Reverse Channel Performance Improvements in CDMA Cellular Communication Systems Employing Adaptive Antennas

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Abstract

In this paper, we examine the performance enhancements that can be achieved by employing adaptive antennas in Code Division Multiple Access (CDMA) cellular radio systems. The goal is to determine what improvements are possible using narrowbeam antenna techniques, assuming that adaptive algorithms and the associated hardware to implement these systems can be realized. Simulations and analytical results are presented which demonstrate that adaptive antennas at the base station can dramatically improve the reverse channel performance of multi-cell radio systems, and new analytical techniques for characterizing mobile radio systems which employ frequency reuse are described. We also discuss the effects of using adaptive antennas at the portable unit.

1. Introduction

Current day mobile radio systems are becoming congested due to growing competition for spectrum. Many different approaches have been proposed to maximize data throughput while minimizing spectrum requirements for future wireless personal communications services [Coo78, Sal90].

The reverse link presents the most difficulty in CDMA cellular systems for several reasons. First of all, the base station has complete control over the relative power of all of the transmitted signals on the forward link, however, because of different radio propagation paths between each user and the base station, the transmitted power from each portable unit must be dynamically controlled to prevent any single user from driving the interference level too high for all other users [Rap92]. Second, transmit power is limited by battery consumption at the portable unit, therefore there are limits on the degree to which power may be controlled. Finally to maximize performance, all users on the forward link may be delay synchronized much more easily than users on the reverse link [Pur77].

Adaptive antennas at the base station and at the portable unit may mitigate some of these problems. In the limiting case of infinitesimal beamwidth and infinitely fast tracking ability, adaptive antennas can provide a unique channel that is free from interference for most users. All users within the system would be able to communicate at the same time using the same frequency channel, in effect providing Space Division Multiple Access (SDMA) [Gar92]. In addition, a perfect adaptive antenna system would be able to track individual multipath components and combine them in an optimal manner to collect all of the available signal energy [Swa90].

The perfect adaptive antenna system described above is not feasible since it requires infinitely large antennas (or alternatively, infinitely high frequencies). This raises the question of what gains might be achieved using reasonably sized arrays with moderate directivities.

For interference limited asynchronous reverse channel CDMA over an AWGN channel, operating with perfect power control with no interference from adjacent cells and with omnidirectional antennas used at the base station, the bit error rate (BER), P_b, is approximated by [Pur77]

$$P_b \approx Q\left(\sqrt{\frac{3N}{K-1}}\right) \qquad \text{Eq. 1.1}$$

where K is the number of users in a cell and N is the spreading factor. $Q(Y)$ is the standard Q-function. Eq. 1.1 assumes that the signature sequences are random and that K is sufficiently large to allow the Gaussian approximation, described in [Pur77], to be applied.

In order to develop simple bit error rate expressions for simultaneous asynchronous interference limited CDMA users when directional antennas are used we assume that the bit error rate expression of Eq. 1.1 can be expressed as

$$P_b \approx Q\left(\sqrt{3N \times CIR}\right) \qquad \text{Eq. 1.2}$$

where CIR is the ratio of the power of the desired signal to the total interference. This approximation is known to be inaccurate when the received power levels from different users are widely different and when the number of users is small [Mor89], however, it provides a reasonable approximation when K is large.

Let us assume that the base station is able to form a directional beam with power pattern $G(\varphi)$, whose two-dimensional directivity is defined as:

$$D = \frac{2\pi}{\int_0^{2\pi} G(\varphi)\, d\varphi} \qquad \text{Eq. 1.3}$$

We assume that the beam is steered such that, in the direction of the desired user, $G(\varphi_0) = 1$.

If we assume that K users are uniformly distributed throughout a cell with radius R, the expected value of interfer-

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ence received at the base station on the reverse link is given by

$$I = (K-1)\int_0^R \int_0^{2\pi} \frac{rP_r}{\pi R^2} G(\varphi)\, dr d\varphi = \frac{(K-1)P_r}{D} \qquad \text{Eq. 1.4}$$

Using the fact that the desired signal power, weighted by the antenna pattern, is simply P_r, and, substituting Eq. 1.4 into Eq. 1.2 we obtain,

$$P_b = Q\left(\sqrt{\frac{3DN}{K-1}}\right) \qquad \text{Eq. 1.5}$$

Eq. 1.5 is useful in showing that the probability of error for a CDMA system is related to the beam pattern of a receiver.

