Simulation of Direction of Arrival and Beamforming Algorithms Used in Smart Antenna System for Software-Defined Radio

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Abstract- **The demand for mobile communication systems with global coverage, interfacing with various standards and protocols, high data rates and improved link quality for a variety of applications has dramatically increased in recent years. The Software-Defined Radio (SDR) is the recent proposal to achieve these. In SDR, new concepts and methods, which can optimally exploit the limited resources, are necessary. Smart antenna system is one of those, which combats the co-channel interference and maximizes the user capacity of mobile communication system. The paper presents the analysis of the beamforming and direction of arrival (DOA) algorithms used in the smart antenna systems. The analysis is carried out for the MUltiple SIgnal Classification (MUSIC) algorithm and The Multiple Sidelobe Canceller and the Maximum SINR Beamformer algorithm using MATLAB as a simulation tool.**

Keywords- **Beamforming, Direction of Arrival (DoA), Signal to Interference Noise Ratio (SINR), Smart Antenna, SDR**

I. INTRODUCTION

The concept of integrated seamless global coverage of mobile communication systems requires that the radio support two distinct features: first, global roaming or seamless coverage across geographical regions; second, interfacing with different systems and standards to provide seamless services at a fixed location. To manage changes in networking protocols, services, and environments, mobile devices supporting reconfigurable hardware also need to seamlessly support multiple protocols. Such radios, known as Software-Defined Radios (SDR) can be implemented efficiently using software radio architectures in which the radio reconfigures itself based on the system it will be interfacing with and the functionalities it will be supporting [1, 2]. Smart Antenna System is the technique used in SDR among many techniques to improve the co-channel interference performance in hostile wireless environment and also to maximize the users [3].

The motivation for smart antennas lies in some of the major problems that the wireless industry is facing today: [4]

- Limited frequency spectrum resulting in limited capacity.
- Signal fading due to multipath propagation.
- The limited battery life at the mobile device poses power constraints.
- Co-channel interference
- Adjacent channel interference

Several researches have been made to overcome these challenges.The outcome of these researches are multiple access schemes, channel coding and equalization and smart antenna employment [4, 8].

Many refer to smart antenna systems as smart antennas, but in reality antennas by themselves are not smart. It is the digital signal processing capability, along with the antennas, which make the system smart. Smart antennas are no different than the conventional antennas i.e. fundamental principles upon which they are based are not new.

In engineering applications, where an incoming wave is detected and/or measured by an array, the associated signals at different points in space can be processed to extract various types of information including their direction of arrival (DOA). Algorithms for estimating the DOA in antenna arrays are often used in wireless communications to increase the capacity and throughput of a network [4].

In this paper we have presented the simulation of a DoA algorithm wherein the desired direction is estimated from reception of multiple random signals. We have also exploited the resolution of such algorithm and studied the effects of noise and mutual coupling. Once the DoA is estimated, the next step is to protrude a beam in the desired direction and a null in the interfering direction [5]. We have presented the simulation of one such algorithm, namely, the Multiple Sidelobe Canceller and the Maximum SINR Beamformer

II. SWITCHED BEAM ARRAY

A switched-beam system is the simplest smart antenna technique. Such a system has several predetermined fixed beams.When an incoming signal is detected , the system decides which of the beams to switch to in order to give a maximum gain to the desird signal .Moreover as the cellular phone moves from one place to another, the system accordingly keeps switching the beam such that the beam is directed towards the intended user.

One of the most widely known multiple beamforming networks is the *Butler matrix*. It is a linear, passive feeding, $N \times N$ network with beam steering capabilities for phased array antennas with N outputs connected to antenna elements and N inputs or beam ports [4]. In Butler Matrix, there are beams which are linear independent combinations of the array element patterns. A Butler matrix-fed array can cover a sector of up to 360^0 depending on element patterns and spacing. Each beam can be used by a dedicated transmitter and/or receiver and the appropriate beam can be selected using an RF switch. The only required transmit/receive chain combines alternate rows of hybrid junctions (or directional couplers) and fixed phase shifters. Fig.-1 shows a schematic diagram of a 4 × 4 Butler matrix.

By connecting a Butler matrix between an antenna array and an RF switch, multiple beamforming can be achieved by exciting two or more beam ports with RF signals at the same time. A signal introduced at an input port will produce equal excitations at all output ports with a progressive phase between them, resulting in a beam radiated at a certain angle in space. A signal at another input port will form a beam in another direction, achieving beam steering.

