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Modeling and Performance Evaluation of 3G CDMA Networks with Beamforming

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Abstract. The second generation (2G) code-division multiple access (CDMA) IS-95A cellular network has been deployed for almost ten years. Although the system design rules and operating procedures for voice services are well established and understood, these rules and procedures need to be re-examined in light of several technology innovations. These innovations include the launch of third generation (3G) cdma2000 1× high-rate data services and the new research results in interference cancellation, antenna array and multiple-input multiple-output (MIMO) technologies.

We have built a 3G cdma2000 1× cellular simulator, which simulates the physical layer using MATLAB and networking layers using OPNET Modeler, to investigate various design issues of cdma2000 1× networks. This paper explores the use of a simple beamforming model and investigates the effectiveness of deploying antenna array techniques in cdma2000 1× networks. The capacity improvement for CDMA networks using antenna array techniques is evaluated under different deployment scenarios (voice versus data services and various number of antenna elements). Based on the performance evaluation results it is proposed to utilize beamforming as one of the elements in quality of service (QOS) provisioning for data services and to couple antenna arrays with dynamic soft handoff threshold adjustment for further improvement in the system capacity.

Keywords: IS-95, cdma2000, antenna array, cellular network, soft handoff, QOS provisioning

1. Introduction

The second-generation (2G) code-division multiple access (CDMA) IS-95A cellular networks have been deployed for almost ten years. The reverse link performance of CDMA systems has been analyzed theoretically considering the use of various technologies, such as beamforming and spatial diversity. Gilhousen et al. [1] estimated CDMA reverse link user capacity, considering voice traffic only, where strength-based power control [2] is assumed in the CDMA systems and total other-cell interference is modeled as Gaussian noise. Using similar methods as [1], Kim and Sung estimated the reverse link user capacity of signal-to-interference ratio (SIR)-based power-controlled CDMA systems in [3]. The effects of a Rake receiver and antenna diversity on reverse link user capacity are further investigated in [4]. The impact of

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beamforming, which is an important technique to suppress interference, on reverse link user capacity is investigated in [5] and a closed-form expression for user capacity is derived in [6]. In these investigations, the user capacity is referred to as the maximum number of users that a CDMA system could support under a target signal-to-interference ratio.

When several technology innovations are considered, including the launch of 3G cdma2000 1× high-rate data services as well as the maturation of interference cancellation, antenna array, soft handoff, and multiple-input multiple-output (MIMO) technologies, system performance, including capacity, needs to be evaluated and the system design rules and operating procedures for voice services be re-examined. However, the computational complexity of theoretical analyses will be increased significantly if several of the technology innovations are considered. Therefore, this paper investigates the use of OPNET and MATLAB to evaluate the reverse link capacity of a CDMA system.

We have built a 3G cdma2000 1× cellular simulator, which simulates the physical layer using MATLAB and networking layers using OPNET Modeler to investigate various design issues of cdma2000 1× networks. Through the use of MATLAB simulation, the forward link target, bit-energy to noise ratio, E_b/N_t, achieved by cdma2000 1× physical layer can be determined. Through the use of OPNET, the cdma2000 1× network protocols [8], call processing procedures and system aspects are modeled. Note that cdma2000 1× is backwards compatible with IS-95A, which means that the cdma2000 1× simulator can be used for the performance evaluation of IS-95A or cdma2000 1× networks. In this paper, we investigate the effectiveness of deploying antenna array techniques in CDMA networks using cdma2000 1× cellular simulator.

A brief description of cdma2000 1× is first given in Section 2. Capacity limitation issues of CDMA networks are addressed in Section 3. In Section 4, a simplified beamforming model is presented. The capacity of CDMA networks is evaluated and noticeable capacity improvement is observed in Section 5 where beamforming is employed at the base station (BS) under different deployment scenarios. In additional to capacity improvement, we propose to use the antenna array as one of the elements in QOS provisioning for data services where there are multiple coverage radii for different data rates due to the difference in processing gain. For example, only users close to the BS can have high-rate data services; by contrast, all users in a cell can have voice or low-rate data services. With the help of the antenna array, we can balance the coverage for different types of services such that a user can have always-available high-rate data services (and voice services).

There are two aspects that differentiate our paper from others in the topics of antenna arrays and 3G CDMA networks. First, we propose to use the antenna array as one of the elements in QOS provisioning for data services. Second, the paper systematically analyzes the capacity improvement under different number of array elements and couples with dynamic soft handoff threshold adjustment to further enhance the achievable capacity.

