An Overview of Adaptive Antenna Technologies For Wireless Communications

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ABSTRACT

Smart antenna systems are rapidly emerging as one of the key technologies that can enhance overall wireless communications system performance. By making use of the spatial dimension, and dynamically generating adaptive receive and transmit antenna patterns, a smart antenna can greatly reduce interference, increase the system capacity, increase power efficiency as well as reduce overall infrastructure costs. In this paper the concept of the smart antenna is reviewed.

Categories and Subject Descriptors

A.1 [**Introductory and Survey**]

General Terms

Performance, design

Keywords

Adaptive antenna arrays, array signal processing, cellular radio, DOA estimation, beamforming, antenna arrays, multipath channels, smart antenna

INTRODUCTION

Over the last few years the demand for wireless services has risen dramatically. This fact introduces a major technological challenge to the design engineer: that is to increase the overall performance and efficiency of the wireless system with an increased number of users under the constraints of spectrum efficiency, power usage and cost. Most of the research on this topic, until very recently, has been largely focused on the development of modulation and coding techniques as well as communication protocols, very little attention has been paid to the overall transceiver structure and antenna technology. Recently developed smart antenna technology may be the solution to satisfying the requirements of next generation wireless networks [3]. The smart antenna, or adaptive array allows the system to manipulate received signals not only in the time and frequency dimensions but in the spatial domain as well, to achieve optimized system goals. The unique ability of the smart antenna to perform spatial filtering on both the receive and transmit signals is the major advantage of smart antennas over existing conventional transceiver techniques [1].

In wireless communications environments, a smart antenna system can achieve a number of major benefits. First, the effect of multipath fading can be greatly reduced. Since the reliability and quality of service (QOS) strongly depends on the depth and rate of fading, a reduction in fading greatly enhances performance. Second any mobile system employing a smart antenna at the base station becomes more power efficient. This comes about because the smart antenna is capable of achieving a better bit error rate (BER) performance than a conventional system at a given signal to noise and interference ratio (SINR), resulting in less power transmitted from the mobile to the base station. This increase in power efficiency forms a trade off with increased range from the mobile to the base station, This may provide further benefits such as a decrease in large scale infrastructure costs. Finally, the capacity of the system is increased through reduction of the signal to interference ratio (SIR) [2].

It has been proven both theoretically and experimentally that smart antennas can provide the benefits stated above, but possibly the most challenging problem related to adaptive antennas is their practical implementation [2]. Digital signal processing (DSP) algorithms related smart antennas come at a high computational expense making their real time implementation difficult. Adaptive antennas use multiple antenna elements (antenna array), increasing the RF hardware complexity of the receiver, and making a fully functional multi-channel transceiver more expensive. Luckily with the emergence of high speed analog to digital converters (ADC), digital signal processors and the dramatic reduction in cost of microwave components the smart antenna has become a feasible system to design and implement. In the following sections a

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thorough review and survey on the technology for the smart antenna system is presented.

1. General Smart Antenna Architecture

Today's smart antennas come in a variety of different forms and employ a number of different methods to achieve the benefits of using multiple antennas. Most intelligent transceiving systems employ some kind of direction of arrival estimation at the receiver to resolve the DOAs of all impinging signals on the array. The receiver then applies an adaptive algorithm to calculate complex weighting factors which multiply the analytic signal at each element of the associated array [3]. These signals are then combined to produce a resulting signal with improved overall SINR. This signal is passed to a demodulator where BER performance is improved. Figure 1 shows the generalized smart antenna receiver architecture.

In this system a four element array consisting of omni-directional antenna elements receives the high frequency RF signal. This high frequency signal is down converted to an intermediate frequency (IF) suitable for sampling. The analog IF signals at each element of the array are then converted to digital format by high speed ADCs, these samples are then passed to the DOA estimation routine, for DOA estimation. Once estimates for the DOAs of the impinging signals have been found beamforming weights can be calculated and applied to each element of the array. It is the application of these complex weights that effectively forms the antenna pattern of the receiver that enables optimized reception of RF signals. Finally the weighted signals are summed and passed to a demodulator.

2. DOA ESTIMATION

Since most RF antennas, amplifiers, mixers, filters and ADC technologies have reached a mature state, accurate estimation of the angles of arrival of signals impinging on an array of antennas becomes the most important parameter regarding the performance of an adaptive array. Assuming a linear and isotropic transmission medium, multiple impinging wave fronts can be modeled as the superposition of these wave fronts impinging on the array. It is therefore necessary for the DOA estimation algorithm to be able to resolve impinging and often fully coherent wave fronts into their respective DOAs. Many DOA estimation algorithms exist, but only a few have found use in smart antennas. A brief review of these algorithms will be discussed here.