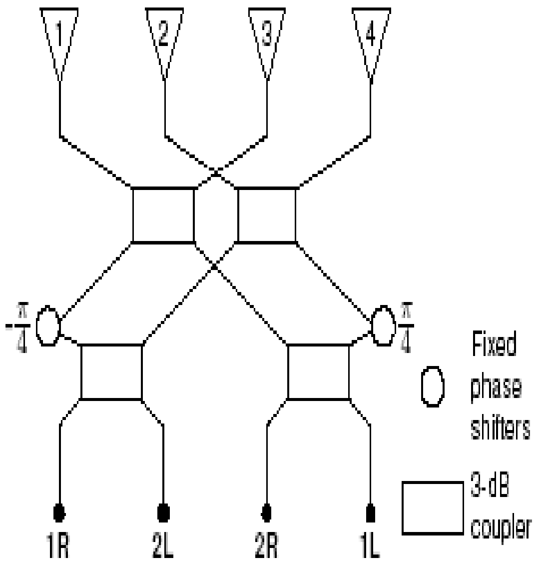

Fig. 1. 4 × 4 Butler matrix

III. ADAPTIVE ARRAY

The adaptive antenna systems approach communication between a user and a base station in a different way by adding the dimension of space [4, 8]. By adjusting to the RF environment as it changes (or the spatial origin of signals), adaptive antenna technology can dynamically alter the signal patterns to optimize the performance of the wireless system. *Adaptive array systems* provide more degrees of freedom since they have the ability to adapt in real time the radiation pattern to the RF signal environment; in other words, they can direct the main beam toward the pilot signal or SOI while suppressing the antenna pattern in the direction of the interferers or SNOIs. To put it simply, adaptive array systems can customize an appropriate radiation pattern for each individual user.

A. MUSIC Algorithm

Schmidt developed the MUSIC algorithm by noting that the desired signal array response is orthogonal to the noise subspace [9]. The signal and noise subspaces are first identified using eigen decomposition of the received signal covariance matrix. Following, the *MUSIC spatial spectrum* is computed, from which the DOAs are estimated. In algorithm, we first define the general *array manifold* to be the set

$$A = \{a(\theta_i \in \Theta \ \}$$

for some region Θ of interest in the DOA space. The array manifold is assumed unambiguous and known for all the values of angle θ, either analytically or through some calibration procedure. The objective is to apply appropriate methods to the received signals so as to extract the region θ out of the range of Θ.

In absence of noise, the observations $\mathbf{x}(t)$ would be confined entirely to the K-dimensional subspace of C^k defined by the span of $\mathbf{A}(\Theta)$. Determining the DOAs for the no-noise case is simply a matter of finding the K unique elements of A that intersect this subspace. A different approach is necessary in the presence of noise since the observations become “full-rank”. The approach of MUSIC, and other subspace-based methods, is to first estimate the dominant subspace of the observations, and then find the elements of A that are in some sense closest to this subspace.
The subspace estimation step is typically achieved by eigen decomposition of the autocovariance matrix of the received data $\mathbf{R}xx$. For MUSIC to be applicable, the emitter covariance $\mathbf{R}ss$ is required to be full-rank, i.e., that $K' = K$. the eigen decomposition of $\mathbf{R}xx$ will give the eigenvalues λ_n such that $\lambda_1 > \lambda_2 > \ldots > \lambda_k > \lambda_{k+1} = \lambda_{k+2} = \ldots = \lambda_N = \sigma_n^2$ and the corresponding eigenvectors $e_N \in C^N$, $n = 1, 2, \ldots N$, of $\mathbf{R}_{xx}$. Furthermore, it is easily shown that $\mathbf{R}_{xx}$ can be written in the following form as in [4]:

Once the subspaces are determined, the DOAs of the desired signals can be estimated by calculating the MUSIC spatial spectrum over the region of interest [4]:

$$P_{MUSIC}(\theta) = \frac{a^H(\theta)a(\theta)}{a^H(\theta)E_n E_n^H a(\theta)}$$

Note that the $a(\theta)$s are the array response vectors calculated for all angles θ within the angle of interest. Because the desired array response vectors $\mathbf{A}(\Theta)$ are orthogonal to the noise subspace, the peaks in the MUSIC spatial spectrum represent the DOA estimates for the desired signals. Due to imperfections in deriving $\mathbf{R}_{xx}$, the noise subspace eigenvalues will not be exactly equal to σ_n^2. They do, however, form a group around the value σ_n^2 and can be distinguished from the signal subspace eigenvalues. The separation becomes more pronounced as the number of samples used in the estimation of $\mathbf{R}_{xx}$ increases (ideally reaches infinity).

