Survey of Recent Beamforming Methods for Adaptive Antenna Array System

[1]Mrs. Mane Sunita Vijay,[2]Prof. Dr. Bombale Uttam L.
[1]Assistant Professor,[2]Associate Professor
Electronics Department,
[1]KBPCOE, Satara, India.

Abstract : Wireless communication techniques are upgrading day by day, because of increasing number of users. There are many methods used to increase the efficiency of the wireless communication system like cell sectoring, cell splitting, directional antenna. Directional antenna is also called as smart antenna. A smart antenna is combination of individual antenna elements and signal processing algorithms. The use of smart or adaptive antenna system has impact on increasing efficiency of wireless network and suppressing the interference signals. Smart antenna system addresses this problem using advanced technology called beamforming. Through adaptive beamforming, the base station can form narrower beam towards the desired user and nulls towards interfering signals. The weights of antenna arrays can be adjusted in such manner to form adaptive beams towards desired users by using beamforming algorithm. This paper gives classification,survey and study of blind, and nonblind beamforming algorithms.

Index Terms **- Beamforming, smart antenna, adaptive antenna, signal processing.**

I. INTRODUCTION

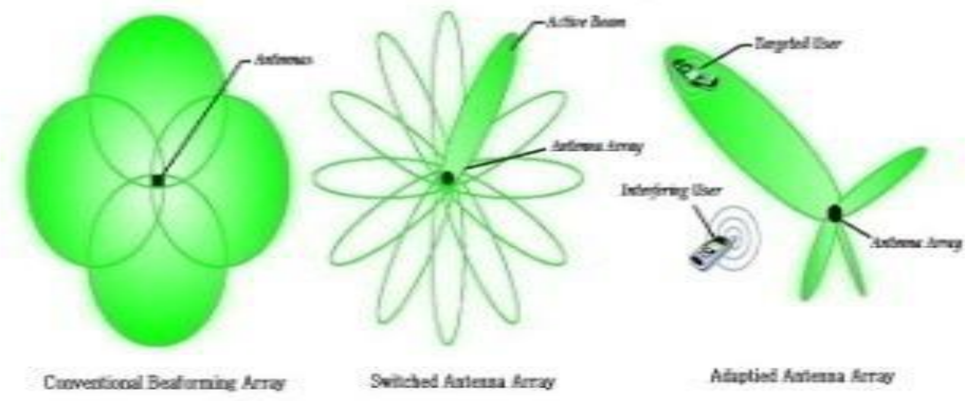
SMART antenna systems using multiple antennas promise accumulated system capability, extended radio coverage and improved quality of service through the power to steer the antenna radiation pattern towards the direction of desired user while placing nulls at interferer locations. While addition of more antennas to the array means higher angle resolution in steering the beam and more degrees of freedom in placing the nulls, it also means an increase in computational complexity and may include delay in calculating the weight vector that is used to combine the received signals at the antennas. Switched-beam approach is a one in which a set of weight vectors are precalculated and stored for different angles and has negligible computational complexity.[2]

The basic types of smart antenna are as shown in Fig 1, the first type is the conventional beamformer array which has fixed radiation pattern. The second type is phased array or multi beam antenna, which consists of either a number of fixed beams with one beam turned on towards the desired signal or a single beam formed by phase adjustment that can be steered towards the specified signal.

The other type is adaptive antenna array, which is an array of multiple antenna elements, with the received signals weighted and combined to maximize the desired signal to interference plus noise power ratio.

Prior to adaptive beamforming, the directions of users and interferes must be obtained using a direction of-arrival (DOA) estimation algorithm. The goal of DOA estimation is to use the information received on the downlink at the base-station sensor array to estimate the directions of the signals from the desired mobile users and also from interferers.

The results of DOA estimation are then used to calculate the weights of the adaptive beamformer so the radiated power is maximized towards the specified users, and radiation nulls placed in the directions of interference signals. Hence, a design of adaptive array depends on the selection of the DOA estimation algorithm which is extremely correct and sturdy.