2. Reverse Channel Performance with Adaptive Antennas at the Base Station

The use of adaptive antennas at the base station receiver is a logical first step in improving capacity for several reasons. First of all, space and power constraints are not nearly as critical at the base station as they are at the portable unit. Second, the physical size of the array does not pose difficulty at the base station [Rap92].

Equation 1.5 is only valid when a single cell is considered. To consider the effects of adaptive antennas when CDMA users are simultaneously active in several adjacent cells, we must first define the geometry of the cell region. For simplicity, we consider the geometry proposed in [Rap92] with a single layer of surrounding cells, as illustrated in Figure 2.1.

Let $d_{i,j}$ represent the distance from the i[th] user to base j. Let $d_{i,0}$ represent the distance from the i[th] user to base station 0, the center base station.

Assume that the received power, at base j from the transmitter of user i, $P_{r;j,i}$, is given by a simple distance dependent path loss relationship

$$P_{r;j,i} = P_{T;i}\left(\frac{\lambda}{4\pi d_{ref}}\right)^2 \left(\frac{d_{ref}}{d_{i,j}}\right)^n \qquad \text{Eq. 2.1}$$

where n is the path loss exponent typically ranging between 2 and 4, and d_{ref} is a close-in reference distance [Rap92].

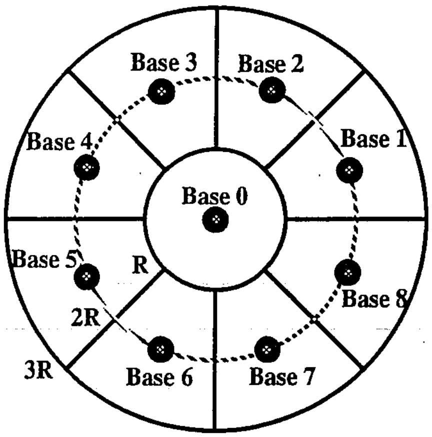

Figure 2.1. The nine cell wedge geometry proposed in [Rap92].

If we assume perfect power control such that the power received by each base from a user within that cell is P_r, then the interference power, $P_{r;0,i}$, received at the central base station from a mobile unit i in adjacent cell j is given by:

$$P_{r;0,i} = P_r\left(\frac{d_{i,j}}{d_{i,0}}\right)^n \qquad \text{Eq. 2.2}$$

which may be expressed as

$$P_{r;0,i} = P_r\left(1 + \left(\frac{2R}{d_{i,0}}\right)^2 - \frac{4R}{d_{i,o}}\cos\varphi_{i,0}\right)^{n/2} \qquad \text{Eq. 2.3}$$

where $\varphi_{i,0}$ is the angle of the mobile unit relative to a line drawn between the central cell base station and base j.

Let χ represent the expected value of the interference power, received at the central base station, from a single user in one of the adjacent cells when omnidirectional base station antennas are used. We can express the expected value of central cell interference power from a single adjacent cell user as

$$\chi = \beta P_r \qquad \text{Eq. 2.4}$$

where β, the average ratio of interference received from a single adjacent cell user to the interference received from a single in-cell user, is given by:

$$\beta = \int_R^{3R}\int_{-\pi/8}^{\pi/8} f_u(r,\varphi)\left(\left(1 + \left(\frac{2R}{r}\right)^2 - \frac{4R}{r}\cos\varphi\right)\right)^{n/2} dr d\varphi \qquad \text{Eq. 2.5}$$

$f_u(r,\varphi)$ is the probability density function describing the geographic distribution of users in a single adjacent cell. Table 2.1 lists values of β for several values of n, assuming that users are uniformly distributed throughout the nine cell region.

β is related to the reuse factor, f, which is defined in [Rap92], for a single layer of eight adjacent cells, as

$$f = \frac{N_0}{N_0 + 8N_{a1}} \qquad \text{Eq. 2.6}$$

where N_0 is the interference from users in the central cell, received at the central base station, on the reverse link. N_{a1} is the total interference seen by the desired central cell user from all users in a single adjacent cell.

