LETTER *Special Section on Information Theory and Its Applications*

Cell Boundary Shifting with Power Ratio Control and Tilted Antenna Arrays in a Cellular Wireless Communications

Jie ZHOU[†a)], **Shigenobu SASAKI**[†], **Hisakazu KIKUCHI**[†], *and* **Yoshikuni ONOZATO**[††], *Regular Members*

SUMMARY In this paper, we propose the soft boundary concept achieved by dynamic tilted antenna to solve the issue of traffic congestion occurred in cellular wireless systems. The tilted antenna array can provide the merit of traffic balance and also achieve the optimization of the signal-to-interference ratio (SIR) at receivers by automatically tilting the antenna and implementing the soft boundary among cells, corresponding to the variation of traffic. According to our results, it is shown that power ratio control do not necessarily improved system performance when there is a large variation in traffic because it only control power levels. Also the properly chosen angle of tilt antenna can relieve the traffic congestion and perform the system performance optimization.
key words: *cellular system, reverse/forward links, traffic balance, tilted antenna array, power ratio control, radiation pattern*

1. Introduction

Through the past decade, many results have shown that a code division multiple access (CDMA) system can achieve higher capacity and spectrum efficiency in cellular wireless systems [1]. Particularly, the researches of tilted antenna array [2], [3] against the multi-cross interference and the hot-spot traffic relief issue have drawn a considerable attention of system designers to design higher quality systems. The capacity of a CDMA cellular system is determined by a volume of the interference including the internal interference and multi-cross interference. Any decrease in the interference will directly result in the increase in the system capacity. From K.C. Whang's research results [2], a tilted antenna array can be used to reduce the interference in hierarchical macrocell/microcell systems, in two tiers sharing the same spectrum. For the tilted antenna, there are many approaches to solve the reflection issues on smooth surface and rough surface [3], [4] and they estimated the effects of the antenna height, antenna gain and the tilting pattern on a cellular mobile system.

In real cellular environments, that is non-uniform radio environments, non-uniform user distributions dominate and thus, the performance characteristics differ among cells, and communication quality varies rapidly. Hence it will seriously degrade the performance of the system. Then as pointed out in Refs. [6] and [7], power control strategy is the most important issue in a CDMA cellular system, but does not necessarily improve system spectrum efficiency when there is a large geographic variation in traffic. Therefore shift of the cell boundary was proposed. Unfortunately, just a simple model was used and quite a special case in mobile system had been solved.

Given these backgrounds, we are trying to deal with the problems in a more practical model for real cellular wireless systems. We propose the soft boundary concept achieved by dynamic titled antenna to solve the issue of traffic congestion occurred in cellular wireless systems. The tilted antenna array can provide the merit of traffic balance and also achieve the optimization of the signal-to-interference ratio (SIR) at receivers by automatically tilting the antenna and implementing the soft boundary among cells, corresponding to the variation of traffic. According to our results, it is shown that power ratio control do not necessarily improved system performance when there is a large variation in traffic because it only control power levels. Also the properly chosen angle of tilt antenna can relieve the traffic congestion and perform the system performance optimization. In the other aspect, this paper also clarifies the difference in both link characteristics regarding traffic distributions and power ratio control.

2. The System Model and a Tilted Antenna Pattern

The CDMA system model under investigation and some related assumptions are described as follows.

1) Because the cellular system is composed with the hexagonal cell, and all cells have the same size as shown in Fig. 1, there is only one side between two cells. If the number of sectors per cell is three [3], at least non-uniform user distributions in three cells have to be con-

Manuscript received January 15, 2003.
Manuscript revised April 17, 2003.
Final manuscript received June 6, 2003.
[†]The authors are with the Department of Electrical and Electronic Engineering, Faculty of Engineering, Niigata University, Niigata-shi, 950-2181 Japan.
[††]The author is with the Department of Computer Science, Faculty of Engineering, Gunma University, Kiryu-shi, 376-8515 Japan.
a) E-mail: zhou@telecom1.egn.niigata-u.ac.jp

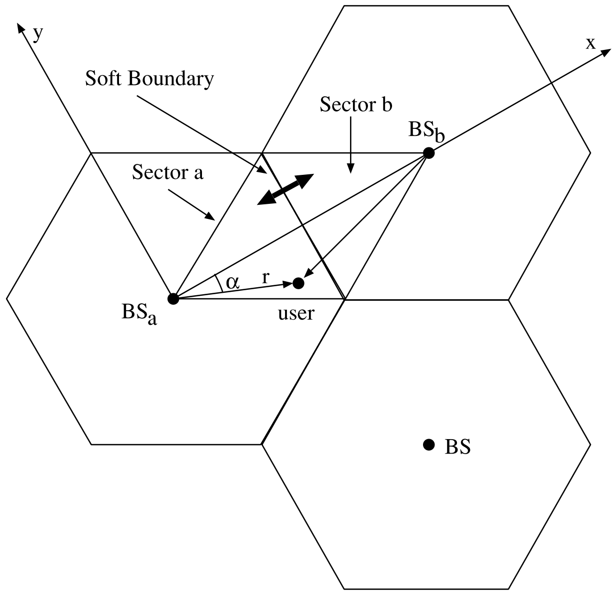


Fig. 1 Cellular and boundary geometry.

sidered and also with the curved boundary (two sides of hexagonal cell). To simply study the tilted antenna array for achieving the cell boundary shifting to release traffic congestion and traffic balance among sectors, we consider the number of sectors per cell is six according to the hexagonal cell characteristics. If the number of sectors per cell is increased [1], the capacity in one cell will increase with the increasing of equipment costs and number of user handover. Then there are issues of increasing the complexity of designing handover algorithms and handover managements.

