Abstract

In this article we discuss current and future antenna technology for wireless systems and the improvement that smart and adaptive antenna arrays can provide. We describe standard cellular antennas, smart antennas using fixed beams, and adaptive antennas for base stations, as well as antenna technologies for handsets. We show the potential improvement that these antennas can provide, including range extension, multipath diversity, interference suppression, capacity increase, and data rate increase. The issues involved in incorporating these antennas into wireless systems using CDMA, GSM, and IS-136 in different environments, such as rural, suburban, and urban areas, as well as indoors, are described. Theoretical, computer simulation, experimental, and field trial results are also discussed that demonstrate the potential of this technology.

Smart Antennas for Wireless Systems

JACK H. WINTERS
AT&T LABS–RESEARCH

Antenna arrays can combat multipath fading of the desired signal and suppress interfering signals, thereby increasing both the performance and capacity of wireless systems. The major digital wireless cellular systems being deployed today include code-division multiple access (CDMA) with IS-95, and time-division multiple access (TDMA) with IS-136 and the Global System for Mobile Communications (GSM) [1]. These digital systems offer significant performance and capacity improvement over first-generation mobile systems, which are analog. In all these systems, antenna arrays with spatial processing can provide substantial additional improvement [2–4]. However, the various types of spatial processing techniques have different advantages and disadvantages in each type of system.

In this article we provide an overview of how antenna array technology can be used to improve digital cellular systems. We describe the potential improvement in coverage and system capacity, and discuss the trade-offs involved for each system.[1]

In the second section, we describe the wireless system impairments. Antenna array techniques to overcome these impairments are discussed in the third section. In the fourth section we show the improvement in coverage and capacity with these techniques in CDMA and TDMA systems. A summary and conclusions are presented in the fifth section.

Impairments

Wireless communication systems are limited in performance and capacity by three major impairments, as shown in Fig. 1. The first of these is multipath fading, which is caused by the multiple paths that the transmitted signal can take to the receive antenna [8]. The signals from these paths add with different phases, resulting in a received signal amplitude and phase that vary with antenna location, direction, and polarization, as well as with time (with movement in the environment). For example, at 2 GHz a 60 mph vehicle speed results in a 179 Hz fading rate. This increases the required average received signal power for a given bit error rate (BER).

The second impairment is delay spread, which is the difference in propagation delays among the multiple paths. When the delay spread exceeds about 10 percent of the symbol duration, significant intersymbol interference can occur, which limits the maximum data rate [9].

[1] *For a more detailed discussion of many of the topics in this article, see the tutorials of [5–7].*

The third impairment is co-channel interference. Cellular systems divide the available frequency channels into channel sets, using one channel set per cell, with frequency reuse (e.g., most TDMA systems use a frequency reuse factor of 7). This results in co-channel interference, which increases as the number of channel sets decreases (i.e., as the capacity of each cell increases). In TDMA systems, the co-channel interference is predominantly from one or two other users, while in CDMA systems there are typically many strong interferers both within the cell and from adjacent cells. For a given level of co-channel interference (channel sets), capacity can be increased by shrinking the cell size, but at the cost of additional base stations.

Smart Antenna Techniques

Let us now consider array technology to overcome these impairments, thereby permitting greater coverage and capacity at each base station.

Figure 2 shows a block diagram of an antenna array, where the signals received by multiple antenna elements are weighted and combined to generate an output signal. With M antenna elements, such an array generally provides an increased antenna gain of M plus a diversity gain against multipath fading which depends on the correlation of the fading among the antennas. Here we define the antenna gain as the reduction in required receive signal power for a given average output signal-to-noise ratio (which is independent of the environment), while the diversity gain (which is possible only with multipath fading) is defined as the reduction in the required average output signal-to-noise ratio for a given BER with fading.

