Hybrid Smart Antenna System using Directional Elements – Performance Analysis in Flat Rayleigh Fading

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Abstract — **In this paper we present a new procedure for implementing smart antenna algorithms. It is a hybrid approach that integrates the features of the switched beam method and the adaptive beam forming approach. Specifically it is shown that by using high gain antenna elements and combining the switched beam process with the adaptive beam forming procedure on a limited number of elements (as low as 2 in an 8-element array), a performance close to that of a more complex 8-element adaptive array may be achieved. The proposed hybrid method, therefore, is fast, computationally efficient, and provides a cost effective approach for exploiting space diversity. Even with the inclusion of interference signals, the proposed hybrid approach out-performed the switched beam method, and provided performance similar to that of an adaptive array with less number of elements (3 in an 8-element array). Implementation of an adaptive array also includes estimations; hence, reducing the number of elements in an array may lead to improved accuracy, in addition to fast convergence and reduced complexity.**

I. INTRODUCTION

The deployment of smart antennas at existing cellular base station installations has gained enormous interest because it has the potential to increase cellular system capacity, extend radio coverage, and improve quality of services [1, 2]. Smart antennas may be used to provide significant advantages and improved performance in almost all wireless communication systems, including time-division multiple-access (TDMA) cellular systems, code-division multiple-access (CDMA) cellular systems, as well as others.

One smart antenna implementation strategy uses an adaptive antenna array, whose outputs are adaptively combined through a set of complex weights (signal amplitude and phase adjustments) to form a single output with beam steering and interference mitigation capabilities. Signal processing aspects for this type of systems have concentrated on the development of efficient algorithms for Direction Of Arrival (DOA) estimation and adaptive beamforming. Another smart antenna implementation strategy uses a switched-beam antenna array, consisting of multiple narrow-beam directional antennas, along with a beam-selection algorithm. The selection of the activated receive beam is based on the received signal-strength. Beam forming is accomplished by using physically directive antenna elements to create aperture efficiency and gain.

In comparing the above two implementation procedures, it may be noted that adaptive implementations have better performance than switched-beam implementations. This comes at the expense of relatively higher implementation cost and complexity constraints, as compared with the switched-beam implementation procedure. Furthermore, adaptive algorithms rely on estimations and this may contribute to slow convergence, compromise accuracy, and generally, lead to less than optimal performance.

Dense scattering and cluster angle distribution phenomena of a multipath environment are well known and are expected to impact the performance of a smart antenna system. It is the objective of this paper to describe the development of a smart antenna system that provides considerable design flexibility to meet changes in propagation environment. Specifically, a hybrid smart antenna system will be proposed and its performance will be simulated and compared with the standard adaptive and switch beam systems.

II. HYBRID SMART ANTENNA SYSTEM

In an N element adaptive smart antenna receiver system, let's assume that the system is required to support M users. The output signal from any element is a particular combination of all M signals and their multipath signals. There are M beam-forming blocks connected to the data bus. Each of these blocks needs to process N digital streams obtained from the data bus, and generate a pattern to receive the signal from one of the M users. An adaptive implementation can dynamically point pattern peaks to desired and multipath signals, and adjust the nulls to cancel unwanted interferences. With the increase in the number of total antenna elements, the system complexity increases significantly. For a switched-beam smart antenna system formed by N directional antenna elements, each antenna covers an angle range of 360/N. The system can automatically switch to an antenna that has its main beam in the domain of the desired signal. Because the preformed pattern has a narrow main beam, most multipath and interference

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signals will fall into the side lobe range, resulting in suppression of these signals and improved system performance. Comparing this with the adaptive implementation, it may be noted that the switched-beam method cannot make full use of the multipath signals, and cannot be used to cancel interferences when located in the main lobe. Thus the performance of a switched-beam system is less optimal when compared with an adaptive system. This will also be confirmed in section IV by simulation of several representative cases.

Fig. 1 shows a proposed alternative hybrid smart antenna system that combines the advantages of both switched-beam and adaptive systems. Unlike traditional adaptive antenna arrays, the proposed system uses directional elements to get additional antenna gain. It does have beamforming capabilities to cancel interferences but uses a smaller number of signals than traditional adaptive systems. Through the proper design of the proposed system, it may be expected that it is possible to achieve a performance similar to that of an adaptive system with the advantage of using a less number of signals in the adaptive process. Similar to the traditional switched beam array process, signal selection will be based on combining the strongest signals in the overall array.

