CHAPTER 4

APPLICATION OF SMART ANTENNAS TO MOBILE COMMUNICATIONS SYSTEMS

Smart or adaptive antenna arrays can improve the performance of wireless communication systems. In this chapter, 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. Multipath mitigation and direction finding applications of arrays are briefly discussed, and potential paths of evolution for future wireless systems are presented. Requirements and implementation issues for smart antennas are also considered.

Smart antennas are most often realized with either switched-beam or fully adaptive array antennas. An array consists of two or more antennas (the *elements* of the array) spatially arranged and electrically interconnected to produce a directional radiation pattern. In a phased array the phases of the exciting currents in each element antenna of the array are adjusted to change the pattern of the array, typically to scan a pattern maximum or null to a desired direction. Although the amplitudes of the currents can also be varied, the phase adjustment is responsible for beam steering [4.1].

A smart antenna system consists of an antenna array, associated RF hardware, and a computer controller that changes the array pattern in response to the radio frequency environment, in order to improve the performance of a communication or radar system. Switched-beam antenna systems are the simplest form of smart antenna. By selecting among several different fixed phase shifts in the array feed, several fixed antenna patterns can be formed using the same array. The appropriate pattern is selected for any given set of conditions. An adaptive array controls its own pattern dynamically, using feedback to vary the phase and/or amplitude of the exciting current at each element to optimize the received signal [4.2].

Smart or adaptive antennas are being considered for use in wireless communication systems. Smart antennas can increase the coverage and capacity of a system. In multipath channels they can increase the maximum data rate and mitigate fading due to cancellation of multipath components. Adaptive antennas can also be used for direction finding, with applications including emergency services and vehicular traffic monitoring. All these enhancements have been proposed in the literature and are discussed in this paper. In addition, possible paths of evolution, incorporating adaptive antennas into North American cellular systems, are presented and discussed. Finally, requirements for future adaptive antenna systems and implementation issues that will influence their design are outlined.

4.1. Strategies for Coverage and Capacity Improvement

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.

4.1.1 Range extension

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 omnidirectional or sector antennas. This approach is shown in Fig. 4-1.

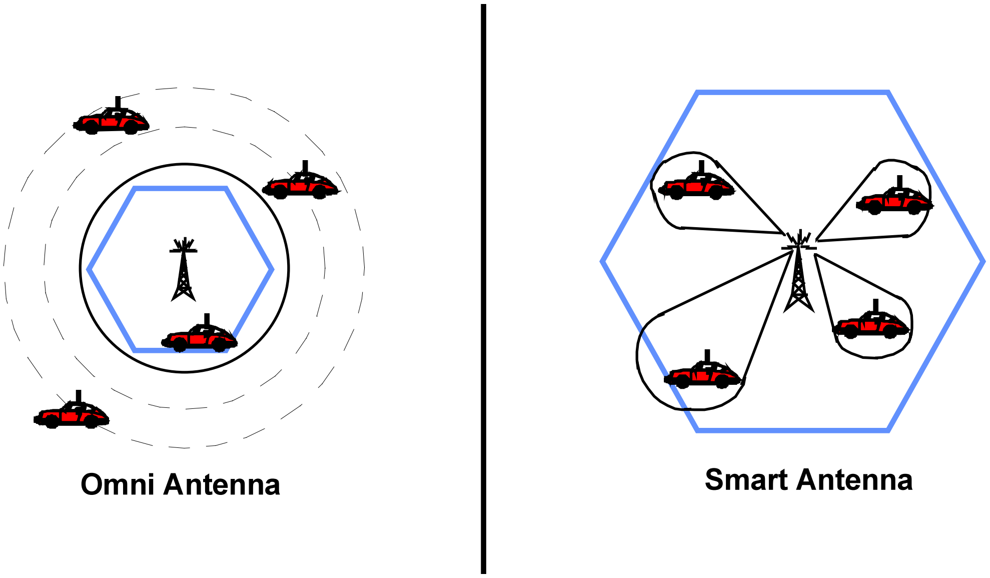

Figure 4-1. Range extension using an adaptive antenna

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

$$A_c = \pi R^2 \tag{4.1}$$

where A_c 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 exponential path loss model. In this model, the power at a receiver, P_r, is given by

$$P_r = P_t G_t G_r PL(d_0)\left(\frac{R}{d_0}\right)^{-\gamma} \tag{4.2}$$

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 (4.2) yields

$$R = d_0 \left(\frac{P_t G_t G_r PL(d_0)}{P_r} \right)^{\frac{1}{\gamma}} \tag{4.3}$$

and from (4.1), coverage area varies with antenna gain as

$$A_c \propto G^{\frac{2}{\gamma}} \tag{4.4}$$

where G is either transmit or receive antenna gain, and the gain of the other antenna is held constant. The following example shows how coverage can be increased by using a base station antenna with steerable or switched directional beams.

