

An Overview of Smart Antenna Technology for Wireless Communication¹

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Abstract— Interest in Smart Antenna Technology for wireless communication systems is increasing in recent years. Considerable amount of research and field trials is being conducted to improve the performance of the system in terms of increasing the capacity and range. In this paper we attempt to discuss the current and future Smart Antenna technology for mobile communication system and illustrate how they allow the wireless service providers to reduce interference and increase capacity. We discuss the different types of Smart Antenna systems using Switched beam and Adaptive antenna array techniques and describe how they can be used in different multiple access schemes in wireless communications, like FDMA, TDMA and CDMA.

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INTRODUCTION

The radio frequency spectrum is a finite and valuable resource. For a fixed bandwidth of spectrum, there is a fundamental limit on the number of radio channels that are realized by a mobile communication system operating over this bandwidth. Anticipating these limits, considerable amount of work has been done on the use of time, frequency and coding techniques to increase the capacity and some of this effort has resulted in multiple-access standards, such as frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). Recently, there has been tremendous increase in

subscribers for cellular and personal communication systems and this trend is expected to continue in the years to come [1]-[4]. Furthermore, growth in data services is pushing these systems beyond their capacities. To meet the demand for subscriber growth, wireless operators need practical, cost-effective infrastructure solutions that enhance network capacity and coverage. This is a major consideration for second generation mobile/cellular operators as they plan for growth. In addition, the proposed third generation (3G) mobile communication networks will also be prone to the problem of spectral congestion as the number of subscriber increases and services are expanded.

Antenna arrays when used in an appropriate configuration, at the base station, in mobile communications offer significant benefits in system performance by increasing channel capacity and spectrum efficiency [5]-[7]. Arrays can also help reduce multipath fading and increasing range coverage. Such an antenna array is known as a smart antenna. Note that several different definitions for smart antennas are used in the literature. One useful and consistent definition is the difference between a smart/adaptive antenna and a fixed antenna is the property of having an adaptive and fixed lobe-patterns, respectively. Normally, the term "antenna" comprises only the mechanical construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable and vice versa. In this paper, we call it the *radiating element*. We define a smart antenna as an array of antenna elements connected to either an analog receiver or a digital signal processor, whose radiation pattern adapts to the current signal environment. The basic block diagram of a smart antenna system is shown in Figure 1, and it consists of a number of radiating elements, a combining/dividing network and a control unit. The control unit can be called the smart antenna's intelligence, normally realized using a digital signal processor (DSP) that receive signal input from

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a smart scanning receiver and outputs to an antenna controller. The processor controls feed parameters of the antenna, based on several inputs, in order to optimize the communications link. Depending on the type of smart antenna system, different optimization criteria can be used as the transmit/receive patterns are automatically updated. This shows that smart antennas are more than just the "antenna," but rather a complete transceiver concept.

TYPES OF SMART ANTENNAS

Smart antennas are a solution to capacity and interference problems [14]-[16]. This technology is often described as

- Digitally Adaptive Beamformers (DAB): These systems use adaptive techniques to enhance the radio link. In such a system, each separate antenna is down converted, digitized and processed.

In general, smart antennas direct their main beam, with increased gain, in the direction of the user, (they may direct nulls in the direction of the interfering signal as well). Although both switched beam and DAB systems have this in common, only the DAB system offers optimal gain, while simultaneously identifying, tracking, and minimizing reception of interfering signals. The DAB system's null forming capability offers substantial performance advantages over the more passive switched beam approach

