Performance Analysis of Digital Beam formers used in Smart Antenna Systems

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Abstract— Smart antennas involve processing of signals induced on an array of sensors such as antennas, microphones, and hydrophones. They have applications in the areas of Radar, Sonar, Medical Imaging and Mobile Communication. In this paper we analyzed the performances of Sample Matrix Inversion (SMI) and Least Mean Square (LMS) adaptive beamforming algorithms. Simulation results clearly show that the SMI is suitable for only less antenna elements. It works properly for less than 10 antenna elements. This limits its application for 5G and above networks. Whereas LMS algorithm works efficiently for both less and more antenna elements. Hence LMS algorithm is much better than the SMI for smart antenna based wireless communication applications.

Key words: 5G, LMS, SMI, Smart Antenna

I. INTRODUCTION

The term “smart antenna” generally refers to any antenna array [1]-[5], terminated in a sophisticated signal processor, which can adjust or adapt its own beam pattern in order to emphasize signals of interest and to minimize interfering signals. Smart antennas generally encompass both switched beam and beamformed adaptive systems. Switched beam systems have several available fixed beam patterns. A decision is made as to which beam to access, at any given point in time, based upon the requirements of the system. Beamformed adaptive systems allow the antenna to steer the beam to any direction of interest while simultaneously nulling interfering signals [6]-[8]. The smart antenna concept is opposed to the fixed beam “dumb antenna,” which does not attempt to adapt its radiation pattern to an ever-changing electromagnetic environment. In the past, smart antennas have alternatively been labeled adaptive arrays or digital beamforming arrays [11]. This new terminology reflects our penchant for “smart” technologies and more accurately identifies an adaptive array that is controlled by sophisticated signal processing [12]. Figure 1.1 contrasts two antenna arrays. The first is a traditional, fixed beam array where the mainlobe can be steered, by defining the fixed array weights w¯. However, this configuration is neither smart nor adaptive. The second array in the figure is a smart antenna designed to adapt to a changing signal environment in order to optimize a given algorithm [13]. An optimizing criterion, or cost function, is normally defined based upon the requirements at hand. In this example, the cost function is defined as the magnitude of the error squared, |ε|2, between the desired signal d and the array output y. The array weights w¯ are adjusted until the output matches the desired signal and the cost function is minimized. This results in an optimum radiation pattern.