Example 1

Assume it has been established that, using an omnidirectional antenna, a particular base station can cover an area of $A_{c,omni} = 100$ km². Furthermore, assume the path loss for the channel has been measured and can be approximated by an exponential path loss model with $\gamma = 3.5$. If a smart antenna system is used which provides an additional 6 dB of gain, then based on (4.4), the system can cover an area given by

$$A_{c,smart} = A_{c,omni} \left(\frac{G_{smart}}{G_{omni}} \right)^{\frac{2}{\gamma}} \tag{4.5}$$

or in this case, $A_{c,smart} = 100 \cdot 4^{\left(\frac{2}{3.5}\right)}$ or 220.8 km².

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.

4.1.2 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/km^2/MHz, is expressed as

$$\begin{aligned} E &= \frac{B_t / B_{ch}}{B_t N_c A_c} \\ &= \frac{1}{B_{ch} N_c A_c} \end{aligned} \tag{4.6}$$

where B_t is the total bandwidth of the system available for voice channels (transmit or receive), in MHz, B_{ch} is the bandwidth per voice channel in MHz, N_c is the number of cells per cluster, and A_c is the area per cell in square kilometers [4.3]. The capacity of a system is measured in channels/km^2 and is given by

$$\begin{aligned} C &= EB_t \\ &= \frac{B_t}{B_{ch} N_c A_c} \\ &= \frac{N_{ch}}{N_c A_c} \end{aligned} \tag{4.7}$$

where $N_{ch} = \dfrac{B_t}{B_{ch}}$ 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 (4.7), 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 RF channel, this will also increase capacity. This paper concentrates on techniques for increasing capacity using adaptive or smart antennas, but Section 4.4 considers other options as well.

4.1.3. 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 beamwidth of the directional beam. This reduces the probability of co-channel interference compared with a system using omnidirectional 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 N_c (which is dictated by co-channel interference) to be reduced, increasing the capacity of the system.

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 omnidirectional antenna. This is depicted in Fig. 4-2. Theoretically, the number of cells per cluster can be decreased, increasing spectral efficiency and capacity as shown in (4.6) and (4.7) [4.3], [4.4].

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.

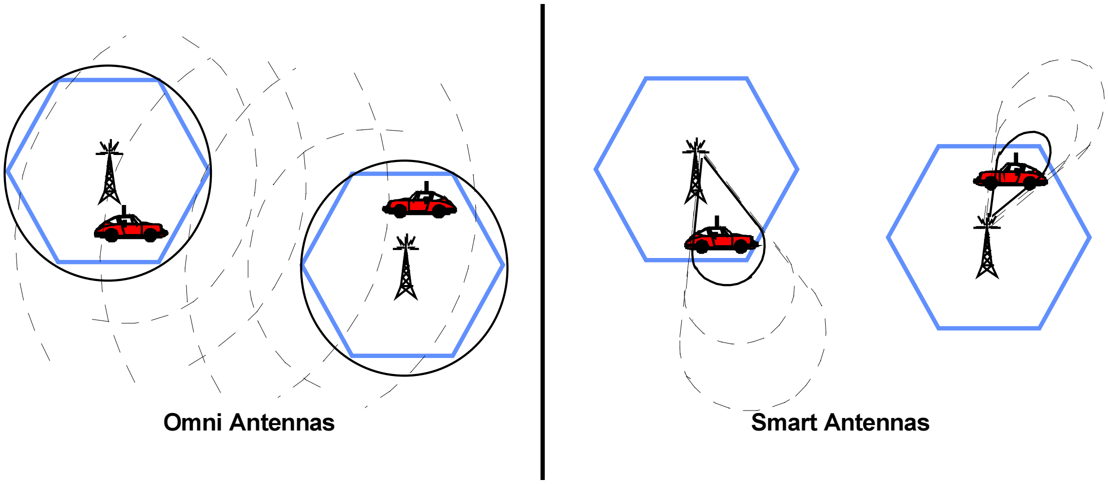

Figure 4-2. Interference reduction using adaptive antennas: directional beams interfere with fewer cells

Example 2

A system with $N_{ch} = 280$ channels and with omnidirectional base station antennas uses a seven-cell frequency reuse pattern ($N_c = 7$). Each cell covers an area of $A_c = 50$ km^2. From (4.7), the capacity is $C_{omni} = \frac{280}{7 \cdot 50}$ or 0.8 channels/km^2. By using smart antennas at the base stations, Co-channel interference is reduced and N_c can be reduced to 4. The new capacity is $C_{smart} = \frac{280}{4 \cdot 50}$ or 1.4 channels/km^2.