Conventional Bealforming Array
Switched Antenna Array
Adaptied Antenna Array

Figure 1. Types of Smart Antenna

The adaptive array puts a main beam in the direction of the desired signal and nulls in the direction of the interference in antenna radiation patterns. Because of this principle a smart antenna can suppress interference, increase the system capacity, increase power efficiency and also reduce overall infrastructure costs. A smart antenna is therefore a phased or adaptive array that adjusts its radiation pattern as per requirement. That is, for the adaptive array, the beam pattern changes as the desired user and the interference move; and for the phased array the beam is steered i.e. different beams are selected as the desired user moves. [10]

II. ADAPTIVE BEAMFORMING

Adaptive beamforming can be done in many ways. Many algorithms exist for many applications varying in complexity, robustness, tracking ability and rate of convergence. Most of the algorithms are concerned with the maximization of the signal to noise ratio. A generic adaptive beamformer is shown in Figure 2. The weight vector w is calculated using the statistics of signal x(t) arriving from the antenna array. An adaptive processor will minimize the error e(t) between a desired signal d(t) and the array output y(t).

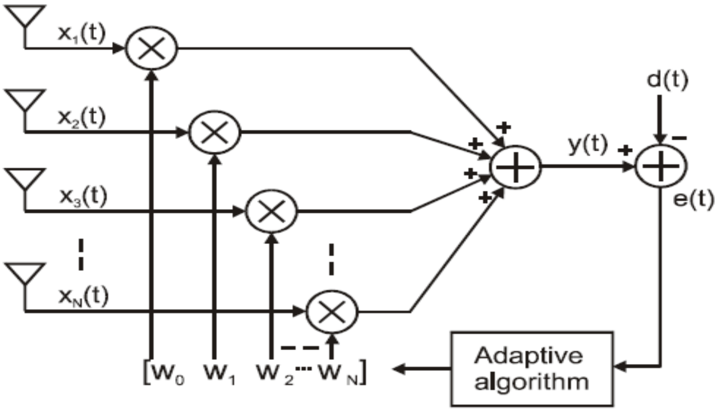


Figure 2. Adaptive beamforming configuration

The two major types of adaptive beamforming algorithms are blind and non- blind beamforming algorithms. Non blind algorithms require training sequence to detect desired signal and adjust the weight and blind algorithm do not require training sequence to detect desired signal.[12]

III. NONBLIND ADAPTIVE BEAMFORMING ALGORITHMS:

1) Least Mean Square (LMS) Algorithm:

Widrow introduced LMS algorithm. This algorithm adjust the filter coefficients by estimating the gradient of the quadratic Mean Square Error (MSE) surface and then moving the weights in the negative direction of the gradient by small amount called step size. We can find the cost function by finding MSE. The error equation is given by,

$$\varepsilon(n) = d(n) - \bar{w}^{H}(n)\bar{x}(n) \tag{1}$$

$$|\varepsilon(n)|^2 = |d(n) - \bar{w}^{H}(n)\bar{x}(n)|^2 \tag{2}$$

The equation for array weights updation is given by,

$$w(n+1) = w(n) + \mu e*(n)\, x(n) \tag{3}$$

Most simplest algorithm for adaptive processing is based on the Least Mean Square (LMS) error. The complexity of this algorithm is very low and its results are found satisfactory in many cases. The algorithm is very stable and it needs few computations, which is important for system implementation. The computational power of many systems is limited and should be used effectively. The algorithm is based on knowledge of the arriving signal. The knowledge of the received signal eliminates the need for beamforming, but the reference can also be a vector that is partly known, or correlated with the received signal. For example, the training sequence in the GSM standard, intended for channel equalization, could be used for beamforming. The rest of the signal is unknown, and beamforming using LMS can only be performed on the known training sequence. When the adaptive algorithm is not using this knowledge, but statistic information of the signal, it is called blind beamforming. There are several algorithms for blind beamforming. For example the Constant Modulus algorithm (CMA) uses the knowledge that the modulus of the signal is constant. There are many modulation schemes where the modulus is kept constant. CMA is one of the most simple blind beamforming algorithms.[15]

