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UNIFORM CIRCULAR ANTENNA ARRAY APPLICATIONS IN CODED DS-CDMA MOBILE COMMUNICATION SYSTEMS

by

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March 2003

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Presently, the uniform linear array (ULA) is the most commonly used antenna system for a sectorized cell system like the commercial cellular systems. However, in many omni-directional cell communication systems, such as the ground-based military communications, interest in using the uniform circular array (UCA) has greatly increased. This thesis examines the use of an equally-spaced circular adaptive antenna array at the mobile station for a typical coded direct sequence code division multiple access (DS-CDMA) communication system.

This thesis analyzed the performance of a randomly orientated adaptive UCA in the forward channel (base station to mobile station) of a coded multi-cell DS-CDMA system. Using a 3- and 4-element UCA, the capacity and performance of different cellular systems under a range of shadowing conditions, with and without antenna sectoring at the base station, and various user capacities were simulated using the Monte Carlo simulation. The results for both ULA, as studied in [7], and UCA were compared and presented in this thesis.

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UNIFORM CIRCULAR ANTENNA ARRAY APPLICATIONS IN CODED DS-CDMA MOBILE COMMUNICATION SYSTEMS

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Presently, the uniform linear array (ULA) is the most commonly used antenna system for a sectorized cell system like the commercial cellular systems. However, in many omni-directional cell communication systems, such as the ground-based military communications, interest in using the uniform circular array (UCA) has greatly increased. This thesis examines the use of an equally-spaced circular adaptive antenna array at the mobile station for a typical coded direct sequence code division multiple access (DS-CDMA) communication system.

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Last but not least, this thesis is dedicated to my family, especially my beautiful wife, Wendy Lim, and my baby boy, whose name we have not decided on yet. I am grateful for their unconditional love and the sacrifices they have made. Their moral support made this whole process more enjoyable.

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EXECUTIVE SUMMARY

The uniform linear array (ULA) has been the most common form of antenna array systems employed in cellular systems. Recently, interest in using uniform circular array (UCA) in omni-directional cell communication systems, such as ground-based military communications, has increased.

The application of the adaptive antenna technology at the mobile station for the third-generation DS-CDMA cellular system can be extended to the military mobile communication systems. Implementing the adaptive UCA on the mobile stations will help to increase the military mobile communication system's capacity and maximum data rates.

The third-generation (3G) cellular system employs direct sequence code division multiple access (DS-CDMA) that allows simultaneous sharing of limited available bandwidth. However, the presence of inter-cell co-channel interference and intra-cell interference has limited the system's capacity.

With the ever-increasing demand to accommodate more users and to provide higher data-rate services within a limited available frequency spectrum, many researchers have explored new options to improve the system's capacity and performance. One of the most promising techniques for increasing the cellular system's capacity is using a spatially distributed array of antennas.

This thesis examines the use of an equally-spaced circular adaptive antenna array at the mobile station for a typical coded direct sequence code division multiple access (DS-CDMA) communication system. The performance of the DS-CDMA system with adaptive UCA in the forward channel (base station to mobile) is analyzed. Convolutional codes are also added to the adaptive UCA in a slow, flat Rayleigh fading and log-normal shadowing environment.

The optimized 3- and 4-element uniform circular array (UCA) in the coded DS-CDMA forward-channel received signal model was developed. Four performance boundaries were established from the Monte Carlo simulations. The worst of the best

(WB) boundary was selected as the performance reference as it was the most representative boundary.

The capacity and performance of the adaptive ULA and the adaptive UCA, under a range of shadowing conditions, with and without antenna sectoring at the base station and for various user capacities, were compared.

The simulation results show that, generally, the performance of the system with the adaptive UCA is better than or at least on par with the system with the adaptive ULA. In addition, the 4-element adaptive array can “null out” up to three interfering signals and thereby increases the system’s capacity further.