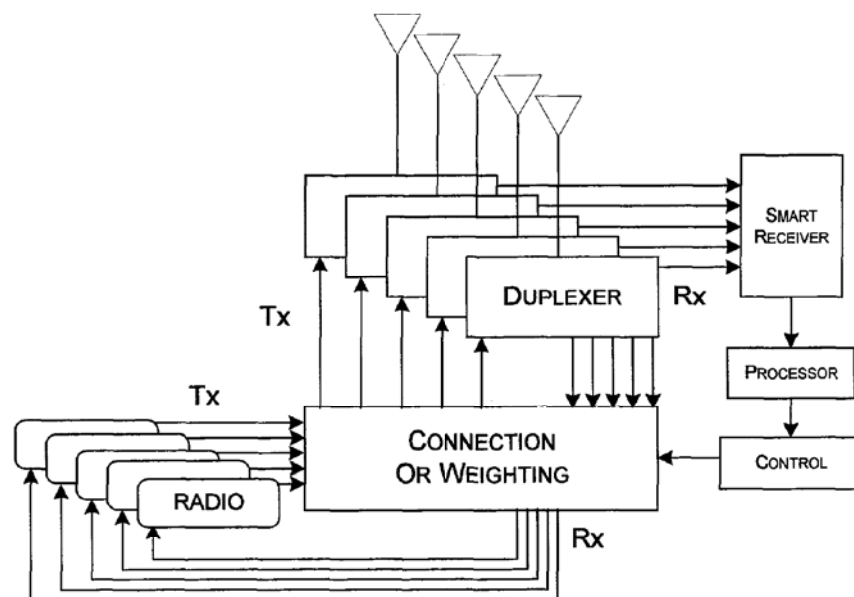


Figure 1. Smart Antenna System

dynamic sectorization, (i.e. the cells are sectorized to reduce interference levels but in a way to enhance the capacity of the cell) or as an adaptive antenna. In either case, most smart antennas form narrow beams directed to each particular user in order to enhance the received signal strength (RSS) and/or signal-to-noise ratio (SNR). In this paper, smart antennas are classified as

- Switched Beam: This type of smart antenna system is simply a controlled RF switch connected to many fixed antennas; i.e. it measures RF power from a set of predefined beams and outputs RF from the selected beam(s) to a specified base-station receiver.

by enabling the maximum interference suppression. Depending on the implementation, different switched-beam and DAB smart antennas control the lobes and nulls with varying degrees of accuracy and flexibility. Let us examine some common approaches for both switched beam and DAB smart antennas.

Switched Beam

The basic philosophy of the switched beam smart antenna system is to make the RF front end transparent to the existing base-stations receivers. It is the simplest technique, and comprises only a basic switching function between separate directive antennas or predefined beams of an array. The switch matrix should quickly and accurately switch the

subscriber's radio channel to the correct beam (in which the user best signal resides) with no degradation to voice quality. The receivers take the RF energy from the multi-beam antennas and choose the beam that gives the best RSS or Signal to Noise ratio (SNR). Normally, each beam has approximately 3-6dB more gain than the traditional sector antennas. Because of the higher directivity of the antenna some increased antenna gain and interference suppression is achieved. In existing cell structures, such an antenna is

i.e. the desired signal power is greater than all co-channel interferes within that beam. Other systems evaluate both C/I and the supervisory audio tones (SATs) on each signal that are unique for each base-station. This allows the processor to select signals with negative (dB) C/I ratios.

For example, a four-beam switched beam antenna system can be used in 120-degree sector. Each of the beams has an approximate 30-degree half power beam width (HPBW). In

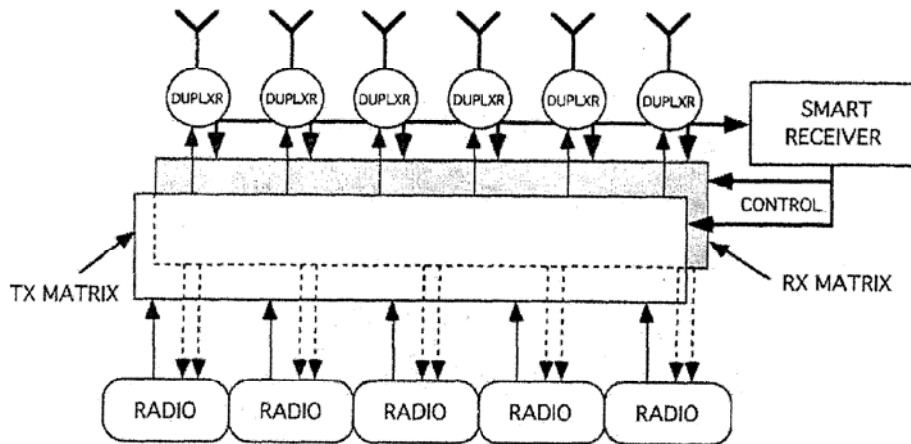


Figure 2. Switched Beam Smart Antenna System

easier to implement than more complex DABs, but it gives a limited improvement.