Diversity

There are three basic ways to provide low correlation (diversity gain): spatial, polarization, and angle diversity [8]. For spatial diversity, the antennas are separated far enough for low fading correlation. The required separation depends on the angular spread, which is the angle over which the signal arrives at the receive antennas. With handsets, which are generally surrounded by other objects, the angular spread is typically 360°, and quarter-wavelength spacing of the antennas is sufficient. This also holds for base station antennas in indoor systems. For outdoor systems with high base station antennas, located above the clutter, the angular spread may be only a few degrees (although it can be much higher in urban areas), and a horizontal separation of 10–20 wavelengths is required, making the size of the antenna array an issue.

For polarization diversity, horizontal and vertical polariza-

 1070-9916/97/$10.00

tion is used. These orthogonal polarizations have low correlation, and the antennas can have a small profile. However, polarization diversity can only double the diversity, and for high base station antennas, the horizontal polarization can be 6–10 dB weaker than the vertical polarization, which reduces the diversity gain.

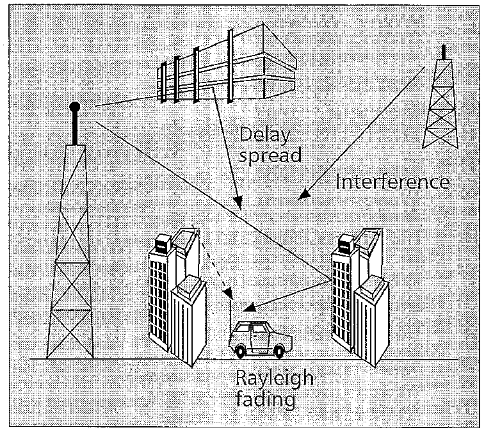
For angle diversity, adjacent narrow beams are used. The antenna profile is small, and the adjacent beams usually have low fading correlation. However, with small angular spread the adjacent beams can have received signal levels more than 10 dB weaker than the strongest beam, resulting in small diversity gain.

Figure 3 shows four antenna diversity options with four antenna elements for a 120° sector system. Figure 3a shows spatial diversity with approximately seven wavelengths (λ) spacing between elements (a 10-ft aperture at 1900 MHz).[2] A typical antenna element has an 18 dBi gain with a 65° horizontal and 8° vertical beamwidth. Figure 3b shows two dual polarization antennas, where the antennas can be either closely spaced ($\lambda/2$) to provide both angle and polarization diversity in a small profile, or widely spaced (7λ) to provide both spatial and polarization diversity. The antenna elements shown are 45° slant polarization antennas, which are also commonly used, rather than vertically and horizontally polarized antennas. Figure 3c shows a closely spaced ($\lambda/2$) vertically polarized array which provides angle diversity in a small profile. This array can also be used as a multibeam antenna by using a Butler matrix [10] to form the beams (e.g., four 30° beams). The Butler matrix uses a bank of phase shifters to basically perform a fast Fourier transform (FFT).

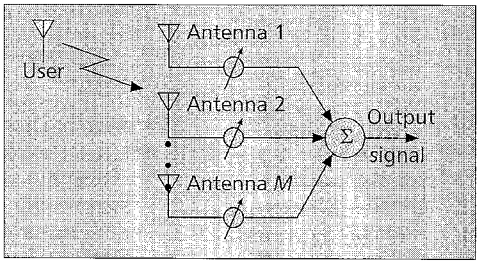
An example comparison of the diversity types shown in Fig. 3 was made in a recent field trial [11], which compared the performance of a conventional two-element spatial diversity receiver in IS-136 to the four-element smart antenna options. At a 10^{-2} bit error rate, the four-element smart antenna provides up to a 6 dB gain in margin against noise versus the two-element array (i.e., ideally, with independent fading at each antenna element). Field trial results showed the highest gain of 4.4 dB with the widely spaced dual polarization antennas (Fig. 3b), while spatial diversity (Fig. 3a), polarization and angle diversity (Fig. 3b with the closely spaced antennas), and angle diversity (Fig. 3c) gave gains of 4.2, 2.9, and 1.1 dB, respectively.

With low fading correlation, diversity gain is typically achieved in current base stations by using selection diversity (selecting the antenna with the highest signal power) or maximal ratio combining (weighting and combining the received signals to maximize the signal-to-noise ratio) with two receive antennas. This provides additional gain on the uplink (mobile to base) to compensate for the higher transmit power of the base station on the downlink — typically only a single transmit and receive antenna is used on the downlink.