2. CDMA2000 1× Description

Due to the improvement on both forward and reverse links, cdma2000 1× provides 1.5 to 2 times voice capacity improvement over IS-95A [9]. The most important enhancements of cdma2000 1× include improved coding gain (1/4 rate vs. 1/2 rate), faster forward power control (800 times per sec vs. 50 times per sec), and coherent demodulation for the reverse link [8]. The coherent demodulation is achieved because each mobile also transmits a pilot signal, which

Table 1. Summary of RC 3 in cdma2000 1×

Forward	1200, 1350, 1500, 2400, 2700, 4800, 9600, 9600 × 2, 9600 × 4, 9600 × 8, and 9600 × 16	1/4 coding
Reverse	1200, 1350, 1500, 2400, 2700, 4800, 9600, 9600 × 2, 9600 × 4, 9600 × 8, 9600 × 16, 9600 × 32	1/4 coding for data rate ≤9600 × 16. 1/2 coding for data rate = 9600 × 32

does not exist in the IS-95A mobile. For cdma2000 1×, the chip rate is 1.2288 Mcps, same as that for IS-95A.

A new term radio configuration (RC) was introduced in cdma2000 1×. RC is defined as a set of forward traffic channel and reverse traffic channel transmission formats that are characterized by physical layer parameters, i.e., data rates, modulation characteristics, and spreading rate.

In IS-95A, there are only two RCs, Rate Set 1 (9.6 kbps) and Rate Set 2 (14.4 kbps). In cdma2000 1×, three new RCs are added for the forward link and two new RCs for the reverse link. With the current implementation of the cdma2000 1× infrastructure vendors, only RC 3 is supported. For RC 3, the Walsh code length is still 64. Since the number of voice users that can be supported in cdma2000 1× is increased noticeably, Walsh code shortage becomes a real possibility.

A new traffic channel, supplemental channel (SCH), is introduced for both forward and reverse links in cdma2000 1×. Although the standards said that each mobile can have 0–2 SCHs, with the current implementation, at most 1 SCH is supported per mobile. Various data rates can be supported on the SCH and a summary of the data rates supported by RC 3 is listed in Table 1. As can be seen, the highest data rate each mobile can get is 153.6 kbps. The SCH is allocated dynamically in burst mode and is shared among all users in the same cell. The SCH has the following characteristics,

- Shorter Walsh code for higher data rate
- Convey radio link protocol (RLP) frames
- Target frame error rate (FER) can be set higher (5–10%)
- Turbo code is allowed (number of bits per frame ≥ 360)
- No rate determination
- Transmission rate is changed via signaling with BS

There are many other new features for the cdma2000 1× air interface such as auxiliary pilots, enhanced access channel, and 4-state medium access control (MAC). However, since most of these new features are not implemented by the infrastructure vendors, we will not describe them in this paper. In additional to the changes on the air interfaces, cdma2000 1× also introduces new nodes for the core network (CN), i.e., packet data service node (PDSN), authentication, authorization, and accounting (AAA), home agent (HA), and foreign agent (FA).

3. Capacity Limitations in cdma2000 1×

In the traditional CDMA IS-95A networks, the voice capacity per cell is about 20–25 users. Although the cdma2000 1× has increased the voice capacity to 35 to 40 users per cell, service providers still desire to have a larger capacity per cell since spectrum can be depleted quickly if the system capacity is not maximized. Conserving the usage of spectrum is the top priority for US cellular service providers because some of the providers have only 5 MHz spectrum. We propose to use antenna array techniques at the BS to further increase the voice capacity per cell; the impact is that the need to deploy another frequency carrier can be delayed.

From field experience, the cdma2000 network capacity is limited on the forward link, not the reverse link. The main reason is that although soft handoff always combats interference, it also introduces overhead on the forward link. If the soft handoff region is not sized properly, the forward link capacity would be degraded. In cdma2000 networks, soft handoff regions are sized to achieve a delicate balance between call quality and network capacity. Soft handoff can be classified into softer or soft handoff, where softer handoff refers to a mobile that maintains connections with multiple sectors of the same cell site, while soft handoff uses multiple cell sites. Note that CDMA softer/soft handoff can occur for a user even if the user is not moving, which means that this user is located in a softer/soft handoff zone. Soft handoff provides diversity for the link (switched diversity for the reverse link and combined diversity for the forward link); as a result, the link quality is improved [10]. However, soft handoff also introduces overhead degradation on the forward link, specifically transmit power, channel element, and Walsh code.

