions. In this way, the system capacity and power efficiency can be increased and therefore, reduce overall cost. Beamforming techniques

Beamforming [1] is the process of performing spatial filtering, the main objective of spatial filtering is to make a beam sensitive towards the signal of interest (SOI) and null or attenuation towards directions of interfering signals or signals of not interest (SNOI).There are various methods of implementation of beamforming techniques, time and frequency domain which depends on the speed of processing and the type of signals to be processed.

Various Time and frequency domain techniques which is being used in the design and implementation of a digital beamformer will be discussed in this paper. Performance parameters like efficiency, complexity and the resulting advantages and disadvantages can then be derived. Beamforming is used in Acoustic (SONAR) and Radar (electromagnetic applications), seismic, ultrasonic imaging and various other applications [2].

Beamforming or Spatial filtering [3] is to make response of the vector sensitive to SOI and provide null to SNOI.Depending upon the array geometry, beamforming can form two or three dimensional image from an array of sensors. There are two main types of beamformers. These are time domain beamformers and frequency domain beamformers.

A graduated attenuation window is sometimes applied across the face of the array to improve side-lobe suppression performance, in addition to the phase shift. Time domain beamformer works by introducing time delays. The basic operation is called "delay and sum". It delays the incoming signal from each array element by a certain amount of time, and then adds them together.

There are two different types of frequency domain beamformers --The first type separates the different frequency components that are present in the received signal into multiple frequency bins (using either DFT or a filterbank). When different delay and sum beamformers are applied to each frequency bin, the result is that the main lobe simultaneously points in multiple different directions at each of the different frequencies. This can be an advantage for communication links, and is used with the radar.

The other type of frequency domain beamformer makes use of Spatial Frequency [4]. Discrete samples are taken from each of the individual array elements. The samples are processed using a Discrete Fourier Transform (DFT). The DFT introduces multiple different discrete phase shifts during processing. The outputs of the DFT are individual channels that correspond with evenly spaced beams formed simultaneously. A 1 dimensional DFT produces a fan of different beams. A 2 dimensional DFT produces beams with a pineapple configuration.

2. ARRAY THEORY

The number of elements in the array should be relatively low (the minimum required), in order to avoid unnecessarily high complexity in the signal processing unit. Array antennas [5] can be one-, two-, and three-dimensional, depending on the dimension of space one wants to access. Figure 1 shows different array geometries that can be applied in adaptive antennas implementations.

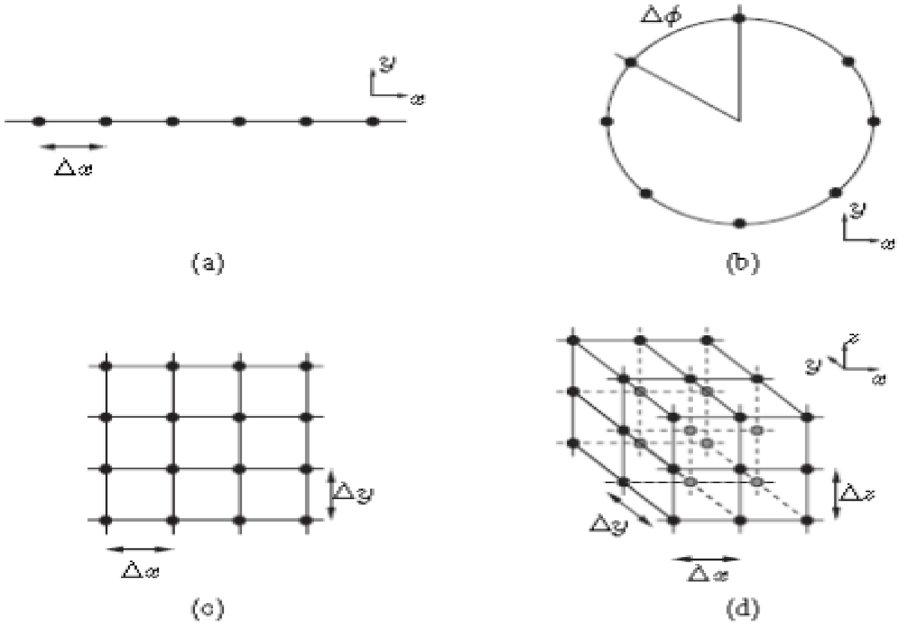

Figure 1. Different uniform array geometries for smart antennas

The first structure is used primarily for beamforming in the horizontal plane (azimuth) only. This will normally be sufficient for outdoor environments, at least in large cells. The first example (a) shows a one-dimensional linear array with uniform element spacing of Δx. Such a structure can perform beamforming in one plane within an angular sector. This is the most common structure due to its low complexity.