On the handset, antenna diversity can also be provided by spatial, polarization, and angle diversity. For spatial diversity, because the handset is typically surrounded by scatterers, an antenna spacing of only $\lambda/4$ is required for low fading correlation, allowing for multiple spatial diversity antennas within a handset, particularly at higher frequencies, such as 2 GHz. Furthermore, dual polarization antennas can be placed close together, with low fading correlation, as can antennas with different patterns (for angle or direction diversity). The main limitation on the handset antennas is typically not the handset size, but the cost and power consumption of the receiver electronics for each antenna.



■ **Figure 1.** *Wireless system impairments.*



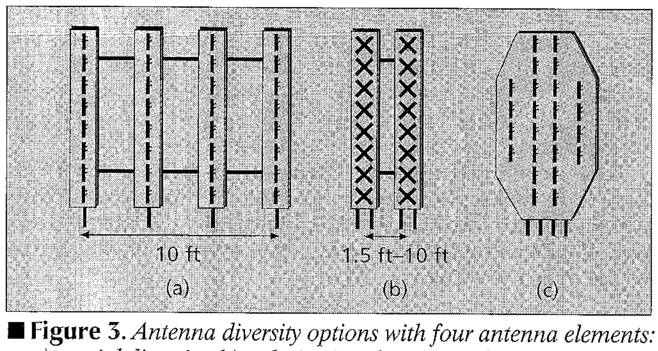
■ **Figure 2.** *Block diagram of an* M *element antenna array.*

Smart Antennas

Today's cellular systems usually use 120° sectorization at each base station. That is, each base station uses three separate sets of antennas for each 120° sector, with dual receive diversity in each sector. Since each sector uses a different frequency to reduce co-channel interference, handoffs between sectors are required. For higher performance, narrower sectors could be used, but this would result in too many handoffs. This leads us to smart antennas, which we define as a multibeam or adaptive array antenna (i.e., diversity antennas) without handoffs between beams.

First consider the multibeam antenna, whereby multiple fixed beams are used in a sector. For example, four 30° beams can be used to cover a 120° sector. An M-beam antenna generally provides an M-fold antenna gain, and can provide some diversity gain by combining the received signals from different beams (angle diversity), or achieve dual diversity by using a second antenna array that uses an orthogonal polarization or is spaced far enough away from the first antenna array. Note that the same beam as on the uplink can be used for the downlink, thereby providing antenna gain (but not diversity gain) on the downlink.

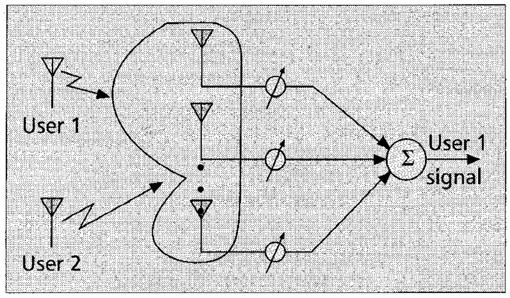
These antennas, though, have nonuniform gain with respect to angle due to scalloping (i.e., the decrease in gain between the beams due to the beam pattern of each beam), with as much as 2 dB less gain between beams. They also can have problems with locking onto the wrong beam due to multipath or interference, and provide limited interference suppression [12], since they cannot suppress interference if it is in the same beam as the desired signal.



■ **Figure 3.** *Antenna diversity options with four antenna elements: a) spatial diversity; b) polarization diversity with angular and spatial diversity; and c) angular diversity.*

[2] *The vertical arrays of dipoles are used to give narrow vertical beamwidth.*

Next consider an adaptive array, whereby the signals received by the multiple antennas are weighted and combined to maximize the signal-to-interference-plus-noise ratio [13]. Note that the antenna elements in the adaptive array should all have similar antenna patterns (although orthogonal polarization is fine), as compared to the multibeam antenna where each antenna element has a different pattern. Adaptive arrays have the advantages of an M-fold antenna gain without scalloping, as well as an M-fold diversity gain with sufficiently low fading correlation. These arrays can theoretically completely cancel N interferers with M antennas ($M > N$) and achieve an $M - N$-fold diversity gain. Significant suppression of $N > M$ interferers is also possible. However, this is at the cost of requiring a receiver for each antenna and tracking the antenna weights at the fading rate (up to 179 Hz at 2 GHz and 60 mph [14]) versus beam switching every few seconds (at most) with the multibeam antenna.