When perfect power control is applied, then equation 2.6 may be expressed as:

$$f = \frac{(K-1)P_r}{(K-1)P_r + 8K\beta P_r} \approx \frac{1}{1+8\beta} \qquad \text{Eq. 2.7}$$

where we have assumed that there are K users in each of the

Table 2.1. Values of β as a function of the path loss exponent, n as determined by Eq. 2.5.

n	β
2	0.14962
3	0.08238
4	0.05513

nine cells. For n=4, from Eq. 2.7, we obtain $f = 0.693$, implying that 31% of the interference power received at the central base station is due to users in adjacent cells. Note that, when omnidirectional antennas are used at both the base station and the portable unit, the value of the reuse factor, f, is determined by the cell geometry, power control scheme, and the path loss exponent.

When omnidirectional antennas are used at both the base station and the portable unit, the total interference seen on the reverse link by the central base station is the sum of the interference from users within the central cell, $(K-1)P_r$, and interference from users in adjacent cells, $8K\beta P_r$,

$$I = (K-1)P_r + 8K\beta P_r \qquad \text{Eq. 2.8}$$

Let us assume that for the m[th] user in the central cell, an antenna beam from the base station, with pattern $G(\varphi)$, may be formed by the base station with maximum gain in the direction of user m. From Eq. 1.4, the average interference power contributed by a single user in the central cell is given by

$$E[P_{r0,i}| (0 < r < R)] = \frac{P_r}{D} \qquad \text{Eq. 2.9}$$

where D is the directivity of the beam with pattern $G(\varphi)$. When $G(\varphi)$ is piecewise constant over $(2p-1)(\pi/8) < \varphi - \varphi_d < (2p+1)(\pi/8)$, for $p = 0...7$, for any angle φ_d between $-\pi/8$ and $\pi/8$, the average interference power at the central base station receiver (after the array weighting), due to a single user in an adjacent cell, can be shown to be:

$$E[P_{r0,i}| (R < r < 3R)] = \frac{P_r\beta}{D} \qquad \text{Eq. 2.10}$$

Using Eq. 2.10 with Eq. 2.9, the total interference power received at the center base station receiver is given by

$$I = \frac{(K-1)P_r + 8KP_r\beta}{D} \qquad \text{Eq. 2.11}$$

Substituting Eq. 2.11 into the Eq. 1.6, using the fact that the desired signal power at the array port is P_r, we obtain an average bit error probability for the CDMA system employing a piecewise constant directional beam is approximated by:

$$P_b \approx Q\left(\sqrt{\frac{3ND}{K(1+8\beta)}}\right) \qquad \text{Eq. 2.12}$$

Eq. 2.12 relates the probability of error to the number of users per cell, the directivity of the base station antenna, and the propagation path loss exponent through the value of β. It is assumed that perfect power control is applied as described earlier in this section.

3. Simulation of Adaptive Antennas at the Base Station for Reverse Channel

To explore the utility of Eq. 2.12 and to verify its accuracy, we considered five base station antenna patterns which are illustrated in Figure 3.1. These antenna patterns are assumed to be directed such that maximum gain is in the direction of the desired mobile user. The first base station antenna pattern, shown in Figure 3.1(a) is an omnidirectional pattern similar to that used in traditional cellular systems.

The second pattern, illustrated in Figure 3.1(b), used 120° sectorization at the base station. In our model, the base station used three sectors, one covering the region from 30° to 150°, the second covering the region from 150° to 270°, and the third covering the region from −90° to 30°.

The third simulated base station pattern, shown in Figure 3.1(c), was a "flat-topped" pattern. The main beam was 30 degrees wide with uniform gain in the main lobe. A uniform side lobe level, which was 6 dB below the main beam gain, was assumed.

The fourth pattern, which used a simple three element linear array, is illustrated in Figure 3.1(d). This is the beam pattern formed by a binomial phased array with elements spaced a half wavelength apart. While the three dimensional gain of a binomial phased array is constant at 4.3 dB regardless of scan angle, the two-dimensional directivity, defined by Eq. 1.3, varies between 2.6 and 6.0 dB, depending on scan angle.