The second example (b) shows a circular array [8]. It has uniform angular spacing between adjacent elements of $\Delta\varphi = 2\pi / N$, where N represents the number of elements. This structure can perform beamforming in any direction, due of its symmetry, is more appropriate for azimuthal beamforming.

The last two structures are used to perform two-dimensional beamforming, i.e. in both azimuthal and elevation angles. Such specifications are usually required for indoor or dense urban environments. The front view of a two-dimensional rectangular array [6] [7] with horizontal element spacing of Δx and vertical element spacing of Δy is shown in (c).

Beamforming in the entire space, within all angles, requires some sort of cubic or spherical structure (three-dimensional configuration). The fourth example (d) shows a cubic structure with element separations of Δx, Δy, and Δz, respectively, in each direction in space.

2.1 Benefits of Arraying

Arraying has many benefits [5] such as: better performance, increased operational robustness, implementation cost saving, more programmatic flexibility, and broader support to the science community.

a. Performance Benefits

For larger antennas, the beamwidth naturally is narrower. As a result, antenna-pointing error becomes more critical. To stay within the main beam and incur minimal loss, antenna pointing has to be more precise. Yet this is difficult to achieve for larger structures.

With an array configuration of smaller antennas, antenna-pointing error is not an issue. The difficulty is transferred from the mechanical to the electronic domain. The wider beamwidth associated with the smaller aperture of each array element makes the array more tolerant to pointing error.

b. Operability Benefits

Arraying can increase system operability. First, higher resource utilization can be achieved. In the case of an array, however, the set can be partitioned into many subsets each tailored according to the link requirements. In so doing, resource utilization can be enhanced.

Secondly, arraying offers high system availability and maintenance flexibility. Suppose the array is built with 10 percent spare elements. The regular preventive maintenance can be done on a rotating basis while allowing the system to be fully functional at all times.

Thirdly, the cost of spare components would be smaller. Instead of having to supply the system with 100 percent spares in order to make it fully functional, the array offers an option of furnishing spares at a fractional level.

Equally important is the operational robustness against failures. With a single resource, failure tends to bring the system down. With an array, failure in an array element degrades system performance but does not result in a complete service shutdown.

c. Cost Benefits

A cost saving is realized from the fact that smaller antennas, because of their weight and size, are easier to build. The fabrication process can be automated to reduce the cost. Many commercial vendors can participate in the antenna construction business, and the market competition will bring the cost down further.It is often approximated that the antenna construction cost is proportional to the antenna volume. The reception capability, however, is proportional to the antenna surface area. For example, halving the antenna aperture reduces the construction cost of a single antenna by a factor of 8; however, four antennas would be needed to achieve an equivalent aperture. The net advantage is an approximate 50 percent cost saving.

d. Flexibility Benefits

Arraying offers a programmatic flexibility because additional elements can be incrementally added to increase the total aperture at the time of need. This option allows for a spread in required funding and minimizes the need to have all the cost incurred at one time. The addition of new elements can be done with little impact to the existing facilities that support ongoing operations.

3. SMART ANTENNA

Practically speaking, antennas by themselves are not smart. It is the digital signal processing (DSP) capability, along with the arrays of antennas, which make the system smart. Digital signal processing (DSP) unit, which computes weighting factors that multiply the signal at each element of the associated array. This weighting calculation can be realized using different beamforming techniques.

Three main concepts of smart antennas are as follow:

a. space-time signal processing,
b. space-frequency signal processing and
c. fully spatial signal processing

The space-time and space-frequency signal processing techniques are based on large banks of delay networks or frequency filters, which result in high cost and high hardware complexity. On the other hand, fully spatial signal processing neglect the use of filters and delay networks, hereby has been identified as the most advantageous of these three technologies and therefore it is attractive for wideband communication.

There are two beamforming algorithms discussed to obtain the optimum weighting coefficients using fully spatial signal processing configuration, based on rectangular array geometry.

