Smart Antennas to Mobile Network Systems

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Abstract: *This paper focuses on the interaction and integration of several critical components of a mobile communication network using smart-antenna systems. Cellular telephone systems are popular worldwide, and the number of users continues to rise rapidly. This has resulted in pressure on the existing cellular network and a drive to develop a more efficient cellular network based on the current spectrum allocations. Research has focused on the use of smart antenna technologies in which identical frequencies can be used in the same cell, increasing the maximum number of users in the cell without allocation of additional radio frequency bands. This paper examines one approach to smart antennas, particular applications to cellular telephone technology. Smart or adaptive antenna arrays can improve the performance of wireless communication systems. In this paper, basic terms such as coverage and capacity are defined. An overview of strategies for achieving coverage, capacity, and other improvements is presented, and relevant literature is discussed.*

Keywords: *Mobile communication network, Smart antenna, Switched beam, adaptive array, spatial division multiple access.*

I. Overview

Smart antenna and intelligent antenna were introduced to describe antenna systems with control of the radiation characteristics-mainly direction-to tackle a number of important problems in wireless communications. These problems include:

(1) Multipath fading, where the signal arrives at the receiver from number of different directions and with a number of different time delays [1];

(2) Electromagnetic compatibility (EMC), where other transmitters in the vicinity degrade the communications network, and the presence of this communications network adversely affects the performance of other nearby systems [2];

(3) Frequency reuse, where the same frequency is used in more than one communications link in the same location [3].

All of these problems result in some form of degradation of the communication link. Since early days of wireless communications, there have been the simple dipole antennas, which radiates and receives equally well in all directions. To find its users, this single-element design broadcasts omni directionally in a pattern resembling ripples radiating outward in a pool of water as shown in Fig (1). While adequate for simple radio frequency (RF) environments where no specific knowledge of the users whereabouts is available, this unfocused approach scatters signals, reaching desired users with only a small percentage of the overall energy sent out into the environment. Also, this single-element approach cannot selectively reject signals interfering with those of served users and has no spatial multipath mitigation or equalization capabilities. Omni directional strategies directly and adversely impact spectral efficiency, limiting frequency reuse. One obvious solution is to use directional antennas i.e.; a single antenna can also be constructed to have certain fixed preferential transmission and reception directions as shown in Fig (2). Sector antennas provide increased gain over a restricted range of azimuths as compared to an omni directional antenna. While sectorized antennas multiply the use of channels, they do not overcome the major disadvantages of standard omni directional antenna broadcast such as co channel interference. Again if the communications network is designed for mobile users or when the communication network is upgraded on regular basis, directional antennas are not flexible [4-5].

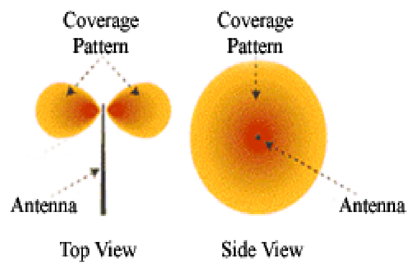

Figure 1.Omni directional Antenna and Coverage Patterns

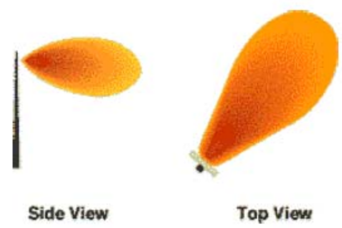

Figure 2.Directional Antenna and Coverage Pattern

The basic function of a transmitting antenna is to convert electrical signals from a radio frequency (RF) generator into an electromagnetic wave is directed toward either a receiver or a target. A receiving antenna converts an incoming electromagnetic wave to an electrical signal, preferably with the exclusion of all other electromagnetic signals in the vicinity. In both cases, this functionality is achieved by designing the antenna to have directionality and frequency selectivity [6].

II. Introduction

A smart antenna system combines multiple antenna elements with a signal processing capability to optimize its radiation and/or reception pattern automatically in response to the signal environment.

In truth, antennas are not smart—antenna systems are smart. Generally co-located with a base station, a smart antenna system combines an antenna array with a digital signal-processing capability to transmit and receive in an adaptive, spatially sensitive manner. In other words, such a system can automatically change the directionality of its radiation patterns in response to its signal environment. This can dramatically increase the performance characteristics (such as capacity) of a wireless system. [7]

Terms commonly heard today that embrace various aspects of a smart antenna system technology include intelligent antennas, phased array, spatial division multiple access (SDMA), spatial processing, digital beam forming, adaptive antenna systems, and others. Smart antenna systems are customarily categorized, however, as either switched beam or adaptive array systems. [8]

The following are distinctions between the two major categories of smart antennas regarding the choices in transmit strategy:

(1) Switched beam—a finite number of fixed, predefined patterns or combining strategies (sectors) Fig (3)

(2) Switched beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choose from one of several predetermined, fixed beams, and switch from one beam to another as the mobile moves throughout the sector.