2) The antenna of each sector is a collinear array, and it is tilted for decreasing the co-channel interference. It locates at the center of a cell. Base stations are expressed as BS_a for sector a and BS_b for the sector b. In Fig. 1, r is the distance between the user and its BS, α is the angle between and the coordinate x.

3) The voice activity factor, υ is assumed to be 3/8 [1] and the voice activity factor is assumed to follow the binomial distribution. The mobility characteristics of users can be neglected.

4) Perfect power control [1] is assumed, so that there are no power control errors and processing delay when applying it.

A. SIR of the reverse link
According to the above assumptions, unless the tilted antennas are adopted, SIR_R of the reverse link communication quality at a BS can be expressed as follow [1], [2]

$$SIR_R = \frac{S}{I^{int} + I^{ext}} \tag{1}$$

where S is the desired signal level. I^{int} and I^{ext} are the interference from the other users located in the same sector and interference from other users located in other sectors, respectively.

B. SIR of the forward link
For the forward link, the situation is somewhat different. In the forward link, signals to users are transmitted orthogonally to each other from a BS. If there are no delayed signals, $SIR_F(i)$, is expressed as [6]

$$SIR_F(i) = \frac{P_T(i) \cdot L(i)}{I^{ext}} \tag{2}$$

where,

$$I^{ext} = \upsilon \sum_{j=1}^{M} P_{BS_j} \cdot L_j(i) \tag{3}$$

$P_T(i)$ is the power transmitted to the i-th reference user from its BS. $L(i)$ is the propagation loss gain between the BS and the reference user. The denominator denotes the sum of the interference from the other BSs at the reference user. P_{BSj} denotes the total transmitted power from BS_j, and M is the number of the other cells considered in this cellular system. $L_j(i)$ is the propagation loss gain between BS_j and the i-th reference user.

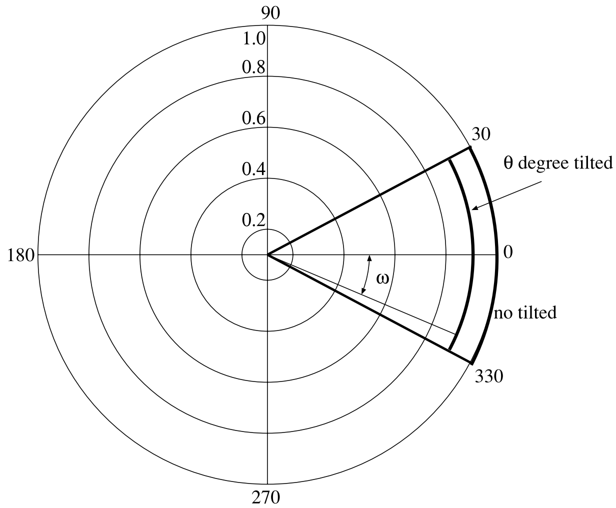
2.1 Tilted Antenna Array

Here, according to the features of CDMA cellular systems, it is advantageous to divide a single cell into six sectors. In each sector, the collinear antenna array is assumed to be used. Figure 2(a) depicts the 60-degree directional antenna pattern that covers a sector with the same antenna gain in the horizontal direction (i.e., $x-y$ plane), where ω is the polar coordinate angle of the antenna horizontal pattern. Of primary concern here is the horizontal antenna pattern when the antenna is tilted down by a angle θ in the vertical plane (i.e., $x-z$ plane). If the vertical pattern of the tilted antenna array is known, the horizontal pattern with tilted angle can be got as shown in Fig. 2. Then, the normalized vertical antenna gain of the main lobe can be approximately expressed by [3]