Much has been written on the subject of interference reduction and rejection using smart antennas. The approaches and results of several interesting papers are summarized below.

It is shown in [4.4] by modeling that for an outage probability of 1% and a required C/I of 20 dB, spectral efficiency is increased by a factor of 3 if the cell is covered by 8 ideal beams in which all energy is concentrated in a main beam with beamwidth $\frac{2\pi}{8}$. Spectral efficiency is increased by a factor of 11 if 32 beams are used. A smaller improvement is seen for a required C/I of 8 dB. This paper considers a channel with both log-normal ($\sigma = 6$ dB) shadowing and Rayleigh fading.

A circular array is proposed in [4.5] to cover 360 degrees from the base station. Only a few of the elements of the array are used to form each beam, so the array can be approximated by a small linear array. Simulations were performed for 7 active elements, a uniform distribution of mobiles and a channel with path loss exponent $\gamma = 4$. An improvement in average C/I of about 10 dB on the reverse channel and 15 dB or more on the forward channel was achieved.

Simulations reported in [4.6] show that adaptive antennas could improve spectral efficiency by up to 15% in a CDMA system with overlaid macro, micro, and pico cells.

A 10 element scanned beam array is compared in [4.7] with a 120 degree sector antenna. The channel model includes Rayleigh fading, log-normal shadowing with $\sigma = 6$ dB, a Doppler shift of 2.5 Hz, and path loss exponent $\gamma = 3.5$. A system with three-cell frequency reuse using the 10 element array on the uplink is simulated. This system can support 0.3 users/cell/channel with a 5 - 6 dB improvement in C/I compared with a similar system using a sector antenna and supporting only 0.1 users/cell/channel.

Complete frequency reuse is proposed in [4.8]. An 8-element circular adaptive antenna is used at the base station for both transmitting and receiving. Both the uplink and the downlink are simulated assuming a time division duplex system using $\pi/4$ - DQPSK. The channel model includes path loss with exponent $\gamma = 3.5$, log-normal shadowing with $\sigma = 6$ dB, and Rayleigh fading. Both a single transmit-receive path and two transmit-receive paths are modeled. In the two-path case, the correlation between the two paths is varied between 0.0 and 1.0.

In the model used in [4.8], uplink and downlink fading are assumed to be uncorrelated, even though the uplink and downlink use the same frequency. As a result, the uplink C/I improves as the correlation between multipath components increases, while the downlink C/I using the same antenna pattern decreases as the correlation increases. For the two-path model, a 16 element circular array provides a 95% probability of signal to interference ratio greater than 13 dB on both the uplink and the downlink. Element spacings from 0.5 to 5.0 λ are considered. Arrays with large element spacings can form narrower beams and nulls than arrays with smaller spacings. For the single path model, the best performance is seen for large interelement spacing despite the presence of grating lobes.

A generalized intelligent cell concept is presented in [4.9]. One realization of this concept involves reducing the required C/I (as measured with an omnidirectional antenna) using adaptive antennas. This allows the system to have fewer cells in a cluster and increases spectral efficiency.

Interference rejection on the uplink can be accomplished directly by forming base station antenna pattern nulls in the directions of interfering signals that come from co-channel mobiles in other cells. This is discussed in [4.10] - [4.13]. Interference rejection can also be accomplished by steering beams of the base station receiving antenna towards mobiles within a cell, in a manner analogous to interference reduction on the downlink. In this case, interference from directions off the main beam will be reduced.

It is shown in [4.10] that an antenna with $L+N$ elements can be used to null N-1 interferers and achieve L+1 fold antenna diversity gain to combat multipath fading. Since the array has $L+N$-1 degrees of freedom, N-1 degrees of freedom can be used to form N-1 nulls and the remaining L degrees of freedom can be used to provide L+1 fold diversity. Simulations for an IS-54 (North American TDMA cellular) system show that with two elements, the system capacity is nearly doubled. With five elements complete frequency reuse is possible, a seven fold improvement in spectral efficiency over a typical seven cell reuse pattern.

As discussed in [4.11], a software radio can be used to implement an adaptive beam forming algorithm. The smart antenna application is said to allow a three-cell reuse pattern, with double the capacity and three times the call arrival rate of seven-cell systems. Three approaches to C/I improvement are considered. The first is increased gain in the direction of the mobile, the second is the mitigation of multipath fading, and the third is the nulling of interferers. A system is described which uses a constant modulus algorithm (CMA) adaptive receive beam on the uplink using the supervisory audio tone (SAT) to distinguish between signals. On the downlink, one of four fixed beams per 120-degree sector is used. The antenna has over 20 dBi gain. The system remodulates the base band signal to RF for reception by standard cell site receivers.