The pattern for the fifth simulated base station configuration, a sectorized adaptive antenna, is shown in Figure 3.1(e). Beginning with the sectorized system whose pattern is illus-

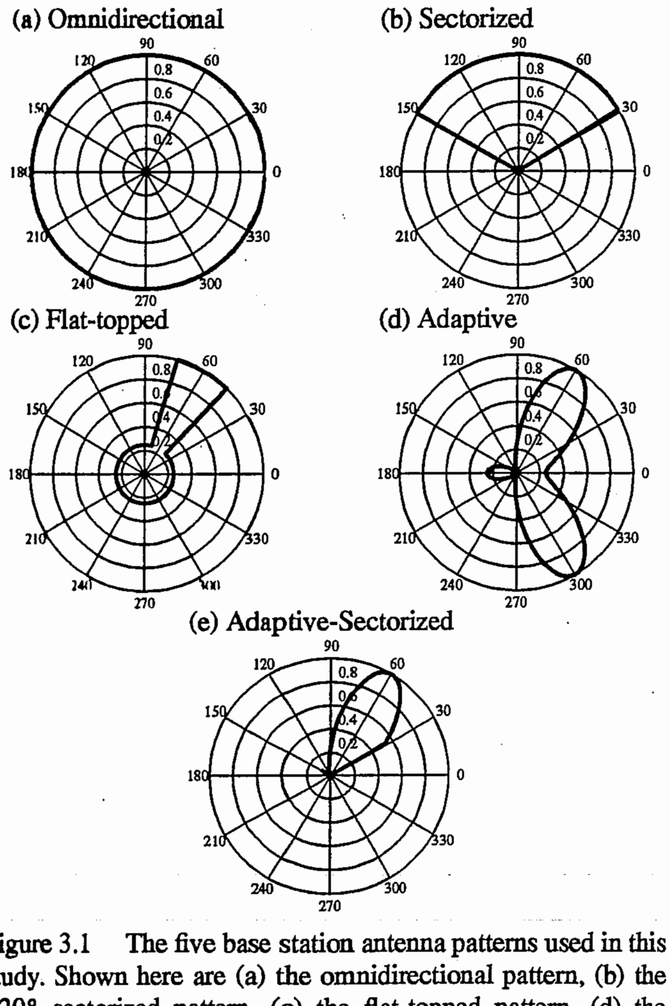

Figure 3.1 The five base station antenna patterns used in this study. Shown here are (a) the omnidirectional pattern, (b) the 120° sectorized pattern, (c) the flat-topped pattern, (d) the binomial phased array, and (e) the binomial phased array pattern overlaid with a 120° sectorization pattern.

trated in Figure 3.1(b), we added a three element linear phased array to each sector. This pattern has a significantly higher gain than the beam pattern shown in Figure 3.1 (d).

To evaluate the link performance when these patterns are used at base stations, a simulation was designed using the cell geometry illustrated in Figure 2.1. Users were randomly placed throughout the region with an average of K users per cell.

Each user was assigned to one of the nine cells based on geographical location. Path loss was assumed to follow the model described in Eq. 2.1, and perfect power control was applied as described in Section 2.

We define $P_{i,j,k}$ as the component of the received power at the base station receiver (weighted by the array pattern) at the kth base station from the ith user associated with cell j. The CIR for the ith user in the central cell was calculated from

$$CIR_i = \frac{P_{i,0,0}}{\sum_{\substack{n=0 \\ n \neq i}}^{K-1} P_{n,0,0} + \sum_{m=1}^{8} \sum_{n=0}^{K-1} P_{n,m,0}} \qquad \text{Eq. 3.1}$$

The bit error rate for the ith user in cell 0 on the reverse link was determined by first calculating the CIR for the ith user from Eq. 3.1 then using that value in Eq. 1.2. A spreading factor of $N = 511$ was assumed.

This calculation was carried out for every user in the central cell and the resulting bit error rates were averaged to obtain an average bit error rate for the cell. Figure 3.2 shows bit error rates resulting from the simulation.

Figure 3.3 shows results calculated using the analytical result of Eq. 2.12 for four of the antenna patterns shown in Figure 3.1. By comparing Figures 3.2 and 3.3, it can be seen that for omnidirectional antennas, 120° sectorization, and the flat-topped pattern, the calculated bit error rates from Eq. 2.12 match the simulation results exactly. For the case of the adaptive binomial phased array, the analytical results for P_b are somewhat different from the simulation results. Unlike the omnidirectional, sectorized, and flat-topped patterns, the adaptive binomial phased array did not exhibit constant two-dimensional gain as a function of scan angle. Nevertheless, these figures demonstrate the accuracy of Eq. 2.12 when compared with simulations.