B. MUSIC Algorithm Simulation Results

An array of 10 antenna elements is used with an inter-elemental spacing of 0.5(wavelength). Here the signals are arriving from -30, -5 and 60 degrees. The above simulation shows that a maximum is indicated in these directions by the algorithm as shown in figure 2. Noise and mutual coupling effect tend to deteriorate the performance of the algorithm.

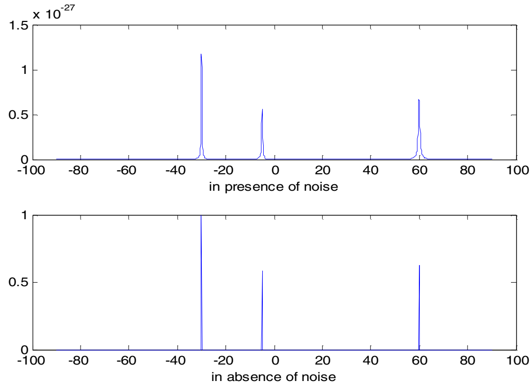

Fig. 2. MUSIC algorithm simulation result when signals are arriving from -30, -5 and 60 degrees.

Next, the directions of arrival are taken as -35, -30 and 60 degrees. In absence of noise and mutual coupling effects the directions are unambiguously detected as shown in figure 3. But in the presence of noise and mutual coupling effects, the antenna system is unable to clearly detect the presence of two closely located sources with their incoming signals spaced spatially apart only by 5 degrees.

C. Multiple Sidelobe Canceller and Maximum SINR Beamformer Algorithm

In the case of more than one user in the communication system, it is often desired to suppress the interfering signals, in addition to noise, using appropriate signal processing techniques [7]. There are some intuitive methods to accomplish this, for example, the *multiple sidelobe canceller* (MSC). The basic idea of the MSC is that the conventional beamforming weight vectors for each of the signal sources are first calculated and the final beamforming vector is a linear combination of them in a way that the desired signal is preserved whereas all the interference components are eliminated.

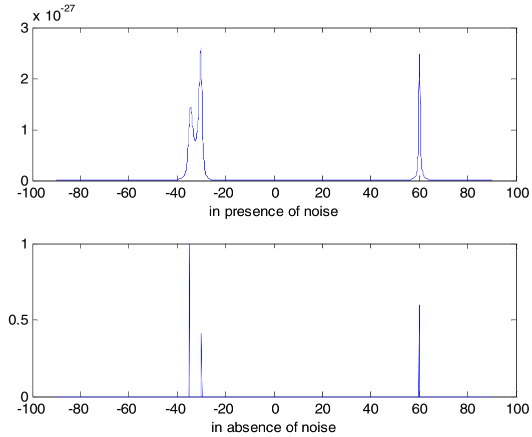

Fig. 3. MUSIC algorithm simulation result when signals are arriving from -35, -30 and 60 degrees.

MSC has some limitations, however. For instance, for a large number of interfering signals it cannot cancel all of them adequately.In contrast the noise components are significantly amplified. The solution to these limitations is the maximum SINR beamformer that maximizes the output signal to interference and noise power ratio.

The output of the beamformer is given by

$$y = w^H x = w^H (s + i + n) = y_s + y_{IN},$$

where all the components collected by the array at a single observation instant are $N \times 1$ complex vectors and are classified as: **s** is the desired signal component arriving from DOA θ_0, $i = \sum_{i=1}^{I} s_i$ is the interference component (assuming I such sources to be present), and **n** is the noise component. We separate the desired signal array response weighted output, $y_s = w^H s$ (where w^H is complex conjugate of the weight vector), and the interference-plus-noise total array response, $y_{IN} = w^H (i + n)$. Consequently, the weighted array signal output power and the weighted interference plus-noise output power is as mentioned in [4].
Therefore, the weighted output SINR can be expressed as [4]

$$SINR = \frac{\mathrm{E}\{|y_s|^2\}}{\mathrm{E}\{|y_{IN}|^2\}} = \frac{w^H R_{ss} w}{w^H R_{IN} w}$$