In this paper we evaluate the capacity improvement by deploying antenna arrays at the BS. We also examine the system design rules to facilitate the deployment of antenna arrays. For example, we may need to balance the coverage area for pilot channel and traffic channels.

In cdma2000 networks, voice service is guaranteed (with 90% of coverage reliability) for any user anywhere within a cell (with 2% grade of service, i.e., call blocking probability). But the same reliability cannot be guaranteed for high-rate data services. The reason is that for high-rate data service, the processing gain becomes smaller. As a result, the coverage area for data services exhibits multi-radii phenomena for different data rates. We propose to use antenna arrays to balance the coverage for data services with different data rates. The result is that a user can expect to have high-rate data services regardless the user location.

4. Simplified Model for Antenna Arrays

Beamforming has been widely used in wireless systems that employ a fixed set of antenna elements in an array. The signals from these antenna elements are combined to form a movable beam pattern that can be steered to a desired direction that tracks mobiles as they move. This allows the antenna system to focus radio frequency (RF) resources on a particular mobile and reduce the impact of interference [11, 12]. At a BS, beamforming for each desired user could be implemented independently without affecting the performance of other links.

A standard linear equally spaced (LES) array is considered here as shown in Figure 1. The distance d between the elements of the LES array is half of the carrier wavelength. ϕ is the azimuth angle and θ is the elevation angle of a plane wave incident on the array. Considering a two-dimensional multi-cell environment (in the horizontal plane), we have $\theta = 90^\circ$. In the

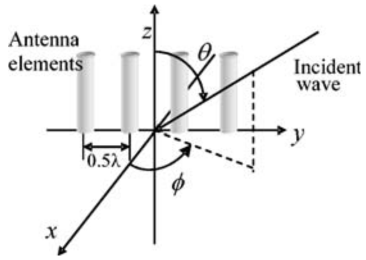


Figure 1. A standard linear equally spaced array.

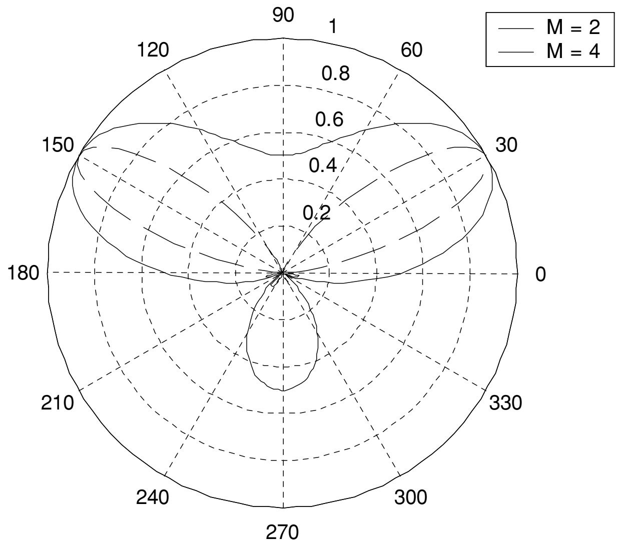


Figure 2. Linear equally spaced array gain pattern with $M = 2, 4$, and $\phi = 30^{\circ}$.

LES array system, a combining network connects an array of low gain antenna elements and could generate an ideal antenna pattern [7]

$$G(\psi, \phi) = \left| \frac{\sin(0.5M\pi(\sin\psi - \sin\phi))}{M\sin(0.5\pi(\sin\psi - \sin\phi))} \right|^2 \tag{1}$$

where M is the number of antenna elements and ψ is a variable. The beam could be steered to a desired direction by varying ψ. Considering $M = 3$ and $\phi = 30^{\circ}$, an LES array gain pattern is shown in Figure 2.