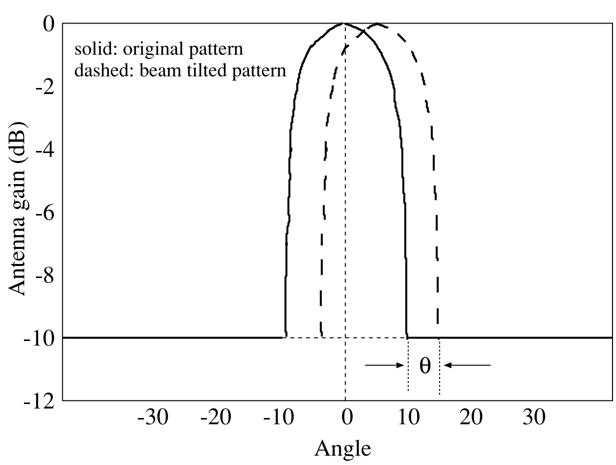
$$G(\phi,\gamma) = \begin{cases} 1-(\frac{\phi}{BW})^2, & 0 \leqq \phi \leqq BW \\ \gamma & \text{otherwise} \end{cases} \tag{4}$$

where BW is the beam-width of the used tilted antenna array that is assumed to be 10 degrees as an example to be investigated. γ is 0.1 (or -10 dB) and ϕ is the angle drifted off by 0 degree in vertical plane and increasing up to BW, which corresponds to -10 dB in antenna gain. φ is the angle between the vertical main lobe of antenna and horizontal line and β is the angle that is equal to $\varphi - BW$ in Fig. 3.

In Fig. 2, the solid line denotes the vertical pattern for an un-tilted antenna (i.e., $\theta = 0$ degree). When $\theta = 0$, it shows $R_s = R$. If increases in positive direction, the antenna pattern is tilted upward. If it decreases in negative direction, the antenna pattern is



(a) Horizontal pattern.



(b) Vertical pattern.

Fig. 2 Radiation pattern of a tilted antenna array.

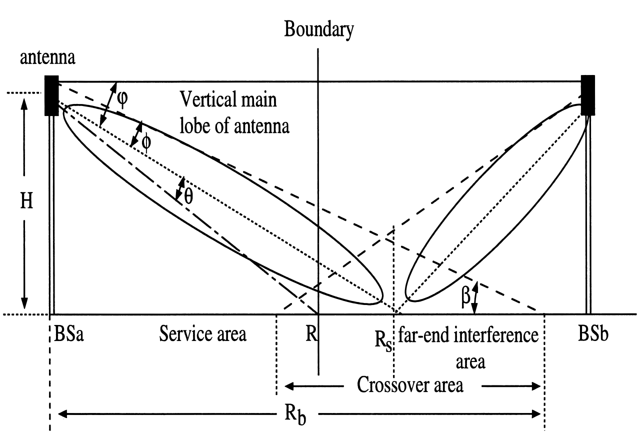


Fig. 3 Tilted antenna and shift of the boundary between cells.

tilted downward. According to the definition, although both of the antenna patterns of BS_a and BS_b will be tilted with different tilted angle, we used tilted angle of BS_a, θ as the calculation criterion as shown in Fig. 3. The antenna gain at the 0 degree for the dashed line curve is less than the antenna gain without being tilted.

The off-center beam with ω from the center is tiled downward by only φ shown in Fig. 3 when the center is tilted downward by an angle of θ. Then, the horizontal radiation pattern and vertical radiation pattern are coupled [3]. The horizontal pattern in Fig. 1 of Ref. [3] is not greatly changed and 6 sectors of one cell is used in our research, not like that 3 sectors in Ref. [3]. Then a change of horizontal pattern may be smaller that that of Ref. [3]. Here, the horizontal pattern with the same gain as shown in Fig. 2 is considered.

Tilted antenna arrays can be applied to reduced both co-channel and long distance interference just as downward tilted directional antenna pattern is [3]. When main lobe of antenna is tilted downward and upward, the cell coverage area is also varied. If summarized these, two effects are caused by using tilted antenna arrays in cellular systems. Firstly, the antenna gain for the users located in far-end interference area shown in Fig. 3 is less than that for the near-end users. This phenomenon can be easily observed in Fig. 3, causing less co-channel interference from these users. This is an advantage, that means higher capacity will be achieved because the capacity with CDMA is directly determined by the interference [1]. Secondly, the tilted antennas may be used to shrink or extend the coverage area to implement our soft boundary shifting and the traffic balance [6], [7].

2.2 Non-uniform User Distribution Models

The uniform user distribution is often assumed for simply investigating the performance of the systems, but the users are randomly located in the cells in the practical cellular systems and the distribution can not be expressed by an expression, in this case simulation approach is adopted to investigate the system performance, such as Ref. [7]. For the theoretical analysis, it is necessary to express the user distribution by an equation, then in Ref. [6], the user distribution is presented by the linear function. In order to investigate the different cases and to express the different user distributions by theoretical expressions, here we consider the user distribution functions that could be expressed by mathematic expressions. They are with the linear function [6], exponential function and sin(x) function. Of course, you can use the other mathematic expressions to simulate the user distributions.