Adaptive arrays can only reject interfering signals that are sufficiently separated in angle from the desired signal. An adaptive array can be combined with a co-channel interference canceller. The array can reject interfering signals with sufficient angular separation from the desired signal. The interference canceller is used to reject interfering signals with angles of arrival that are near that of the desired signal [4.12].

The uplink of a system with a 10 element uniform linear array with half-wavelength inter-element spacing was simulated in [4.13]. Only the uplink is simulated. Two approaches were considered. The first is direction finding using weighted subspace fitting, followed by linear least-squares estimation (LLSE) beamforming. This is also referred to as the direction of arrival (DOA) approach. In the second approach, each mobile transmits a reference signal, which is not correlated with the reference signals of the other mobiles. The reference signals are used to distinguish between mobiles. A Rayleigh fading channel is modeled, in which scatterers are assumed to be in a circle around the mobile, with 20 reflections per mobile. Two co-channel mobiles in the same cell are considered, and interferers in other cells are ignored. Improvements in SINR with the DOA method were greater than 15 dB, while the reference method showed less improvement, for small differences in the angles of arrival of scattered components. The reference method performed better than the DOA method for larger variations in the arrival angles of scattered components.

4.1.4 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. This approach is shown in Fig. 4-3.

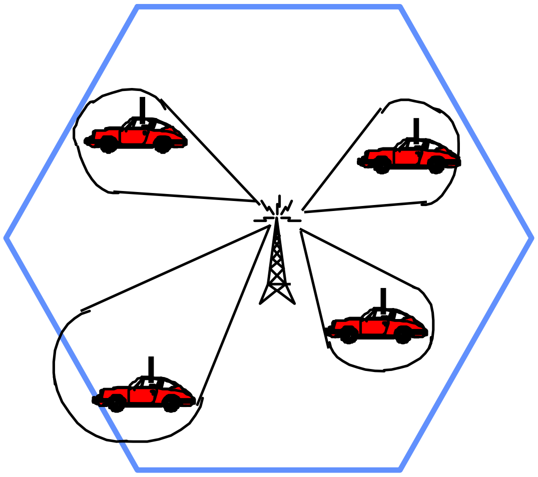

Figure 4-3. Spatial division multiple access (SDMA) using adaptive antennas

If SDMA can be achieved, the spectral efficiency can be increased dramatically [4.14], [4.15]. In an SDMA system the spectral efficiency becomes

$$E = \frac{N_{SDMA}}{B_{ch} N_c A_c} \tag{4.8}$$

and capacity becomes

$$\begin{aligned} C &= \frac{N_{SDMA} B_t}{B_{ch} N_c A_c} \\ &= \frac{N_{SDMA} N_{ch}}{N_c A_c} \end{aligned} \tag{4.9}$$

where N_{SDMA} is the average number of simultaneous spatial channels per RF channel.

Example 3

An SDMA approach using smart antennas is proposed for the system discussed in Example 2. If the system uses seven-cell frequency reuse, an average of $N_{SDMA} = 1.5$ users can occupy each RF channel. The resulting capacity from (4.8) is $C_{SDMA} = \frac{1.5 \cdot 280}{7 \cdot 50}$ or 1.2 channels/km^2, compared to 0.8 channels/km^2 using omnidirectional antennas.

The results of investigations into the use of smart antennas in SDMA systems are summarized below.

An SDMA approach is proposed in [4.14]. Signal recombination, in which multipath components are delayed and combined to form a stronger signal, and interference canceling are simulated for the uplink only. A BPSK signal at 1 GHz is considered. Both signal recombination and interference cancellation improve the signal constellation diagram, but interference cancellation provides a greater improvement. A coherence matrix is used to identify associated multipath components. Direction finding using fixed beams is also discussed.

Measurements presented in [4.15] have implications for increasing capacity through the use of SDMA. While both uplink and downlink are considered, it is acknowledged that feedback from the mobiles would be necessary to form beams for the downlink. A five-element uniform (presumably linear) dipole array with 10 cm inter-element spacing at 1.6 GHz is used at the base station. Signals are down converted to baseband for direction of arrival (DOA) estimation and beam forming. This approach is envisioned for use with a TDMA system. An extra time slot is proposed for each user to transmit on both the uplink and downlink frequencies so the base station can determine spatial signatures at both frequencies.