As shown in Fig. 1, the proposed system inherits part of the characteristics of the switched-beam system, in that it adopts directional antenna elements. It will be described in section IV that different coverage angles should be chosen in different multipath scenarios to get the best performance. The arrangement in Fig. 1 also borrows some digital beamforming technology used in adaptive systems, but in this case the beamforming will be done more efficiently using a reduced number of signals. There are additional blocks (N to NS selector) that select only the NS (NS<N) strongest signal streams from total N streams on the data bus. Considering the slow angle movement of mobile users and the relatively wide beamwidth of the radiation pattern of antenna elements, the N to NS switches do not need to be updated in real time. It will be shown that in most cases when using the arrangement in Fig. 1, performance similar to that of an 8-element adaptive system can be achieved by using a value of NS as small as 2. It will also be shown that as NS increases, the performance will continue to improve, but the system complexities will also increase and ultimately converge, to a fully adaptive antenna array.

III. SIMULATION MODEL ASSUMPTIONS AND DESCRIPTION

Fig. 2 shows a block diagram of an N-element beam forming smart antenna system. The baseband signal $\boldsymbol{x}(t)$ received by the antenna array is given by

$$\boldsymbol{x}(t) = \mathbf{U}^d \boldsymbol{s}^d + \mathbf{U}^i \boldsymbol{s}^i + \boldsymbol{n} \tag{1}$$

where $\mathbf{U}^d$ and $\mathbf{U}^i$ are matrices of the channel transfer functions of the multipath signal and interferences, respectively. $\boldsymbol{s}^d$ and $\boldsymbol{s}^i$ are vectors of the multipath signals and interferences, respectively. $\boldsymbol{n}$ is the system noise. The channel transfer functions and the signal vectors are given by

$$\boldsymbol{x}(t) = (x_1(t), x_2(t), \ldots, x_N(t))^T \tag{2}$$

$$\mathbf{U}^d = \begin{pmatrix} u^d_{1,1} & \cdots & u^d_{1,P} \\ \vdots & u^d_{n,p} & \ddots \\ u^d_{N,1} & \ddots & u^d_{N,P} \end{pmatrix}_{N*P} \bullet \begin{pmatrix} f_1(\theta^d_1) & \cdots & f(\theta^d_P) \\ \vdots & f_n(\theta^d_p) & \ddots \\ f_N(\theta^d_1) & \ddots & f_N(\theta^d_P) \end{pmatrix}_{N*P} \tag{3}$$

$$\mathbf{U}^i = \begin{pmatrix} u^i_{1,1} & \cdots & u^i_{1,I} \\ \vdots & u^i_{n,i} & \ddots \\ u^i_{N,1} & \ddots & u^i_{N,I} \end{pmatrix}_{N*I} \bullet \begin{pmatrix} f_1(\theta^i_1) & \cdots & f(\theta^i_I) \\ \vdots & f_n(\theta^i_i) & \ddots \\ f_N(\theta^i_1) & \ddots & f_N(\theta^i_I) \end{pmatrix}_{N*I} \tag{4}$$

$$\boldsymbol{s}^d = (s^d_1(t), \ldots, s^d_p(t), \ldots, s^d_P(t))^T \tag{5}$$

$$\boldsymbol{s}^i = (s^i_1(t), \ldots, s^i_i(t), \ldots, s^i_I(t))^T \tag{6}$$

$$\boldsymbol{n} = (n_1, n_2, \ldots, n_N)^T \tag{7}$$

where operator ($\bullet$) indicates the dot product. The element $u^d_{n,p}$ in the multipath channel transfer function represents the propagation transfer function of the pth multipath signal to the nth antenna. The matrix element $u^i_{n,i}$, on the other hand, represents the propagation transfer function of the ith interference to the nth antenna. Both $u^d_{n,p}$ and $u^i_{n,i}$ are complex Gaussian random variables. The function $f_n(\cdot)$ describes the antenna amplitude pattern of the nth antenna element. θ^d_p is the angle of arrival of the pth multipath of the desired signal and θ^i_i is the angle of arrival of the ith interference. $s^d_p(t)$ is the pth multipath of the desired signal. $s^i_i(t)$ is the ith interference. n_n is the noise at the nth antenna, and is modeled as a stationary, complex, Gaussian process of zero mean and specially white in the processed frequency band. Without loss of generality, all powers were normalized to noise variance. Thus, n_n has complex Gaussian distribution $CN(0,1)$; $u^d_{n,p}$ and $u^i_{n,i}$ also have complex Gaussian distribution $CN(0,1)$.