■ **Figure 4.** *An adaptive array beam pattern in a line-of-sight system.*

A key issue for adaptive arrays in wireless systems is their performance in multipath versus line-of-sight (LOS) environments. First, consider adaptive arrays in LOS environments, as studied in most textbooks. In this case, with $\lambda/2$ antenna element spacing, when the adaptive array weights and combines the signals to enhance desired signal reception and null interference, it generates an antenna pattern that has a main beam in the direction of the desired signal and a null in the direction of interferers, as shown in Fig. 4. Under these conditions, with the number of antennas much greater than the number of arriving signal rays, it is easier to express the array response in terms of a small number of angles of arrival, rather than the received signal phase at each antenna. Techniques that exploit this fact for improved performance include the MUSIC and ESPRIT algorithms [15], which determine the direction of arrival of the rays (see [6] for a discussion of these types of techniques). Note that such an array with M antennas can form up to $M - 1$ nulls to cancel up to $M - 1$ interferers. Such angular domain methods can be useful in some wireless situations with near-LOS, such as at mobile radio base stations in flat rural environments with many (e.g., eight) high antennas.

However, with multipath the signals arrive from each user via multiple paths and angles of arrival. Thus, it becomes impossible to form an antenna pattern with a beam in the direction of each arriving path of the desired signal and nulls in the directions of all interfering signals, since the number of required nulls would be much greater than the number of antennas. Furthermore, to provide diversity gain, the antennas at a base station can be spaced many wavelengths apart, which results in many grating lobes (i.e., many repetitions of the antenna pattern in the field of view), and with dual polarization antennas there is a different pattern for each polarization. Thus, the antenna pattern is meaningless. However, no matter how many paths each signal uses, the result is a given phase and amplitude at each antenna for each signal. Thus, there is an array response for each signal, and the performance of the array depends on the number of signals, not the number of paths, with analysis in the signal space domain rather than the angular domain. This holds true as long as the delay spread is small; if not, delayed versions of the signals must be considered as separate signals (see below). Thus, an adaptive array can null $M - 1$ interferers independent of the environment (LOS or multipath).

An important feature of adaptive arrays in multipath environments is the ability to cancel interferers independent of the angle of arrival, that is, even if the interferer is a few inches away from the desired mobile and several miles from the base station. Note that in an LOS environment the separation of such closely spaced signals is not possible. However, with multipath, objects around the antennas act as a huge reflecting antenna (with the actual antennas acting as feeds), which permit the receiving array to separate the signals. In particular, if the receiving antennas are spaced far enough apart such that beams can be formed which are smaller than the angular spread, the signals from two closely spaced antennas can usually be separated using adaptive array combining techniques. The number of signals that can be separated increases with the number of receive antennas, the angular spread, and the density of the multipath reflections within the angular spread [16]. Thus, in this case multipath can be beneficial.

With delay spread, the array treats delayed versions of the signals as separate signals. Specifically, an adaptive array with M antennas can eliminate delay spread over $(M - 1)/2$ symbols [17] or cancel $M - 1$ delayed signals over any delay. However, to keep the array from having to use its spatial processing on temporal distortion, temporal equalizers are typically used in combination with the array. For example, a linear equalizer on each antenna branch [18] and maximum likelihood sequence estimation (MLSE) [19] with an adaptive array have been used effectively.

Applications

Now consider the application of antenna arrays for range and capacity increase in the IS-136 and GSM TDMA systems, as well as in the IS-95 CDMA system.