Instead of shaping the directional antenna pattern with the metallic properties and physical design of a single element (like a sectorized antenna), switched beam systems combine the outputs of multiple antennas in such a way as to form finely sectorized (directional) beams with more spatial selectivity than can be achieved with conventional, single-element approaches. [9].

(1) Adaptive array—an infinite number of patterns (scenario-based) that are adjusted in real time. Fig (4)

Adaptive antenna technology represents the most advanced smart antenna approach to date. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception.

Both systems attempt to increase gain according to the location of the user; however, only the adaptive system provides optimal gain while simultaneously identifying, tracking, and minimizing interfering signals [10].

Figure 3.Switched Beam System Coverage Patterns (Sectors)

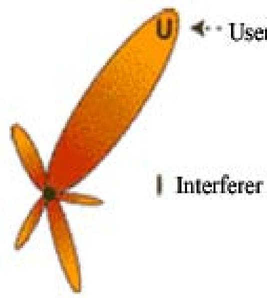

Figure 4. Adaptive Array Coverage: A Representative Depiction of a Main Lobe Extending toward a User with a Null Directed toward a Co channel Interferer

III. Strategies for Coverage and Capacity

Adaptive antennas can increase the coverage area and/or the capacity of a wireless communication system. The coverage, or coverage area, is simply the area in which communication between a mobile and the base station is possible. The capacity is a measure of the number of users a system can support in a given area. Three strategies that employ smart antennas are considered in this section. Range extension is a means of increasing coverage, while the interference reduction/rejection and spatial division multiple access (SDMA) approaches seek to increase the capacity of a system [8, 1].

3.1. Coverage

In sparsely populated areas, extending coverage is often more important than increasing capacity. In such areas, the gain provided by adaptive antennas can extend the range of a cell to cover a larger area and more users than would be possible with omni directional or sector antennas. This approach is shown in Fig. (5).

The coverage area is the area of useful communications around a base station antenna. In a homogeneous propagation environment the maximum transmit-receive range is the same in all azimuthal directions and the coverage area is given by

$$A_c = \pi R^2 \qquad (1)$$

where Ac is the coverage area of the cell and R is the maximum transmit-receive range. Of course, this is only a rough approximation of the situation in a real environment, in which terrain, buildings, vegetation, etc. affect propagation.

The approximate relationship of coverage area to antenna gain can be derived using a simple exponenential path loss model. In this model, the power at a receiver, Pr, is given by

$$P_r = P_t G_t G_r PL(d_0)\left(\frac{R}{d_0}\right)^{-n} \qquad (2)$$

where:

P_t is the transmitter power,
G_t and G_r are the transmit and receive antenna gains, respectively,

$PL(d_0)$ is the free space path loss at some reference distance d_0 from the transmitter (on the order of 1 km for a cellular system),
R is the transmit-receive range, in the same units as d_0, and
γ is the path loss exponent, which is typically between 3 and 4.

This model assumes $R \geq d_0$. Rearranging (2) yields

$$R = d_0\left(\frac{P_t G_t G_r PL(d_0)}{P_r}\right)^{\frac{1}{\gamma}} \qquad (3)$$

and from (1), coverage area varies with antenna gain as

$$A_G \propto G^{2/\gamma} \qquad (4)$$

where G is either transmit or receive antenna gain, and the gain of the other antenna is held constant.
Range extension is best suited to rural areas, where the user density is low and it is desirable to cover as much area with as few base stations as possible. If the user density is high, simply expanding the coverage area will result in a cell containing more users than the base station can serve with its limited number of channels. In this case, range extension is only practical if it can be combined with one of the other approaches discussed in this section.