Now, our basic aim is to estimate the weight vector for which the SINR is maximized.In the above equation all the terms are known but, R_{IN}. With appropriate factorization of R_{IN} and manipulation of the SINR expression, the maximization problem can be recognized as an eigen decomposition problem. The expression for **w** that maximizes the SINR is found to be

$$w_{\max SINR} = R_{IN}^{-1} a(\theta_0)$$

This is the statistical optimum solution in maximizing the output SINR in an interference plus noise environment, but it requires a computationally intensive inversion of R_{IN}, which may be problematic when the number of elements in the antenna array is large.

D. Simulation Results

This algorithm can be used to fire a beam in the desired direction and steer nulls in the unwanted directions. An array of 10 antenna elements is used with an inter-elemental spacing of half-wavelength. Here the desired angle of arrival is -30 degrees where a maximum is formed. The interfering signals arrive from 40, 60 and 80 degrees where a null is formed. The simulated pattern is shown in figure 4.

E. Capacity Improvement

Use of smart antenna improves the signal-to – interference ratio which in turn leads to improved spectrum efficiency which is defined as the number of channels available / frequency bandwidth (MHz) / square kilometers [10]:

$$E_c = 1 / (C * B_w * A)$$

In which, B_w is the channel bandwidth (MHz), C is the cluster size, A is the area of each cell. As the co-channel interference decreases, we can bring clusters closer to each other by reducing the cluster size and consequently increase the number of clusters in a given area. The enhancement of capacity using smart antenna reflects on the decrease of C.

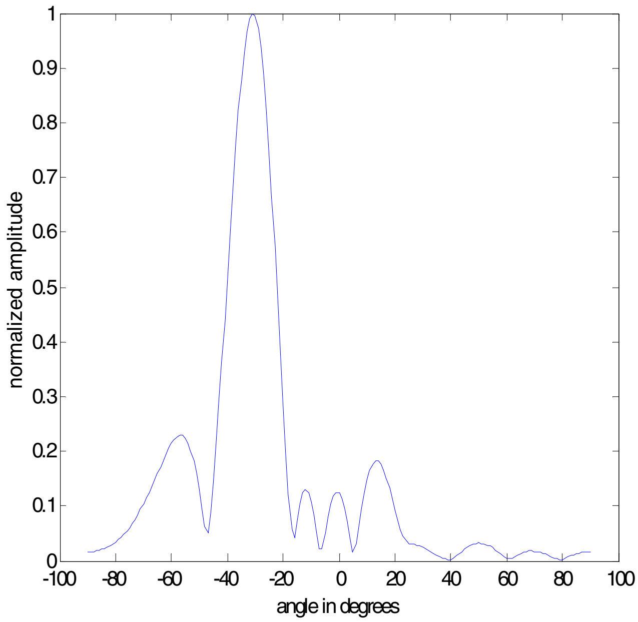

Fig. 4. Simulated Pattern with the direction of arrival at –30^0 and the interferers at 40^0, 60^0 and 80^0.

IV. CONCLUSION

The introduction of smart antennas is expected to have a large impact on the performance of SDRs used in wireless communication. The best asset of smart antennas is the increase in capacity and range. In densely populated areas the main source of noise is the interference from other users. Using transmit and receive beams that are directed toward the mobile user of interest, the multipath and the inter-symbol-interference are mitigated. The use of adaptive arrays helps simultaneously increase the useful received signal level and lower the interference level, thus providing significant improvement in the Signal to Interference Ratio (SIR)[7]. An immediate impact to the increase of the SIR is the possibility for reduced frequency reuse distance and consequently less number of cells in a cluster. This will lead to a large capacity increase since more carriers can be allocated per cell. An immediate advantage will be noticed in TDMA systems (GSM), which are more concerned about increased SIR.

Finally, due to the spatial detection nature of smart antenna systems, the network will have access to spatial information about users. This information may be exploited in estimating the positions of the users much more accurately than in existing networks. Consequently, exact positioning can be used in services to locate humans in case of emergency calls or for any other location-specific service.

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