Figure 2 shows the basic block diagram of the switched beam smart antenna. At the RF front end, an array of M antennas are combined using a Butler Matrix, which sums up the signals at the RF stage and generates output for M different beams. This method uses a separate receiver or group of receivers to monitor the signal power at each antenna port for each subscriber, and determines the port with the highest RSS for a specified user. A separate switch unit then generates a path from the antenna output port (switch matrix input) to the desired radio channel (switch matrix output). As shown, the switch matrix outputs are cabled to the base station receivers, each operating at different frequencies.

The control receiver unit monitors all beams and radio frequencies in the cell site (or the sector). For each frequency channel (i.e. receiver), the optimum beam is chosen and a command is sent to the switch matrix to generate the RF path from the selected beam to the receiver. Many smart antenna systems simply choose the beam with the highest power level. This method assumes that the desired carrier signal power to interference (C/I) is positive;

a typical switched beam system M antenna beams are formed within a sector using a butler matrix array. For a given sector containing M antenna beams, the resultant increased antenna gain is

$$\text{Gain} = 10\log(M) \quad (1)$$

Thus for a sector containing 4 beams (M=4) as shown in Figure 3, the gain increase is 6dB over the original sector antenna. For example if the existing 120-degree sector antenna has a +14 dBi gain, then the gain using a 4 beam antenna to cover the sector will be +20 dBi (assuming of course the elevation beamwidths of the antennas is equal). This improved directive antenna gain increases the radio link budget by 6dB. Consequently, there are number of significant improvements with respect to range, interference and capacity with such a system. The first is extending the range of the base-station or cell. This approximately yields a 40% increase in the range of the sector. However this gain is not realized everywhere in the cell site because of the beam overlap at the 3dB crossover. This scalloping of the antenna pattern reduces the array gain at the crossover by approximately 3dB. Hence the average increase to the link budget throughout the cell is about 4-5dB, with the actual improvement falling between 3-6dB depending on location

of the mobile subscriber.

There are other advantages resulting from using the switched beam system. Due to 3-6dB increase in the gain of the receive antenna, the mobile can now reduce its transmit power by 3-6 dB, which reduces interference introduced into

system does not distinguish between a desired signal and interfering ones as depicted with Mobiles 2 and 3. If the interferer (say Mobile 3) is in the center of the selected beam and the user (say Mobile 2) towards the edge of the beam, then the interfering signal could be far more enhanced than the desired signal resulting in poor quality due to low