In a CDMA system, a mobile station (MS) is power controlled by a base station in its home cell to ensure that the received power at the BS is maintained at a constant level, assuming strength-based power control is in use. If beamforming is used at the base stations, the antenna gain (G) is maintained at unity and the interference can be effectively reduced. The computational complexity considering the exact beam pattern such as (1) to evaluate the reverse link CDMA performance is very high. A simple Bernoulli model is introduced in [6] in which a signal is considered to be within a mainlobe ($G = 1$) or out of the mainlobe ($G = 0$) and the half-power beamwidth is defined as the beamwidth. This model is easy to use, but it neglects the impact of sidelobes and the effect of any specific beam patterns. Reference

[13] provides a beamforming model with a triangular pattern to characterize the beam head. In the following, we explore the use of an accurate, yet simple, beamforming model [14] to account the impact of sidelobes and the real beam patterns. Assuming that the beamwidth is B (normalized by 2π), the gain of the mainlobe is normalized to unity, and the gain out of the mainlobe is α. This implies that the probability that one interferer is in the mainlobe is B. Considering the Bernoulli distribution, the first and second moments of the antenna gain with respect to all incident angles are $B + (1-B)\alpha$ and $B + (1-B)\alpha^2$, respectively. We set the first and second moments of the real beam pattern equal to that in the simplified model and obtain

$$B + (1 - B)\alpha = E[G(\psi, \phi)] \tag{2}$$

and

$$B + (1 - B)\alpha^2 = E[G^2(\psi, \phi)] \tag{3}$$

Solve this equation set, we have

$$\begin{cases} B = \dfrac{b - a}{a - 1} \\ \alpha = \dfrac{b - a^2}{b + 1 - 2a} \end{cases} \tag{4}$$

where

$$a = E[G(\psi, \phi)] = \frac{1}{4\pi^2} \int_0^{2\pi} \int_0^{2\pi} G(\psi, \phi) d\psi d\phi \tag{5}$$

and

$$b = E[G^2(\psi, \phi)] = \frac{1}{4\pi^2} \int_0^{2\pi} \int_0^{2\pi} G^2(\psi, \phi) d\psi d\phi \tag{6}$$

The antenna gains are all averaged with respect to uniformly distributed random variables, ϕ and ψ, in the region from 0 to 2π. Figure 3 shows simplified beam patterns with $M = 2$ and 4.

5. OPNET/MATLAB Simulations

5.1. Matlab Simulation Models

The channels considered in our forward link-level simulation model consist of the pilot channel, paging channel, sync channel, and multiple traffic channels. The forward and reverse link physical layer simulation models have been developed using MATLAB. MATLAB is used to derive the forward target bit energy to noise density ratio, E_b/N_t. The overhead channels (such as pilot, paging and sync) are sent over the common omni-directional antenna. The traffic channel is sent over the individual beam (formed by the antenna array) pointing toward the user.

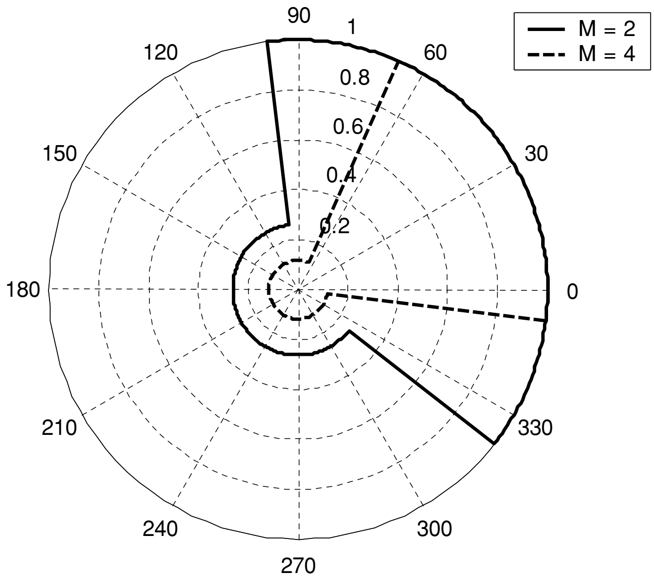


Figure 3. A simplified model for beamforming with $M = 2$ and 4.

The gain of the main lobe of the individual beam is set to be the same as that of the omnidirectional antenna. This procedure/setting is required to balance the coverage of pilot and traffic channels. The gain patterns of individual beams for various number of array elements are specified in Table 2. The mainlobe beamwidth is $360B$. The isotropic antenna gain is assumed to be 17.1 dB, thus the side lobe gain is $(17.1 + 10\log_{10}\alpha)$ dB and the side lobe beamwidth is $360(1 - B)$. In generating Table 2, a simplified model for the beam pattern presented in Section 4 is used, in which a Bernoulli random variable is used to characterize the in-beam (main lobe) and out-beam (side lobe) scenarios. The cases with 2 and 4 array elements are plotted in Figure 3.