Furthermore, sectoring techniques significantly reduced the amount of inter-cell interference and improved the system’s performance, thereby increasing the number of mobile stations allowed within the cell. The capacity of the system with the 3- and 4-element adaptive UCA was increased by 5.8 times (with 60^0 sectoring) and 2.8 times (with 120^0 sectoring), respectively.

I. INTRODUCTION

The Uniform linear array (ULA) has been the most common form of antenna array systems employed in cellular systems. Recently, interest in using uniform circular array (UCA) in omni-directional cell communication systems, such as ground-based military communications, has increased.

The application of the adaptive antenna technology at the mobile station for the third-generation DS-CDMA cellular system can be extended to the military mobile communication systems. Implementing the adaptive UCA on the mobile stations will help to increase the military mobile communication system's capacity and maximum data rates.

In the early days of mobile radio, when the availability of radio spectrum was not an issue, communication between a central tower and multiple users was accomplished by assigning different carrier frequencies to different users. At that time, the availability of additional frequencies accommodated additional users. Interference between various users was minimized by adopting frequency division multiple access, in which different users occupied different frequency bands within the radio spectrum.

Unfortunately, this type of system does not fully use the available spectrum. The number of users supported in a given bandwidth per unit area is small and the system cannot simultaneously support multiple users with multiple information messages owing to the limited radio spectrum. The cellular system has evolved to overcome this deficiency and can perform satisfactorily in a densely populated area with numerous users.

With the ever-increasing demand to accommodate more users and to provide higher data-rate services within a limited available frequency spectrum, many researchers have explored new options to improve the system's capacity and performance. One of the most promising techniques for increasing the cellular system's capacity is using a spatially spaced array of antennas.

A mobile communication system often encounters inter-cell co-channel interferers who occupy the same channel as the desired user. This limits the system's performance and capacity. Although the present method of using dual diversity with maximum ratio combining (MRC) at the receiver, can accommodate more users with higher data rate, this method cannot reduce the high interference. This is because the strategy of selecting the strongest signal or extracting the maximum signal power from the antennas is not appropriate when a strong interfering signal is present. The interfering signal rather than the desired signal will be enhanced.

However, if the direction of arrival (DoA) of the interferers and the desired signal could be estimated, an adaptive antenna array could be used to suppress the interference by steering a null toward the interfering signal and forming a beam toward the desired signal continuously with time. This could improve the system's performance significantly.

This thesis analyzes the performance of the forward channel (base station to mobile) of a direct sequence code division multiple access (DS-CDMA) system employing convolutional codes in a slow, flat Rayleigh fading and log-normal shadowing environment. Generally, data services are asymmetric, with the downstream requiring a higher data rate. The forward channel will be used to download data from sources, such as the Internet, at a high data rate from the base station to the mobile terminal.

Most of the performance analyses of the DS-CDMA cellular system have focused on the reverse channel even with the use of an adaptive antenna. Moreover, most of these performance analyses have only incorporated a subset of the channel effects (fading and shadowing) and parts of the benefits of forward error correction with soft decision decoding.

In this thesis, an equally spaced circular antenna array with a different number of elements at the mobile terminal was implemented. The performance of a randomly positioned mobile terminal with a randomly oriented adaptive antenna array in a multi-cell DS-CDMA network was simulated and four performance boundaries were established.

The tighter optimized array antenna boundary was selected as the performance reference, as it represents a more conservative situation. The optimized 3- and 4-element UCA with the DS-CDMA forward-channel received signal model was developed. The effects of the adaptive antenna and log-normal shadowing and Rayleigh slow flat fading were incorporated in the model.

The benefit of forward error correction with soft decision decoding was also integrated to enhance the new system model presented in this thesis. This thesis further compares the capacity and performance of ULA and UCA, under a range of shadowing conditions, with and without antenna sectoring at the base station and for various user capacities, using a Monte Carlo simulation.