Operator (*) denotes complex conjugate and H denotes complex conjugate transpose. For omni-directional antenna elements; ($f_n(\cdot) = 1$), the received signal at any antenna element will be the sum of identically distributed Gaussian signals. The magnitude of the received signal will thus have a Rayleigh distribution. A Rayleigh channel corresponds to a multipath environment where all the arrived signals are multipath signals and where there is no-line-of sight propagation path for the desired signal. When there is a line-of-sight signal, the channel should be modeled as a Rician Channel.

The interference-plus-noise covariance matrix is given by

$$\mathbf{R} = \mathbf{U}^i(\mathbf{U}^i)^H + \mathbf{I}_{N*N} \tag{9}$$

where **I** is an identity matrix. Assuming all propagation vectors are known, the optimum-combining weights of an adaptive antenna array that will result in interference cancellation is given by

$$w = \left(\sum_{p=1}^{P} \mathbf{U}^d_{N*1,p}\right)^H \mathbf{R}^{-1} \tag{10}$$

The optimum-combining output in this case will be given by

$$y(t) = wx(t) \tag{11}$$

Fig. 3 shows the pattern used in the simulation of the proposed hybrid smart antenna system. The pattern has a main beam with a ϕ-degree beamwidth. Neglecting the side lobe power, the power gain of the main beam may be approximately estimated as 360° divided by ϕ. The pattern has a –20 dB sidelobe, and it should be noted that the initial simulation results showed no observable difference in the system performance results when the sidelobe level was varied by as much as ±10 dB from the utilized –20 dB value. For the case of an 8-element array with ϕ equal to 45°, the main beam of all the elements will be placed side-by-side to provide the 360° coverage. If ϕ is less than 45° there will be gaps that cannot be covered by the collective main beams of the 8-element array, and if ϕ is larger than 45° there will be overlap between the patterns from the various antenna elements.

Two kinds of communication systems, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA), were simulated in this paper. For a TDMA system, smart antennas are only used to overcome multipath fading, and no co-channel interference is assumed. For a CDMA system, all users share the same frequency and channels are distinguished by different codes. Each user thus interferes with other users who are occupying the same frequency band. In a CDMA system, therefore, a smart antenna is used to overcome both multipath fading and interference.

Binary Phase Shift Keying (BPSK) modulation is used in all simulations, therefore, the output of an optimum combining in equation (11) can be simplified to $\mathrm{Re}(y(t))$. Also, 500,000 random cases were simulated for each SNR value and for each operating case of the proposed antenna structure.

IV. Example SIMULATION RESULTS

Fig. 4 shows an example of the simulation results for a TDMA communications system. Fig.5 shows an example of the simulation results for a spread-spectrum system, thus simulation results will include both multipath and inference signals.

Results in Fig. 4 confirm the expected performance and show an improved BER with the increase in the number of elements used in the adaptive process. It may also be noted that results for more than 2 elements in the proposed hybrid smart antenna array system superpose those for the traditional adaptive array, and hence, the increase in the number of signals is unnecessary and just adds to the complexity of the system.

Fig. 5 shows simulation results for the case of spread-spectrum (CDMA) type systems. In this case, it is assumed that there are 20 users in the frequency band besides the desired user. All other users were uniformly distributed in the 360° range. The expected interference power from each co-frequency band user is 1/20 of that of the total noise. Since noise is normalized to one, the expected power of total interferences will, therefore, be 1, and this means that the expected interference to noise ratio is equal to 1. We also assumed 5 multipath signals and 30° multipath DOA spread.

Fig. 5 shows the effect of the number of selected signals NS on the performance of the proposed hybrid smart antenna system. As shown in Fig. 5, 3 signals (instead of 2 as in earlier no-interference simulations) provide excellent combining results and the SNR needed to keep BER less than 10^{-3} is 0.7 dB higher than that for a traditional adaptive array.

Many other simulations results illustrating wide variety of communications variables such as the antenna beamwidth, the DOA spread of the multipath signals, and impact of the number of interferences in CDMA system will be presented. In all cases it will demonstrated that the proposed hybrid smart antenna system out perform the switch beam method and provided an almost equal performance to an adaptive array but with much less number of elements.