The IS-136 TDMA system has 3 users/channel, with 162 symbols/time slot using $\pi/4$ dispersion quaternary phase shift keying (DQPSK) modulation at 48.6 kb/s. An equalizer is required to handle delay spreads up to one symbol duration, although it is rarely needed. A 14-symbol synchronization sequence is present in each time slot, which is used for equalizer training, but can also be used to determine the adaptive array weights [20]. However, because with rapid fading the channel can change significantly across a time slot, the adaptive array weights must be adjusted across the time slot, with recalculation of the weights for each symbol. Since the equalizer is relatively simple, though, joint spatial-temporal processing (i.e., adaptive array combining with equalization) is practical, for example, using MLSE [19].

The GSM TDMA system, on the other hand, has 8 users/channel, with 156.25 b/time slot using Gaussian modulated shift keying (MSK) at 270.833 kb/s. Because of the higher data rate, the equalizer must operate with delay spread over several symbols, and thus is more complicated than that for IS-136. However, at typical mobile radio fading rates, the channel does not change significantly over a time slot, and the equalizer and adaptive array weights need only be calculated once per frame (a 26-symbol synchronization sequence is present in each time slot). However, because the equalizer is more complex, joint spatial-temporal processing is more difficult in GSM.

The IS-95 CDMA system has multiple simultaneous users in each 1.25 MHz channel, with 8 kb/s (typically) per user and a spreading gain of 128. A RAKE receiver, which combines delayed versions of the CDMA signal, overcomes the delay spread problem and provides diversity gain. The CDMA spreading codes can provide the reference signal for adaptive array weight calculation.

Range Increase

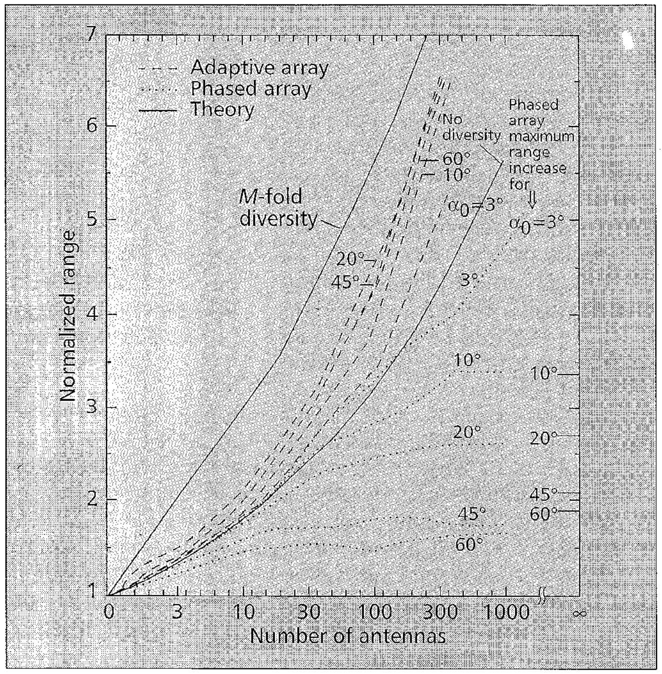
With small angular spread, both an M-element adaptive array and a multibeam antenna provide an M-fold increase in antenna gain. This increases the range by $M^{1/\gamma}$, where γ is the propagation loss exponent (typically, $\gamma = 4$), and reduces the number of base stations required to cover a given area by $M^{2/\gamma}$. The adaptive array also provides diversity gain, and for a given array size with spatial diversity, the diversity gain increases with angular spread (as the fading correlation decreases), thus providing greater range. However, the diversity gain of the multibeam antenna is limited (since angle diversity generally provides only small diversity gain). Furthermore, the antenna gain of the multibeam antenna is limited by the angular spread. That is, the multibeam antenna cannot provide additional antenna gain when the beamwidth is less than the angular spread because smaller beamwidths exclude signal energy outside the beam.

