An Overview of Adaptive Antenna Systems

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***Abstract*— The use of adaptive antenna systems enables the network operators to increase the wireless network capacity, where such networks are expected to experience an enormous increase in the traffic. This is due to the increased number of users as well as the high data rate service and applications. In addition, adaptive antenna systems offer the potential of increased spectrum efficiency, extended range of coverage and higher rate of frequency reuse.**

The purpose of this article is to give an overview of the technology and the fundamental system model and used algorithms.

***Keywords*—Adaptive antenna, smart antenna, steering vector.**

I. Introduction

With the rapid development of mobile communications and the deployment of the 3rd generation WCDMA networks, a need for more radio frequencies. However, the radio frequency spectrum is a finite and valuable (and expensive) resource. For a fixed bandwidth of spectrum there is a fundamental limit on the number of radio channels that are realized by wireless communication systems. Anticipating such limits, considerable amount of work has to be done on the use of time, frequency, and coding techniques to increase the capacity. The adoption of adaptive antenna techniques is expected to have a significant impact on the efficient use of the spectrum, the minimization of the cost of establishing new wireless networks, and optimization of service quality.

Adaptive antenna systems consist of multiple antenna elements at the transmitting and/or receiving side of the communication link, whose signals are processed adaptively in order to exploit the spatial dimension of the mobile radio channel. Depending on whether the processing is performed at the transmitter, receiver, or both ends of the communication link, the adaptive antenna technique is defined as multiple-input single-output (MISO), single-input multiple-output (SIMO), or multiple-input multiple-output (MIMO).

Exploitation of the spatial dimension can be increase the capacity of the wireless network by improving the link quality through the mitigation of a number of impairments of mobile communications, such as multipath fading and co-channel interference.

This paper presents a short survey of the adaptive antenna systems, their mathematical system model, the proposed algorithms, and their applications.

II. Research Efforts

To this date, the current research effort in the area is focusing on the following critical issues:

- The design and development of advanced adaptive antenna processing algorithms that allows adaptation to varying propagation and network conditions and robustness against network impairments.
- The design and development of innovative adaptive antenna strategies for optimization of performance at the system level and transparent operations across different wireless systems and platforms.
- Realistic performance evaluation of the proposed algorithms and strategies based on the formulation of accurate channel and interference models, and the introduction of suitable performance metrics and simulation methodologies.
- Analysis of the implementation, complexity and cost efficiency issues involved in realization of the proposed adaptive antenna techniques for future-generation wireless systems.

III. Adaptive Antenna Benefits

Multipath propagation, defined as the creation of multipath signal paths between the transmitter and the receiver due to the reflection of the transmitted signal by physical obstacles, is one of the major problems of mobile communications. It is well known that the *delay spread* and resulting *intersymbol interference* (ISI) due to multiple signal paths arriving at the receiver at different times have a critical impact on communication link quality. On the other hand, co-channel interference is the major limiting factor on the capacity of wireless communication systems, resulting from the reuse of the available network resources (e.g., frequency and time) by a number of users.

Adaptive antenna systems can improve link quality by combining the effects of multipath propagation or constructively exploiting the different data streams from different antennas. More specifically, the benefits of adaptive antennas can be summarized as follows:

- **Increased range/coverage**: the *array* or *beam forming gain* is the average increase in signal power at the receiver due to a coherent combination of the signal received at all antenna elements. The adaptive antenna gain compared to a single element antenna can be increased by an amount equal to the number of array elements, e.g., an eight element array can provide a gain of eight (9 dB).
- **Increased Capacity**: One of the main reasons of the growing interest of adaptive antennas is the capacity increase. In densely populated areas, mobile systems are normally interference-limited; meaning that interference from other users is the main source of noise in the system. This means that the signal to interference ratio (SIR) is much larger than the signal to thermal noise ratio (SNR). Adaptive antennas will on average, increase the SIR. Experimental results report up to 10 dB increase in average SIR in urban areas. For UMTS networks, a fivefold capacity gain has been reported for CDMA.
- **Lower power requirements and/or cost reduction**: Optimizing transmission toward the wanted user achieves lower power consumption and amplifier costs.
- **Improved link quality/reliability**: Diversity gain is obtained by receiving independent replicas of the signal through independently fading signal components. Based on the fact that one or more of these signal components will not be in a deep fade, the availability of multiple independent dimensions reduces the effective fluctuations of the signal.
- **Increased spectral efficiency**: Spectral efficiency is a measure of the amount of information –billable services- that carried by the wireless system per unit of spectrum. It is measured in bits/second/Hertz/cell, thus it includes the effect of multiple access methods, modulation methods, channel organization and resource reuse (e.g., code, timeslot, carrier). Spectral efficiency plays an important role since it directly affects the operator cost structure. Moreover, for a given service and QoS, it determines the required amount of spectrum, the required number of base stations, the required number of sites –and associated site maintenance-, and ultimately, consumer pricing and affordability. Equation (1) shows a simplified formula to estimate the required number of cells per square kilometer. (the offered load is in bits/seconds/km^2).

$$\text{number of cells/Km}^2 = \frac{\text{offered load}}{\text{available spectrum} \times \text{spectral efficiency}} \tag{1}$$

  As can be predicted from equation (1), increasing the spectral efficiency would improve the operator economics by reducing the number of cells per square kilometer.
- **Security**: It is more difficult to tap a connation, since the intruder has to be position himself in the same direction of arrival as the user.
- **Reduction of handoff**: there is no need for splitting the cells for the sake of capacity increase, and in consequence less amount of handoff.
- **Spatial information**: the spatial information about the user would be available at any given time, which enables the introduction of Location Based Services.

In addition to the above-mentioned benefits, one must point out the following drawbacks (or costs) of the adaptive antennas:

- **Transceiver Complexity**: It is obvious that the adaptive antenna transceiver is much more complex than the conventional one. This comes from the fact that the adaptive antenna transceiver will need separate transceiver chains for each of the array elements and accurate real-time calibration of each of them.
- **Resource Management**: Adaptive antennas are mainly a radio technology, but they will also put new demands on network functions such as resource and mobility management. When a new connection is to be set up or the existing connection is to be handed over to a new base station, no angular information is available to the new base station and some means to "find" the mobile station is necessary.
- **Physical Size**: For the adaptive antenna to obtain a reasonable gain, an array antenna with several elements is necessary. Typically arrays are consisting of six to ten horizontally separated elements have been suggested for outdoor mobile environments. The necessary element spacing is 0.4-0.5 wavelengths. This means that an eight-element antenna would be approximately 1.2 meters wide at 900 MHz and 60 cm at 2 GHz. With a growing public demand for less visible base stations, this size, although not excessive, could provide a problem.

IV. Basic Principles

The technology behind the adaptive antennas is not new. The techniques has for many years been used in the electronic warfare (EWF) as a countermeasure to electronic jamming.

There are in principle a number of different ways in which an adaptively adjustable antenna beams can be generated.

The main philosophy is that the interferers rarely have the same geographical location as the user. By maximizing the antenna gain in the desired direction and simultaneously placing minimal radiation pattern in the direction of the interferer, the quality of the communication link can be significantly improved.

Several different definitions for adaptive antennas are used in the literature. One useful and consistent can be that the difference a smart/adaptive antenna and the "dump"/fixed one is the property of having and adaptive and fixed lobe pattern, respectively. Figure 1 illustrates the concept of adaptive antenna.

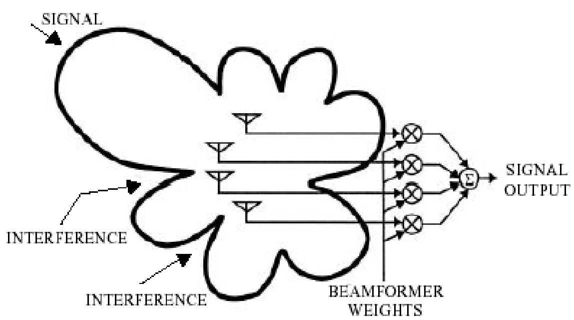

Figure (1) Adaptive antenna basic concept.

