Intelligent Antennas: Spatial Division Multiple Access

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Introduction

Antennas collect radio frequency energy from space for reception purposes and distribute energy into space for transmission. To date, they have been the most neglected of all the components in personal communications systems. Yet the manner in which radio frequency energy is distributed into and collected from space has a profound influence upon the efficient use of spectrum, the cost of establishing new personal communications networks, and the service quality provided by those networks. The combination of the enormous increase in low-cost computing capacity and the development of new algorithms for processing signals from arrays of simple antennas make possible "intelligent antennas" for cellular-like communications systems, providing greater coverage area for each cell site, the rejection of interference, and substantial capacity improvements.

There are many methods for utilizing data from antenna arrays in wireless communications systems, the most advanced of which is called spatial division multiple access (SDMA). At the base station, SDMA continually adapts to the radio environment, providing each user with uplink and downlink signals of the highest possible quality. At the network level, this improved base station performance can be exploited to increase base station range — thereby reducing network cost — or to increase system capacity and, hence, spectral efficiency. SDMA is compatible with any practical modulation method or frequency band. Practical SDMA intelligent antenna systems have been constructed and demonstrated. Such systems will appear in commercial communications networks by the end of 1995. This essay describes the principles of SDMA, explains the benefits of SDMA, and compares SDMA with other smart antennas.

Antenna Principles

Radio antennas couple, more or less efficiently, electromagnetic energy from one medium, space, for example, to another, such as wire, coaxial cable, or waveguide. The simplest antennas radiate and receive equally well in all directions.[1] Antennas can also be constructed to have certain fixed, preferential directions (such antennas are used in so-called sectorized systems). One might reasonably ask, "Why use anything more than a single omnidirectional (no preferential direction) antenna at a base station?". The goal of the next several sections is to answer this question by describing, in order of increasing benefits, the principal schemes for employing multiple antennas at a base station.

Sector Antennas

Antennas can be constructed to cover a fixed arc or sector of, say, 120 degrees. Three antennas could therefore cover all directions. Everything else being equal, these sector antennas provide increased gain over a restricted range of azimuths as compared to an omnidirectional antenna. In a cellular radiotelephone system, each sector would typically be treated as a different cell whose range is greater than in the omnidirectional case. Sector antennas increase the reuse possible in such systems by reducing potential interference, and they are widely used for this purpose. As many as six sectors per cell have been used in practical service. This results in a single antenna per (effective) base station and, therefore, does not really qualify as "multiple antennas at a base station" in our context. In the sequel, a sector will be considered to be the same as an independent base station.

Diversity Systems

Small displacements in an antenna's location can have a significant effect on the signal amplitude that appears at its output. This effect results from a propagation phenomenon known as fading. A class of antenna system called "diversity antennas" employs a group of physically separated antennas with the assumption that at least one of the antennas will be in a favorable location at any given time. So-called "switched diversity" systems continually switch among the antennas so as always to use the antenna with the largest output. Other diversity systems, such as maximal ratio combining systems, for example, combine the outputs of all the antennas to maximize the ratio of combined received signal energy to noise. These diversity systems can be useful in environments where fading is the dominant mechanism for signal degradation. In environments with significant interference, however, the simple strategies of locking onto the strongest signal or extracting maximum signal power from the antennas are clearly inappropriate and can result in crystal-clear reception of an interferer at the expense of the desired signal.

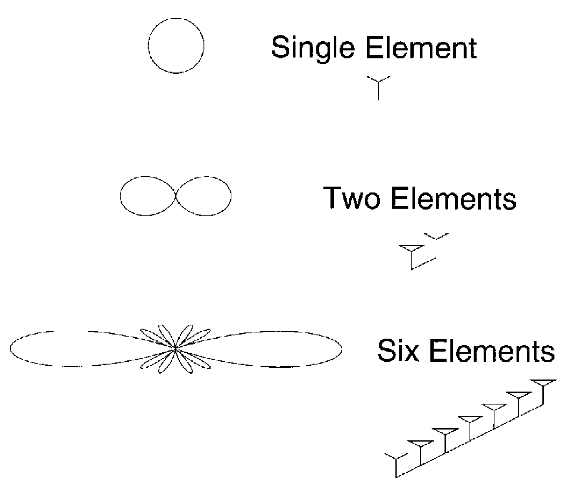
Principles of Antenna Arrays

By combining the outputs of the individual antennas in an array, a single effective antenna can be created with gain and directional characteristics that are very different from those of the individual elements comprising the array. For example, consider a row of, *m*, simple and identical, antenna elements (called a linear array) with elements spaced one-half wavelength apart. Suppose that one simply adds the outputs of all the elements. Signals arriving at the array from broadside, or perpendicular to the axis of the array, arrive simultaneously at each element of the array, and their sum will therefore be *m* times as large (m^2 times as powerful) as the signal received by a single antenna. Simply adding the outputs of the *m* element array therefore results in an amplitude gain of *m* for signals arriving from broadside.

