CELLULAR MOBILE RADIO COMMUNICATION CHANNELS IN VIEW OF SMART ANTENNA SYSTEMS

Smart antenna systems use signal processing methods in conjunction with multiple antennas to achieve significant improvements in capacity and range for wireless mobile communications. Temporal and spatial filtering techniques are devised to effectively mitigate co-channel interference and remove multipaths in all of their forms. Numerous temporal/spatial processing techniques have been proposed for uplink as well as downlink communications. Each technique is most applicable to a specific multiple access air interface and for deployment under specific operating environments. An understanding of the effects of mobile radio communication channels on signals collected from multiple receivers has proven to be instrumental in evaluating the potentials and limitations of smart antenna technology. In this article, the different parameters defining the radio communication channel are discussed and variables that are important in view of multi-antenna systems are emphasized.

The key role of multi-antennas at cellular mobile radio communications base stations is to sample, at different points in space, the waveforms propagating from users who are accessing the same communication channel. The effectiveness of spatial sampling in reducing co-channel interference and mitigating multipath effects depends on the employed signal processing technique that combines the information over time from the different antennas. The aim of any smart antenna system is to recover the user signal of interest (SOI) and produce an output with a significantly improved carrier-to-interference (C/I) ratio. However, for uplink processing, the offerings and expectations of smart antennas depend on how they exploit the communication channel characteristics and remove its effect on the statistical and deterministic properties of the desired and undesired components of the waveforms incident on the base station.

In order to test any smart antenna system, the communication channel should be simulated comprehensively by incorporating its three main spreading effects: delay, Doppler and angular. Delay spread gives rise to frequency-selective fading, whereas Doppler spread causes time-selective fading. Angular spread is responsible for space-selective fading and varies depending on whether the transmitted signal is reflected from objects local to the mobile, base station or remote objects. This type of spreading along with the directions of arrival of all scattered and unscat-

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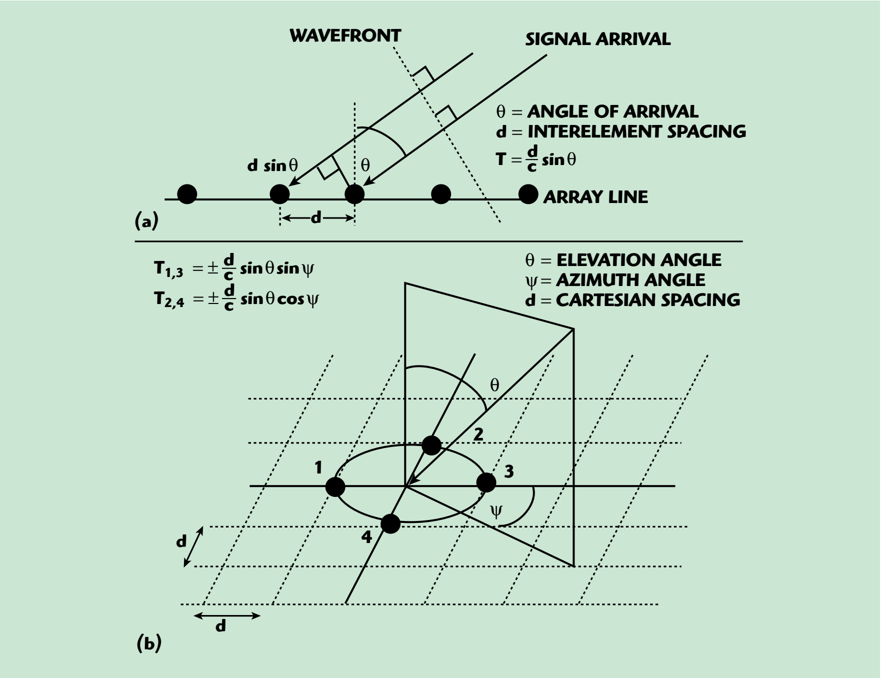


▲ *Fig. 1 Signal angle determination in (a) linear and (b) circular arrays.*

tered signals are transparent to a single antenna base station. However, these factors are considered important parameters that influence smart antenna systems significantly.

ARRAY GEOMETRY AND INTERELEMENT SPACING

In smart antenna systems, an antenna array is used at the base station to receive information from users of wireless networks operating under the same or different multiple access schemes, such as frequency-division multiple access (FDMA), time-division multiple access (TDMA) and code-division multiple access (CDMA). The antenna array may assume different geometries. In a linear array, the locations of the antennas form a straight line, whereas in a planar array (such as the circular array), the positions of the antenna elements are specified by two variables representing polar or Cartesian coordinates. While the propagation delay T between antennas encountered as the signal travels across a linear array is only a function of the elevation angle, both elevation and azimuth angles of arrival define the propagation delay in the case of planar arrays, as shown in ***Figure 1***.