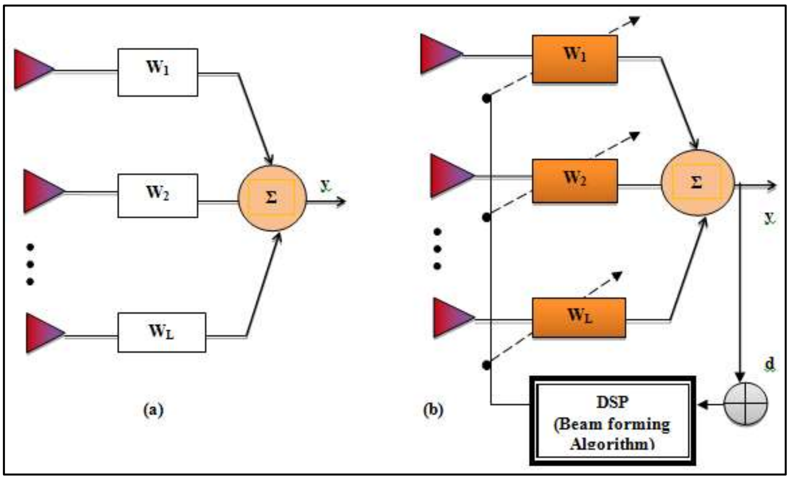

Fig. 1(a): Traditional array (b): Smart antenna

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II. NEED FOR SMART ANTENNA

The rapid growth in demand for smart antennas is fueled by two major reasons. First, the technology for high speed analog-to-digital converters (ADC) and high speed digital signal processing is burgeoning at an alarming rate. Even though the concept of smart antennas has been around since the late 50s, the technology required in order to make the necessary rapid and computationally intense calculations has only emerged recently [14]. Early smart antennas, or adaptive arrays, were limited in their capabilities because adaptive algorithms were usually implemented in analog hardware. With the growth of ADC and digital signal processing (DSP); what was once performed in hardware can now be performed digitally and quickly. ADCs, which have resolutions that range from 8 to 24 bits, and sampling rates approaching 20 Giga samples per second (GSa/s), are now a reality. In time, superconducting data converters will be able to sample data at rates up to 100 GSa/s. This makes the direct digitization of most radio frequency (RF) signals possible in many wireless applications. At the very least, ADC can be applied to IF frequencies in higher RF frequency applications [15].

Thus, the benefits of smart antenna integration will only flourish, given the exponential growth in the enabling digital technology continues. Second, the global demand for all forms of wireless communication and sensing continues to grow at a rapid rate. Smart antennas are the practical realization of the subject of adaptive array signal processing and have a wide range of interesting applications. These applications include, but are not limited to, the following: mobile wireless communications, software-defined radio, wireless local area networks (WLAN), wireless local loops (WLL), mobile Internet, wireless metropolitan area networks (WMAN), satellite based personal communications services, radar, ubiquitous radar, many forms of remote sensing, mobile ad hoc networks (MANET), high data rate communications, satellite communications , multiple-in-multiple-out (MIMO) systems, and waveform diversity systems[16]-[18].

- Improved system capacities
- Higher permissible signal bandwidths
- Space division multiple access (SDMA)
- Higher signal-to-interference ratios
- Increased frequency reuse
- Side lobe canceling or null steering
- Multipath mitigation
- Constant modulus restoration
- Blind adaptation
- Improved AOA estimation
- Instantaneous tracking of moving sources

III. PROBLEM FORMULATION

In recent years a substantial increase in the development of broadband wireless access technologies for evolving wireless internet services and improved cellular systems has been observed. Because of them, it is widely foreseen that in the future an enormous rise in traffic will be experienced for mobile and personal communications systems. This is due to two facts, first is an increase in number of users and second is introduction of high bit rate data services. This becomes a major challenging problem for the service providers to solve[19]. There exist certain negative factors in the radiation environment contributing to the limit in capacity and one such negative factor is co-channel interference caused by increase in number of users. The other impairments contributing to the reduction of system performance and capacity are multipath fading, delay spread caused by signals being reflected from structures (e.g. buildings and mountains) and users traveling on vehicles. The deployment of smart antennas (SAs) for wireless communications has emerged as one of the leading technologies for achieving high efficiency networks that maximize capacity and improve quality and coverage [20].

In the SMI algorithm is used for the purpose of beam forming. However the weight expression of the SMI algorithm involves inversion of the array correlation matrix. Also as the number of antenna elements increases the radiation pattern produces radition in multiple several directions. To overcome this disadvantage Least Mean Square algorithm was introduced. The LMS algorithm will form the main beam in such a way that the Mean Square Error is the lowest.

IV. ADAPTIVE BEAM STEERING SIGNAL MODEL

Considering a problem of wiener filtering, with reference to a non-stationary process. Let $w(n)$ denote unit sample response of the FIR wiener filter that produces minimum mean square estimate of desired signal $s(n)$. The output of the filter is given by

$$y(n) = \sum_{k=0}^{L} w(k)\, x(n-k) \tag{1}$$

Where ' L ' is the order of filter. If $x(n)$ and $s(n)$ are wide sense stationary processes then error signal is given by

$$e(n) = s(n) - y(n) \tag{2}$$

The filter coefficients or Beam steering array weights $w(n)$ that minimizes the Mean Square Error $|e(n)|^2$ is found by solving the Weiner-Hopf equation given by

$$w(n) = R_{xx}^{-1} r_{sx} \tag{3}$$

Where, R_{xx} is the autocorrelation of induced signal $x(n)$ and r_{sx} is the cross correlation between reference signal $s(n)$ and induced signal $x(n)$. In many aspects, the design of adaptive Beamformer is much more difficult than design of beam former based on Weiner Hopf equation. This problem can be simplified by considering the weight update equation to be

$$w(n+1) = w(n) + \Delta w(n) \tag{4}$$

Where, $\Delta w(n)$ is the correction applied to calculate new weights. This type of weight updating for $w(n)$ forms the heart of every Beamsteering algorithm and each of the Beamsteering algorithms varies in terms of computation of weights.