Now let us consider these situations when the user distribution within the sectors as shown in Fig. 1 is non-uniform. Because each cell is sectorized by the tilted antennas, only the related sectors are in consideration, such as sector a and sector b shown in Fig. 1. For simplicity, we consider the simple one-dimensional models in which users are located continuously over the whole cell area (sector area) as shown in Fig. 4. The number of users at a point is defined as traffic density that is

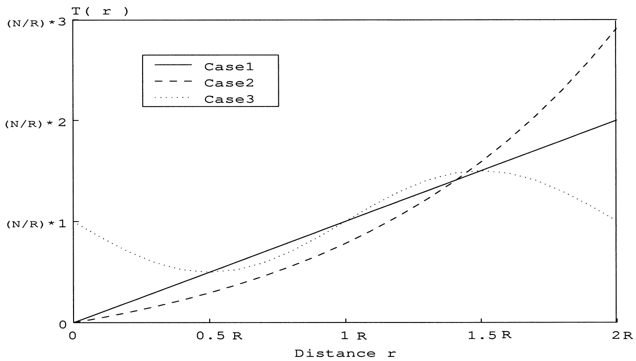


Fig. 4 Non-uniform user distribution models.

considered as only the function of distance r (the distance between a point to base station) that means it is non-uniform distribution to r and uniform distribution to the angle α. Then, three types of user distribution functions, $T(r)$ are assumed as follows [6], [7]

$$Case\ 1: \quad T(r) = \frac{N}{R^2} \cdot r \tag{5}$$

$$Case\ 2: \quad T(r) = \frac{2N}{e^{2R} - 2R - 1} \cdot (e^r - 1) \tag{6}$$

$$Case\ 3: \quad T(r) = \frac{N}{R}\left[1 - m \cdot \sin\ \left(\frac{\pi}{R}r\right)\right] \tag{7}$$

In Eq. (7), m is the user distribution control parameter that is $0 \leqq m \leqq 1$. It is used to change the situations of user distribution. When $m = 0$, it shows the uniform user distribution. If $m = 1$, the most users are distributed at the area of $r = 1.5R$ and few users are at the area of $r = 0.5R$. We see the user distribution will be changed with the variation of m.

In these three models, the traffic loads outside adjacent two sectors are assumed to be constant in order to simplify the calculation, that means our studies are focused on two adjacent sectors (a sector and b sector) in where the total numbers of users are $2N$. The traffic load between two tilted antennas is correspondent to the distance r in the continuity around the sector boundary. Owing to the non-uniform user distribution, the sector boundary can be shifted by adjusting the tilted angle of the antenna array to control traffic balance. The desired power in the reverse link and the total transmission power in the forward link are adjusted at any necessary time instance.

3. Performance Evaluation

An effective model is developed for analyzing the performance of the system. The propagation loss is only given as the path loss and the distance attenuation is assumed to be constant at κ [1], [2]. We ignore thermal noise in the investigation because the interference from other links is much larger than the thermal noise. The communication quality of the service (QoS) is evaluated as a SIR.

3.1 Modified Formula of SIR in the Reverse Link

As described in Sect. 2, perfect power control [1], [2] is used, that means the target power level at a BS for each user is constant and is the same as S in Eq. (1). A careful investigation must be focused on the evaluation of boundary shift point, $R_s = \frac{H}{\tan(\arctan(H/R)-\theta)}$, and the impact of tilted angle, θ, in respective user distribution models. In order to study the reverse link, we modify Eq. (1) in consideration of the effect of tilted antenna and non-uniform user distribution models as follows [1], [2]

For the BS_a, SIR_a is given by the form

$$SIR_a = \frac{1}{\upsilon(N_a - 1) + I_{ba}^{ext}/S_a}$$
$$SIR_b = \frac{1}{\upsilon(N_b - 1) + I_{ab}^{ext}/S_b} \tag{8}$$

where N_a and N_b are the total number of users in sector a and b, respectively. S_a is the received signal at BS_a for one located in sector a and S_b is the received signal at BS_b for one user in sector b. They are the constants according to the perfect power control [1]. I_{ba}^{ext} is the external interference from the adjacent sector b to BS_a. I_{ba}^{ext} is the external interference from the adjacent sector a to BS_b. According to the propagation model and the user distribution models, N_a, N_b and I_{ba}^{ext} are approximately expressed as

$$N_a = \frac{\pi}{3}\int_0^{R_s} T(r)rdr, \qquad N_b = \frac{\pi}{3}\int_{R_s}^{2R} T(r)rdr \tag{9}$$

and

$$\frac{I_{ba}^{ext}}{S_a} = \upsilon\frac{S_b}{S_a}\int_{R_s}^{R_b}\int_{-\pi/6}^{\pi/6}\left\{\frac{r}{\sqrt{D^2 + r^2 - 2Dr\cos\alpha}}\right\}^{\kappa} \cdot G_a(\phi,\gamma)T(r)rdrd\alpha \tag{10}$$

Here D is the distance between BS_a and BS_b and $G_a(\phi,\gamma)$ is the normalized vertical antenna gain of BS_a. R_b is the maximum distance of the far-end interference areas by BS_a as shown in Fig. 3, that is $R_b = H/\tan(\beta)$. If using the same method for the BS_b, I_{ab}^{ext} is also obtained in the same form.