LMS algorithm is very simple and easy to implement. It has very low computational complexity. It does not involve matrix inversions and calculations. Instead it uses weight adaptation principle.LMS algorithm has very low convergence rate. This can be proved by analysing its performance on the basis of beam pattern. The performance can be evaluated from a rectangular plot or polar plot and mean square error value (MSE). LMS beamformer has demonstrated its ability to direct the antenna beam in the direction of the mobile user as well as its ability to null out the interferers.

Following are the two improved algorithms called NLMS and BBNLMS based on LMS algorithm.

a) Normalized Least Mean Square (NLMS)Algorithm:

NLMS algorithm is an extension of LMS algorithm and also they have same practical implementations. In NLMS algorithm step size parameter is chosen based on current input values. Thererfore step size is said to be normalized. It shows greater stability with unknown signals.

NLMS algorithm has improved convergence rate. It has been analyzed that, normalized-LMS performs better than LMS algorithm. The radiation pattern is better and more directed when we implement NLMS algorithm. These can be shown using linear beam pattern and polar beam pattern formats in the graphs.

NLMS algorithm provides better balance between simplicity and performance. In future the analysis can be for different channels such as Rayleigh and Racian channels.

b) Block Based Normalized Least Mean Square (BBNLMS) Algorithm:

In BBNLMS algorithm, the extra calculations are required to calculate μ(n), a step size, which can be reduced in which the input data is portioned into blocks and maximum magnitude within each block is used to calculate μ(n). With this the weight update relation for $x_m \neq 0$ and $p = 0$ takes the following form,

Where x_m is the maximum of x(n) in the block. Using such an approach the number of multiplications reduces in the computation on μ(n). Analysis reveals that when compared with LMS and NLMS algorithms BBNLMS algorithm has more increase in convergence rate in multipath and multiple signal environment which can be proved on the basis of radiation pattern and mean square error [2]

2) Sample Matrix Inversion (SMI) Algorithm:

SMI algorithm provides good performance in a discontinuous traffic. However, it requires that the number of interferers and their positions remain constant during the duration of the block acquisition. If a priori information about the desired and the interfering signals is known, then the optimum weights can be calculated directly by equation,

$$\bar{w}_{opt} = \bar{R}_{xx}^{-1}\bar{r} \qquad (4)$$

Where,

$$\bar{r} = E[d^* \cdot \bar{x}] \qquad (5)$$

$$\bar{R}_{xx} = E[\bar{x}\bar{x}^H] \qquad (6)$$

This algorithm is based on an estimate of the correlation matrix and cross correlation vector of the adaptive array output samples.

Then for the kth block of length K the SMI weights can be given as,

$$\begin{aligned}\bar{w}_{SMI}(k) &= \bar{R}_{xx}^{-1}(k)\bar{r}(k) \\ &= \left[\bar{X}_K(k)\bar{X}_K^H(k)\right]^{-1}\bar{d}^*(k)\bar{X}_K(k) \qquad (7)\end{aligned}$$

SMI improves the convergence speed but it has more computational complexity and singularity problem of correlation matrix. It has been proved that it provides good performance in a discontinuous traffic. However, it requires that the number of interferers and their positions remain constant during the duration of the block acquisition. SMI includes direct matrix inversion therefore convergence of this algorithm is much faster compared to the LMS algorithm. Performance of SMI algorithm can be verified in multiple paths and multiple signal environments.