The multiple antennas at the base station may be omnidirectional or have a nonuniform sensitivity to the angle and frequency signature of the incident waveform. The antennas may be equally or unequally spaced across the array. Unlike the arrays in the linear and circular array diagrams, the interelement spacing of the antenna array may change along the array axes, allowing both closely and widely spaced antennas to be part of the same base station. In a wireless communication environment, antenna spacing plays an important role in developing the proper processing method to resist the distortion caused by users accessing the same communication channel and by local and remote scattering of the SOI.

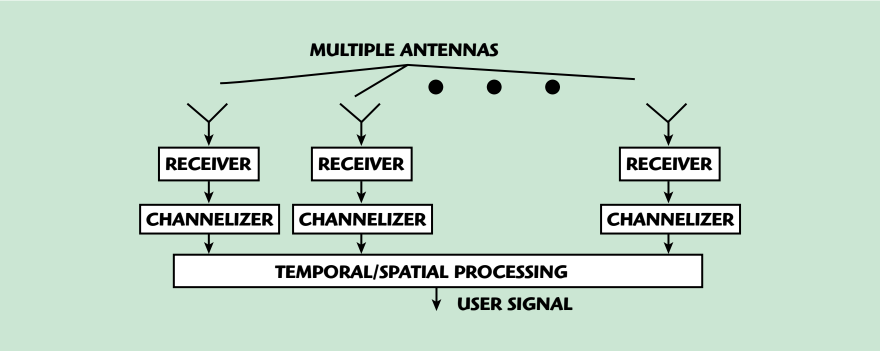
If the antennas are widely spaced (often eight wavelengths apart), then the data received by one antenna element are likely to be independent or uncorrelated from the data received by the adjacent antenna element of the array. This condition is due to the difference in the scattering effects on the signal amplitude and phase at different points in space, each occupied by one antenna. This space-sampling method is referred to as spatial diversity. To make use of spatial diversity, the outputs of the antennas at the base station are compared and the antenna with the strongest signal then is chosen to feed into the receiver. However, choosing from or combining the antenna outputs when they are diverse in space is known to yield a meager improvement in the received signal.

With the antennas closely spaced (often apart by a distance smaller than or equal to half a wavelength), the waveforms incident on the different antennas no longer can be assumed uncorrelated or independent. The relationship among the antenna outputs is one of the prime characteristics of smart antennas in wireless communications. These outputs are linearly or nonlinearly combined through optimum or adaptive signal processing techniques to significantly increase the quality of the communication links, reduce the required amount of transmitted power and increase the number of users that can be served by the base station without a corresponding increase in frequency channel allocations.

The spatial correlation across the antenna array carries information about the user and interference angular positions, spatial spread and scattering bandwidth of each user and characteristics of the propagation channels between the transmitter and receiver. This correlation changes with both the operating environment and the array manifold. The array manifold depends on the array geometry as well as the spatial and frequency sensitivity of each antenna element. The operating environment includes the signals' direct paths and multipaths, number of users and cochannel interferers in the frequency band, and/or time burst of interest, delay spread, Doppler spread, local and remote scatterers, and number and geolocations of all sources seen by the antenna array aperture. The spatial correlation function is also affected by the antenna height and location. Antennas at the base station can be located on a variety of structures, including rooftops, sides of buildings, sides of water towers and inside offices operating through windows. Each structure will influence the scattering patterns and propagation delay across the array.

SMART ANTENNA TECHNIQUES

Smart antenna approaches for wireless communications range from switched beam to fully adaptive and uplink only to uplink and downlink, with the benefits provided by the various approaches differing accordingly.[1] Most smart antenna systems are deployed at the base station for uplink



▲ *Fig. 2 A typical communications system receiver using multiple antennas.*

signal processing. By equipping the base with antenna arrays, it is possible to fully exploit the spatial dimension in a wireless communication system, as shown in ***Figure 2***. Multiple antennas can provide processing gain to increase the base station range and improve coverage. The capabilities of the antenna array to discriminate between signals based on their angles of arrivals lead to reduced interference power, which in turn can be traded for increased system capacity. A wide range of wireless communication systems may benefit from spatial processing, including high mobility cellular systems, low mobility short-range systems and wireless local loop applications. To further increase the system capacity, spatially selective reception as well as spatially selective transmission may be adopted.