3.2 Modified Formula of SIR in the Forward Link

Since the tilted antenna array is adopted in the forward link, $SIR(i)$ of i-th user that communicates with a BS, can be modified from Eq. (2). On the other aspect, for the forward link, since the in-cell transmissions are synchronous and hence can be made orthogonal [6], multiuser interference can be made to reduce significantly (For example, Walsh-Hadamard codes or Gold codes are qualified to differentiate the forward channels). We note that some amount of multi-path propagation degrades the orthogonality. It will result in some in-cell interference, but this will be small compared with the out-cell interference. This is especially true if RAKE receivers are adopted and some scrambling codes are used for improving cross correlations of the orthogonal sequence. However the deduction in the orthogonality is still necessary to be studied. Therefore, we define the orthogonal factor, F_O $(0 \leqq F_O \leqq 1)$ [7], in the investigation to express the degree of orthogonality loss due to the multi-path effects. In practical situations, it is difficult to predict the value of F_O, and instead we use a uniform orthogonal factor for simplicity. By taking into account of all contributions, $SIR_a(i)$ for i-th user in sector a can be expressed as

$$SIR_a(i) = \frac{P_{Ta}(i) \cdot L(i)}{I_a^{int} + I_{ba}^{ext}} \tag{11}$$

where,

$$I_a^{int} = (1 - F_O) P_a L(i) \tag{12}$$

$$I_{ba}^{ext} = \upsilon P_b L_j(i) G_a(\phi, \gamma) \tag{13}$$

$$P_a = \sum_{k=1, k \neq i}^{N_a} P_{Ta}(k), \ \ P_b = \sum_{k=1}^{N_b} P_{Tb}(k) \tag{14}$$

$P_{Ta}(i)$ is the signal power sent from BS_a to user i. The first part of interference, $(1 - F_O)P_a L(i)$ in Eq. (11) is generated by the other users located at the same cell and is not the interference generated by itself code because of multi-path. $P_{Tb}(i)$ is the signal power sent from BS_b to its user i. N_a and N_b are calculated by Eq. (9). By the same approach, $SIR_b(i)$ can be derived in the similar format of Eq. (11).

3.3 Capacity and Bit Error Rate (BER) of the System

For reliable system operation in CDMA cellular systems, it is important to keep the bit energy to noise density ratio E_b/N_0 at the same required level. The bit energy to noise density ratio can be interpreted as the desired signal to noise ratio, SIR, after correlation at the receiver. For having good communication quality, it is assumed that SIR must be larger than a threshold ratio, SIR_{req}, expressed by the inequality

$$SIR \geqq SIR_{req} \quad \text{with} \quad SIR_{req} = \frac{1}{G_p}(E_b/N_0)_{req} \tag{15}$$

Here, G_p is the processing gain that is equal to W/R_{BIR} [1], where W and R_{BIR} are the allocated spread bandwidth and the bit information rate. From Refs. [1] and [2], it is found that $(E_b/N_0)_{req}$ is 7 dB for the reverse link in the case of non-coherent reception and 5 dB for the forward link in the case of coherent reception. Capacity is defined as the maximum number of users in the cell in which $SIR \geqq SIR_{req}$ for each user. Substituting Eq. (8) for reverse link and Eq. (11) for forward link into the inequality Eq. (15), we can calculate the capacity, such as N_a and N_b.

In this paper, the CDMA signal is assumed to be based on QPSK modulation/coherent demodulation format with Gold codes. The power of the interference in the system has been evaluated in the previous sections. Since the received signal is multiplied by the orthogonal codes for de-spreading at a CDMA receiver, the narrow-band interference is spread out and its power spectrum density will be reduced. Therefore the total average interference power is determined just by the total interference to the processing gain ratio. In an AWGN channel, BER of a CDMA signal with cellular structure is determined by the sum of the thermal noise, internal interference and external interference as [8]

$$P_{BER} = \frac{1}{2} erfc \left\{ \sqrt{\frac{E_b}{N_0 + \frac{2}{3} E_b \frac{N-1}{G_p} + \frac{I^{ext}}{W}}} \right\} \tag{16}$$

where W is the spread bandwidth and $\frac{I^{ext}}{W}$ is hence the spectral density of the interference generated by the other cells.

4. Numerical Results and Discussion

As a numerical example, the calculation parameters in investigation are listed as follows [1], [2]

·Allocated spread bandwidth, $W = 1.25$ MHz(IS-95B)
·Bit information rate, $R_{BIR} = 9.6$ kbps(IS-95B)
·Radius of cell, $R = 10000$ m
·Tilted angle of antennas, $0 \leqq \theta \leqq 1.5$ degrees
·Height of the antenna, $H = 50$ m
·User distribution control parameter, $m = 1/2$
·Path loss exponent, $\kappa = 3.5$

4.1 SIR and BER

The dependence to the tilted angle of a used antenna and $SIRs$ of BS_a and BS_b are shown in Fig. 5. From the figure, one can see whether the users are uniformly