Normally, the term "antenna" comprises only the mechanical construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable or vice versa. In the context of "adaptive antenna" the term "antenna" has an extended meaning. It consists of a number of radiating elements, a combining/dividing network and a control unit. The control unit can be called the adaptive antenna's intelligence, normally realized using digital signal processing (DSP). The processor controls feeder parameters for the antenna, based on several inputs, in order to optimize the communications link. Different optimization criteria can be used.

V. Implementation

The adaptive antennas technology is based on array antennas where radiation pattern is altered by adjusting the amplitude and relative phase on the different array elements.

A. Antenna Arrays

Electrically steerable antenna patterns are most often generated using array antennas. These are antennas consisting of a number of antenna elements on which the signal is divided or combined in both phase and amplitude. Generally, any combination of elements can form an array. However, usually equal elements in a regular geometry are used.

Using an array antenna, it is possible to obtain a very good control of the radiation pattern, e.g., the shape of the main lobe and the side lobe level (SLL).

One of the simplest geometries is the *One-dimensional Linear Equidistant Array*. All the array elements are placed along a line with equal distance between them.

B. System Model

To develop the system mathematical model, consider Figure (2).

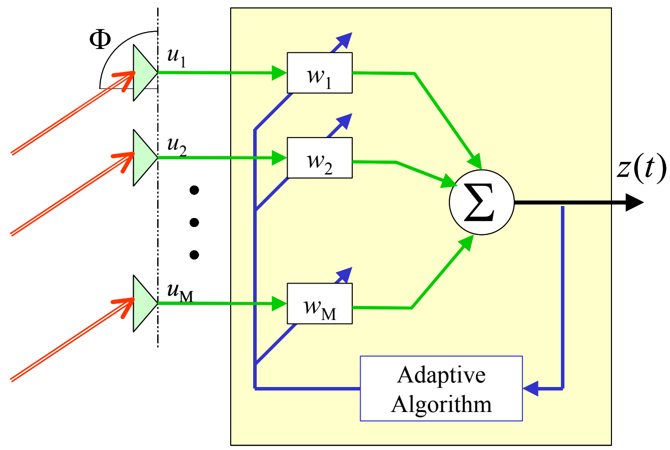

Figure (2)

The phase difference between the antenna element *m* and a reference element at origin is given by

$$\Delta\Psi_m = \beta\Delta d_m$$
$$= \beta\left(x_m \cos(\Phi)\sin(\Theta) + y_m \cos(\Phi)\sin(\Theta) + z_m \cos(\Phi)\sin(\Theta)\right) \quad (2)$$

where Φ and Θ are the elevation and azimuth angles respectively, β is the phase propagation factor, and x_m, y_m, z_m are the Cartesian coordinates of the antenna element *m* with respect to a reference element at origin. The output signal can be expressed as the following:

$$z(t) = \sum_{i=1}^{M} u_i(t) w_i \quad \ldots\ldots\ (3)$$

If the received signal at the reference antenna element is $u_1(t)$, the received signal at other elements will be phase-shifted replicas of $u_1(t)$. Hence, and for more than one user, we can expand (3) to:

$$z(t) = \sum_{i=1}^{M} u_1(t) e^{-j\beta\left(x_i \cos(\Phi)\sin(\Theta) + y_i \cos(\Phi)\sin(\Theta) + z_i \cos(\Phi)\sin(\Theta)\right)} w_i \quad (4)$$

And in more compact form, (4) can be rewritten as the following:

$$z(t) = \underline{w}^{H} \underline{u}(t) \quad \text{.........} (5)$$

where

$$\begin{aligned} \underline{u}(t) &= u_1(t)\left[e^{-j\Delta\Psi_1} \quad e^{-j\Delta\Psi_2} \quad \cdots \quad e^{-j\Delta\Psi_M}\right]^{T} \\ &= u_1(t)\underline{a}(\Phi,\Theta) \end{aligned} \quad \text{.......} (6)$$

