An Overview Of Smart Antenna And A Survey On Direction Of Arrival Estimation Algorithms For Smart Antenna

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ABSTRACT : *Smart Antenna Systems is one of the most rapidly developing areas of communication. With effective direction of arrival (DOA) and Beam forming techniques Smart Antenna Systems prove to be most efficient in terms of quality of signals in wireless communication. In this paper a brief overview of Smart Antenna along with a survey on high resolution direction of arrival estimation algorithms for array antenna systems is presented and compared for different parameters. It can help one understand the effectiveness of the DOA algorithms over others under certain parametric conditions.*

Keywords - *Antenna array, DOA estimation, ESPRIT, MUSIC ,Smart antenna.*

1. INTRODUCTION

1.1 Smart Antenna System:

A smart antenna system combines multiple antenna elements with a signal processing capability to optimize its radiation and/or reception pattern automatically in response to the signal environment.

Smart Antenna systems are classified on the basis of their transmit strategy, into the following three types ("levels of intelligence"):

- Switched Beam Antennas
- Dynamically-Phased Arrays
- Adaptive Antenna Arrays

1.1.1 Switched Beam Antennas:

Switched beam or switched lobe antennas are directional antennas deployed at base stations of a cell. They have only a basic switching function between separate directive antennas or predefined beams of an array. The setting that gives the best performance, usually in terms of received power, is chosen. The outputs of the various elements are sampled periodically to ascertain which has the best reception beam. Because of the higher directivity compared to a conventional antenna, some gain is achieved. Such an antenna is easier to implement in existing cell structures than the more sophisticated adaptive arrays, but it gives a limited improvement [1].

1.1.2 Dynamically-Phased Arrays:

The beams are predetermined and fixed in the case of a switched beam system. A user may be in the range of one beam at a particular time but as he moves away from the center of the beam and crosses over the periphery of the beam, the received signal becomes weaker and an intra cell handover occurs. But in dynamically phased arrays, a direction of arrival (DOA) algorithm tracks the user's signal as he roams within the range of the beam that's tracking him. So even when the intra-cell handoff occurs, the user's signal is received with an optimal gain. It can be viewed as a generalization of the switched lobe concept where the received power is maximized [1].

1.1.3 Adaptive Antenna Arrays:

Adaptive antenna arrays can be considered the smartest of the lot. An Adaptive Antenna Array is a set of antenna elements that can adapt their antenna pattern to changes in their environment. Each antenna of the array is associated with a weight that is adaptively updated so that its gain in a particular look-direction is maximized, while that in a direction corresponding to interfering signals is minimized. In other words, they change their antenna radiation or reception pattern dynamically to adjust to variations in channel noise and interference, in order to improve the SNR (signal to noise ratio) of a desired signal. This procedure is also known as 'adaptive beamforming' or 'digital beamforming'.

Conventional mobile systems usually employ some sort of antenna diversity (e.g. space, polarization or angle diversity). Adaptive antennas can be regarded as an extended diversity scheme, having more than two diversity branches. In this context, phased arrays will have a greater gain potential than switched lobe antennas because all elements can be used for diversity combining [1].

2. 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 [2]. 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.
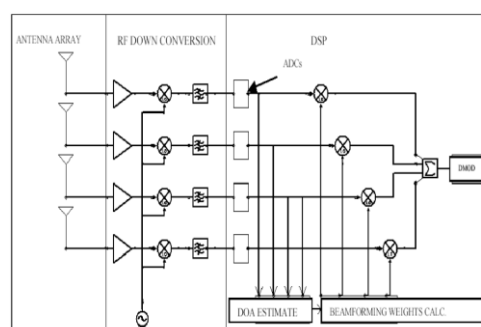

Figure 1 General Smart Antenna Architecture.

3. DOA ESTIMATION ALGORITHMS

The DOA algorithms are classified as quadratic(non subspace) type and subspace type . The Barltett and Capon (Minimum Variance Distortion less Response) are quadratic type algorithms. The both methods are highly dependent on physical size of array aperture, which results in poor resolution and accuracy.