The forward link capacity (performance) can be measured as a required E_b/N_t to achieve a target FER. The required E_b/N_t to achieve a target FER 1% for the forward traffic channel is 7 dB for IS-95A and 5.5 dB for cdma2000. In the OPNET simulation, we use 7 dB as the target E_b/N_t instead of 5.5 dB. The reason is that this paper is to evaluate the capacity improvement due to deploying antenna array at CDMA base stations; the same conclusion can be derived using either IS-95A or cdma2000 as the physical layer. The advantage of using IS-95A as the physical layer is that we do not need that many mobiles (as compared to cdma2000) to overload the network in the simulation (in OPNET simulation models).

Table 2. Antenna array gain patterns

Array elements	Main lobe beamwidth	Main lobe gain	Side lobe beamwidth	Side lobe gain
1	360°	17.1 dB	N/A	N/A
2	138°	17.1 dB	222°	11.3 dB
4	76°	17.1 dB	284°	7.8 dB
6	54°	17.1 dB	306°	5.9 dB

5.2. OPNET Simulation Models

A system-level simulator is built using OPNET Modeler to create a cdma2000 1× cellular network with varying cell sizes, shapes, and realistic propagation environments. Omni-directional antenna, antenna array, and HATA-Okumura propagation loss models are used to produce cell coverage contours. HATA-Okumura models are chosen because they have been widely used in the cellular industry and they are tunable using drive test data.

Each cell is modeled as an OPNET node. Each mobile (or user) is also modeled as an OPNET node. Nineteen cells are simulated, with statistics collected only for the center cell. To be consistent with the RF design link budget, users within a cell congregate proportionally in larger number at the cell edge. The total number of mobiles in the network is 836. This number is chosen to ensure that there are enough mobiles to stress the load of the network. The following is a summary of the cell site configurations for the simulation. The BS antenna height is assumed to be 30 meters and a PCS band (1.9 GHz) is considered.

In cellular system RF engineering, a link budget is used to dimension cell size. From the voice link budget analysis, the cell radius is 675 meters. The soft handoff procedure follows that specified in IS-95A. The improvement of the soft handoff procedure in IS-95B is not considered in this paper. Specifically, most operators will choose to implement at least two pilots in the active set regardless of what the decision is from the IS-95B handoff algorithm. This implies that IS-95B is effective in combating 3-way or higher soft/softer handoff, but is not effective in reducing the percentage of 2-way soft/softer handoff. The T_ADD and T_DROP are set to −14 dB and −17 dB, respectively.

The admission control is implemented for both forward and reverse links of a cell. There are two thresholds, upper and lower. The upper threshold is used to admit new and handoff calls while the lower threshold is only for the new calls. The calls can be either voice or data calls.

For the forward link, when a new call request is received at a base station controller (BSC), the BSC estimates the initial transmit power required to support the call in the cell. If the estimated transmit power plus the existing transmit power in the cell exceeds the lower threshold, the new call is rejected. When a handoff call request is received at the BSC, the BSC checks if the estimated transmit power plus existing transmit power in the new cell(s) exceeds the upper threshold. If it does, the handoff call is rejected; however the call is still maintained by its original serving cell. The principle of the admission control for the reverse link is similar to that for the forward link.

5.3. Simulation Interface Between OPNET, MATLAB and Antenna Array Models

Due to the running time speed incompatibility between OPNET and MATLAB, instead of using a real-time interface, the following offline method is used. The physical layer performance is simulated for various environments using MATLAB in advance. And then the results are fed into OPNET simulation during system level simulation. The shape, gain and beamwidth formed by the antenna array are also pre-loaded into OPENT simulation as tables.

5.4. Simulation Results for Center Cell

As previously mentioned, to be consistent with RF link budget assumption, the mobile distribution leads to more mobiles at the cell edge (Figure 4(a)). The probability mass function of the distance between mobiles and best serving cell is shown in Figure 4(b). In the simulation, we evaluate two traffic/service scenarios, with voice only and the other with both voice and high-rate data.

In Scenario 1, we deploy an antenna array at every BS of the network. It is assumed that all users request voice services. The voice service uses Rate Set 1, i.e., 9.6 kbps. As previously discussed, the required E_b/N_t to achieve the target FER 1% for the forward voice channel is 7 dB.