In a practical case, if $s(n)$ is the signal samples corresponding to look direction, i(n) is interfering signal samples corresponding to jamming directions and $n_0(n)$ is noisy signal samples due to receiver components.

The induced signal is given by

$$x(n) = s(n)a(\theta_0) + \sum_{i=1}^{M} i_i(n)a(\theta_i) + n_0(n) \tag{5}$$

Where, M is number of jamming sources, $a(\theta_0)$ is desired steering vector and $a(\theta_i)$ is the steering vector corresponding to i^th^ interference signal. Since jamming signals (or interfering signals) are of no interest, it is assumed $i(n)_1 = i(n)_2 ...... = i(n)_M = i(n)$ with this modification equation (3.5) can be written as

$$x(n) = a(\theta_0)s(n) + i(n)\sum_{i=1}^{M} a(\theta_i) + n_0(n) \tag{6}$$

In matrix notation, induced signal can be written as

$$X = A_{\theta_0} S + A_{in} I_i + N \tag{7}$$

Where, X represents L x N$_s$ induced signal matrix, N$_s$ is total number of samples, 'L' represents number of array elements, 'S' represents reference signal samples. A_{θ_0} is desired steering vector of order Lx1, I_i represents interference signal samples matrix of order 1xN$_s$, N represents Gaussian noise matrix of order LxN$_s$ and A_{in} is Lx1 column vector that is obtained by adding all columns of array manifold vector as shown

$$A_{in} = \begin{bmatrix} 1 \\ e^{i2\pi d \sin\theta_1} \\ \vdots \\ e^{i2\pi d (L-1)\sin\theta_1} \end{bmatrix} + \begin{bmatrix} 1 \\ e^{i2\pi d \sin\theta_2} \\ \vdots \\ e^{i2\pi d (L-1)\sin\theta_2} \end{bmatrix} + ... + \begin{bmatrix} 1 \\ e^{i2\pi d \sin\theta_M} \\ \vdots \\ e^{i2\pi d (L-1)\sin\theta_M} \end{bmatrix} \tag{8}$$

Where, 'd' is the distance between antenna elements, $\theta_1, \theta_2, ..., \theta_M$ are directions of jamming signals and M is number of jamming signals.

V. SAMPLE MATRIX INVERSION (SMI)

SMI is used if the desired and interference signals are known before or have been estimated. This provides the direct and fastest solution to compute the optimal weights. However, if the signals are not known exactly, then signal environment undergoes frequent changes. Thus, the signal processing unit must continuously update the weight vector to meet the new requirements imposed by the varying conditions. The weight vector must be updated without a priori information which, leads to estimation of covariance matrix R_{xx} and cross-correlation vector r_{xs} in a finite observation interval given by equations

$$R_{xx} = E[X X^H] \tag{9}$$

$$r_{xs} = E\left[XS^H\right] \tag{10}$$

Where, X is induced signal matrix, X^H is hermitian transpose of X, E is the expectation operator and S is reference signal matrix.

A. Simulation Methodology of SMI Algorithm

1) *Compute the Lx1 steering vector for desired direction* θ_0 *using*

$$a(\theta) = \begin{bmatrix} 1 \\ e^{i2\pi d \sin\theta} \\ \vdots \\ \vdots \\ e^{i2\pi d (L-1)\sin\theta} \end{bmatrix}$$

2) *Compute the LxM array manifold vector corresponding to M interference source directions* $\theta_1, \theta_2, \dots\dots\dots, \theta_M$

$$A = \begin{bmatrix} 1 & 1 & \dots\dots & 1 \\ e^{i2\pi d \sin\theta_1} & e^{i2\pi d \sin\theta_2} & \dots\dots & e^{i2\pi d \sin\theta_{M-1}} \\ \vdots & \vdots & \vdots & \vdots \\ e^{i2\pi d (L-1)\sin\theta_1} & e^{i2\pi d (L-1)\sin\theta_2} & \dots\dots & e^{i2\pi d (L-1)\sin\theta_{(M-1)}} \end{bmatrix}$$