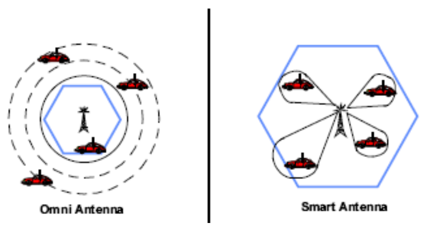

Figure 5. Range extension using an adaptive antenna

3.2. Capacity

Capacity is related to the spectral efficiency of a system, as well as the amount of traffic offered by each user. The spectral efficiency E, measured in channels/km2/MHz,is expressed as

$$E = \frac{B_t / B_{ch}}{B_t N_c A_c} = \frac{1}{B_{ch} N_c A_c} \qquad (5)$$

where Bt is the total bandwidth of the system available for voice channels (transmit or receive), in MHz, Bch is the bandwidth per voice channel in MHz, N c is the number of cells per cluster, and Ac is the area per cell in square kilometers [3-4]. The capacity of a system is measured in channels/km2 and is given by

$$C = EB_t = \frac{B_t}{B_{ch} N_c A_c} = \frac{N_{ch}}{N_c A_c} \qquad (6)$$

where $N_{ch} = B_t/B_{ch}$ is the total number of available transmit or receive voice channels in the system. The actual number of users that can be supported can be calculated based on the traffic offered by each user and the number of channels per cell.

From (6), it is evident that capacity can be increased in several ways. These include increasing the total bandwidth allocated to the system, reducing the bandwidth of a channel through efficient modulation, decreasing the number of cells in a cluster, and reducing the area of a cell through cell splitting. If somehow more than one user can be supported per radio frequency (RF) channel, this will also increase capacity. [8, 10-12].

3.2.1. Interference reduction and rejection

In populated areas, increasing capacity is of prime importance. Two related strategies for increasing capacity are interference reduction on the downlink and interference rejection on the uplink. To reduce interference, directional beams are steered toward the mobiles. Interference to co-channel mobiles occurs only if they are within the narrow beam width of the directional beam. This reduces the probability of co-channel interference compared with a system using omni directional base station antennas. Interference can be rejected using directional beams and/or by forming nulls in the base station receive antenna pattern in the direction of interfering co-channel users. Interference reduction and rejection can allow Nc (which is dictated by co-channel interference) to be reduced, increasing the capacity of the system. [13-14].

Interference reduction can be implemented using an array with steered or switched beams. By using directional beams to communicate with mobiles on the downlink, a base station is less likely to interfere with nearby co-channel base stations than if it used an omni directional antenna. This is depicted in Fig. (6). theoretically, the number of cells per cluster can be decreased, increasing spectral efficiency and capacity as shown in (5) and (6) (3), (4). [15].

There will be a small percentage of time during which co-channel interference is strong, e.g., when a mobile is within the main beam of a nearby co-channel base station. This can be overcome by handing off the mobile within its current cell to another channel that is not experiencing strong co-channel interference. [16].

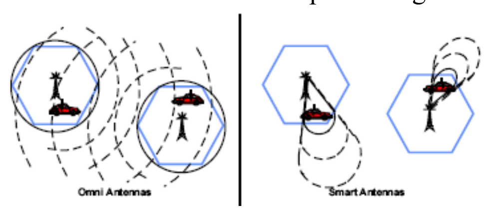

Figure 6. Interference reduction using adaptive antennas: directional beams interfere with fewer cells

3.2.2. Spatial division multiple access

Adaptive antennas also allow a base station to communicate with two or more mobiles on the same frequency using space division multiple access (SDMA). In spatial division multiple access (SDMA), multiple mobiles can communicate with a single base station on the same frequency. By using highly directional beams and/or forming nulls in the directions of all but one of the mobiles on a frequency, the base station creates multiple channels using the same frequency, but separated in space [17]. This approach is shown in Fig. (7).

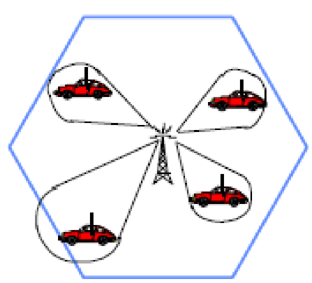

Figure 7. Spatial division multiple access (SDMA) using adaptive antennas

3.2.3. Tradeoff between interference reduction and spatial division multiple access (SDMA)

Range extension, interference reduction, and spatial division multiple access (SDMA) can be used singly or in various combinations, depending on the nature of a particular system. Interference reduction using a single narrow beam per channel and spatial division multiple access (SDMA) using multiple beams per channel are somewhat contradictory approaches. It may be desirable to combine them for some applications, but the maximum benefits of both these approaches can not be achieved simultaneously. For example, if spatial division multiple access (SDMA) is taken to its extreme, a base station will transmit on many directional beams covering the entire 360 degrees. Interference reduction will not be achieved because energy will be radiated in all directions, and all nearby co-channel cells will experience interference. Conversely, if a system has a reduced frequency reuse factor due to interference reduction, spatial division multiple access (SDMA) cannot be fully implemented without increasing C/I to unacceptable levels [18-19].