Figure 5 illustrates this effect on the normalized maximum range versus the number of antenna elements for multibeam (phased array) and adaptive arrays with half wavelength antenna spacing, neglecting delay spread [21]. Computer simulation results are shown for different fixed scattering radii around the mobile, with the angular spread α_o for the baseline case of one antenna element given. We also show the theoretical range due to the antenna gain without diversity, and due to antenna gain and M-fold diversity. Also, the predicted maximum range with multibeam antennas is shown. With the multibeam antenna, the range is shown to be limited to the predicted range limitation. However, the range improvement is degraded due to the angular spread for M less than the theoretical value corresponding to the range limitation, and it requires many times more antennas to actually reach this limitation. For example, with a 20° angular spread, the predicted range limitation is 2.6, corresponding to 46 antennas, but with 46 antennas the range is only 2.3. Note that at a range of 2.6, the angular spread is reduced to about 8° for the 20° baseline curve.

For the adaptive array, the range exceeds the no-diversity theoretical range for all angular spreads, due to antenna diversity. The diversity gain increases with M as well as with angular spread and antenna spacing, which decreases the fading correlation. However, the diversity gain does not increase for angular spreads greater than about 20°. Thus, because the adaptive array has greater range with increased angular spread, the difference between the multibeam and adaptive array increases dramatically with angular spread.

The above range increase applies to the uplink. For the downlink, since (in IS-136, GSM, and IS-95) downlink frequency is different from the uplink frequency, the same adaptive array techniques cannot be used for transmission by the base station. A multibeam antenna can be used, but to achieve diversity gain transmit diversity must be used [22] or the handset must have multiple antennas. Although these techniques may provide less gain on the downlink than on the uplink, this may be compensated for by the higher transmit power of the base station as compared to the handset.

The above uplink results (Fig. 5) apply to TDMA systems. With CDMA, the RAKE receiver generally provides threefold diversity, and different beams can be used for each finger of the RAKE receiver. The net effect is that the additional diversity gain of the adaptive array is much smaller, and the antenna gain limitation is much less [21]. Thus, adaptive arrays provide only a slightly larger range increase than multibeam antennas. Since multibeam antennas require less complexity (particularly with respect to weight/beam tracking and to the downlink), the multibeam antenna appears preferable for CDMA, while an adaptive array may be preferable for TDMA, particularly in environments with large angular spread.



■ **Figure 5.** *Normalized maximum range versus the number of antenna elements for multibeam (phased array) and adaptive arrays with half-wavelength antenna spacing, neglecting delay spread.*

Capacity Increase

In CDMA systems the capacity (considered here as the bits per second per hertz per base station) depends on the spreading gain and the corresponding number of equal-power cochannel interferers. A multibeam antenna with M beams reduces the number of interferers per beam by a factor of M, and thereby increases the capacity M-fold. Adaptive arrays, though, can provide only limited additional interference suppression, because the number of interferers is generally much greater than the number of antennas. Thus, since multibeam antennas are less complex than adaptive arrays, particularly since beams need to be switched at most every few seconds versus tracking 179 Hz fading signals in adaptive arrays, multibeam antennas are generally preferred in CDMA systems.

TDMA systems, on the other hand, are limited in capacity by a few dominant interferers. A multibeam antenna reduces the probability of the interferer being in the same beam as the desired signal, and thus permits higher capacity through greater frequency reuse (particularly with small angular spread). However, adaptive arrays can cancel the dominant interferers with just a few antennas, with an M-element array having the potential to permit greater than an M-fold increase in capacity (independent of the angular spread). Computer simulation results indicate that a four-element adaptive array can permit frequency reuse in every cell (in a three-sector system) for a sevenfold increase in capacity over current systems, while a four-beam antenna can permit a reuse of three or four for a doubling of capacity (with small angular spread).

The above adaptive array results apply to the uplink only. For the downlink, multibeam antennas can be used at the base station in combination with adaptive arrays on the uplink, although the multibeam antenna is less effective in reducing interference in TDMA systems. The problem is even worse in IS-136, because the handsets require a continuous downlink, and therefore the same beam pattern must be used for all three users in a channel, which further reduces the effectiveness of multibeam antennas against interference. Therefore, TDMA systems may require multiple antennas on the handset to achieve high frequency reuse. However, interference is typically worse on the uplink than on the downlink for two reasons. First, it is possible that the signal from an interfering mobile could be stronger than that from the desired mobile at the base station, while at the mobile the signal from an interfering base station should not be stronger since the mobile chooses the base station with the strongest signal. Second, the base stations are typically more uniformly spaced (near the center of cells) than the mobiles. Thus, more interference suppression on the uplink than on the downlink may be desirable.