Subspace based DOA estimation method is based on the eigen decomposition. The subspace based DOA estimation algorithms MUSIC and ESPRIT provide high resolution, they are more accurate and not limited to physical size of array aperture [3].

3.1 NON-SUBSPACE TECHNIQUES

These methods depend on spatial spectrum, and DOAs are obtained as locations of peaks in the spectrum. These methods are conceptually simple but offer modest or poor performance in terms of resolution. One of the main advantages of these techniques is that can be used in situations where we lack of information about properties of signal [3].

3.1.1 Delay-And-Sum Method

The delay-and-sum method [3] also referred to as the classical beam former method or Fourier method is one of the simplest techniques for DOA estimation.

3.1.2 Maximum Likelihood Technique

Maximum likely hood estimation seeks the parameter values that are most likely to have produced the observed distribution. Maximum likelihood (ML) techniques were some of the first techniques investigated for DOA estimation. Since ML techniques were computationally intensive, they are less popular than other techniques. However, in terms of performance, they are superior to other estimators, especially at low SNR conditions. Moreover, unlike subspace based techniques can also perform well in correlated signal conditions.

Maximum Likelihood (ML) direction-of-arrival (DOA) estimation techniques play an important role in sensor array processing because they provide an excellent trade-off between the asymptotic and threshold DOA estimation performances. One of the key assumptions used in formulation of both the deterministic and stochastic ML estimators is the so-called spatially homogeneous white noise assumption [3].

3.1.3 Capon's Minimum Variance Technique

The delay-and-sum method works on the premise that pointing the strongest beam in a particular direction yields the best estimate of power arriving in that direction. Capon's minimum variance technique

attempts to overcome the poor resolution problems associated with classical beam forming (delay-and-sum method) [3].

3.2 SUBSPACE TECHNIQUES

Subspace-based methods depend on observations concerning the Eigen decomposition of the covariance matrix into a signal subspace and a noise subspace. Two of these methods MUSIC and ESPRIT were applied here to determine DOA [3].

3.2.1 MUSIC

MUSIC stands for Multiple Signal Classification. It is one of the earliest proposed and a very popular method for super-resolution direction finding, which gives the estimation of number of signals arrived, hence their direction of arrival. MUSIC is a technique based on exploiting the Eigen structure of input covariance matrix. Eigen vectors are easily obtained by either an Eigen decomposition of sample covariance matrix or a Singular Value Decomposition (SVD) of the data matrix.

By MUSIC algorithm the powers and cross correlations between the various input signals can be readily obtained and the DOAs of the multiple incident signals can be estimated by locating the peaks of a MUSIC spatial spectrum.

3.2.2 Root MUSIC

Various modifications to the MUSIC algorithm have been proposed to increase its resolution performance and decrease the computational complexity. One such improvement is the Root-MUSIC algorithm developed by Barbell, which is based on polynomial rooting and provides higher resolution, but is applicable only to a uniform spaced linear array. Another improvement proposed by Barbell uses the properties of signal space Eigen vectors (principal Eigen vectors) to define a rational spectrum function with improved resolution capability [3].

3.2.3 ESPRIT

A new approach (ESPRIT) to the signal parameter estimation problem was recently proposed. ESPRIT is similar to MUSIC in that it exploits the underlying data model and generates estimates that are asymptotically unbiased and efficient. In addition, it has several important advantages over MUSIC.

The ESPRIT method for DOA estimation was first proposed by Roy and Kailath. ESPRIT stands for Estimation of Signal Parameter via Rotational Invariance Technique**.** This algorithm is more robust with respect to array imperfections than MUSIC. Computation complexity and storage requirements are lower than MUSIC as it does not involve extensive search throughout all possible steering vectors. But, it explores the rotational invariance property in the signal subspace created by two sub arrays derived from original array with a translation invariance structure.

Unlike MUSIC, ESPRIT does not require that array manifold vectors be precisely known, hence the array calibration requirements are not stringent decomposed into two equal-sized identical sub arrays with the corresponding elements of the two sub arrays displaced from each other by a fixed translational (not rotational) distance.