Measurements in [4.15] indicate that the spatial signature (the received signal as a function of azimuth angle at the receiver) of a base station transmitter is stable over a period of minutes if a line of sight is present and varies more if propagation is by reflections only. SDMA is thus considered feasible for LANs, static networks, and maybe PCS, in which the users do not move rapidly. The spatial signature of a moving (walking speed) transmitter showed significant variation in 10 s, but not much within 1 s if a direct path was present. If only multipath was present, there was little change in 20 ms. An update rate of 100 Hz may be sufficient for mobile speeds of 55 mph. Spatial signature varies with frequency so the receive pattern cannot be used to transmit. Spatial signatures can be very different even for closely spaced transmitters, indicating that spatial diversity may be available even if two or more mobiles are in close proximity.

A pseudo-SDMA approach combining adaptive antennas with CDMA is considered in [4.16]. In this approach, steerable directional antennas are shown to increase the capacity of a cellular system. Theoretical expressions for total interference power and BER were derived, and computer simulations were performed. The paper neglects multipath and assumes perfect power control. The reverse link is considered, with adaptive antennas at the base station only and with adaptive antennas at both the base and the mobile. A reduction in BER of 1 to 3 orders of magnitude compared to a system using an omnidirectional antenna is achieved for a given simulated scenario. The number of users who can be supported with a 10^{-3} BER on the reverse link is increased by a factor of 2 to 4. True SDMA is not achieved, since each user requires a distinct code, but capacity is increased substantially. In addition to increased capacity, some improvement in frequency reuse efficiency is possible if adaptive antennas are used at the mobiles.

In [4.17] a base station antenna with multiple directional beams centered on the users is proposed to increase capacity. A circular array is used to form the beams. The paper considers a channel with path loss exponent $\gamma=4$, Rayleigh fading, log-normal shadowing (σ_S = 6 - 12 dB), multiple access interference, and thermal noise. A voice activity factor of 0.375 is also used. Perfect power control is assumed. Both the uplink and the downlink are considered. CDMA is used. Downlink beamforming using feedback from the mobile units is proposed. For Pr(SNR<7 dB) = 10^{-3}, downlink capacity is increased by a factor of five if five elements are used instead of one, and by a factor of 6.5 if seven elements are used. On the uplink, capacity is improved by approximately a factor of three times that achieved with an omnidirectional antenna for base station antenna beams having a beamwidth of 120°. Capacity is improved by a factor of 5.5 for a beamwidth of 60° and by a factor of 11 when a beamwidth of 30° is used. These uplink capacity improvements are achieved for Pr(BER>0.001)=10^{-3}.

4.1.5 Tradeoff between interference reduction and SDMA

Range extension, interference reduction, and 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 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 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, SDMA cannot be fully implemented without increasing C/I to unacceptable levels.

In [4.18] the basic trade-off between interference reduction and SDMA as approaches to increasing cellular system capacity is identified. Benefits of adaptive antennas are discussed, including lower power consumption and possibly increased cell size, and reduced multipath fading. The paper also recommends paths by which cellular systems in various settings can evolve to serve an increasing number of users.

Another paper [4.19] proposes increasing the capacity of a cellular system using adaptive base station antennas by finding the optimum tradeoff between SDMA and interference rejection approaches. The base stations use an unspecified direction finding algorithm, a channel allocator, and a weight selector (beam former). A channel with Rayleigh and log normal fading is assumed, and mobiles are distributed uniformly between $\pm\pi$ in wave number $\frac{2\pi}{\lambda}\sin\theta$, where θ is the angle from broadside. The cells considered here are 120^o sectors, and the base stations use linear arrays of 120^o sector antennas spaced $\frac{1}{\sqrt{3}}$ wavelength apart. The analysis is done for the downlink, and cluster sizes of 3, 12, and 21 sectors are considered. Improvements in capacity by factors from 2 to 12 are obtained, depending on the number of antennas in the base station array, and on the distribution of scatterers about the mobile. The optimum tradeoff between interference rejection and SDMA is obtained for a cluster size of 12 (equivalent to 4 120^o sectorized hexagonal cells).

4.2 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.

Adaptive antennas are used in [4.20] to reduce BER in a multipath fading channel with Doppler shift. BER is reduced by the least squares constant modulus algorithm (LSCMA), which "performs an optimal tradeoff between combining the fully-coherent multipath received by the array, and nulling the remaining components that have been rendered incoherent due to their delay or Doppler-shift from the direct path waveform."