Data Rate Increase

As noted previously, in a multipath environment, an adaptive array can separate signals from closely spaced antennas. This enables multiple spatial channels to be used to greatly increase the data rate between a mobile and a base station [3, 16].

For example, consider IS-136 with 48.6 kb/s in a single 30 kHz channel. Using M antennas at the handset as well as at the base station, M spatially separate channels are possible in the multipath environment of mobile radio (or indoor radio) systems, permitting $M \cdot 48.6$ kb/s to a user in a single 30 kHz channel. Implementation techniques such as space-time coding [23] and layered space-time processing [16] offer the potential to make practical many bits per second per hertz to mobile users (e.g., hundreds of kilobits per second in a 30 kHz channel).

Field Trials and Commercial Products

Field trials of both multibeam antennas and adaptive arrays have demonstrated the performance improvements discussed in this article. For example, Metawave has extensively studied the range increase of multibeam antennas [24], Ericsson has demonstrated increased interference tolerance of 9 dB in an IS-136 system with a four-element adaptive array [25], and Lucent/AT&T has demonstrated operation with an equal-power interferer next to the desired mobile several miles from the base station in an IS-136 system with a four-element adaptive array [11]. Field trials have also been done for DECT systems under the European TSUNAMI project [26]. Commercial products include a four-beam smart antenna incorporated into a GSM base station product by Nortel, and adaptive array processing using two base station antennas incorporated into an IS-136 base station product by Ericsson.

Discussion

Smart antennas are currently being deployed in selected base stations with coverage or interference problems. Range extension is particularly important in PCS systems at 1.9 GHz because the propagation loss is higher than at 900 MHz. In the future, for capacity increase in TDMA systems, adaptive arrays with four antenna elements in IS-136 or multibeam antennas with four or eight beams in GSM may be deployed at all base stations within a cellular system region to decrease the frequency reuse factor from 7 to 4, nearly doubling capacity. However, additional research is needed on adaptive arrays with temporal equalization (space-time processing) to handle both co-channel and intersymbol interference optimally, particularly with short training sequences. A key issue is to make sure that new standards have the necessary "hooks" for future smart antenna deployment (such as adequate length and distinguishable training sequences) so that smart antennas can be less costly and more effective.

Conclusions

In this article we discuss multibeam and adaptive antenna arrays for wireless systems and the improvement in range and capacity these antennas can provide. For CDMA systems, we describe how multibeam antennas can increase the gain (for greater range) and capacity M-fold. For TDMA systems, we discuss the limitations of multibeam antennas, but show that adaptive arrays can provide greater than an M-fold increase in gain and capacity.