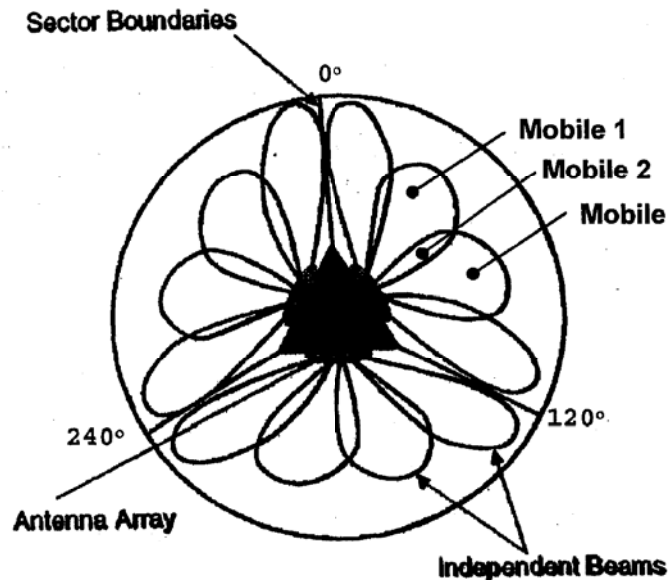


Figure 3. Switched Beam Smart Antenna Coverage

co-channel cells. Alternatively the base-station can reduce its transmit power by 3-6 dB. Thus, the forward link antenna gain allows lower power amplifiers to be used in the transmitter. Amplifiers that consume less power are attractive to wireless carriers that are always trying to minimize operations costs.

Another very practical benefit of the switched beam smart antenna system is the interference reduction. A 120-degree cell sector is shown in Figure 3 with a 30-degree beam steered towards a desired signal. Mobiles 1 and 3 would have been the interferers for the original 120-degree sector antenna, but in the switched beam system, they do not fall within the same 30-degree antenna beams. Typically, the interference suppression will vary depending on the distribution of interfering mobile terminals relative to the desired mobile.

There are, however limitations to switched beam systems. Because the beams are predetermined, the signal strength varies as the user moves through the sector. As a mobile unit moves the edge of the beam, the signal strength can degrade rapidly before the user switched to another beam. Another limitation occurs because when a switched beam

C/I. Hence, the interference suppression is limited by the antenna beamwidth of the switched beam.

Digitally Adaptive Beamformers (DAB)

Digitally adaptive beamformer (DAB) or adaptive antenna technology has developed and matured in the defense community. This technology is used to detect and monitor signals in heavy interference environments. Note that DAB benefits are similar to that of the switched beam smart antennas, but also offer significantly greater interference reduction performance. However, this approach is often more expensive, requiring significantly greater amounts of development, and is more complex to integrate into the existing base-station architecture. In the digitally adaptive beamformer (DAB), the signals are first downconverted to an IF frequency, then digitized and then weighted and summed in a pre-defined processing algorithm.

DAB systems can further be classified as dynamically phased arrays, in which a direction of arrival (DoA) algorithm for the signal received from the mobile subscriber is applied, allowing continuous tracking of the user. The second type of DAB is called the Adaptive Antenna Array (AAA). In this type of smart antenna, a DoA for

determining the direction of interfering sources is introduced steering null patterns towards interferers [7]-[10] and [13]. In addition, by using special algorithms and branch diversity techniques, the AAA can process and resolve separate multipath signals, which can later be combined. These techniques can maximize the carrier-to-interference ratio, (C/I) or (signal-to-interference and noise ratio, (SINR)). Conventional mobile systems usually employ some sort of antenna diversity (e.g., space or polarization diversity). Adaptive antenna arrays with M antennas can be regarded as an M-branch diversity scheme, providing more than the traditional two diversity branches. In this context, phased arrays will have a greater gain potential than switched beam antennas because all elements are used for beamforming [2, 3]. We expect that AAA may be used for multi-branch diversity in next generation wireless networks (see Section Three).

each radio channel. For example, in a particular CDMA channel, the beamformer can steer a beam to a desired mobile signal and null to up to three (M-1) interferers sharing that channel. In the case of CDMA, these three interferers are co-channel signals. However in TDMA and FDMA systems, these may be interference transmitted from other users on the same re-use channels in different cells.

Similar to the switched beam system, a DAB system can achieve directional (array) gain of the order M, the number of elements. Again, for a four-element adaptive antenna, the system will have roughly +6 dB array gain over that of individual element. The range extension potential, therefore, is similar to that of the switch beam system. However, the DAB system can use M omnidirectional antennas and be used for whole cell rather than sectorizing.