We compare the capacity improvement by varying the number of elements in the antenna array to produce beams with different shapes and beamwidths. The definition of voice capacity is the maximal number of voice users supported by a cell. However, due to soft handoff, a voice user may be served by more than one cell at the same time. As a result, we have two capacity metrics. The first is to allocate the voice user to a cell based on the strongest serving cell. For example, if a voice user is served by cell 0 and cell 1 at the same time, and the pilot strength from cell 0 is -8 dB and that from cell 1 is -10 dB, the user is allocated to cell 0 for capacity consideration. The second is to allow a voice user to be allocated to multiple cells if this user is served by multiple cells. Using the same example, the voice user will be allocated to both cell 0 and cell 1 for capacity consideration. Typically, we need to consider only the first metric as the voice capacity. The reason we include the second metric is to demonstrate that if the capacity enhancement technique is not used properly, the improvement on the first metric can be insignificant, but there is a big increase on the second metric. If this is the case, it indicates there is really no real capacity improvement since most of the system resources are used (wasted) to support users in soft handoff.

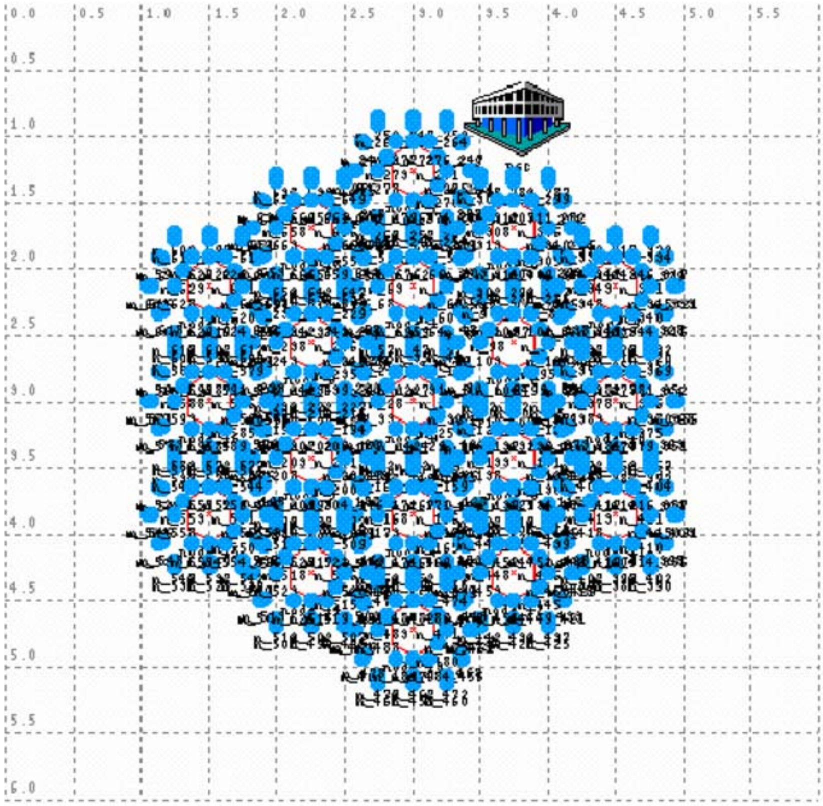
The simulation results show that with the deployment of antenna arrays at the BS, the network capacity can be improved. The amount of improvement is a function of the number of elements used in the antenna array (Table 3). Furthermore, if the soft handoff thresholds can be optimized, the capacity can be further improved, which will be discussed in Section 5.5.

In Scenario 2, we have a mixture of voice and high-rate data users. It is assumed for packet data users, the data rate requested is always 153.6 kbps regardless the user location.