2.1 Eigenstructure DOA Methods

The family of DOA estimation algorithms that depend on an Eigen decomposition of the array covariance matrix are so named the Eigenstructure methods. These methods rely on the following properties of the array covariance matrix **R**:

$$\mathbf{R} = \mathbf{X}\mathbf{X}^{H}$$

Where **X** is the data matrix whose rows are N samples from each element of the array, H denotes Hermitian Transpose. First, the space spanned by its eigenvectors can be partitioned into two subspaces, namely, the signal subspace and the noise subspace. Second, vectors that correspond to directional sources are orthogonal to the noise subspace, and are contained in the signal subspace [1].

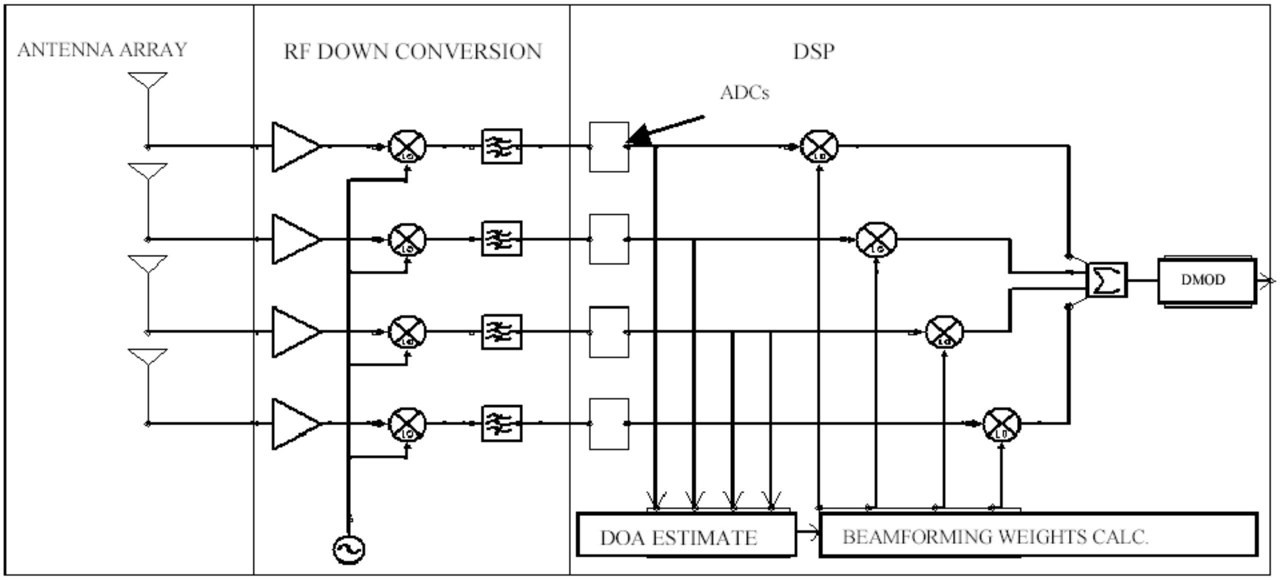

Figure 1 General Smart Antenna Architecture

Consequently vectors pertaining to the direction of sources can be found. In principle, the eigenstructure techniques search for directions such that steering vectors associated with these directions are orthogonal to the noise subspace and are contained in the signal subspace [1]. Two of the most popular eigenstructure methods are the ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) and MUSIC (Multiple Signal Classification) algorithms, these methods have shown excellent accuracy and resolution in many experimental and theoretical studies.

2.2 Spectral Estimation Methods

DOA estimation methods that first compute a spatial spectrum, then estimate DOAs by local maxima of this spectrum are called the Spectral Estimation Methods [1]. Essentially these methods apply weights to each element in the array so as to steer the antenna pattern towards a known look direction. The received power is then estimated for a large number of look directions and the look directions with maximum received power are chosen as the DOAs. Variants of the spectral estimation methods differ by how the weights are calculated to steer the main beam. Methods that fall under this class of DOA estimators include the Maximum Likelihood method, Bartlett Method and the Linear Prediction Method [1]. These methods are inherently simple, but suffer from lack of resolution. For this reason the high resolution eigenstructure methods are most often used.

3. SPATIAL FILTERING

The ability of the smart antenna to use the spatial dimension is they key factor to achieving the performance gains of adaptive arrays. Once accurate estimates of the DOAs impinging on the array have been made, desired signals can be passed through to the demodulator to further enhance the accuracy while attenuating interfering signals. This process effectively changes the receive antenna pattern from omni-directional to directional, which can increase the BER rate performance and leads to the concept of spatial division multiple access (SDMA).