3) *Obtain signal samples 'S' by sampling continuous time signal of baseband frequency.(for simulation cosine wave samples are considered)*
4) *Compute Lx1 cross-correlation matrix* r_{xs} *by using* $r_{xs} = E[XS^H]$
5) *Compute LxL covariance matrix* R_{xx} *by using* $R_{xx} = E[X\ X^H]$
6) *The inverse of covariance matrix* R_{xx} *is found.*
7) *The weight vector is computed by using equation* $w(n) = R_{xx}^{-1}\, r_{xs}$
8) *The array factor is computed by using equation*

$$AF = \sum_{i=1}^{L} w^H(i)\, e^{j2\pi d \sin(\theta)} \qquad -90^0 \le \theta + 0.001 \le +90^0$$

The value of θ in equation varies between $-90^0 \le \theta + 0.001 \le +90^0$ and $w^H(i)$ is hermitian transpose weight update vector $w(n)$.

9) *Array factor versus angles are plotted.*

VI. LEAST MEAN SQUARE BEAMFORMER

The LMS algorithm is a member of a family of stochastic gradient algorithms since the instantaneous estimate of the gradient vector is a random vector that depends on the input data vector x(k)**.** The LMS algorithm requires 2M+1complex multiplications and 2M complex additions per iteration, where *M* is the number of weights (elements) used in the adaptive array.

A. Pseudo Code of LMS algorithm

1) *Initialize the weight vector to zeros (N, 1)*
2) *Find the Rxx (the autocorrelation of input signal)*
3) *Select the step size*
4) *Calculate the output y = W*X*

$$w(n+1) = w(n) + \mu\, e(n)\, x^*(n)$$
$$e(n) = error \quad signal$$
$$x^*(n) = recieved \quad signal$$
$$\mu = step \quad size$$
$$\mu = \frac{2}{3tr(R_{xx})}$$

5) *Find the error e =d – y*
6) *Update the weight equation =W (k + 1) = W (k) +µ X (k) e * (k)*
7) *Repeat the steps (4-6) until the error is minimized*
8) *End of the simulation*
9) *Plot the result*

VII. RESULTS & DISCUSSIONS

This work is implemented in digital signal processing (DSP) lab using MATLAB simulation software. The specifications and requirements of the project are summarized in the Table I:

Sl. No	Parameters	Values
1	Type of antenna array	Uniform Linear Array

2	Number of array elements	Variable
3	Passband Frequency range	(3-4) GHz
4	Voltage range for AOA	(1-5)v
5	Direction range for AOA	0 to ± 90^0
6	Simulation Language	MATLAB
7	Simulation Version	MATLAB 2008a

Table 1: Simulation parameters

A. Simulation results of Adaptive Beamforming using SMI and LMS algorithms

The LMS and SMI algorithms are simulated using Matlab software. Uniform linear array with more than two hundred samples is taken for the simulation. Spacing between the array elements plays very important role in the beamforming techniques and it taken as 0.5 lambda. The angle of arrival (AOA) for the desired user is zero degrees.