4. Simulation of Adaptive Antennas at the Portable Unit and at the Base Station

In this section, we examine how the reverse channel is affected by using adaptive antennas at a portable transmitter. A flat-topped beam was used to model an adaptive antenna at the portable transmitter. It is assumed that through retrodirectivity, the portable unit is able to adapt a beam pattern based on the received signal and transmit using that same pattern. Since space is extremely limited on the portable unit, the gain achievable by the portable unit antenna will be considerably less than

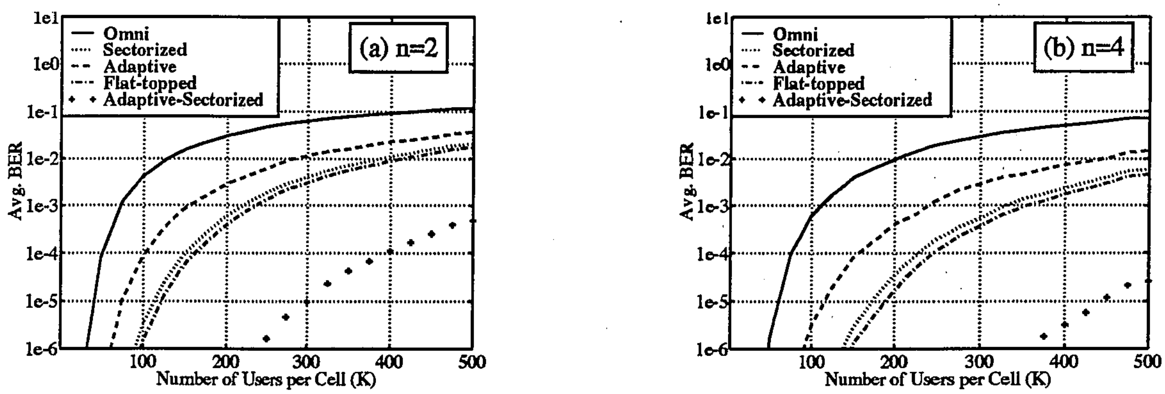

Figure 3.2 BER using adaptive antennas at the base station for (a) n=2, and (b) n=4. These results were developed through simulation by averaging the BER of every user in the center cell.

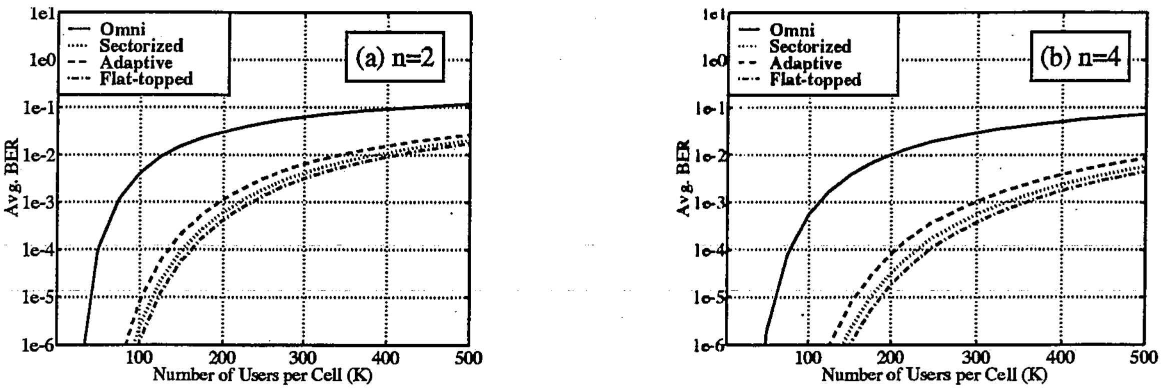

Figure 3.3 Plots of analytical results using equation 2.12 with two-dimensional directivities of 1.0, 2.67, 3.0, and 3.2 for the omni, adaptive, sectorized and flat-topped patterns, respectively, for (a) n=2, and (b) n=4.

that at the base station. For this study, it was assumed that the portable unit could achieve a beamwidth of 60 degrees with a uniform side lobe level that was 6 dB down from the main beam. This corresponds to an antenna with a gain of 4.3 dB. The pattern is similar to that shown in Figure 3.1(c) except that the beamwidth is wider in this case.