4. FULLY SPATIAL SIGNAL PROCESSING BEAMFORMING USING RECTANGULAR ARRAYS

Rectangular linear arrays, when subjected to an almost fixed elevation angle, may be used to fully spatial signal processing of wideband signals.In this processing technique, the sharpness of the beams is maintained not only in the broadside but at the endfire directions of the array as well. The beamwidth [1] of the directional pattern can be controlled at all angles.Frequency domain filtering [7] is easily achieved in the design procedure.this property is called as frequency selective widebamd beamforming (FSWB).It can compensate for the frequency dependence of the elements.

The configuration of the wideband beamformer, constituted by a rectangular array of $N_1 \times N_2$ antenna elements alongwith amplifiers or attenuators and a summing network, is shown in Fig.2.Incoming signal arriving at rectangular array with azimuth angle φ and elevation angle θ. Each element is connected to a real multiplier as shown in the figure 2.

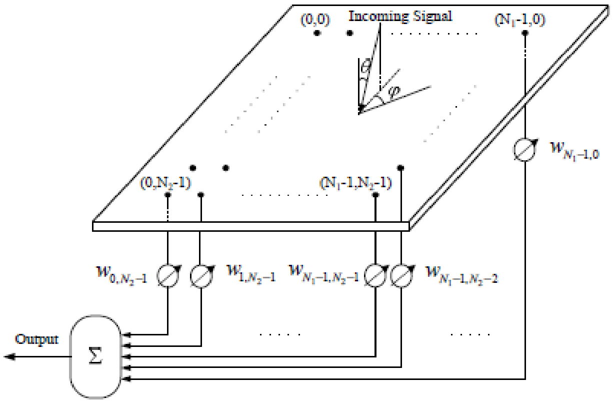

Figure 2. Rectangular array of *N* antenna elements with amplifiers and summer

Each antenna element has a frequency-dependent gain and is denoted by (n_1,n_2),
Where, $0 \leq n_1 \leq N_1 - 1$ and $0 \leq n_2 \leq N_2 - 1$.
The inter-element distances are d_1 and d_2 in the direction of n_1 and n_2, respectively.

The direction of the arriving signal is determined by the azimuth angle ϕ, and the elevation angle θ. As in most practical cases, it is assumed that the elevation angles of the incident signals to the base station antenna array are almost constant, and without loss of generality, we consider $\theta \approx 90^{\circ}$. Assuming that the phase reference point is located at $(n_1 = 0, n_2 = 0)$, the phase of the signal at the element (n_1 , n_2) is:

$$\emptyset(n_1,n_2) = (2\pi f/c)(d_1 n_1 \sin\varphi - d_2 n_2 \cos\varphi) \tag{1}$$

Where f is the frequency and c is the velocity of an electromagnetic wave in free space. Therefore, the array frequency-angle response can be written as:

$$H(f,\varphi) = G_a(f,\varphi) \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} W_{n_1 n_2}\, e^{j\left(\frac{2\pi f}{c}\right)(d_1 n_1 \sin\varphi - d_2 n_2 \cos\varphi)} \tag{2}$$

There are two main beamforming algorithms discussed to develop fully spatial signal processing [1] [7] [8] based on a rectangular array antenna. The first one is a matrix inversion technique which is simple and produces wider beam and has low beamwidth.

The second technique is inverse discrete fourier transform (IDFT) [1] [7], which produces sharper beams and more controlled performance. The main and the most important advantage of the above two technique is that both yields real weighing coefficients which are easily implemented by attenuators and amplifiers.

4.1. Beamformer Using Matrix Inversion

For this method, we need to define two vectors as follow:

$$\bar{b} = [b_1, b_2, \ldots . b_L]^T \tag{3}$$

$$\overline{H_0} = \left[H\left(S_{10_{1,}}S_{20_{1,}}\right), H\left(S_{10_2}, S_{20_{2,}}\right), \ldots H\left(S_{10_{L,}}S_{20_{L,}}\right)\right] \tag{4}$$

Assume that $H(s_1, s_2)$ is expressed by the multiplication of two basic polynomials as follow:

$$H(S_1, S_2) = \sum_{l=1}^{L} b_l \left(\sum_{n_{1=0}}^{N_1-1} e^{j2\pi n_1 (s_1 - s_{10})} \right) . \left(\sum_{n_{2=0}}^{N_2-1} e^{-j2\pi n_2 (s_2 - s_{20})} \right) \tag{5}$$

The relationship between b_l and $w_{n1,n2}$ can be obtained rearranging (5) as:

$$H(S_1, S_2) = \sum_{n_1=0}^{N_1-1} \sum_{n_2}^{N_2-1} \left\{ \sum_{l=1}^{L} b_1 e^{-j2\pi n_1 s_{10}} e^{j2\pi n_2 s_2} \right\} . e^{j2\pi n_1 s_1} e^{-j2\pi n_2 s_2} \tag{6}$$

Therefore, after calculation of b, we can find $w_{n1,n2}$ from above equation.