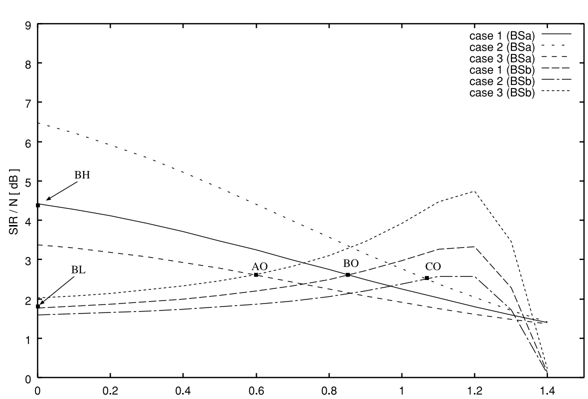


Fig. 5 $SIRs$ of BS_a and BS_b in the reverse link versus different tilted angle θ ($\frac{S_a}{S_b} = 1$, $m = 0.5$, $BW = 10$ degrees).

or non-uniformly distributed in the coverage service area that the tilted antenna is capable of releasing a serious hot area by shifting the boundary (also termed as soft boundary). It is also expectable to provide a better balance of services, which is especially important in the multi-service wireless systems. In Fig. 5, we classify the radiation pattern of the antenna array by defining a ridge of balance as $SIR_a = SIR_b$. AO, BO and CO are the best points in terms of balance of services. From this figure, with the very smaller tilted angle ($\theta \leqq 1.5$ degrees), there is greatly variation in $SIRs$, we have two reasons as follows:

1) General, $R \gg H$, if there is a small change in the tilted angle, the coverage area by the tilted antenna pattern will be changed greatly.

2) From Fig. 3, if the pattern of BS_a is tilted upward with a tilted angle, the soft boundary will move to BS_b. The number of users will be greatly increased in sector a. It will also greatly decrease SIR of BS_a. On the contrary, SIR of BS_b will be increased greatly. Then, because of the above two reasons, SIRs of BS_a and BS_b varied greatly when there is a small tilted angle. As the practical application, because of its small, the pattern of antenna arrays will be adjusted difficultly. If the tilted antenna arrays are used in the cases of microcell (several hundred meters) and picrocell with near $R = 50$ m in road-vehicle communication (RVC) systems, the cases are very different. On the other aspects, we can also increase the antenna height, the tilted angle will not be so small and can be implemented easily. We can clearly see the benefit of the tilted antenna arrays used for decreasing co-channel interference, increasing system capacity and releasing from the traffic congestion.

Figure 6 shows the BER results for the three example points, BH, BL and BO described above. Curves labelled "Case 1 BL Point, Case 1 BH Point" were calculated with tilted angle $\theta = 0$ degree for BS_b and BS_a, respectively. These results show there are great difference of BER performance for the sector a and b because of non-uniform user distribution.

For the forward link, the situation is somewhat different, because the reference target is the mobile user who travels any area in the system. The worst case happens when the reference user is located at the boundary. Figure 7 shows $SIRs$ of reference users located at the soft boundary of BS_a and BS_b against various tilted angle when the transmitted power ratio $P_a/P_b = 1$ and orthogonal factor $F_O = 0.5$. As shown in the plots, it is impossible to find the same $SIRs$, because there are no intersection points between SIR_a and SIR_b. This implies that, once again, the balancing ridge in SIR_a and SIR_b cannot be obtained, as long as only the tilted angle control other than else is involved with finding an optimal solution.

Figure 8 shows the relationship between SIR and

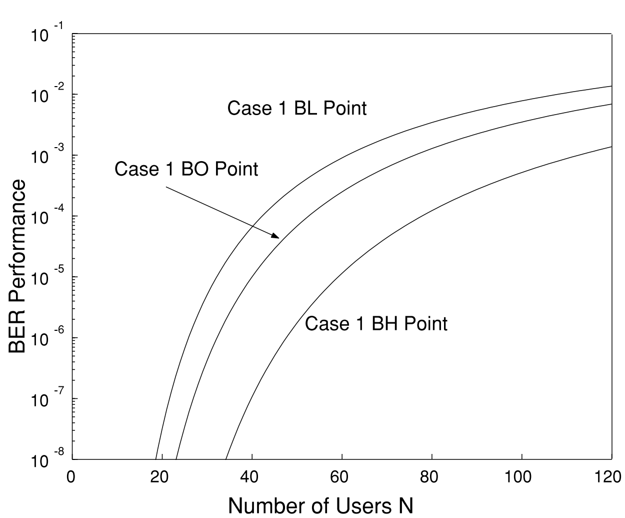


Fig. 6 BER performance versus the number of users N for reverse link (SIR Lower point BL, Higher point BH and Optimization point BO shown in Fig. 5).