It was assumed that each portable unit was capable of perfectly aligning the boresight of its adaptive antenna with the base station associated with that portable unit. In this manner, portable units could radiate maximum energy to the desired base station.

Portable units with adaptive antennas were simulated for each of the five base station patterns described in Section 3. As in Section 3, average values of P_b were found by averaging the bit error rates of each user in the central cell, subjected to interference from the central cell and all immediately adjacent cells. The resulting bit error rates for these systems are shown in Figure 4.1. Note that, comparing Figure 3.2 and Figure 4.1, the bit error rates for the reverse channel are improved when directional antennas are used at the portable unit. For omnidirectional base stations, the average BER is only decreased by a small amount (20% or less) for K>200 when steerable directional antennas are used at the portable unit. However, for highly directional base station antenna patterns such as the adaptive-sectorized pattern, the average BER was decreased by an order of magnitude for K>300.

The relatively small improvements obtained by using adaptive antennas at the portable unit can be explained by the fact that when omnidirectional antennas are used at the mobile unit, no more than 1-0.455, or 0.545, of the total interference power is due to users in adjacent cells (see Table 4.1). When using adaptive antennas at the mobile unit, all users in the central cell will appear no different to the central base station than if they had used omnidirectional antennas. Thus, adaptive antennas at the portable unit will only reduce out-of-cell interference levels. Therefore, the maximum improvement in CIR, on the reverse link, that can be achieved by using adaptive antennas rather than omnidirectional antennas at the portable unit is only 3.5 dB.

Table 4.1 shows several values of the reuse factor, f, defined in Eq. 2.6 as the ratio of in-cell interference to total interference, for several base station patterns when omnidirectional antennas are used at the portable unit. Similarly, Table 4.2 shows values of f when steerable, directional antennas, with directivities of 4.3 dB, are used at the portable units.

Comparing Tables 4.1 and 4.2, it can be concluded that the use of adaptive antennas at the base station does nothing to improve the reuse factor, f, however the use of adaptive anten-

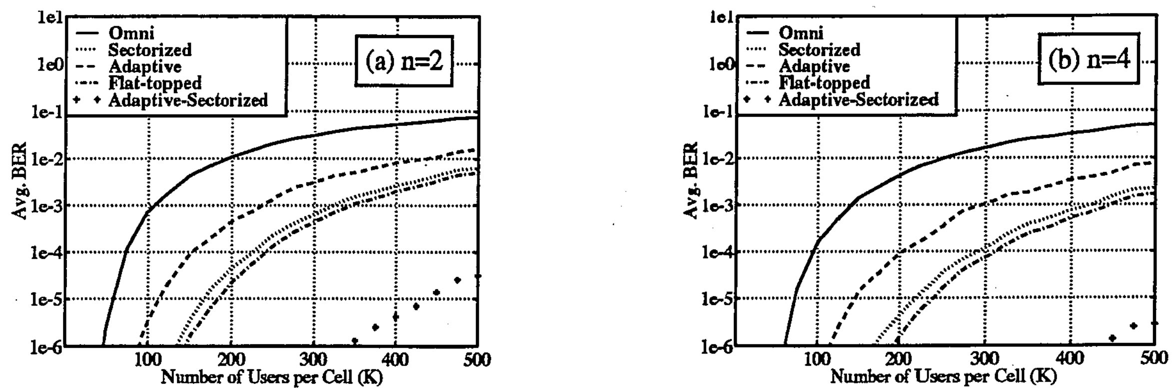

Figure 4.1 BER for five different base station configurations using adaptive antennas at the portable unit for (a) n=2 and (b) n=4. These results were obtained by simulation.

Table 4.1. Ratio of in-cell interference to total interference, f, as a function of path loss exponent when omnidirectional antennas are used at the portable units.

Base station pattern	Path Loss Exponent		
	n=2	n=3	n=4
Omni	0.454	0.601	0.693
Sectorized	0.453	0.601	0.692
Adaptive	0.452	0.600	0.692
Flat-topped	0.453	0.601	0.693
Adaptive-sectorized	0.453	0.601	0.692
$\frac{1}{1+8\beta}$ (Eq. 2.7)	0.455	0.603	0.694

Table 4.2. Ratio of in-cell interference to total interference, f, as a function of path loss exponent when antennas with directivities of 4.3 dB are used at the portable units.