3.2.4 The TLS ESPRIT algorithm is summarized as follows:

* Using the multiplicity , of the smallest Eigen value , estimate the number of signals .
* Obtain the signal subspace estimate and decompose it into sub array matrices,
* Compute the Eigen decomposition And partition into sub matrices,
* Calculate the Eigen values .
* Estimate the Angle-Of-Arrival.

As seen from the above discussion, ESPRIT eliminates the search procedure inherent in most DOA estimation methods. ESPRIT produces the DOA estimates directly in terms of the Eigen Values[3].

4. Comparative study of DOA estimation algorithms

4.1 Comparative Study of High-Resolution Direction-of-Arrival Estimation Algorithms for Array Antenna System.

In this paper the receiving system used in the DOA detection process of uncorrelated RF signals of a linear array of four omnidirectional receiving antennas spaced by $\lambda/2$ and operating at frequency 2.4 GHz and a network of four five port demodulators realized in microstrip technology.

DOA estimation methods can be grouped into two categories. In the first category, called global or classical methods provide a representation of the sources field (power and angular positions of the sources) by projecting the model vector (directional vector) on the space of observations without beforehand considering the determination of the number of sources. However, these conventional methods do not get a good resolution. The second category concerns methods known as "parametric" or high-resolution methods which require prior knowledge of the number of uncorrelated sources before estimating their characteristics (angular position,

power...). The estimation problem is first solved by estimation methods of the number of sources. Then a high-resolution method is applied to estimate the angular position of these sources. These high-resolution methods are known to be more robust than conventional techniques [4].

4.1.1 MUSIC

The amplitude of the peaks of the MUSIC pseudo-spectrum is not related quantitatively to that of the corresponding component of the model because resulting peaks only serve to indicate precisely the position of sources. Qualitatively, if the amplitude so the SNR (Signal to Noise Ratio) is more important, the pseudo-spectrum will be less disrupted, resulting in a higher peak value. The amplitude or SNR can be obtained without difficulty by an optimization method of least squares. MUSIC algorithm does not allow obtaining directly the DOA of wave fronts. To know exactly the angles of arrival of the signals, we need to calculate an average over all vectors of an orthonormal basis of the noise space. In other words, we have to calculate the pseudo-spectre on the extent of the parameters space and seek the minima of this function, which limits its performance in terms of speed and computational resources.

Several variants of MUSIC method have been proposed to reduce complexity, increase performance and resolution power.

4.1.2 ROOT-MUSIC

The advantage of this method lies in the direct calculation of the DOA by the search for zeros of a polynomial, which so replaces the search for maxima, necessary in the case of MUSIC. This method is limited to networks of linear antennas uniformly spaced out. In addition, it allows a reduction in computing time and so an increase in the angular resolution by exploiting certain properties of the received signals. It has been shown in [4] that Root-MUSIC algorithm has better resolution than spectral MUSIC algorithm.

4.1.3 ESPRIT

The main advantage of this method is that it avoids the heavy research of maxima of a pseudo spectrum or a cost function (therefore a gain calculation) and the simplicity of its implementation. In addition, this technique is less sensitive to noise than MUSIC and Root-MUSIC.

It has been shown that MUSIC and ESPRIT algorithms achieve almost identical performance in the case of unmodulated sinusoids, but that ESPRIT is slightly better than MUSIC. The study conducted in the more general case of exponentially modulated sinusoids goes to the same direction. Ultimately, ESPRIT appears less sensitive to noise than MUSIC[4].

4.1.4 Performance comparison:

- For a single source located at 18° and a power signal of 5 dBm, the DoA estimated by the three algorithms is obtained with excellent precision.
- When two sources located at -40° and +40° respectively, are estimated, good performances are obtained using all the three techniques.
- When two neighboring sources located at 16° and 20° are estimated, respectively, We notice that the picks are only obtained with ESPRIT and Root-MUSIC. The MUSIC algorithm becomes unable to distinguish those two sources.
- Finally, when tested the case where a high power source tends to hide another source of low power by considering two sources placed at -8° and 8°, the three algorithms have provided an excellent estimated DOA of the source of high power, while the estimate of the other source was tainted with a certain inaccuracy due to the low value of signal to noise ratio.