The simulation in [4.20] uses a 4 element (presumably linear) array with half wavelength interelement spacing (0.5 ft. at 984.25 MHz). A 25 kb/s BPSK signal is considered. Dynamic and static implementations of the LSCMA algorithm are considered. The channel is characterized by multiple paths with equal amplitude and uniformly distributed phase and three-dimensional angle of arrival (the Parsons and Turkmani model). Mobile speeds of 60 and 120 mph are considered. The dynamic implementation lowers the required S/N for a given BER by over 4 dB at 60 mph and about 2 dB at 120 mph. The static implementation performs better, with an improvement of over 10 dB at 60 mph and 4-20 dB at 120 mph. At the 1% BER level, the static implementation provides an 8-9 dB improvement at both speeds. Implications of this paper are possible increased spectral efficiency due to lower S/N requirements, or possibly higher data rates for existing levels of S/N.

In [4.21], a 4-element square or diamond shaped array of monopoles, spaced 0.444 wavelength apart, is mounted on the mobile. These array configurations are shown in Fig. 4-4. In a system using 256 kbps GMSK and TDM, measurements of the downlink show the effectiveness of the CMA algorithm in reducing intersymbol interference due to multipath components. The CMA algorithm also removes the irreducible error floor in the channel. The diamond orientation provides better performance, probably because of its better resolution along the direction of the road, which is the general direction of most multipath components. Vehicle speeds averaged less than 20 km/h, with a maximum of about 60 km/h for a Doppler shift between 27 and 83 Hz at the operating frequency of 1431.5 MHz. Computer simulations show that in most cases the algorithm will capture the correct angular component to minimize delay spread and hence intersymbol interference.

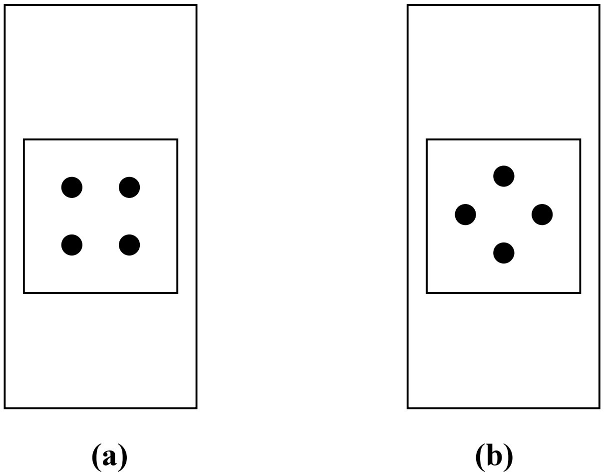

Figure 4-4. Top view of vehicle-mounted array configurations from [4.21]: (a) square, (b) diamond

An approach that reduces multipath fading and increases C/I to improve capacity in cellular systems is presented in [4.22]. An 8-element array of unspecified configuration with a DSP-based receiver is used as a base station antenna. Adaptive algorithms are implemented off-line. This allows comparison of various algorithms on the same data. Measurements were taken using a system operating at 1.89 GHz with a bandwidth of 1.728 MHz. Both a temporal reference method, in which a known reference signal or training sequence is transmitted, and a decision directed approach, in which demodulator decisions are remodulated to form the reference, were used. Adaptive algorithms are simulated for a signal with co channel interference. The DECT standard, which uses TDMA with GMSK modulation, is considered. Data were collected in an outdoor area with many nearby buildings and in an open plan office. Decision-directed normalized LMS is used. Measurements indicate that with 8-element selection diversity a 5 dB increase in uplink SNR is achieved, and with optimal combining a 10 dB increase is achieved.

Fading can also be regulated using a 360-degree scanning cylindrical array antenna at a cellular base station [4.5]. In this system, the antenna beam can be dithered to reduce fading by altering the relative phases of received components.

In [4.11] the mitigation of multipath fading is considered as an approach to improving C/I. A typical 8 dB fade margin can be reduced or eliminated.

4.3 Direction Finding

An important use of adaptive antennas in future wireless systems will be direction finding. Direction finding will be crucial to enhanced emergency 911 services. A recent experimental application of the software radio in [4.11] has been monitoring traffic congestion. The system monitors traffic by monitoring the progress of vehicles equipped with cellular phones, using geolocation techniques. The geolocation techniques use direction of arrival and time differences in the received signal at multiple base stations to locate the mobiles to within about 100 m. In [4.15], a method of direction finding using multiple fixed beams is presented.

4.4 System Evolution

As the number of subscribers increases, the cellular system must evolve to provide the required coverage and capacity. The way in which a system evolves depends on the changing subscriber population and on technical, economic, and regulatory factors.

The flow charts in Fig. 4-5, taken from [4.18], depict possible paths of evolution for European digital cellular and PCS systems. By using lower rate codecs, the required bit rate for each conversation can be decreased and more conversations can occupy the same bandwidth. Codec rate reduction is proposed as the first step to increased capacity, since it requires replacing all the subscriber units. This is best done early in the growth of the system, when there are relatively few subscriber units to replace. A spectrum upgrade (the allocation of additional spectrum to the service) was considered another possible step in increasing the system's capacity. Cell splitting occurs last because it is very expensive to increase the number of base stations.