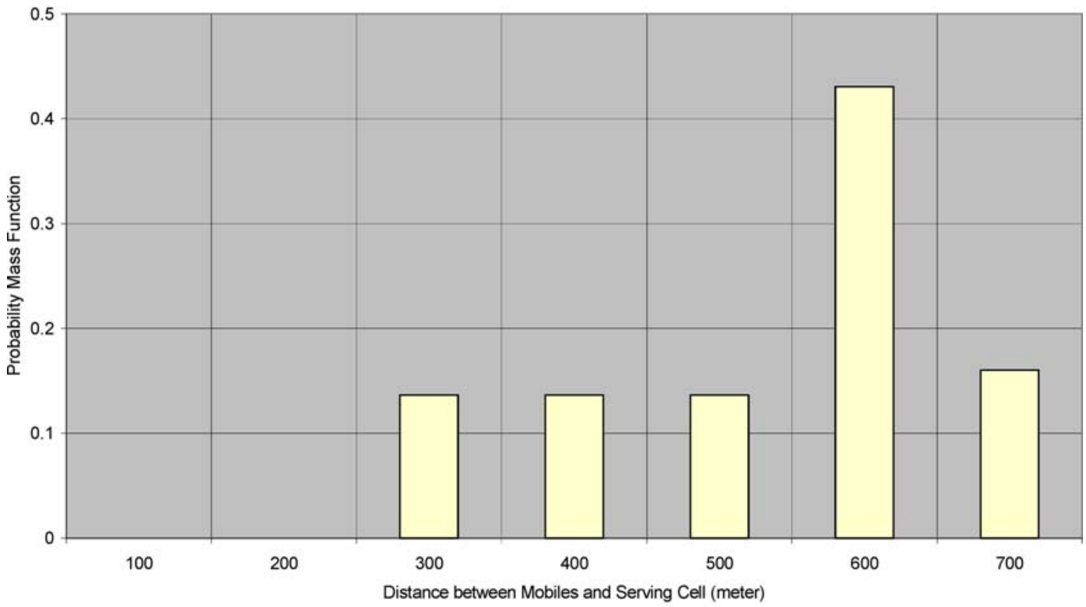
At the BS, the forward transmit power required to support 153.6 kbps SCH is computed assuming the data rate is 9.6 kbps, i.e., with the help of the antenna array, we can assume that data rate requested by the user is 9.6 kbps (even though the actual data rate is much higher than 9.6 kbps, i.e., 153.6 kbps). Beamforming is used to compensate the difference in processing

Table 3. Voice capacity comparison for Scenario 1

Voice capacity	Strongest serving cell is cell 0	Serving cells include cell 0
$M = 1$	22	27
$M = 2$	26	38
$M = 4$	29	51
$M = 6$	34	63



(a)



(b)

Figure 4. (a) Distribution of mobile stations, (b) The probability mass function of the distance between mobiles and best serving cell.

Table 4. Voice capacity comparison for Scenario 2

Voice capacity	Strongest serving cell is cell 0	Serving cells include cell 0
$M = 1$	N/A	N/A
$M = 2$	N/A	N/A
$M = 4$	N/A	N/A
$M = 6$	32	60

Table 5. Voice capacity comparison for Scenario 1 with soft handoff thresholds adjusted (T_ADD $= -12$ dB)

Voice capacity	Strongest serving cell is cell 0	Serving cells include cell 0
$M = 1$	N/A	N/A
$M = 2$	29	36
$M = 4$	35	49
$M = 6$	38	65

gain to support different data rates. Notice that the adjustment of gain patterns on the data users does not affect the gain patterns on the voice users. By using beamforming, the impact of supporting high-rate data connection to voice capacity can be minimized.

With one always-on SCH, the voice capacity is shown in Table 4. The simulation results show that only beams formed by at least 6 array elements can support 153.6 kbps data rate at any location. The reason is that the beams formed by more array elements are narrower and created less interference; consequently, the data connection can close the link. By comparing Tables 3 and 4, with beamforming, the degradation on voice capacity is minimal by supporting one 153.6 kbps data connection in each cell.

5.5. Optimization of Soft Handoff Thresholds

Since the interference is reduced using antenna array techniques, the pilot E_b/N_t seen by the user also becomes stronger. As a result, more users are in 2-way and 3-way soft handoff. The voice capacity can be further improved if the soft handoff thresholds are optimized. In the first experiment, we increase the T_ADD by a fixed 2 dB regardless the number of elements used in the antenna array. The capacity improvement is shown in Table 5.

However, with a larger number of array elements, the T_ADD needs to be increased proportionally. We propose to adjust T_ADD based on the average interference reduction factor, i.e., if the overall interference of a mobile is reduced by α dB, T_ADD is also increased by α dB. The interference reduction factor is determined by the shape and beamwidth of individual beams, the number of users supported in each cell (more users can be supported by a cell with antenna arrays compared to a cell with an omni-directional antenna), mobile distribution, and mobile handoff state. We selected a few mobiles in the center cell as the representatives for collecting interference from all cells. The interference collected from these mobiles is used

Table 6. Average interference reduction factor for Scenario 1

Interference reduction factor	
$M = 1$	N/A
$M = 2$	1.2 dB
$M = 4$	2.55 dB
$M = 6$	3.2 dB

Table 7. Voice capacity comparison for Scenario 1 with dynamic soft handoff thresholds adjustment

Voice capacity	Strongest serving cell is cell 0	Serving cells include cell 0
$M = 1$	N/A	N/A
$M = 2$	27	36
$M = 4$	36	49
$M = 6$	42	59

to compute average interference reduction factor. The average interference reduction factor is shown in Table 6. The capacity improvement using dynamic soft handoff thresholds adjustment is shown in Table 7. Comparing Tables 5 and 7, the voice capacity with larger number of array elements is seen to be further improved.