3) Recursive Least Square (RLS) Algorithm:

The problem of slow convergence of LMS algorithm is solved with RLS algorithm by replacing gradient step size with gain matrix $\bar{g}(k) = \hat{R}_{xx}^{-1}(k)\bar{x}(k)$ at the kth iteration, producing weight update equation given by,

$$\begin{aligned}\bar{w}(k) &= \bar{w}(k-1) - \bar{g}(k)\bar{x}^H(k)\bar{w}(k-1) + \bar{g}(k)d^*(k) \\ &= \bar{w}(k-1) + \bar{g}(k)[d^*(k) - \bar{x}^H(k)\bar{w}(k-1)] \qquad (8)\end{aligned}$$

RLS algorithm overcomes the problem of SMI algorithm showing better null depth. RLS algorithm shows best main lobe formation as it has maximum signal strength in desired direction. In case of RLS we have narrowest beam width, complete rejection of interference and fastest convergence at the cost of high computational burden but has greater power in side lobes as compared to LMS. RLS is the best choice and has also its application where quick tracking of the signal is required. RLS algorithm is found to have minimum BER and error signal magnitude, therefore it has been proved the best algorithm for implementation on Base Station Smart Antenna System. As the recent developments in digital signal processor (DSP) kits and field-programmable gate arrays (FPGA) have made it possible to implement RLS algorithms in real time systems, and complexity to an extent is not a problem anymore, RLS can be thought of a good choice for beamforming applications.

4) Conjugate Gradient Method (CGM) Algorithm:

CGM algorithm increases the rate of convergence by iteratively searching for the optimum solution by choosing conjugate (perpendicular) paths for each new iteration. Thus, the path taken for the (n+1) th iteration is perpendicular to that for the nth iteration. The weights are updated according to the following equation,

$$\bar{w}(n+1) = \bar{w}(n) - \mu(n)\bar{D}(n) \qquad (9)$$

where, μ(n) is the step size and D(n) is the direction vector.

The CGM algorithm calculates the array weights by orthogonal search at each iteration. It shows good beamforming pattern and a high convergence rate. It also has a better resolution compared to the previous algorithms because the main beam pointing towards the desired user is quite sharp with a high directivity and the side lobes are very less and have power level very low than what was achieved in the previous algorithms. In CGM algorithm by replacing the gradient step size with a gain matrix, it is noticed that increasing the number of elements of the antenna array ensures better performance. CGM has also narrow beam width, complete rejection of interference, fast convergence as compared to LMS. It finds its application in mobile communication where it is used to eliminate multipath fading.

IV. BLIND ADAPTIVE ALGORITHM:

1) Constant Modulus Algorithm (CMA):

CMA is a well known algorithm of adaptive beamforming of blind adaptation. This algorithm is derived keeping in view the constant complex envelope (amplitude) property of the signal. CMA does not require a pilot signal. These signals generally include FM, FSK, PSK, QAM and PAM modulation types. If the arriving signal has constant amplitude then this algorithm maintains and restores the amplitude of desired signal. The weights can be calculated using following equations,

$$\bar{w}(n+1) = \bar{w}(n) + \mu e^{*} n \bar{x}(n) \qquad (10)$$

the error signal in equation (10) is given by

$$e(n) = \left(y(n) - \frac{y(n)}{|y(n)|}\right) \qquad (11)$$

Here, $w(n+1)=w(n) + \mu\, e^{*}(n)\, x(n)$ (12)

and $y(n) = wH(n)\, x(n)$ (13)

$e(n)$=error signal, $y(n)$=output signal and $x(n)$=input signal

CMA has widest beam width in the desired direction, suppress interference to some extent and unstable behaviour in case of convergence due to which CMA can be used in applications where complex envelope of the signal should ideally be constant. CMA doesn't use any reference signal but automatically selects one or several of the multipaths as the desired signal. When array vector is updated it does not need to know the arrival timings of the incident rays. It does not need to synchronously sample the received signal with the clock timing. CMA bears maximum error but focusing on cochannel interference it gives more reliable results than LMS and RLS. Results obtained from simulation assert that capability to reject the interfering signal by placing nulls in undesirable direction is really accomplished by CMA. But when angle of arrival of interference and user were quite close to each other then CMA had BER even more than single antenna element.