References

[1] D. J. Goodman, "Trends in Cellular and Cordless Communications," *IEEE Commun. Mag.*, vol. 29, June 1991, pp. 31–40.
[2] J. H. Winters, "Optimum Combining in Digital Mobile Radio with Cochannel Interference," *IEEE JSAC*, vol. SAC-2, no. 4, July 1984.
[3] J. H. Winters, "Optimum Combining for Indoor Radio Systems with Multiple Users," *IEEE Trans. Commun.*, vol. COM-35, no. 11, Nov. 1987.
[4] J. H. Winters, J. Salz, and R. D. Gitlin, "The Impact of Antenna Diversity on the Capacity of Wireless Communication Systems," *IEEE Trans. Commun.*, Apr. 1994.
[5] L. C. Godara, "Application of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations," *Proc. IEEE*, July 1997.
[6] L. C. Godara, "Application of Antenna Arrays to Mobile Communications, Part II: Beamforming and Direction-of-Arrival Considerations," *Proc. IEEE*, Aug. 1997.
[7] A. J. Paulraj and C. B. Papadias, "Space-Time Processing for Wireless Communications," *IEEE Signal Processing Mag.*, Nov. 1997.
[8] W. C. Jakes, Jr. *et al.*, *Microwave Mobile Communications*, New York: Wiley, 1974.
[9] P. A. Bello and B. D. Nelin, "The Effect of Frequency Selective Fading on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers," *IEEE Trans. Commun. Sys.*, vol. CS-II, June 1963, pp. 170–86.
[10] J. Butler and R. Lowe, "Beamforming Matrix Simplifies Design of Electronically Scanned Antennas," *Elect. Design*, vol. 9, no. 7, Apr. 1961.
[11] J. H. Winters and G. D. Golden, "Adaptive Antenna Applique Field Test," *4th Wksp. Smart Antennas in Wireless Mobile Commun.*, Stanford, CA, July 24, 1997.
[12] P. Zetterberg and B. Ottersten, "The Spectrum Efficiency of a Basestation Antenna Array System for Spatially Selective Transmission," *IEEE VTC*, June 1994.
[13] R. A. Monzingo and T. W. Miller, *Introduction to Adaptive Arrays*, New York: Wiley, 1980.
[14] R. L. Cupo *et al.*, "A Four-Element Adaptive Antenna Array for IS-136 PCS Base Stations," *IEEE VTC*, May 1997.
[15] R. H. Roy, "ESPRIT, Estimation of Signal Parameters via Rotational Invariance Techniques," Ph.D. thesis, Stanford Univ., CA, Aug. 1987.
[16] G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment when Using Multi-Element Antennas," *Bell Labs Tech. J.*, vol. 1, Autumn 1996, pp. 41–59.
[17] D. D. Falconer *et al.*, "Advances in Equalization and Diversity for Portable Wireless Systems," *Digital Signal Processing*, vol. 3, pp. 148–62, 1993.
[18] P. Balaban and J. Salz, "Optimum Diversity Combining and Equalization in Digital Data Transmission with Applications to Cellular Mobile Radio," *IEEE Trans. Vehic. Tech.*, May 1991, pp. 342–54.
[19] G. E. Bottomley and K. Jamal, "Adaptive Arrays and MLSE Equalization," *Proc. VTC*, Chicago, IL, June 25–28, 1995, pp. 50–54.
[20] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in the Digital Mobile Radio System IS-54 with Flat Fading," *IEEE Trans. Vehic. Tech.*, Nov. 1993.
[21] J. H. Winters and M. J. Gans, "The Range Increase of Adaptive versus Phased Arrays in Mobile Radio Systems," *Proc. 28th Asilomar Conf. Signals, Sys. & Comp.*, Pacific Grove, CA, Oct. 30–Nov. 2, 1994, pp. 109–15.
[22] N. Seshadri and J. H. Winters, "Two Signaling Schemes for Improving the Error Performance of Frequency-Division-Duplex (FDD) Transmission Systems Using Transmitted Antenna Diversity," *Int'l. J. Wireless Info. Networks*, Jan. 1994.
[23] N. Seshadri, V. Tarokh, and A. R. Calderbank, "Space-Time Codes for Wireless Communication: Code Construction," *IEEE VTC*, May 1997.
[24] Y. Li *ET AL.*, "Gain Improvement of a Cellular Base Station Antenna Multibeam Antenna," *IEEE VTC*, Apr. 28–May 1, 1996.
[25] B. Hagerman *et al.*, "Field Test Performance for D-AMPS in PCS Bands with Array Processing," *IEEE VTC*, May 1997.
[26] G. Tsoulos, M. Beach, and J. McGeehan, "Wireless Personal Communications for the 21st Century: European Technological Advances in Adaptive Antennas," *IEEE Commun. Mag.*, Sept. 1997, p. 102–9.

Biography

JACK H. WINTERS (jhw@research.att.com) [F '96] received his B.S.E.E. degree from the University of Cincinnati, Ohio, in 1977, and M.S. and Ph.D. degrees in electrical engineering from The Ohio State University, Columbus, in 1978 and 1981, respectively. Since 1981 he has been with AT&T Bell Laboratories and now AT&T Laboratories — Research, where he is a technology consultant in the Wireless Systems Research Department.