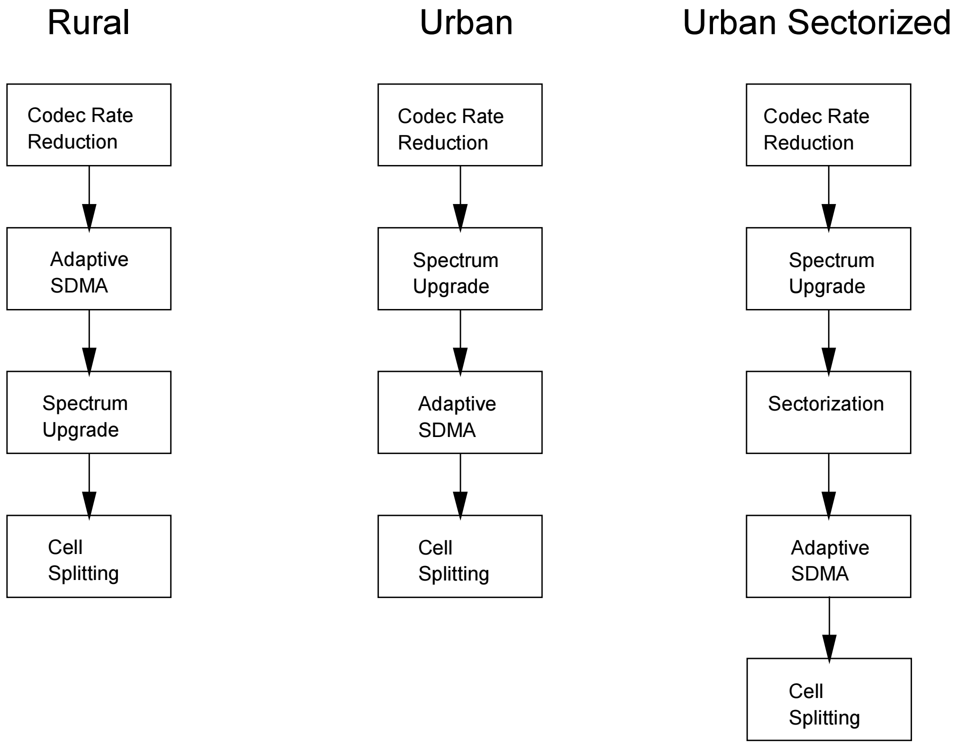

Figure 4-5. Paths of evolution for European digital cellular/PCS systems (from [4.18])

The current North American cellular system is in a different stage of evolution. Much of the system still uses the analog AMPS standard. Codec rate reduction will not be an issue until the system is converted to the first generation of digital cellular standards. Additional spectrum allocation seems unlikely. Logical paths of evolution for North American cellular systems are shown in Fig. 4-6 and Fig. 4-7.

Rural systems may evolve as shown in Fig. 4-6 for the following reasons. In rural areas the subscriber density is relatively low, so the first concern is maximizing coverage with as few base stations as possible, to keep costs low. By introducing adaptive antennas at rural base stations, the range and coverage area of each base station can be increased. It may also be possible to reduce the frequency reuse factor due to the reduced interference that will occur in such a system. Eventually AMPS systems will be converted to TDMA or CDMA, either to increase capacity or to maintain compatibility with other systems. In a CDMA system, pseudo-SDMA (as discussed in Section 4.4.1) can be introduced at this point, and can be optimized for the frequency reuse factor, if a further capacity increase is desired. It is unlikely that cell splitting will be required in a rural area after all these other capacity improvements, but if the area becomes more heavily populated, cell splitting may be necessary.