2) Decision Directed Algorithm (DDA):

For BPSK communication with low bit error rate (BER), the complex limited Constant Modulus Reference Signal $y(n)/|y(n)|$ can be replaced by a decision directed term defined as $\mathrm{sgn}(\mathrm{Re}\,(y(n)))$. Decision directed form uses the demodulated signal to reference the variation in the modulus of array output.

Equation for weight calculation is given by,

$$w(n+1) = w(n) - 1/2\, \mu\, x(n)\, e*(n) \qquad (14)$$

$$\text{where, } e(n) = y(n) - \mathrm{sgn}(\mathrm{Re}(y(n))) \qquad (15)$$

$$y(n)=wH(n)\, x(n) \qquad (16)$$

The algorithm uses symbol decisions made on initial signal estimate which generate a reference signal used to estimate minimum of mean squared error (MSE). An asymptotic analysis technique is used for this purpose.

As mentioned above we have seen overview of various non-blind and blind adaptive beamforming algorithms. In this paper main focus is given on the review of implementation, analysis and performance issues of all these adaptive algorithms.[12]

V. LITERATURE REVIEW:

Rodrigo C. de Lamare proposed robust Linearly constrained minimum variance (LCMV) reduced rank beamforming algorithm based on constrained robust joint iterative optimization(RJIO) of parameters. It has high computational complexity and outperforms in convergence, tracking performances[1].

The dependence of angular-resolution on the hardware capabilities, amount of memory if digital processing is employed, and limiting the performance to prespecified angles are the major drawback of switched-beam-based systems. In fully adaptive systems, however, a new weight vector is calculated with the change in the angle of the user and an interferer. The adaptive approach, therefore, offers accurate tracing of the user angle at the cost of increased computational complexity. Taking into account these advantages and limitations, a hybrid smart antenna system was proposed that combines the advantages of the adaptive and the switched beam smart antenna approaches. In the proposed hybrid system that number of antennas in the array can be higher than the number of channels available at the receiver. A smart switch selects a subset of antennas and then a beamforming algorithm is applied to calculate the weights for the selected antennas. Smart switch selects the subset consisting of neighbor elements with highest total power. It was suggested that a subset of elements that receive the strongest signals should be selected, but to prevent possible beam splitting and the formation of high levels of side lobes it was necessary to limit selection to neighboring elements with highest total power. By means of selecting a subset of antennas via a smart switch, the computational complexity of beamforming weight calculation is reduced thus resulting in a smaller latency in addition to savings in the hardware cost due to reduced number of channels at the receiver. The use of directional antennas instead of isotropic elements as a performance enhancement to the hybrid smart antenna systems is proposed in this work.

In the last decade, smart antenna techniques have attracted a significant interest from researchers and engineers, and found applications in radar, sonar, wireless communications and seismology. The optimal linearly constrained minimum variance (LCMV) beamformer is designed in such a way that it minimizes the array output power while maintaining a constant response in the direction of a signal of interest (SOI). However, this technique requires the computation of the inverse of the input data covariance matrix and the knowledge of the array steering vector. Adaptive versions of the LCMV beamformer were subsequently reported with stochastic gradient (SG) and recursive least squares (RLS) algorithms. A key problem with this techniques is the impact of uncertainties which can result in a considerable performance degradation. These mismatches are caused by local scattering, imperfectly calibrated arrays, insufficient training and imprecisely known wave field propagation conditions [2].

MOHAMMAD Tariqul Islam, ZAINOL Abidin Abdul Rashid present a new beamforming algorithm that is easy to implement with less complexity and having faster convergence speed and accurate tracking capability. The individual advantages of both block adaptive and sample by sample techniques are employed to solve these issues.