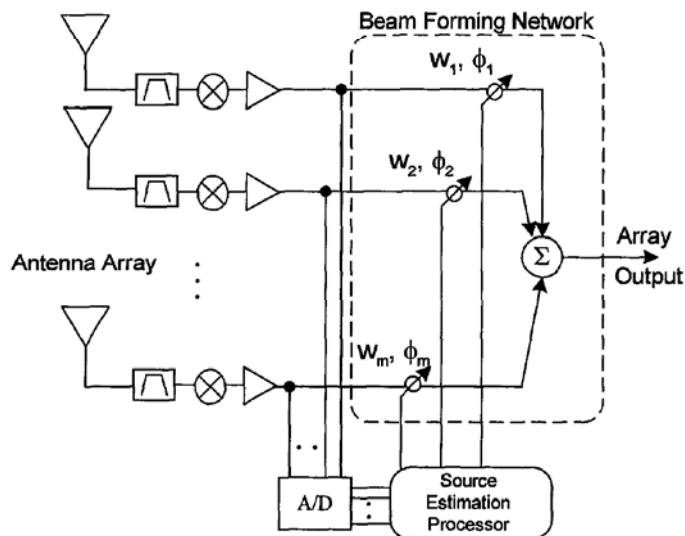


Figure 4. Digitally Adaptive Beamformer (DAB)

Figure 4 shows the block diagram of a digitally adaptive smart antenna. The RF signals from the M antennas are coherently down-converted to an IF frequency, low enough for quality digitization of the signals. The beamformer then process the digital outputs for each channel. The process includes amplitude adjustments as well as phasing adjustments, which results in beam and null steering. The adaptive antenna system can be viewed as a spatial filter in which the pass and stop band is created along the direction of the signal and interferers respectively.

The beamformer can steer a beam to each independent user for a specific radio channel. For a four-element (M=4) beamformer, there are four antenna output ports receiving

The null depth for each interferer will be dependent on the geometry scenario between the various signals. A digitally adaptive beamformer first works to minimize the signal-to-interference noise ratio (SINR) or C/I, thereby canceling as many interferers as possible to pass the desired signal with minimum distortion. This is termed null steering. After this has been achieved, the beamformer uses the remaining degrees of freedom to steer the desired beam towards the source to maximize the background signal-to-noise ratio (SNR). This is termed as beam steering. The greatest advantage of DABs is the high interference rejection potential. This allows maximum improvement of C/I for each subscriber. Another advantage is the degrees of freedom.

But DABs also have a number of disadvantages when compared to the switched beam approach. Unlike the switched beam system, which is fairly easy to integrate in to the base-station architecture, the integration of DAB into the base station is complex and difficult. The base station receivers take in RF, where as the DAB outputs beamformed pre-modulated signals. One technique is to digitally sum the beamformer and, convert back to analog, and up-convert back to RF. However, this process will add complexity and expense. Another potential approach is to remove the base-station receivers (since DAB already performs most of the receiver process) and perform the demodulation function digitally.

SMART ANTENNAS FOR 1ST, 2ND AND 3RD

GENERATION NETWORKS

Research on adaptive antenna arrays for cellular systems dates from early to mid-80s [46] but research and development on smart antennas for cellular systems has intensified in recent years. As mentioned previously, smart antennas, whether switched-beam or adaptive, offer substantial performance and capacity improvement. There has been significant amount of work on the performance gains achieved with different wireless systems [22]-[29]. The extent to which each of these techniques is beneficial, and how a smart antenna is design and implemented, depends on the type of the air interface standard and channel conditions.

First Generation Systems

The first generation cellular systems were based on the analog modulation techniques. In United States the analog system is called the Advanced Mobile Phone System (AMPS). These systems use frequency modulation and frequency division multiple access method and are the least spectrally efficient multiple-access technique. Adaptive arrays have been investigated for FDMA [1]. It has been shown that both, switched beam and adaptive arrays for AMPS can significantly increase cell capacity, improve signal quality and reduce transmitter power requirement [2].

Second Generation Systems

Digital modulation was introduced in the second-generation systems, which are in operation worldwide. These systems offer increase in capacity due to introduction of time slotting and channel coding mobile subscribers on a common frequency channel. The major systems in operation today are the IS-95 system in North America, which uses the code-division multiple-access (CDMA); the European Global System for Mobile Communications (GSM), and IS-136, which uses time-division multiple-access (TDMA).