3.1 Delay and Sum Beamforming

The delay and sum beamformer is the simplest of all spatial filtering schemes. If a desired signal from a known DOA is chosen then the main beam of the antenna array can be steered towards this direction by simply multiplying each element by a complex weight, corresponding to a delay, so that when the signals are combined the signal from the desired direction at each element add completely in phase. Consider the case of an M element Uniform Linear Array (ULA), an array whose elements are placed in a straight line equidistant apart. If a desired signal impinges on the array at an angle θ then there will be a constant time delay of this signal across the array τ. If the analytical signal received at each element is then multiplied by the complex weighting factor:

$$\mathbf{w}_i = e^{j(i-1)\tau}$$

Here i corresponds to the i th antenna element, the main beam of the array will be pointed in the direction θ. In general a vector whose elements correspond to the above weight factors is called a steering vector [1]. Figure 2 shows a plot of an M = 4 element array antenna pattern (-90° to 90°) after delay and sum weights have been applied. Two signals are impinging on the array from -32° and 15° at an SNR of 10 dB, the DOA estimation is done using ESPRIT and the simulation is done in Matlab. The axis represents the relative gain of the receive pattern.

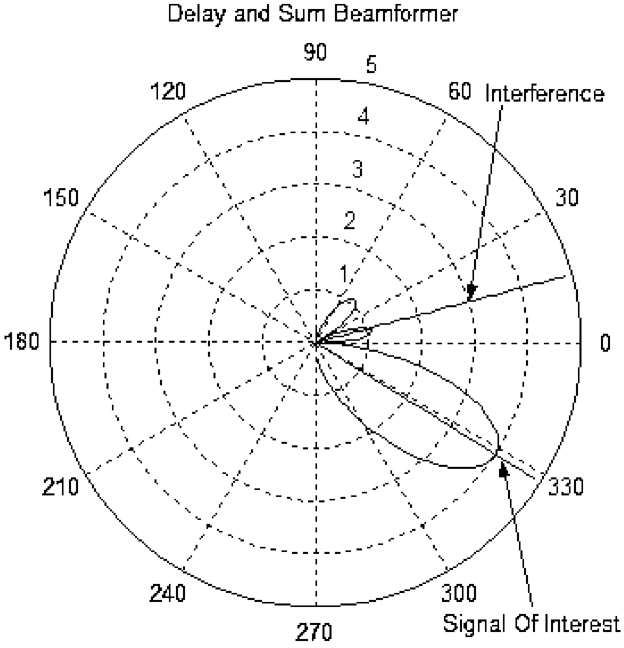

Figure 2

3.2 Null Steering Beamforming

The delay and sum beamformer is attractive because of its simplicity and ease of implementation. The limiting factor in the overall performance of this method is that though it can steer its main beam it has no control over its side lobes. This is evident from figure 2 where a side lobe of the antenna pattern allows the interfering signal, although attenuated, to reach the receiver after the weights are applied. The solution to this problem is the null steering or pseudo inverse beamformer.

The null steering beamformer adapts the antenna pattern to steer the main beam towards the desired user and place nulls in the direction of interfering users. This method in theory should minimize the signal to interference ratio (SIR).

If $\mathbf{s_0}$ is the steering vector associated with the desired signal of interest and vectors $\mathbf{s}_1,\ldots,\mathbf{s}_k$ are the k steering vectors associated with k interfering signals on an M element array, then the desired weight vector **w** is the solution of the following set of simultaneous equations [1]:

$$\mathbf{w}^H \mathbf{s_0} = 1$$

$$\mathbf{w}^H \mathbf{s}_i = 0$$

$$i = 1,\ldots, k$$

therefore the weights can be calculated as the first column of the pseudo inverse of the matrix whose i th column is the i th steering vector, multiplied by M. Figure 3 shows the antenna pattern of a four element uniform linear array (-90˚ to 90˚) under the same conditions of figure 2. Notice that a deep null has been steered in the direction of the interference, while gain is maintained in the direction of the signal of interest.