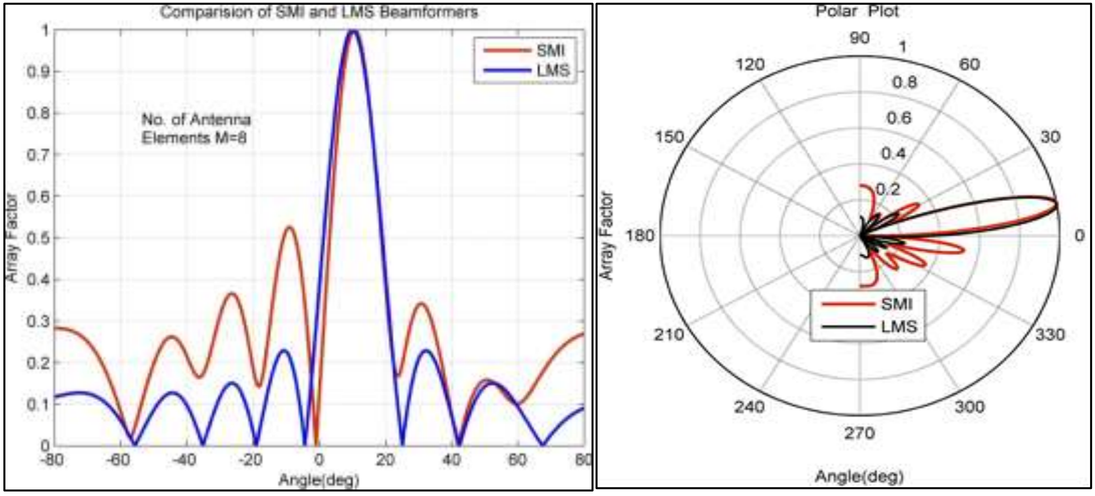

Fig. 2: Plot of normalized array factor versus AOA using less array elements (M=8)

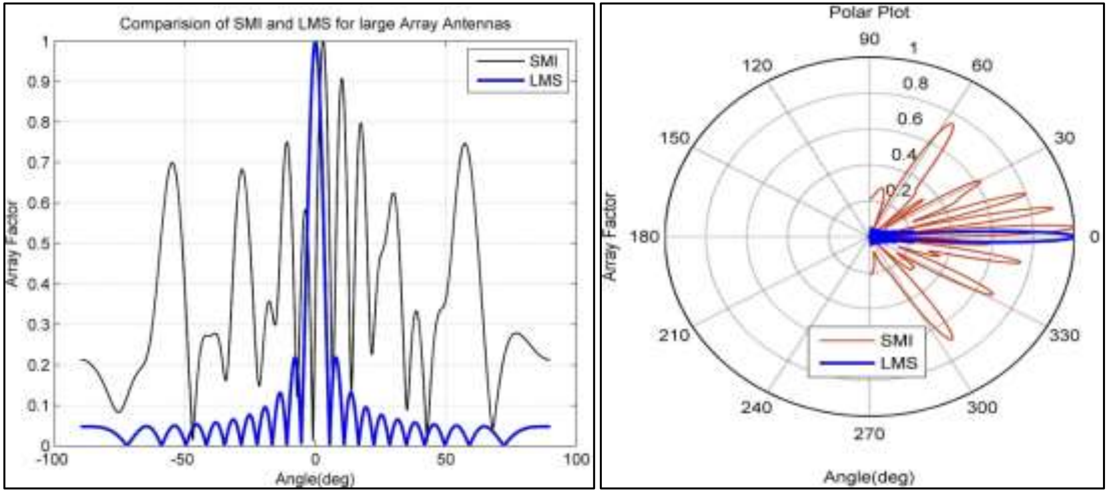

Fig. 3: Plot of normalized array factor versus AOA using more array elements (M=20)

VIII. CONCLUSION

In the paper, the Beam steering algorithms namely; SMI and LMS were simulated and compared. These algorithms were able to produce main beam towards desired direction and direct nulls towards interference directions. Each of the algorithms has their own advantages and disadvantages. The LMS provides faster convergence as compared to SMI. The weight calculation is performed by varying the step size with an upper limit on the step size so that the algorithm does not diverge from the optimum value. Finally, it is found that the SMI algorithm works only for less antenna elements viz less than 10 whereas LMS algorithm works for less as well large antenna array elements. Hence LMS algorithms can be used for real time wireless communication application.

We know that the 5G network require massive MIMO antennas. Recently QUALCOMM released prototype mobile phone suitable for 5G network, which has 128 antenna elements. Hence SMI beamforming algorithm can be used only up to 4G networks, it is not suitable for 5G and above as it is able to form beam only for less antenna elements. Since LMS algorithm work efficiently for both less and more array elements, it can be used for 5G and above networks for adaptive beamforming.

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