Thus it is true that MUSIC is widespread for its robustness and accuracy, but in certain cases, Root-MUSIC or ESPRIT can be much better. However, other parameters may be considered such as the number of array elements, size and spacing, as well as the angular separation between incident signals and computation time of each algorithm[4].

4.2 Performance Analysis of MUSIC and ESPRIT DOA Estimation Algorithms for Adaptive Array Smart Antenna in Mobile Communication.

In this paper a uniform linear array with M elements has been considered , spacing between elements is assumed to be 0.5λ[5].

4.2.1 Performance comparison:

- The MUSIC spectrum for uniform linear array with varying elements and SNR=20 dB and (snap shots) K=100 shows that when number of elements in array is increased MUSIC spectrum takes the form of sharper peaks in which angular resolution is improved.
- Also the number of signal snapshots used to generate realistic signal model is a key factor in the realization of practical antennas. Increased snapshots leads to sharper MUSIC spectrum peaks indicating more accurate detection and better resolution.
- DOA Estimation Using ESPRIT For varying Angular Separation for linear array with four elements carried out by varying different parameters of linear array with SNR=20 dB,(snap shots) K=100 shows

that the percentage error in DOA detection using ESPRIT algorithm decreases as angular separation between arriving signals increases.
- Also, when number of samples are increased the error becomes small.
- It also shows that the ESPRIT algorithm can successfully detect 2 incident signals on array of 4 elements but it completely fails if the number of incident signals increased to 4.
- DOA estimation by both MUSIC and ESPRIT for varying SNR for input $\square=25^0$,(number of array elements) M=4, SNR=20 dB, (number of snap shots) K=100, shows that MUSIC provides high resolution and accurate detection of an angle of arrival than that of ESPRIT.

Thus the performance of both MUSIC and ESPRIT improves with more elements in the array, with large snapshots of signals and greater angular separation between the signals. These improvements are seen in form of the sharper peaks in the MUSIC and smaller errors in angle detection in the ESPRIT. However there are more errors in DOA estimation by using ESPRIT compared to the MUSIC algorithm. Clearly MUSIC is more stable and accurate and provides high resolution [5].

4.3 Spatial Differencing Method for DOA Estimation Under the Coexistence of Both Uncorrelated and Coherent Signals.

In this work For the DOA estimation problem of a number of uncorrelated and coherent narrowband signals simultaneously impinging on the far field of a uniform linear array (ULA) an effective Spatial Differencing Method is used . In this method, the uncorrelated sources are firstly estimated using conventional subspace methods, and then they are eliminated by exploiting the spatial differencing technique, that is, only coherent components remain in the spatial differencing matrix.

An eight-sensor ULA with interelement spacing d = λ/2 is employed, when estimating the uncorrelated and coherent sources, respectively, the search range is from -90^0 to +90^0 with a step size of 0.1^0[6].

4.3.1 Performance comparison:
- With the spatial differencing method, under the coexistence of both uncorrelated and coherent signals. The root-mean-square-error (RMSE) of the DOA estimates versus the SNR curves show that spatial differencing method performs better than the FBSS-MUSIC method, the FBSS-ESPRIT method, the ESC method and TLS-MP method.
- When the number of incident signals goes beyond that of array elements the maximal number of incident signals which can be found by this method is equal to 10, when an eight-sensor ULA is employed. Thus, all ten DOAs can be detected by this method.
- Neither the FBSS-MUSIC method nor the ESC algorithm can work under this case, since they cannot estimate more than M-L+1+[2M/3] = 9 signals.
- The RMSE curves of the DOA estimates versus the input SNR show that this method has good estimation performance.
- Also, the estimate with this method will be more accurate as the number of snap shot increases.
- Investigating the effect of the number p of sub arrays on the DOA, we see that this method can provide better DOA estimation even using fewer number (p=2) of sub arrays.
- Also, the estimate by this method will be more accurate as the number of snap shots and the SNR increases respectively.