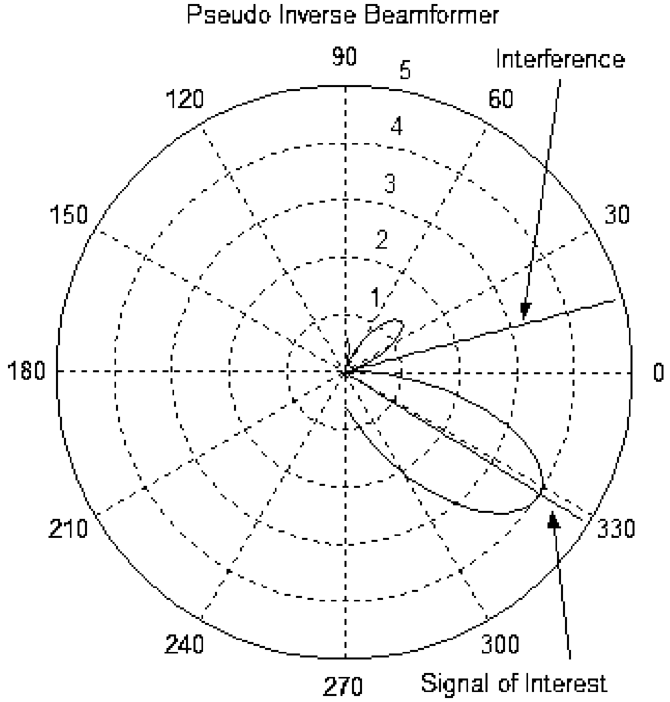

Figure 3

3.3 MVDR Beamforming

The null steering scheme described in the previous section maximizes the SIR but does not maximize the overall output SNIR, that is it does not minimize the total noise including interferences and uncorrelated noise. It has been shown in [4] that the solution vector to the following optimization problem will yield the weights that maximize the output SNIR:

$$\text{Minimize} \quad \mathbf{w}^H \mathbf{R}\mathbf{w}$$

$$\text{Subject to} \quad \mathbf{w}^H \mathbf{s}_0 = 1$$

This is equivalent to minimizing the mean output power while maintaining gain equal to the number of antenna elements in the direction of the signal of interest. The solution is given as:

$$\mathbf{w} = (\mathbf{R}^{-1}\mathbf{s_0}) / (\mathbf{s_0}^H\mathbf{R}^{-1}\mathbf{s_0})$$

Figure 4 shows a simulation of a 4 element array antenna pattern (-90˚ to 90˚) after MVDR (Minimum Variance Distortionless Response) weights have been applied. Two signals are impinging on the array from -32˚ and 15˚ at an SNR of 10 dB, the DOA estimation is done using ESPRIT.

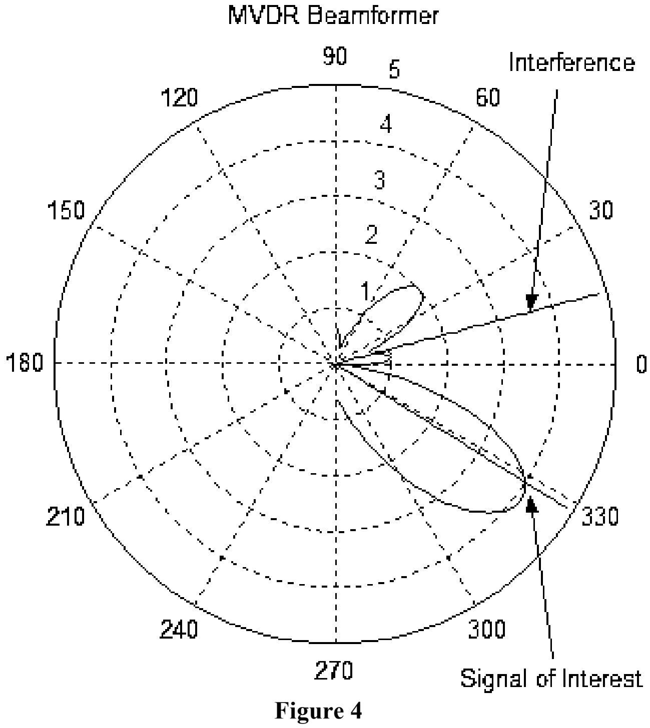

Figure 4

3.4 Transmit Beamforming

It should be mentioned here that the same beamforming algorithms applied at the receiver can also be applied at the transmitter. This allows the smart antenna to focus its transmit main beam in the direction of desired users and steer nulls in the direction of non desired users. This is beneficial because energy is focused towards the desired target and away from others, from a system point of view this will decrease the effect of multipath fading and lower the amount of interference received by each mobile.

3.5 Spatial Division Multiple Access (SDMA)

The concept of spatial filtering leads to the idea of a new multiple access scheme that could be used on its own or to complement existing schemes such as FDMA, TDMA or CDMA. The idea behind SDMA is that users can be separated based on there spatial position rather than by a unique time slot, frequency allocation or chip code. This arises naturally from smart antennas where desired users can be selected and interferers can be rejected based on their angle of arrival. The SDMA concept is the focus of many research groups and its potential to enhance existing wireless systems is very real, in fact it has been proven in [5] that the spectral efficiency of a system employing some kind of SDMA at the receiver can be improved by at least a factor of $M^{(1/2)}$.

4. FUTURE RESEARCH

Perhaps the reason why only a handful of companies are producing viable commercial smart antenna products is because their practical implementation is extremely difficult. DOA and beamforming algorithms require a large number of computations which makes it difficult for them to keep up with the high data rates of today’s wireless systems; this makes research into highly efficient and robust DOA and beamforming methods an extremely important research topic. Efficient and inexpensive application of smart antennas to existing wireless standards such as IEEE 802.11, CDMA systems and GSM, as well as a software radio approach to smart antennas is also a focus of this research group.

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