Each antenna array output represents a weighted sum of the desired signal, undesired signals and noise. The simplest form of smart antennas is obtained by applying an appropriate complex weight to each sensor and then summing the outputs. The sensor weights are described by the equalizer weight vector. If the weight vector is adapted in real time in an optimum manner, it is possible to cancel the undesired interference and enhance the desired signal above the noise level. Thus, performance that is far superior to both the single-antenna case and multiple-antenna fixed-beam systems can be achieved.

There are numerous techniques that could be employed to process the data received by the multiple antennas. Smarter antennas yield performance improvement over the single-receiver case. The most powerful smart antenna techniques are those that are devised for specific multiple access schemes such as FDMA, TDMA or CDMA. These techniques are often structured to utilize both the temporal and spatial characteristics of the signals over time and space, and aim to provide some sort of temporal/spatial equalization to mitigate the effects of multipath and co-channel interference. In principle, spatial equalization is concerned primarily with the removal of the co-channel interferers based on their angles of arrival, which are different from that of the SOI, as well as their uncorrelation with the SOI. On the other hand, temporal equalization primarily targets the multipath and mitigates its effect by utilizing the coherence properties of the delayed versions of the signal. Spatial and temporal equalization can be performed independently or both processes may be combined under one optimization criterion, which can be formulated to be consistent with a specific multiple access scheme.

A SMART ANTENNA TESTING APPROACH

Since the primary goal of the smart antenna system is to spatially filter the co-channel interference and possibly the multipath components of the SOI, it is important to simulate a communication channel where each signal arrival at the base station is tagged with its angle of arrival and angular spread or scattering bandwidth.

In order to test the performance of a smart antenna system, the operating environment that is most applicable to the mechanism behind co-channel interference nulling and source localization capabilities of that specific system must be simulated. The number of co-channel interferers along with propagation channel dispersive effects over the angle, time and frequency variables may be tuned to emulate a specific wireless communication channel, which may be favorable or unfavorable to the underlying system.

Each smart antenna technique is based on a set of assumptions about the propagation channel. When these assumptions are satisfied, high performance is achieved and improvements in bit error rates, C/I, drop-off rates and outage probability become evident, as well as improvements in any other evaluation criterion and measure of performance. However, it is equally important to test the same system with an operating environment that may actually violate one or more of the assumptions made by the employed smart antenna system. Only a complete understanding of the theory behind the signal processing technique implemented in the receiver can permit a comprehensive test for performance evaluation of the capabilities of the respective smart antenna system to be devised.

The two previous extreme cases along with numerous other propagation environments can be simulated easily by properly choosing the data at the different antenna array elements. For example, when small antenna systems are applied to a rural environment with few significant scatterers and a high likelihood of line-of-sight propagation, they are likely to be based on the users' angle-of-arrival estimation (geolocation). In this case, to test whether the underlying smart antenna system will function poorly or properly for obstructed line of sight, the data entering the different sensors are easily chosen to simulate only multipath propagation.

COMMUNICATION CHANNEL PARAMETERS

Several parameters affect the performance of smart antenna systems. Some of these parameters are attributed to the wireless radio communication channel,[2,3] while others are introduced by the antenna array geometry and structure.

Interelement Spacing

The larger the distance between adjacent antennas, the smaller the spatial correlation function across the array will be. In this case, spatial selectivity and estimation of the signal bearing become more difficult.

Number of Co-channel Interferers

Most smart antenna systems can handle one or a few co-channel interferers easily. The number of interferers that can be spatially located and effectively nulled is equal to one less than the number of antennas mounted at the base station (at most). Therefore, operating in an environment with large co-channel interferers will be difficult for a smart antenna system with a small number of degrees of freedom.

Angular Spread and Scattering Bandwidth

The larger the scattering bandwidth, the weaker the spatial correlation between the data across the array will be. In turn, exploitation of the information gathered from the different antennas will be less effective. Also, a large scattering bandwidth will cause problems in resolving the signals originated from two close mobiles where their scattering radii overlap. ***Figure 3*** shows an example of the effects of angular spread and scattering.

Array Calibration

Imprecise information about the antenna spatial coordinates and the gain and phase sensitivity of each antenna array element as a function of frequency and bearing may present a difficult problem in fully or partially utilizing the data received by the multi-antenna array. Antenna element displacements and ambiguity in the array manifold will significantly hinder the performance of those smart antenna systems that base their performance on the ability to obtain unbiased low variance estimates of the angles of arrival of the transmitted signals. In this case, a well-calibrated array is important.