GSM Smart Antennas

The GSM TDMA system provides 8 users per channel, with 156.25 b/time slot using the Gaussian modulated shift keying (GMSK) at 270.833kb/s [22]. The system's base stations require a broadcast control channel to be transmitted to all its users at all times. But at typical mobile radio fading rates, the channel does not change significantly over a time slot, and the equalizer and adaptive weights need to be calculated only once per frame. This makes possible the use of switched beam smart antennas in GSM systems. Different switched beam architectures have been proposed and studied for GSM systems [42]-[43].

Application of the adaptive antenna array has been proposed for GSM [39]-[41]. In this study, the adaptive processing is divided into two stages with regards to two different data sections of a GSM user slot, the training sequence section and the user data section. By using the training sequence as a reference signal, the optimum adaptive weights are obtained (by using the LSM method). Because of the rapidly changing mobile environment these weight vectors may not be optimum. Hence the array weight vectors are still updated during the user data period. This technique has been shown to be effective in suppressing interference. However, a combination of adaptive antenna array and frequency hopping in GSM networks offer the greatest potential for increasing network capacity. Frequency hopping provides frequency diversity and interference diversity which is independent of traffic load, and features like discontinuous transmission and power control. Both aspects combine to improve overall system performance. Furthermore, frequency hopping GSM networks employing adaptive antennas can be planned for a very tight frequency reuse. This allows the traffic loading to approach 100%.

IS-136 TDMA

The IS-136 TDMA system divides the available frequency spectrum into channel sets, using one channel set per cell, with frequency reuse. The system typically employs a frequency reuse of 7 and has three users per-channel. The system is limited in capacity by a few dominant co-channel interferers. The co-channel interference can be reduced with increase in the frequency reuse to 21 (i.e. sectorizing cell sites into 3 sectors per cell). Examples of a TDMA system employing smart antenna arrays can be found in [30]-[32]. Adaptive antenna arrays at the base-station have been shown to increase the range by 70% and double the capacity [33]-[35]. In these systems, a 14-symbol synchronization, which is present in the 162 symbols of a time slot, is used to determine the adaptive weights [22]. However in IS-136 TDMA system a continuous downlink is required for all three users (or time slots) per channel. In other words the beam pattern and transmit power of the channel has to remain the same for all time slots, i.e. each user. This restricts the use of adaptive antennas in downlink. The use of multibeam antennas at the base station for the uplink can reduce the probability of the interferer being in the same

beam as the user, also increasing the overall capacity of the IS-136 TDMA system, by improving SINR and C/I.

IS-95 CDMA

The IS-95 CDMA scheme is a direct sequence spread-spectrum method that uses a separate code for each user. These codes are pseudo-random (PN) sequences that spread the spectrum over a larger bandwidth than the baseband signal, simultaneously reducing spectral density of the signal. Note CDMA signals for each mobile subscriber occupy same bandwidth and therefore, appear as random noise to each other. A detailed discussion on various characteristics of the CDMA scheme, its design considerations, and related issues is provided in [15], [18]-[21].

In a CDMA system, multiple mobiles share the same frequency channel. Thus there are many interferers both within the cell and from adjacent cells reducing the capacity of the cell. It has been shown [23]-[25] that in a CDMA system switched beam smart antenna provides better performance than adaptive antenna array. Two factors contribute to this; first, CDMA systems inherently have significant diversity capabilities through the RAKE receiver, which combines delayed versions of the original signal, and also from base station diversity via soft handoff. Also, CDMA spreading codes are designed to provide very low correlation between successive codes. Therefore, most of the propagation delay spread in the radio channel merely provides multiple versions of the transmitted signal at the receiver [22], [45]. Provided that multipath components are delayed in time by more than a chip duration (800 nanoseconds in IS-95), they can be extracted and combined to improve the E_b/N_0 (similar to SNR) in the RAKE receiver.