6. Conclusion

We have built a complete cdma2000 1× cellular simulator using MATLAB and OPNET to investigate various system design issues. With the help of the cellular simulator, we conclude that the network capacity increase is proportional to the antenna array capability at the BS. When the base stations are equipped with antenna arrays, the network capacity is noticeably improved (almost doubled with sufficient number of array elements) compared to a network without antenna arrays. This improvement is impressive since with the major enhancements for cdma2000 1× (such as improved coding gain, faster forward power control, and coherent demodulation for the reverse link), the capacity improvement of cdma2000 1× compared to IS-95 is only between 1.5–2 times.

Based on the evaluation results, we suggest deploying at least 6 array elements per antenna array to double the cdma2000 1× voice capacity. The cdma2000 operators can dynamically adjust the soft handoff thresholds based on the average interference reduction factor at the mobiles to further improve the voice capacity. Additionally, our recommendations for deploying antenna arrays in cdma2000 network should balance the coverage of pilot channel and traffic channels and use antenna arrays to perform QOS provisioning for high-rate data users, i.e., increasing the coverage range for high-rate data connections.

References

1. K.S. Gilhousen, et al., "On the Capacity of a Cellular CDMA System", *IEEE Trans. on Veh. Technol.*, Vol. 40, No. 2, pp. 303–312, May 1991.
2. M. Xiao, N.B. Shroff, and E.K.P. Chong, "Resource Management in Power-Controlled Cellular Wireless Systems", *Wirel. Commun. Mob. Comput.*, Vol. 1, No. 2, pp. 185–199, Apr. 2001.
3. D.K. Kim and D.K. Sung, "Capacity Estimation for a Multicode CDMA System with SIR-Based Power Control", *IEEE Trans. on Veh. Technol.*, Vol. 50, No. 3, pp. 701–710, May 2001.
4. D.K. Kim and F. Adachi, "Theoretical Analysis of Reverse Link Capacity of an SIR– Based Power-Controlled Cellular CDMA System in a Multipath Fading Environment", *IEEE Trans. on Veh. Technol.*, Vol. 50, No. 2, pp. 452–464, March 2001.
5. A.F. Naguib, A. Paulraj, and T. Kailath, "Capacity Improvement with Base-Station Antenna Arrays in Cellular CDMA", *IEEE Trans. Veh. Technol.*, Vol.43, No. 3, pp. 691–698, Aug. 1994.
6. J. Yu, Y.-D. Yao, and J. Zhang, "Reverse Link Capacity of Power-Controlled CDMA Systems with Beamforming", *IEEE Trans. on Vehicle Technology,* Vol. 53, No. 5, pp. 1423–1433, Sep. 2004.
7. D.N.C. Tse and S. V. Hanly, "Linear Multiuser Receivers: Effective Interference, Effective Bandwidth and User Capacity", *IEEE Trans. on Inform. Theory*, Vol. 45, No. 2, pp. 641–657, March 1999.
8. IS-2000 Specifications, *www.3gpp2.org*.
9. D.J. Shyy, "Impact of Deploying cdma2000 Data to Voice Capacity Using Cellular Simulator", OPNETWORK Conference, Aug. 2002.
10. A. Viterbi, et al., "Soft Handoff Extends CDMA Cell Coverage and Increases Reverse Link Capacity", *IEEE JSAC*, Vol. 12, No. 8, pp. 1281–1288, Oct. 1994.
11. J.C. Liberti and T.S. Rappaport, "Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications", NJ, Prentice Hall, 1999.
12. S. Haykin, *Adaptive Filter Theory*, Third Edition, Prentice Hall, NJ, 1986.
13. U. Spagnolini, "A Simplified Model for Probability of Error in DS CDMA Systems with Adaptive Antenna Arrays", *IEEE ICC Conf.*, pp. 2271–2275, 2001.
14. J. Yu and Y.-D. Yao, "Evaluation of Reverse Link Performance of a CDMA System with Imperfect Beamforming", *IEEE 59th VTC 2004-Spring*. Milan, Italy, May 17–19, 2004.