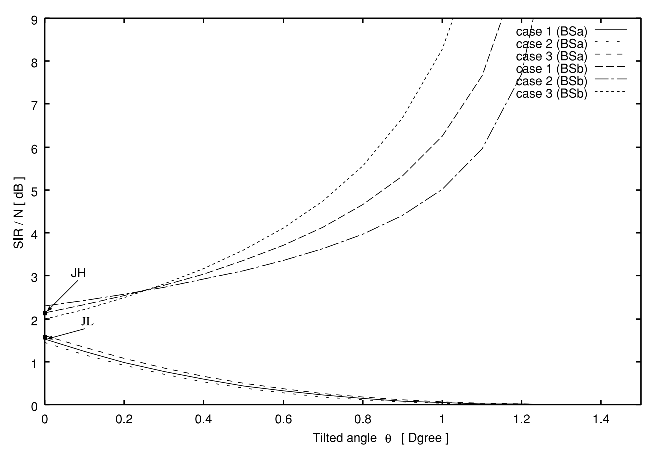


Fig. 7 $SIRs$ of the users located at the soft boundary between the sectors in the forward link versus different tilted angle θ ($\frac{P_a}{P_b} = 1$, $m = 0.5$, $BW = 10$ degrees, $F_O = 0.5$).

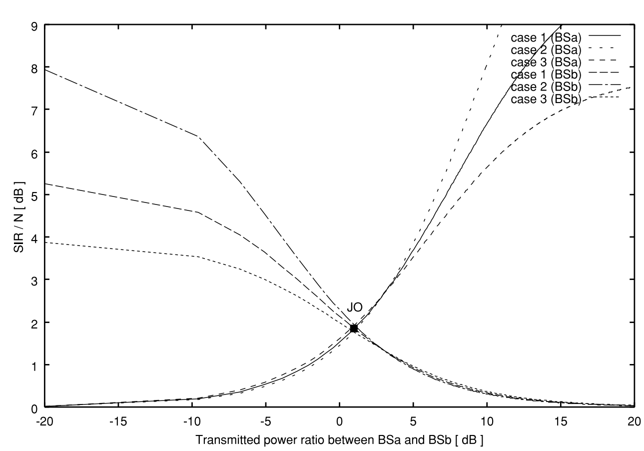


Fig. 8 $SIRs$ of the users located at the soft boundary between sectors in the forward link versus different power ratio $\frac{P_a}{P_b}$ ($\theta = 0$ degree, $m = 0.5$, $BW = 10$ degrees, $F_O = 0.5$).

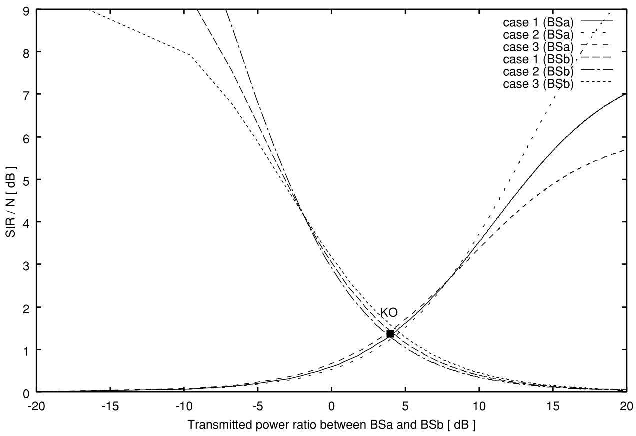


Fig. 9 $SIRs$ of the users located at the soft boundary between sectors in the forward link versus different power ratio $\frac{P_a}{P_b}$ ($\theta =$ 0.4 degree, $m = 0.5$, $BW = 10$ degrees).

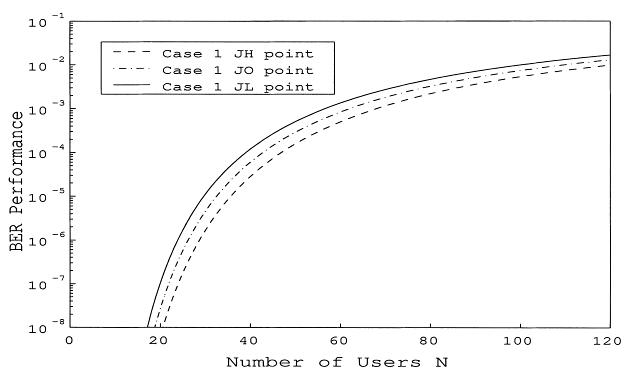


Fig. 10 BER performance versus the number of users N for forward link (SIR Lower point JL, Higher point JH and Optimization point JO shown in Figs. 7 and 8).

transmitted power ratio when $\theta = 0$. There are almost the same three ridge points of the balance in SIR, which are marked with JO in the figure, when P_a/P_b is around 1.5 dB. Note that lower P_a/P_b will be beneficial to those users around the soft boundary in sector b, and higher P_a/P_b benefits the users around the soft boundary in sector a.

The effects of an increased tilted angle in the forward link are shown in Fig. 9, where $\theta = 0.4$. Comparing Figs. 8 and 9, one can see that the intersection point marked with KO moves rightward when $P_a/P_b = 4.0$ dB. The SIR ridge value of point KO decreases by 25 percent than that of point JO, but there are some other merits that will be discussed in the following subsection.

Figure 10 shows the BER results at the three example points, JL,JH and JO described in Figs. 7 and 8 for forward link. These results show there are little difference of BER performance for JL, JH and JO.