4.2. Beamformer Using IDFT

This method is mostly used in small arrays, where it is assumed that the origin point (0,0) is located at the center of the antenna array. Using this new location, the array's symmetry can be exploited. With this assumption the frequency-angle response can be written as:

$$H(f, \varphi) = G_a(f, \varphi) \sum_{m_1=-M_1}^{M_1} \sum_{m_2=-M_2}^{M_2} W_{m_1 m_2} e^{j\left(\frac{2\pi f}{c}\right)(d_1 m_1 \sin\varphi + d_2 m_2 \cos\varphi)} \tag{7}$$

A careful examination of above equation reveals that it resembles a discrete Fourier transform (DFT). Therefore, by taking the IDFT of the values of $H(s_1, s_2) / G_a(s_1, s_2)$
in the $s_1 - s_2$ plane enables to calculate weighing coefficients as follow:

$$W_{n_1,n_2} = \left(\frac{1}{N_{S_1} N_{S_2}}\right) . \sum_{S_1=-0.5}^{0.5} \sum_{S_2=-0.5}^{0.5} \frac{H(S_1, S_2)}{G_a(S_1, S_2)} \times e^{-j2\pi f_{s_{1m_1}}} e^{-j2\pi f_{s_{2m2}}} \tag{8}$$

5. RESULTS AND ANALYSIS

5.1 Matrix Inversion Method

Results are obtained for $N_1 = 6$ & $N_2 = 4$ (Rectangular array size)

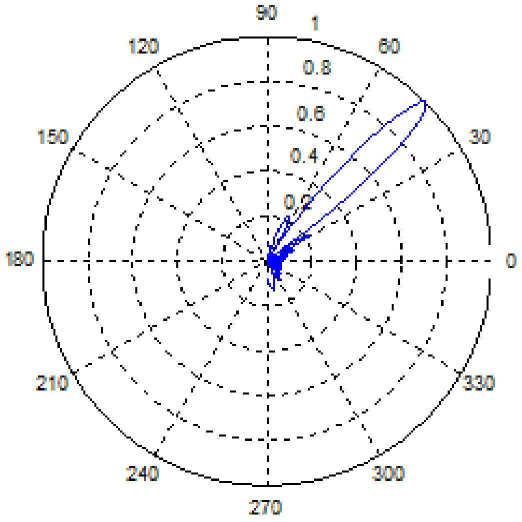

Figure 3. Beamformation at A.O.A

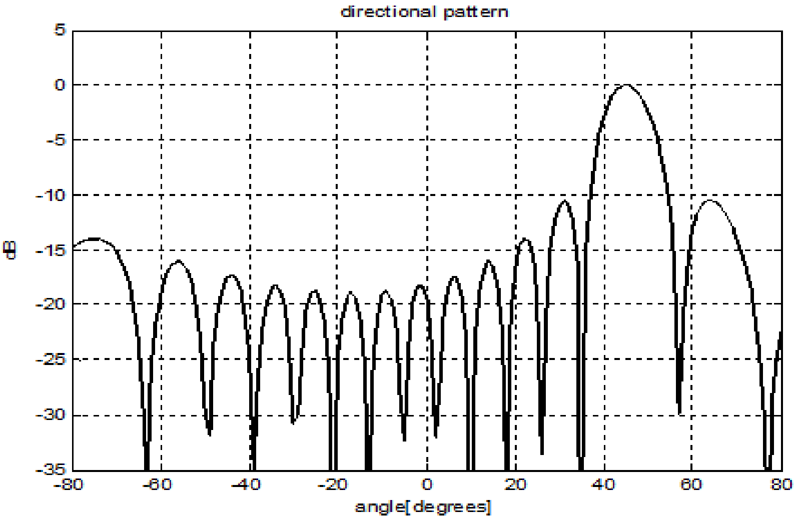

Figure 4. Directional pattern

In Matrix inversion method, we get wider beam at A.O.A of 45* (figure 3) and in the directional pattern (figure 4) also we can observe the same at given A.O.A.This method is easy to impement compare to IDFT method.