Figure 1 depicts the effective antenna pattern resulting from the above strategy for linear arrays consisting of a single antenna, two antennas, and six antennas (omnidirectional element patterns and half-wavelength spacing in all cases). The radius of the pattern in *Figure 1* is proportional to the gain or strength of the signal at the output of the array. The increased gain in the broadside direction and the increases in gain with the number of array elements are evident in the figure. It is also evident that there are certain directions in which the effective antenna has reduced sensitivity, or nulls.

FIGURE 1

Broadside Antenna Patterns for Arrays with Different Numbers of Elements



Classical phased-array antenna systems have gain patterns or beam patterns that look very much like the one in the figure, except that the direction of maximum gain might not be the broadside direction. More advanced systems have patterns that are optimized to enhance a particular user's signal while simultaneously rejecting interferers. Another differentiator of antenna array systems is whether or not the beam patterns can change with time. Antenna arrays can be built with combining strategies that are fixed. From an operational standpoint, this sort of array is no different from a conventional antenna with the same directional sensitivity. Alternatively, arrays can be equipped with combining hardware and software that make it possible for the pattern to be changed over time and adapted to the current operational scenario.

Because radio reception and transmission are reciprocal, directive transmission with gain is also possible from an array. Any directivity pattern achievable for reception is also achievable for transmission.

Switched-Beam Antennas

It is possible, using array antennas, to create a group of overlapping beams that together result in omnidirectional coverage. For example, one might design overlapping beam patterns (combining strategies) similar to the ones in *Figure 1* but pointing in slightly different directions so that the patterns' main lobes are adjacent like the petals of a flower. Every so often, the system scans the outputs of each beam and selects the beam with the largest output power. If the signal/user moves from one beam to another, the antenna switches to the new beam. Only a single beam pattern is employed at any given time; on average its gain will be slightly less than the factor of *m* described above.

Switched-beam antennas are normally used only for reception of signals since there can be ambiguity in the system's perception of the location of the received signal. The consequences of transmitting in the wrong beam are evident. Switched-beam antennas offer range extension as their primary feature but also suppress interference arriving from directions away from the active beam's center.

Adaptive Array Antenna Systems

Adaptive array antenna systems continually monitor their coverage areas, attempting to adapt to their changing radio environment, which consists of (often mobile) users and interferers. In the simplest scenario — that of a single user and no interferers — the system adapts to the user's motion by providing an effective antenna pattern that follows the user, always providing maximum gain in the user's direction. The base station component of spatial division multiple access (SDMA) is an advanced adaptive array system, described below in greater detail. The principle of SDMA is quite different from the beam-forming approaches described above. In fact, SDMA's operation is analogous to that of human hearing.

Consider the following analogy: if you close your eyes and listen to a sound source, you can identify the direction from which the sound is coming with remarkable accuracy. You accomplish this by using your ears as an array of acoustic sensors, not unlike antennas that are sensing radio energy. Each ear receives the sound at a different time depending upon the direction from which the sound is coming. Your brain processes the information from both ears (now not sound at all but rather some form of neural signal) and computes the direction from which the sound is coming. Your brain then combines the sounds, coming from the direction you selected, constructively. Sound from other directions adds together incoherently. The net effect is that you can hear the sound you have decided to listen to twice as loud as sounds from other directions, and you know what direction the sound is coming from.

Of course, the radio frequency array is not limited to two "ears" (array elements) and can thus "hear" with even greater gain and selectivity. Further, the radio frequency array can respond with multiple "mouths" (array elements) and achieve the reciprocal advantages.

The following sequence of events occurs many times each second in an SDMA system:

1) A "snapshot," or sample, is taken of the signals coming from all of the antenna elements, converted into digital form, and stored in memory.

2) A computer, the SDMA processor, then analyzes the sample to obtain an estimate of the radio environment, identifying users and interferers and their locations.

3) The processor calculates the combining strategy for the antenna signals that optimally recovers the users signals. With this strategy, each user's signal is received with as much gain as possible and with the other users' and interferers' signals rejected as much as possible.

4) An analogous calculation is done to allow spatially selective transmission from the array. Each user's signal is now effectively delivered through a separate communications channel — a spatial channel.

5) The system now has the ability to both transmit and receive information on each of the spatial channels making them two-way channels.