Table 1 Capacity and bit error rate performance when the system achieves the balance in SIR. (SIR = SIRa = SIRb and BER = 10^{-3})

Perfor. / Points	Capacity, N (Users)	SIR (dB)	Eb/No (dB)
AO	73	-14.033	7.109
CO	72	-14.073	7.066
BO	76	-14.108	7.031
BL	60	-14.032	7.108
BH	112	-14.920	7.047
JO	62	-16.124	5.016
JL	55	-15.904	5.236
JH	66	-15.995	5.144
KO	50	-15.590	5.549

4.2 Discussions

1) Effectiveness of tilted antenna array: Fig. 5 shows $SIRs$ of BS_a and BS_b for the reverse link. If the tilted angle is increased, the soft boundary shifts close to BS_b. The in-cell interference to BS_a is increased and the in-cell interference to BS_b is decreased because of the soft boundary shifting. To BS_a, SIR will be decreased. On the contrary, SIR of BS_b will be increased. With the increasing of the tilted angle, the soft boundary will be more close to BS_b and a large number of the users are located near the boundary area according to the non-uniform user distributions shown in Fig. 4. These users are also controlled by BS_a to ensure the received signal as the constant S_a (Here, assuming $S_a = S_b$). Then the required transmitted power will be very large because of a great distance away from BS_a. Because they also close to BS_b and the transmitted signal is corresponding to exponential loss with the distance, the interference generated from these users will be too serious that makes SIR_b decreased rapidly if the soft boundary is too close BS_b.

For the forward link, the balance ridge of $SIR_a = SIR_b$ can be implemented only by the power ratio control as JO shown in Fig. 8 ($\theta = 0$), and also by the combined control of the tilted angle and power ratio control as KO shown in Fig. 9. We see SIR of the balancing point KO is smaller than that of JO. They are also smaller than that of AO, BO and CO shown in Fig. 5, we can conclude the tilted antenna mechanism for the forward link is not effective to achieve the balance of service unlike in the reverse link.

2) Capacity and E_b/N_0: Table 1 shows the capacity, N, SIR and the E_b/N_0 of the system when there are $2N$ active users in the sectors. The user distributions are assumed to obey Eqs. (5),(6) and (7). We only calculated the capacity when satisfying $SIR_a = SIR_b$ and $BER = 1.0E - 03$. One can see the optimization points are found at points AO, BO and CO in the reverse link, and the capacity reaches 72 and 73 users respectively when the user distributions are modelled by Eqs. (6) and (7). For the forward link, the optimization point is point JO. Its capacity will reach 62 users

which is almost independent of the user distributions.

5. Conclusions

This paper has presented a method to relieve user congestion in a CDMA cellular system with a tilted antenna mechanism that generates a soft boundary and a ridge of balance. According to the numerical results, it is quite effective for user congestion relief. Especially, it is suitable for the reverse link in which the user congestion problem is treated with various user distributions to address the balance of services. We also see the approach by tilted antenna array may be combined with the power ratio allocation control to optimize problems.

Acknowledgment

The authors are grateful for the many helpful comments provided by the anonymous reviewers and Prof. F. Adachi.

References

[1] K.S. Gilhousen, I.M. Jacobs, R. Padovani, and A.J. Viterbi, "On the capacity of a cellular CDMA system," IEEE Trans. Veh. Technol., vol.40, no.2, pp.303–311, May 1991.
[2] D.H. Kim, D.D. Lee, H.J. Kim, and K.C. Whang, "Capacity analysis of macro/microcell CDMA with power ratio control and tilted antenna," IEEE Trans. Veh. Technol., vol.49, no.1, pp.34–42, Jan. 2000.
[3] J.S. Wu, J.K. Chung, and C.C. Wen, "Hot-spot traffic relief with a tilted antenna in CDMA cellular networks," IEEE Trans. Veh. Technol., vol.47, no.1, pp.1–9, Feb. 1998.
[4] F. Tong and Y. Akaiwa, "Effect of beam tilting on bit-rate selection in mobile multipath channel," IEEE Trans. Veh. Technol., vol.46, no.2, pp.257–261, May 1997.
[5] E. Benner and A.B. Sesay, "Effect of antenna height, antenna gain, and pattern downtitling for cellular mobile radio," IEEE Trans. Veh. Technol., vol.45, no.2, pp.217–224, May 1996.
[6] K. Takeo, S. Sato, and A. Ogawa, "Uplink and downlink communications qualities in CDMA cellular systems considering effects of traffic distribution," IEICE Trans. Fundamentals, vol.E82-A, no.12, pp.2677–2685, Dec. 1999.
[7] K. Takeo, S. Sato, and A. Ogawa, "Optimum cell boundary for uplink and downlink in CDMA system," IEICE Trans. Commun., vol.E83-B, no.4, pp.865–868, April 2000.
[8] T. Matsuda, S. Hara, and N. Morinaga, "Feasibility study on DS-CDMA/TDMA frequency sharing system," Proc. IEEE Globecomm'97, pp.974–979, Nov. 1997.