Base station pattern	Path Loss Exponent		
	n=2	n=3	n=4
Omni	0.675	0.816	0.883
Sectorized	0.675	0.815	0.882
Adaptive	0.675	0.815	0.882
Flat-topped	0.675	0.815	0.883
Adaptive-sectorized	0.675	0.815	0.882

nas at the portable unit does allow f to be improved. When omnidirectional antennas are used at the portable unit, f is entirely determined by the cell geometry, the power control scheme, and path loss exponent, n, which is a function of propagation and not easily controlled by system designers. Using adaptive antennas at the portable unit, it is possible to tailor f to a desired value. Ideally, driving f to unity would allow system design to much less sensitive to the inter-cell propagation environment, when perfect power control is assumed.

This is important in CDMA cellular systems, since it indicates that use of adaptive antennas at the portable unit could help to allow for more frequent reuse of signature sequences.

5. Conclusions

It was shown in this study that adaptive antennas at the base station, with relatively modest beamwidth requirements, and no interference nulling capability, can provide large improvements in BER, as compared to omnidirectional systems.

Simple analytical expressions which relate the average BER of a CDMA user to the antenna directivity and propagation environment were derived and used to determine bit error rate improvements offered by a number of base station antenna patterns. In terms of capacity, the results of Section 3 indicate that using adaptive antennas at the base station can allow the number of users to increase by 200% to 400%, while maintaining an average BER of 10^{-3} on the reverse link.

The bit error rate on the reverse channel is further improved by adding adaptive antennas at the portable unit. Using a 4.3 dB gain antenna at the portable, the bit error rate for the directional base station antenna patterns was less than half of the bit error achieved without directional antennas at the portable unit.

In Section 4, it was demonstrated that while only modest improvements in bit error rate were achieved by using adaptive antennas at the portable unit, adaptive antennas at the portable unit allow the reuse factor to be altered. In this way, the impact of adjacent cell interference may be controlled.

In short, adaptive antennas at the base station can have a major effect on bit error rate performance, but cannot impact the reuse factor, f. Conversely, it has been shown in this paper that adaptive antennas at the portable unit can provide no more than a 3.5 dB improvement in reverse channel CIR, however, they allow the reuse factor, f, to be altered.

Neither interference nulling or the multipath channel were considered in this study, however, both of these factors will be significant in developing algorithms for successfully adapting array elements. Furthermore, work is currently underway to establish more accurate expressions for bit error rate in systems employing adaptive antennas.

6. References

[Coo78] G.R. Cooper and R.W. Nettleton, "A spread-spectrum technique for high-capacity mobile communications," *IEEE Trans. on Vehicular Technology,* vol. VT-27, no. 4, Nov. 1978.

[Sal90] A. Salmasi, "An overview of advanced wireless telecommunication systems employing code division multiple access," *Conf. on Mobile, Portable & Personal Communications,* Kings College, England, Sept., 1990.

[Gar92] W.A. Gardner, S.V. Schell, and P.A. Murphy, "Multiplication of cellular radio capacity by blind adaptive spatial filtering," *IEEE Int. Conf. on Sel. Topics in Wireless Commun. Mobile,* Vancouver, B.C., Can. Jun 1992.

[Swa90] S.C. Swales, M.A. Beach, D.J. Edwards, and J.P. McGeehan, "The performance enhancement of multibeam adaptive base-station antennas for cellular land mobile radio systems," *IEEE Trans. on Vehicular Technology,* vol. 39, no. 1, Feb. 1990.

[Pur77] M.B. Pursley, "Performance evaluation for phase-coded spread spectrum multiple-access communications with random signature sequences," *IEEE Trans. Commun.,* vol. COM-25, Aug. 1977.

[Rap92] T.S. Rappaport and L.B. Milstein, "Effects of radio propagation path loss on DS-CDMA cellular frequency reuse efficiency for the reverse channel," *IEEE Trans. on Veh. Tech.,* vol. 41, no. 3, Aug. 1992.

[Mor89] R.K. Morrow, and J.S. Lehnert, "Bit-to-Bit Error Dependence in Slotted DS/SSMA Packet Systems with Random Signature Sequences," *IEEE Trans. Comm.,* Vol 37, No. 10., Oct, 1989.

7. Acknowledgment

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