3.3. Multipath Mitigation

In most mobile channels, there is more than one propagation path between each transmitter and receiver, and a received signal consists of two or more components, each of which traveled a different path from the transmitter. Each multipath component arrives with a delay that depends on the path length. Delayed multipath components can cause inter-symbol interference (ISI), and impose an upper limit on the data rate that the channel can support without the use of expensive equalizers. Fading is another problem in a multipath channel. This "multipath fading" occurs because in general multipath components arrive with different phases. At some points in space, the components cancel each other, causing deep fades in the received signal level. Both ISI and fading can be mitigated using adaptive antennas [20].

IV. The Architecture of Smart Antenna Systems

Traditional switched beam and adaptive array systems enable a base station to customize the beams they generate for each remote user effectively by means of internal feedback control. Generally speaking, each approach forms a main lobe toward individual users and attempts to reject interference or noise from outside of the main lobe [8].

4.1 Switched Beam Systems

In terms of radiation patterns, switched beam is an extension of the current microcellular or cellular sectorization method of splitting a typical cell. The switched beam approach further subdivides macro sectors into several micro sectors as a means of improving range and capacity. Each micro sector contains a predetermined fixed beam pattern with the greatest sensitivity located in the center of the beam and less sensitivity elsewhere. The design of such systems involves high-gain, narrow azimuthal beam width antenna elements [21].

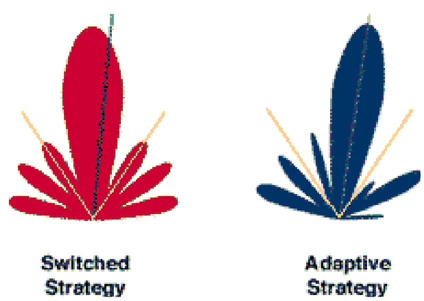

Figure 8. Beam forming Lobes and Nulls that Switched Beam (Red) and Adaptive Array (Blue) Systems Might Choose for Identical User Signals (Green Line) and Co channel Interferers (Yellow Lines)

Smart antenna systems communicate directionally by forming specific antenna beam patterns. When a smart antenna directs its main lobe with enhanced gain in the direction of the user, it naturally forms side lobes and nulls or areas of medium and minimal gain respectively in directions away from the main lobe [22].

Different switched beam and adaptive smart antenna systems control the lobes and the nulls with varying degrees of accuracy and flexibility as shown in Fig. (8).

4.2 Adaptive Antenna Approach

The adaptive antenna systems approach communication between a user and base station in a different way, in effect adding a dimension of space. By adjusting to a radio frequency (RF) environment as it changes (or the spatial origin of signals), adaptive antenna technology can dynamically alter the signal patterns to near infinity to optimize the performance of the wireless system [21].

Adaptive arrays utilize sophisticated signal-processing algorithms to continuously distinguish between desired signals, multipath, and interfering signals as well as calculate their directions of arrival. This approach continuously updates its transmit strategy based on changes in both the desired and interfering signal locations. The ability to track users smoothly with main lobes and interferers with nulls ensures that the link budget is constantly maximized because there are neither microsectors nor predefined patterns [22].

Both types of smart antenna systems provide significant gains over conventional sectored systems. The low level of interference on the left represents a new wireless system with lower penetration levels. The significant level of interference on the right represents either a wireless system with more users or one using more aggressive frequency reuse patterns. In this scenario, the interference rejection capability of the adaptive system provides significantly more coverage than either the conventional or switched beam system [23].

V. Conclusion

Smart Antenna offer several advantages over omni directional or sector antennas. These include increased coverage through range extension, increased capacity achieved through interference reduction or spatial division multiple access (SDMA), and mitigation of multipath fading and inter-symbol interference. Smart antennas are a practical, economical solution to many of the toughest challenges faced by wireless operators. Today, smart antennas have been widely deployed in many of the top wireless networks worldwide to address wireless network capacity and performance challenges.

Several different versions of smart antennas are either in development or available on the market today. Appliqué smart antenna systems provide greater flexibility in controlling and customizing sector antenna pattern beamwidth and azimuthal orientation over that of standard sector antennas.

A second approach, embedded smart antennas, uses adaptive array processing within the channel elements of a base station. The smart antenna processing takes place in the base station signal path, using a custom, narrow beam to track each mobile in the network. Embedded smart antenna system trials have been proven to deliver 2.5-3 times the capacity of current 2-2.5G base stations.

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