Thus, CDMA has an inherent diversity provided by the fact that the multipath components are practically uncorrelated from each other. The net effect is that the additional gain of the adaptive array antenna is much smaller, and the antenna gain limitation is much less [22]. Thus, the adaptive arrays provide only a slightly larger range increase than multibeam antennas. Also as mentioned earlier, a multibeam antenna with M elements reduces the number of interferers per beam by a factor of M (or provides M -fold increase in gain) and thus increases the capacity M -fold. Adaptive antennas can provide additional interference suppression by providing nulls at $M-1$ interferers. Since the typical number of interferers is much more than the number of elements, adaptive antennas can give only limited additional interference suppression. Furthermore, if the number of interferers is high, the estimates of the direction of the direction of arrival may not be accurate [23]-[25]. Since the switched beams systems are less complex to implement than adaptive arrays, we often find switched multibeam antennas are preferred in CDMA systems over the DAB.

Another smart antenna approach [47] introduced for IS-95 does not employ beam switching for each CDMA traffic channel. Instead, the approach is based on sector synthesis to provide load balancing between adjacent sectors in a cell.

The system uses beamforming smart antenna technology with a 12-beam (4-beams per sector) antenna array to shape each sectors antenna pattern in order to manipulate the sector coverage. Sector synthesis allows operators to control cell site sectorization in 30° increments. Also the gain can be changed to expand or contract coverage in highly localized areas. The system has improved the capacity by up to 30%.

FUTURE GENERATION (3G) NETWORKS AND SMART ANTENNAS

The next generation of mobile communications, the 'third-generation' systems, will provide new wideband multimedia and Internet services and is likely to appear in commercial service by the year 2001. These systems build on the investment already made in the current second-generation systems infrastructure. The requirements of these 3G systems far exceed those of the 2G systems and can be satisfied by employing a flexible air interface. There are two possible paths from present 2G to 3G systems, a GSM/TDMA path and a CDMA path. Details on various systems can be found in [1], [3], [36], [37] and [38]. The chosen system will have to meet a number of criteria as follows:

- Capacity – support for the increased level of voice and data traffic
- Hardware – low cost, compact and power efficient mobile terminals and base stations.
- Flexibility – support for a wide range of voice and data services requiring varying bit rates

Smart antennas are regarded as one of the components in the 3G systems. There is considerable interest in the application of smart antenna technology forming an integral part of these next generation systems. The 3G systems proposed will include, other than the ordinary 2G pilot, a diversity pilot, an auxiliary pilot, an auxiliary diversity pilot, and a dedicated pilot, using which, switched, and spot beams and adaptive antenna array, will provide increase in capacity and performance benefits. It has been shown [48] that adaptive antennas can alleviate the problems, which emerge in 3G direct-sequence code-division multiple access (DS-SS), popularly known as wideband CDMA (WCDMA), mixed cell structure. The system offer advantages such as better performance against the near-far effect, more efficient hand over, ability to support high data rates and better coverage in problematic areas. In the 3G systems, fixed spot beams can be generated to increase capacity or coverage in a specific geographic area. In such a case, the spot beam is not associated with a specific user and does not track a user as he moves through the coverage area. But a spot beam can

be directed at a user using the dedicated pilot if he enters an area having poor coverage and the beam is steered as the user moves through the coverage area. A study of capacity performance of 3G CDMA wireless system in multi rate traffic scenarios of reverse link has been examined under various vector channel models and user population mixtures [48]. Both, switched beam and adaptive antenna arrays were used in the simulations. The overall study supports the use of adaptive arrays to increase the capacity of the system due to their interference suppression capabilities.

SUMMARY

We have reviewed the fundamental concepts of smart antenna technology for wireless communications. We have divided the technology into two distinct categories, switched beams and DABs, and briefly described the two techniques. Applications of smart antenna technology to the most common wireless air interfaces are presented. We hope this overview serves as useful reference to those interested in the development of smart antenna technology for wireless communications.

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