Taking the first element as the reference so that $\Delta\Psi_1 = 0$, we can define the *steering vector* as the following:

$$\underline{a}(\Phi,\Theta) \quad \text{.......} (7)$$

The input signal at each antenna element is the convolution between the transmitted signal and the channel impulse response as in the following equation:

$$u_{ij}(\tau,t) = s_i(t) * h_{ij}(\tau,t) \quad \text{.........} (8)$$

where $s_i(t)$ is the transmitted signal from user *i*, and $h_{ij}(\tau,t)$ is the channel response between user *i* and antenna element *j*. The channel between the mobile station and the base station can be modeled using the Vector Channel Impulse Response (VCIR) as:

$$\underline{h}_i(\tau,t) = \sum_{k=1}^{B_i} \underline{a}_i(\phi_k,\theta_k)\alpha_{ik}(t)\delta(t-\tau_k) \quad \text{.....} (9)$$

where $\underline{a}_i$ is the steering vector, $\underline{h}_i$ is the channel impulse response, τ_k is the time delay of signal of user *i* to the base station through path *k*, B_i is the assumed number of paths of user *i*, and α_{ik} is the complex channel gain, given as:

$$\alpha_{ik}(t) = \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik}t+\psi_{ik})} \quad \text{........} (10)$$

where ρ_{ik} is the channel gain given by:

$$\rho_{ik} \approx \frac{A_{ik}}{d_{ik}^{\eta_{ik}}} \quad \text{.........} (11)$$

where A_{ik} is the log-normal shadowing effect for path *k* of user *i*, d_{ik} is the distance between user *i* and the base station through path *k*, η_{ik} is the path loss exponent of user *i* through path *k*, f_{ik} is the Doppler Shift, and ψ_{ik} is the phase shift.

Hence, the output signal at antenna element j can be expressed as:

$$\begin{aligned} u_{ij} &= s_i(t) * \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik}t+\psi_{ik})}\delta(t-\tau_k) + \underline{n}_i(t) \\ &= \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik}t+\psi_{ik})} s_i(t-\tau_k) + \underline{n}_i(t) \end{aligned} \quad \ldots (12)$$

where $\underline{n}_i(t)$ is the additive noise at the antenna element *j*.

In channels where the time difference between paths are small relative to the symbol period $s(t)$ we can approximate the latest equation as:

$$\begin{aligned} u_{ij} &= s_i(t-\tau_0)\sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik}t+\psi_{ik})} + \underline{n}_i(t) \\ \Rightarrow \underline{u}_i &= s_i(t-\tau_0)\sum_{k=1}^{B_i} \underline{a}(\phi_{ik})\alpha_{ik}(t) + \underline{n}_i(t) \\ &= s_i(t-\tau_0)\underline{b}(t) + \underline{n}_i(t) \end{aligned} \quad \ldots (13)$$

In (13), $\underline{b}(t)$ is called the spatial signature of the narrowband (flat fading) channel.

VI. Adaptation Techniques

A. Conventional Beamformer

In the conventional Beamformer, the weights are selected to be the conjugate of the steering vector, i.e., for one path case, the weights are selected as:

$$\underline{w}^{H}\underline{a} = c \quad \text{........} (14)$$

where *c* is real constant > 0.

The main advantages of this method are its simplicity and it provides maximum output SNR if the noise is uncorrelated and there are no directional jammers. It is clear that this method is not reasonable to be used in mobile communication systems where there are many users sharing the same frequency (for CDMA) so there are many unintentional jammers.