V. Conclusion

In this paper we described a hybrid approach that integrates features of the switched beam smart antenna method with the beam forming approach of the adaptive antenna array technology. Unlike adaptive antenna array, the proposed method utilizes high gain antennas, and unlike the switched beam smart antenna approach, the proposed method performs a beam forming process on a smaller number of elements within the array. In the simulation results we assumed an antenna pattern that consists of one main lobe and a –20 dB side lobe arrangement. An 8-element antenna array was used throughout this study. Parameters studied include the beam width of the radiation pattern of the array elements, the number of multipath signals, the DOA spread, and the number of elements involved in the beam forming process. In all cases and even after the inclusion of interference signals, it is shown that the proposed hybrid process is more efficient as it utilizes a smaller number of signals (2-3 instead of 8) in the beam forming process while providing BER values similar to those that can be achieved when using the entire 8 signals in the adaptive array. The reduced number of elements also suggests reduced complexity and cost in performing the adaptive signal processing, and even possible improvement in performance as the adaptive process often involves a number of estimations.

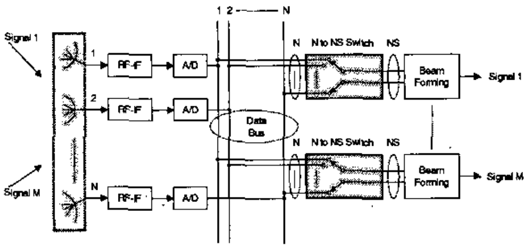

Fig. 1. The proposed hybrid smart antenna system. N antenna elements are used to receive M signals. The beam-forming process is performed on a smaller number (NS<N) of signals.

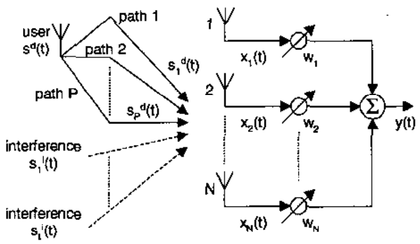

Fig. 2. Block diagram of an N-element beam forming smart antenna system

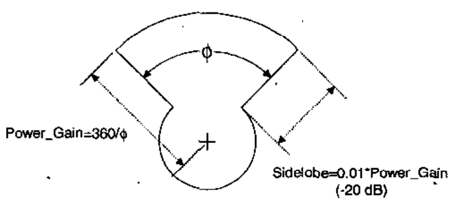

Fig. 3. Antenna pattern used for the hybrid smart antenna simulations

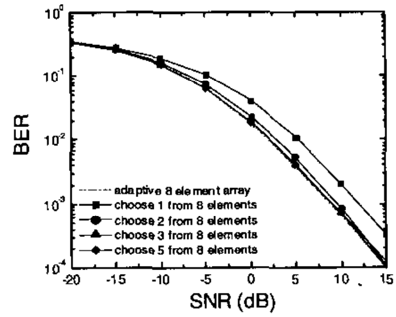

Fig. 4. Performance of a hybrid smart antenna system versus number of elements used by the optimum combining adaptive process. Simulation assumes no interference, and the number of signals was changed from 1 to 5 in an 8-element array. Simulations were performed for 120° beamwidth and 30° DOA spread.

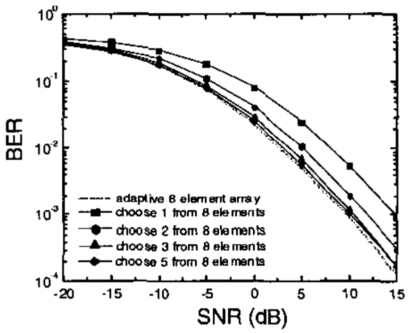

Fig. 5. Performance of hybrid smart antennas versus number of elements used by optimum combining. Interference was included in the simulation, and the hybrid array was assumed to choose 1 to 5 signals from 8 directional elements. 120° beamwidth and 30° DOA spread were also assumed.

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[2] M. Win, J. H. Winters, "Virtual branch analysis of symbol error probability for hybrid selection/maximal-ratio combining in Rayleigh fading," IEEE Trans. Communications, Vol. 49, No. 11, pp. 1926-1934, Nov. 2001.