Delay Spread

Delay spreading occurs when two signals follow separate paths enroute to a receiver in such a way that the distance traveled and the time in which the signals arrive will be different for each signal. Flat fading refers to cases where the latest copy of the signal arrives at the base station after a time duration that is smaller than the symbol bit period. When this time difference becomes an appreciable percentage of the symbol bit period, intersymbol interference (ISI) can occur. For flat fading, which is typical in large cells under FDMA and TDMA schemes, smart antenna systems tend to perform only spatial equalization where a single coefficient for each antenna is adjusted over time to combat co-channel-type interference. On the other hand, in frequency-selective fading, smart antenna systems must perform both temporal and spatial equalization to individually or jointly suppress ISI as well as the co-channel interference.

Doppler Spread

Large Doppler spreads imply fast time-varying channels, that is, small coherence times. Hence, smart antennas that perform any sort of time averaging of the data must do so over short time intervals to account for the nonstationary effects of the channel. Smart antenna systems that employ adaptive spatial or temporal filtering techniques must tune the filter coefficients at a speed consistent with the rate of channel variations.

Line of Sight

The presence of a line of sight between the mobile unit and base station is important for smart antennas aiming for geolocation of the wireless communication channel users.

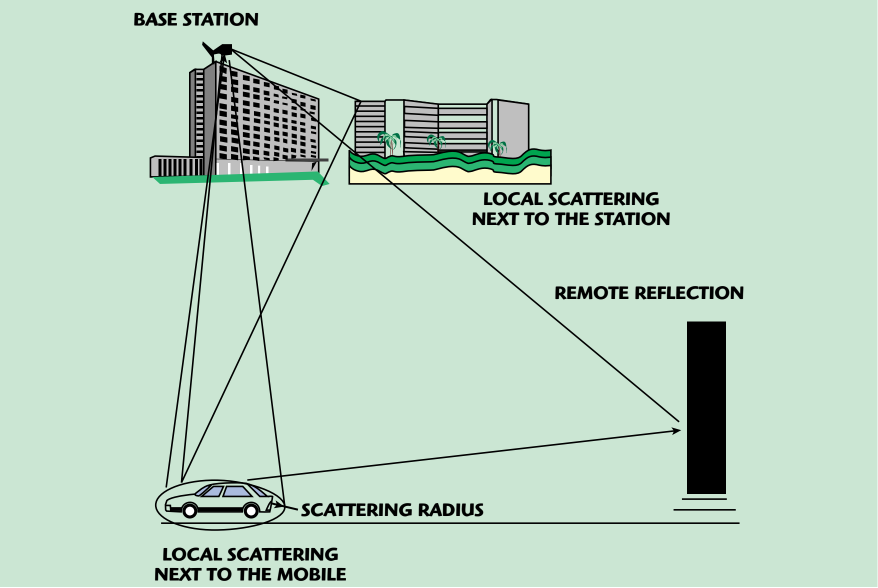
SCATTERERS IN A MOBILE RADIO ENVIRONMENT

The data received by the different array sensors can be selected to simulate single or combined effects of scattering in a cellular environment. This selection also can be made to emphasize one type of scattering over others, depending on whether the base station antenna is located in urban, suburban or rural areas. A brief summary of the three main types of scattering in large cells and their corresponding effects on smart antennas is presented. The description given is for the reverse-link channel (mobile to base) but applies equally to the forward-link channel.

Local-to-mobile scattering is caused by buildings in the vicinity of the mobile within a few tens of meters and gives rise to Doppler spread, that is, selective time fading. It is known that for a vehicle moving at a speed of 55 miles per hour, the Doppler spread is ±200 Hz in the 1900 MHz band. For this type of scattering, delay and angle spread are significant. With a small delay spread, the ISI becomes negligible and temporal equalization is not necessary. With a small angle spread, the assumption of a point source (rather than a spatially distributed source) is invoked and algorithms for direction-of-arrival estimation can be implemented.

Remote scatterers can be terrain or high-rise buildings and produce specular multipath. In addition, remote scatterers cause significant delay spread (frequency-selectivity fading) as well as significant angle spread (space-selective fading). In the case of

Fig. 3 Effects of angular spread and scattering.



angle spread, temporal equalization is important to mitigate the intersymbol interference. Also, with a large angle spread, the multipath is resolvable spatially and an array spatial pattern can, in principle, be formed to null the multipath components.

Local-to-base scattering is caused by buildings or other structures in the vicinity of the base. This type of scattering causes severe angle spread.

CONCLUSION

The spatial correlation function between the data received at different antennas at the base station or handset carries valuable information about the communication channel and, if fully or partially utilized, will lead to improved channel equalization over the single-receiver case. Smart antenna systems can only be evaluated properly through comprehensive testing, which establishes various settings for the key parameters influencing their performance. ■

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