A novel adaptive beamforming algorithm “MI-NLMS” is presented for smart antenna system which combines the normalized LMS (NLMS) and SMI algorithms to improve the convergence speed with small bit error rate (BER).[3]

Training sequence algorithms like Recursive Least Squares (RLS) and Least Mean Squares (LMS) give better results for beamforming to form main lobes towards desired user but they are not providing accurate results towards interference rejection. While Constant Modulus Algorithm (CMA) has satisfactory response towards beamforming and it gives better result for interference rejection, but Bit Error Rate (BER) is maximum in case of single antenna element in CMA. It is verified that convergence rate of RLS is faster than LMS so RLS is proved the best choice.[4]

The convergence speed of the LMS algorithm depends on the eigen values of the array correlation matrix. In an environment yielding an array correlation matrix with large eigen values spread the algorithm converges with a slow speed. This problem of slow speed is solved with the RLS algorithm by replacing the gradient step size μ.[5]

SMI has a fast convergence rate. It is suitable for burst traffic adaptation where it is unlikely that signal environment will change during block acquisition. SMI algorithm is based on matrix inversion, which tends to be computationally intensive. The high convergence rate is very important property of the SMI algorithm when it is used in combination with other algorithms. Again like LMS, SMI algorithm requires information about the desired signal.[6]

Chintan S. Jethva and Dr. R.G. Karandikar give comparative study of five adaptive algorithms Least Mean Square (LMS), Normalized Least Mean Square (NLMS), Sample Matrix Inversion (SMI), Recursive Least Square (RLS) and Conjugate Gradient Method (CGM) for computing the array weights. When LMS and NLMS are compared it is observed that NLMS has quick convergence. The RLS algorithm shows high rate of convergence, but the side lobes are not completely cancelled. The recursive equations used in the RLS algorithm allow faster update of array weights. The Sample Matrix Inversion algorithm is a time average estimate of the array correlation matrix using k time samples i.e. dividing the input samples into *k* number of blocks and each number of blocks is of length k. Hence SMI has advantage of increased convergence rate and reduction in computational complexity. [7]

The RLS algorithm does not require any matrix inversion computations as the inverse correlation matrix is computed directly. It requires reference signal and correlation matrix information. An important feature of the recursive least square algorithm is that its rate of convergence is typically an order of magnitude faster than that of the simple least mean square.[8]

AMARA PRAKASA RAO and N.V.S.N. SARMA present performance comparison of LMS, RLS and CMA algorithms for linear array, circular array and planer array geometry. In Least Mean Square algorithm, the convergence speed of the algorithm depends on the step size, which depends on the correlation matrix.[9]

The most important feature of a smart antenna system is its beam forming capability. Smart antennas usually include both switched beam forming and adaptive beam forming systems. Several fixed beam patterns are available in Switched beam systems i.e. a decision is made as to which beam to access, at a particular time. Whereas beamformed adaptive systems allow the antenna to steer the beam to any direction of interest while simultaneously nullifying interfering signals.[10]

IV. CONCLUSION

Smart antenna is the most effective innovation for maximum coverage, improved quality and more capacity. Smart antenna technology increases the efficiency of system using advanced technology called beamforming. Through adaptive beamforming, the base station can form narrower beam towards user, that is wanted signal and nulls towards interfering users, that is unwanted signals. In this paper the various types of non-blind and blind algorithms are described with their benefits and limitations.

From the above review it is concluded that, there are various adaptive beamforming algorithms given for smart antennas which have ability to provide maximum gain in desired direction neglecting the interference condition. These algorithms are found to be implemented and evaluated considering different parameters such as radiation pattern, mean square error, convergence rate under different conditions of number of users, number of antenna elements and element spacing along with the cost due to hardware and computational complexity. Considering all these facts and comparing them on the basis of advantages and limitations as mentioned in the above review, a proper beamforming algorithm can be chosen that can satisfy the system and user requirements.

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