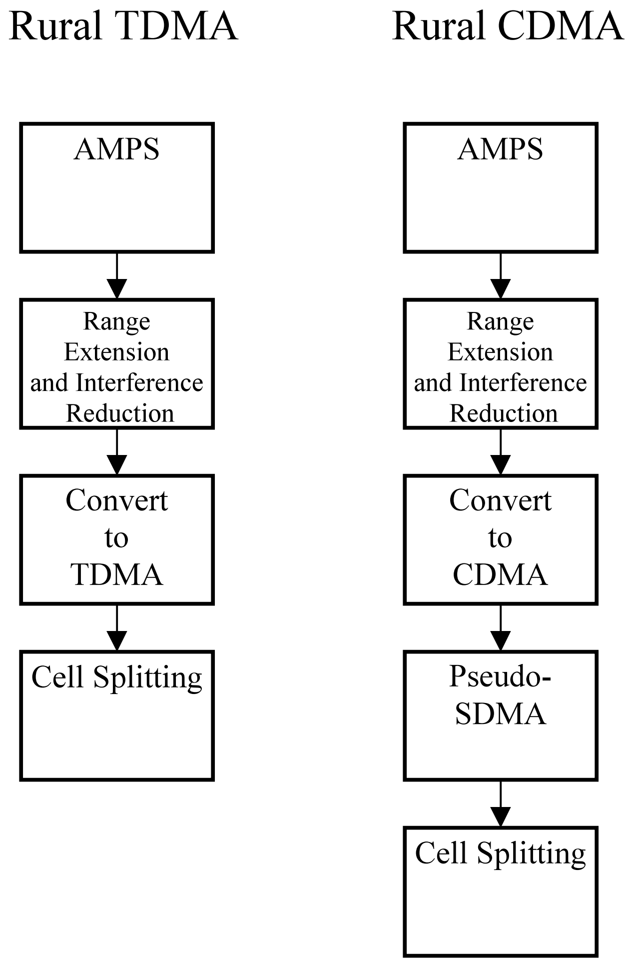

Figure 4-6. Paths of evolution from AMPS for rural North American cellular systems

Flow charts for the evolution of urban systems are shown in Fig. 4-7. In urban systems capacity is the prime issue. Many urban systems are already sectorized. The next step will be conversion to TDMA or CDMA. Adaptive antennas may be introduced to further increase capacity via interference reduction and decreased frequency reuse factor (in TDMA systems) or by pseudo-SDMA (in CDMA systems). Again, cell splitting is an expensive last resort.

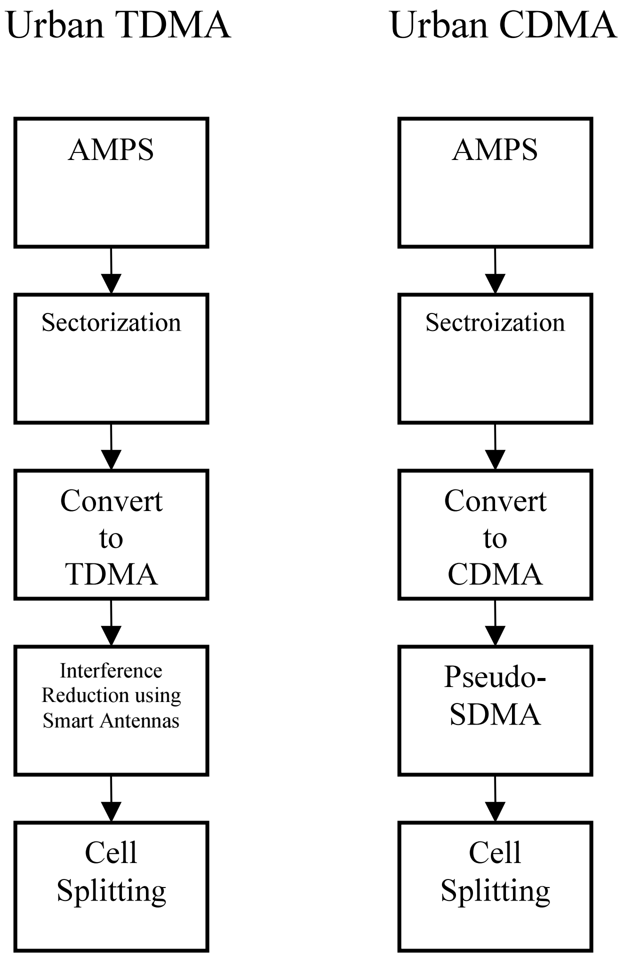

Figure 4-7. Paths of evolution from AMPS for urban North American cellular systems

4.5 Requirements and Implementation Issues

Future smart antenna systems must be compatible with TDMA and/or CDMA standards. Direction finding will be a useful application of smart antennas, both to allow geolocation of users and to facilitate beam forming for the downlink.

Smart antennas must be able to form beams on reverse control channel access requests, and interface to existing base stations without a proprietary interface and without disrupting handoff management. Smart antenna systems must also maintain linearity over a large dynamic range due to their high gain, and possibly with more channels per base station [4.11].

4.6 Conclusions

Smart antennas offer several advantages over omnidirectional or sector antennas. These include increased coverage through range extension, increased capacity achieved through interference reduction or SDMA, and mitigation of multipath fading and inter-symbol interference. Smart antennas can be integrated into evolving North American cellular and PCS systems to keep pace with the increasing number of subscribers.

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