B. Null Steering Beamformer

If there are Q users in the cell, and the weights are calculated for user *i*, then the desired weight vector is the solution of the following system of nonlinear equations:

$$\begin{aligned} \underline{w}_i^{H}\underline{a}_i &= 1 \\ \underline{w}_i^{H}\underline{a}_k &= 0, \quad \forall k \in [1,Q]\, and\ k \neq i \end{aligned} \quad \text{.......} (15)$$

The above system of linear equations can be solved perfectly if the number of users is less than or equal to the number of antenna elements. Generally, the problem could be solved as:

$$\underline{w}_i^{H} = \underline{D}^{T}\left(\underline{A}^{H}\underline{A}\right)^{-1}\underline{A}^{H} \quad \text{.......} (16)$$

where $\underline{D} = \begin{bmatrix}0 & \cdots & 1 & 0 & \cdots & 0\end{bmatrix}^{T}$, 1 at the i^{th} element, $\underline{A} = \begin{bmatrix}a_1 & \cdots & a_M\end{bmatrix}$.

C. Minimum Variance Distortionless Response Beamformer (MVDR)

The concept of MVDR beamformer is based on minimizing the average output array power while marinating unity response in the look direction. The problem can be described mathematically as:

$$\min_{w} E\left[\left|z(t)\right|^2\right], \quad \text{subject to} \quad \underline{w}_i^H \underline{a}_i = 1 \quad \ldots\ldots (17)$$

The weights obtained by solving the above optimization problem will minimize the total noise, including interferences and uncorrelated noise. Thus, MVRD beamformer maximizes the output SINR.

Lagrange multiplier method can be used to solve the problem, and to get:

$$\underline{w}_i = \frac{\underline{R}^{-1}\underline{a}_i}{\underline{a}_i^H \underline{R}^{-1}\underline{a}_i}, \quad \textit{where} \quad \underline{R} = E\left[\underline{u}\underline{u}^H\right] \ldots (18)$$

D. Minimum Mean Square Error Beamformer

If the transmitter sends a reference signal known to the receiver (e.g., pilot signal), then this signal can be used to calculate the optimum weights even if there is no information about the Direction of Arrival (DoA) or about the channel characteristics. One of the methods which uses a reference signal is MMSE which is based on finding the optimum weights that minimizes the mean square error as

$$\hat{\underline{w}}_i = \arg\min E\left[\left|\underline{w}_i^H \underline{u}(k) - d_i(k)\right|^2\right] \ldots\ldots (19)$$

where $d_i(k)$ is the training sequence for user i at time k.

The weight vector that achieves (19) is

$$\hat{\underline{w}}_i = \underline{R}^{-1}\underline{P} \quad \ldots\ldots (20)$$

where

$$\underline{R} = E\left[\underline{u}\underline{u}^H\right] \text{ and } \underline{P} = E\left[\underline{u} d_i^*\right]$$

E. Least Square Despread Respread Multitarget Array (LS-DRMTA)

This algorithm is based on the respreading of the received data bits. The respreaded signal is compared with the received signal (before the despreading) and the difference is used as an error signal. This error is minimized by adjusting the antenna weights. Figure (3) shows the block diagram of the LS-DRMTA for user *i*.

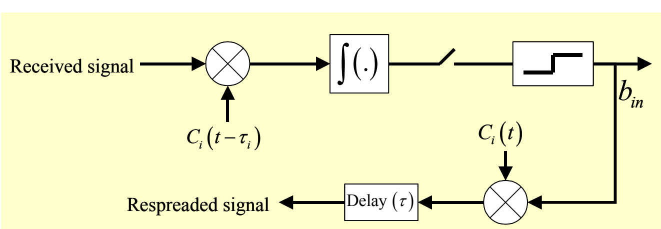

Figure (3)

The respreaded signal is given by:

$$r_i(t) = b_{in} C_i(t-\tau_i), \quad (n-1)T_b \le t \le nT_b \quad \ldots (21)$$

The LS-DRMTA is used to minimize an error function by adjusting the weight vector $\mathbf{w}_i$. The cost function is given by:

$$F(\underline{w}_i) = \sum_{k=1}^{K}\left|y_i(k) - r_i(k)\right|^2 = \sum_{k=1}^{K}\left|\underline{w}_i^H \underline{x}(k) - r_i(k)\right|^2 \quad (22)$$

VII. Conclusion

The objective of this paper was to give an insight into adaptive antenna systems, as well as a general overview of its benefits, techniques, and algorithms.

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