Thus the spatial differencing method can improve the DOA estimation accuracy as well as increase the maximal number of detectable signals. It has better performance even when the total number of incident sources exceeds that of array elements [6].

4.4 Performance evaluation of DOA estimation using matlab.

In this work for the incident signal obtained from an omnidirectional linear antenna array containing 6 antenna elements from which 1024 snap shots are collected and the signals are assumed to be arriving in end fire direction. The elements are separated from each other by distance of about 0.5 in terms of wavelength. The SNR = 20dB[3].

4.4.1 Performance comparison:
- MUSIC with uncorrelated signals
  It is assumed that noise signals are uncorrelated with each other.
  The MUSIC can estimate uncorrelated signals very well.
- MUSIC with correlated signal condition
  The MUSIC fails when it comes to detecting correlated input signals.
- **ROOT MUSIC**
  For number of antenna elements equal to 10, the interelement spacing in terms of wavelength is 0.5. The number of snap shots taken from antenna is 1024. The noise signals are uncorrelated with each other and SNR = 10 dB.
  ROOT MUSIC detects the sources fairly.

- **ESPRIT**

  For 6 element antenna array and with 1000 snap shots, SNR = 12 dB, the ESPRIT algorithm detects the sources with maximum accuracy.

- While studying the Non-subspace and Subspace DOA algorithms have been studied for different source estimations. Non-subspace estimation techniques yield poor resolution results. For more than one source, subspace estimation techniques can be used efficiently [3].

  Thus, we see that, the high resolution MUSIC algorithm is based on a single RF port smart antenna has been proposed. From the results the technique for a high-resolution DOA estimation of 1 degree, is as good as a conventional MUSIC algorithm. However, ESPRIT has proven to be the most accurate method to be used as DOA algorithm [3].

4.5 Application of MUSIC, ESPRIT and ROOT MUSIC in DOA Estimation.

While investigating the performance of the DOA algorithms like MUSIC, ESPRIT and ROOT MUSIC on the uniform linear array in the presence of white noise, the simulation results show that MUSIC algorithm is the best. The resolution of the DOA techniques improves as number of snapshots, number of array elements and signal-to-noise ratio increases [7].

4.5.1 Performance comparison:

- MUSIC spectrum for varying number of array elements:

  As array size increases, peaks in the spectrum become sharper and hence resolution capability of MUSIC increases.

- MUSIC spectrum for varying number of SNR:

  As SNR value decreases, peaks in spectrum start to disappear and hence resolution capability of MUSIC for closely spaced signals decreases.

- MUSIC spectrum for varying number of snapshots:

  The ability of MUSIC to resolve closely spaced signals is a function of number of snapshots. As snapshots increase from, resolution capability of MUSIC increases, and the two signals can be clearly identified. Peaks in the spectrum become further sharper for more number of snapshots.

- DOA estimation for varying number snapshots (SNR=10dB, array size=16 and four angles (14º, 28º, 35º and 55º) show that, if number of snapshots increases, peaks in the spectrum become sharper and deeper, and thus means improvement of the resolution capability of MUSIC. ESPRIT and ROOT MUSIC identify the four signals, but the MSE is close, but not exactly zero. For lower snapshot value, both MUSIC and ESPRIT fail to detect closely spaced signals, but ROOT MUSIC identifies them very well. MSE by MUSIC for varying number of snapshots almost zero. For closely spaced signals MUSIC gives MSE zero for same snapshots compared to other two techniques.

- Also, as SNR decreases, the both: ESPRIT and ROOT MUSIC are unable to detect the angle correctly as compared to MUSIC. It is noted that ESPRIT gives more error compared to ROOT MUSIC.

  The performance of the three algorithms for different value of SNR, results in giving the highest ranking to MUSIC, as the most stable and accurate algorithm, which provides high resolution despite lower value of SNR.

5. Conclusion

The modern high resolution methods based on the concept of subspace such as MUSIC, ROOT-MUSIC and ESPRIT are among the most efficient for estimating the directions of arrival (DOA) of signals using array antennas. Some other algorithms like spatial differencing method for DOA estimation prove to be more effective under the coexistence of both uncorrelated and coherent signals.

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