5.2 I.D.F.T Method

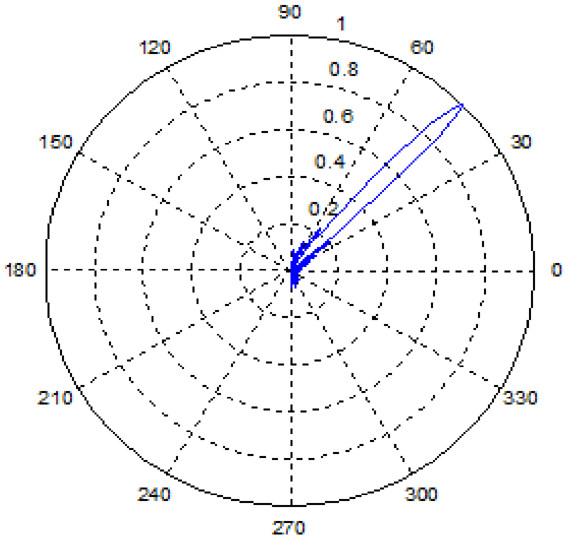

Figure 5. Beamformation at A.O.A

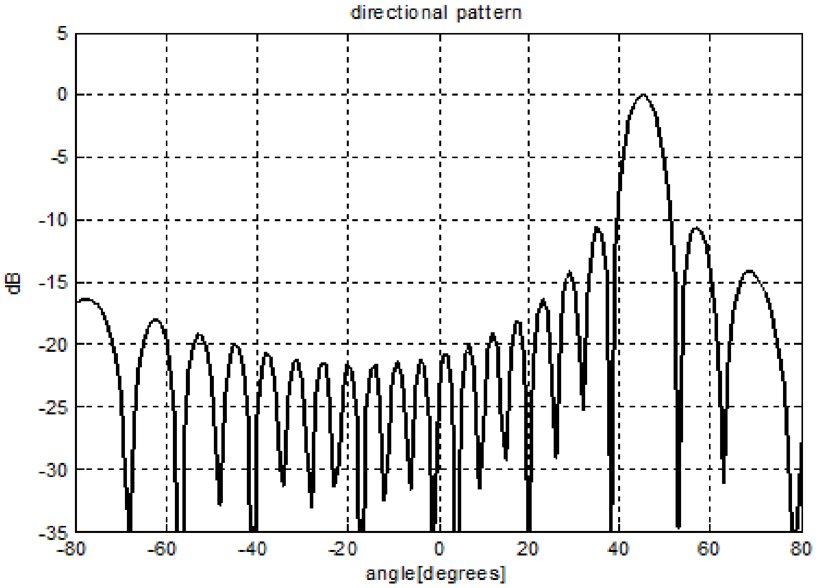

Figure 6. directional pattern

After comparing results, we can say that using IDFT method, we get sharper beam pattern that can be seen in the figure 5 and same is reflected in figure 6.
Comparing both the techniques as follow:

Martix inversion	I.D.F.T.Method
❖ Simple	❖ Complex
❖ Produces wider beam and	❖ Produces sharper beams and
❖ Has low fractional bandwidth.	❖ Has higher fractional bandwidth
❖ Used in small size array.	❖ More controlled performance, hence can be used in large size arrays.
❖ Less coverage.	❖ More coverage area.
❖ More prone to interference.	❖ Less interference.More power is transmitted in desire direction
❖ Less power is transmitted in desire directon.	

6. CONCLUSION

In this paper, fully spatial signal processing [1] is discussed using rectangular array geometry.It eliminates TDL's and filters which were used in space time and space frequency processing techniques. Hence, it reduces hardware complexity, and therefore, the overall cost of the system.The main problem in this processing techniques is to find out the optimum weighting coefficients. To solve this problem, there are two beamforming algorithms proposed, based on rectangular array geometry [7]. The algorithms based on rectangular array yields real number weights hence, practically it can be easily implemented using attenuators or amplifiers. The IDFT [1] method is more complex but provides sharper beams, and the Matrix Inversion method [1], is simpler but has wider beam and lower fractional bandwidth.

Many different approaches have been proposed for implementing optimum beamformer. Future work will likely address signal cancellation problems, further reduct ions in computational load for large arrays and improvised structures for implementation.Beamforming truly represents a versatile approach to spatial filtering.

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