The net result of the above process is that the SDMA system can create a number of two-way spatial channels on a single conventional channel, be it frequency, time, or code. Each of these spatial channels enjoys the full gain and interference rejection capabilities of the array. In theory, an array with m elements can support m spatial channels per conventional channel. In practice, the number is somewhat less and depends on the environment.

The benefits of an SDMA system include the following:

- Range extension – the coverage area of the array is greater than that of any element as a result of the gain provided by the array. When a system is constructed using SDMA, the number of cells required to cover a given area can be substantially reduced. A ten-element array offers a gain of ten, which typically doubles the range of the cell and thereby quadruples the coverage area.

- Interference from other systems and from users in other cells is significantly reduced. In "noisy" areas where range is limited by interference, spatially selective transmission and reception result in range extension.

- The destructive effects of multipath signals – copies of the desired signal that have arrived at the antenna after bouncing from objects between the signal source and the antenna — can often be mitigated. In certain cases, the multipath can actually be used to reinforce the desired signal.

- The capacity of the system is increased in two distinct ways:

  a) Channel reuse patterns in cellular systems can be significantly tighter because the average interference resulting from co-channel signals in other cells is markedly reduced (e.g., moving from a 7-cell to a 4-cell reuse pattern nearly doubles capacity).

  b) Separate spatial channels can be created in each cell on the same conventional channel. In other words, intra-cell reuse of conventional channels is possible.

- Because SDMA employs spatially selective transmission, an SDMA base station radiates much less total power than a conventional base station. One result is a reduction in network-wide RF pollution. Another is a reduction in power amplifier size. First, the power is divided among the elements, and then the power to each element is reduced because the energy is being delivered directionally. With a ten-element array, the amplifiers at each element need only transmit one-hundredth the power that would be transmitted from the corresponding single-antenna system.

- The direction of each spatial channel is known and can be used to accurately establish the position of the signal source, a prerequisite for location-based services.

- SDMA is compatible with almost any modulation method, bandwidth, or frequency band including AMPS, GSM, PHP, DECT, IS-54, IS-95, and other formats. SDMA can be implemented with a broad range of array geometries and antenna types.

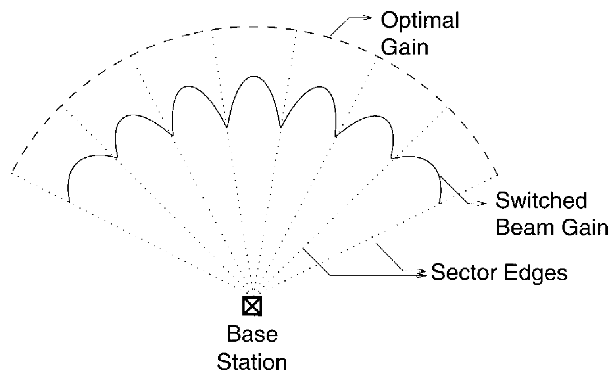
Designers of a communications system will avail themselves of the benefits described above in different ways and in different mixtures as each system matures. When a communications system is initially constructed, costs can be minimized and roll-out can occur more rapidly by using the range extensions available from SDMA. Because the cells are large, better channel reuse is possible than would be with small cells. It is unnecessary to add sites and reduce cell size until required by subscriber demand and then only after the benefits of spatial channels have been absorbed. The major benefit of SDMA is in the flexibility offered to the system implementer.

Comparison of Switched Beam and SDMA Antenna Systems

In clean environments with little or no interference, switched-beam antennas can provide range extension. Because the effective pattern of a switched-beam antenna is scalloped (*Figure 2*) and because the peak gain provided by the switched-beam antenna is generally less than that provided by SDMA, the range extension provided by switched-beam systems will be less than that provided by

FIGURE 2

Gain Patterns for Switched-beam and Ideal Systems



SDMA, assuming comparable antenna arrays. Switched-beam antennas do not offer significant capacity increase since they are customarily used only in the receive direction for range extension. In high-interference areas, switched-beam antennas are further limited since their pattern is fixed and they lack the ability to adaptively reject interference.

Conclusion

It is unlikely that new personal wireless systems will be built a few years from now without the use of some form of smart antenna. Smart antennas, properly applied, can substantially reduce the initial cost of such systems. Additionally, intelligent antenna systems such as SDMA can improve signal quality and increase system capacity. Most importantly, SDMA technology offers system designers the tools to create communications systems that are continually and automatically optimized.

End Note

1. More precisely, when we speak of direction@ we are generally referring to azimuth. It is impossible to build a truly omnidirectional antenna and, for a number of good reasons that are beyond the scope of the present discussion, base-station antennas are typically designed to have a small window of elevation angles over which they operate efficiently.