Chapter II briefly discussed co-channel interference in a DS-CDMA system and the various methods to minimize the interference. The characteristics and constraints of an equally spaced circular adaptive array system are also introduced in Chapter III. This adaptive array will be modeled and analyzed in the DS-CDMA environment. The forward channel propagation model for the DS-CDMA system is introduced in Chapter IV. Finally, Chapter V compares the performance between the ULA and the UCA in various conditions.

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II. THE CELLULAR CONCEPT AND APPLICATIONS OF ADAPTIVE ANTENNA ARRAY

This chapter provides the background on direct sequence code division multiple access (DS-CDMA) cellular communication and the constraints faced with ever increasing demand for more users with high data rates. It also discusses the present techniques used by service providers, the advantages of the adaptive antenna systems and finally the assumptions made in this thesis.

A. EXPANDING SYSTEM CAPACITY

The rapid increase in the number of users of cellular phones and personal communication devices poses challenges, such as limited frequency spectrum and co-channel interference, for mobile communications. The honeycomb cell is conceptualized to solve the problem of spectral congestion and limited user capacity. It offers very high capacity in a limited spectrum allocation without any major technological changes. The cellular concept is a system-level idea that calls for replacing a single, high power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area.

Each base station is allocated a portion of the total number of channels available in the entire system. The surrounding base stations are assigned different groups of channels so that all the available channels are equally distributed. Neighboring base stations are assigned different groups of channels so that the interference between base stations and the mobile users under their control is minimized. By systematically spacing base stations and their channel groups, the available channels are distributed throughout the geographic region and may be reused as many times as necessary.

As the demand for service increases, the number of base stations may be increased to provide additional capacity with no additional increase in the radio spectrum. This is the basis for all modern wireless communication systems, as it enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region.

The US digital cellular system based on CDMA was standardized as interim standard 95 (IS-95) by the US Telecommunication Industry Association (TIA). CDMA allows each user within a cell to use the same frequency spectrum, as the other users in the adjacent cells as shown in Figure 2.1. This completely eliminates the need for frequency planning within a market.

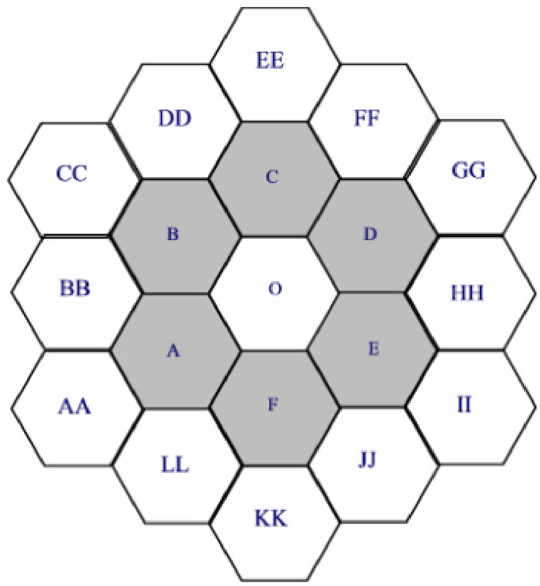

Figure 2.1 Reference Cell (O) with First (gray shaded) and Second Tier Co-channel Cells (After Ref. [5].)

The user data rate also changes in real time, depending on the voice activity and the requirements in the network. Furthermore, CDMA uses a different modulation and spreading technique for the forward and reverse links. The base station simultaneously transmits the user data for all mobile stations in the cell by using a different spreading sequence for each mobile in the forward link. A pilot code, with a higher power level, is also transmitted simultaneously. This is to ensure that all the mobile stations can use coherent carrier detection while estimating the channel condition. On the reverse link, all mobile stations respond in an asynchronous fashion and ideally have a constant signal level due to power control applied by the base station.

B. INTERFERENCE

Interference is the major limiting factor in the performance of the cellular radio systems. The two main sources of interference in the DS-CDMA system are other mobile stations in the same cell (intra-cell interference) or in the adjacent cells (inter-cell interference) or both.

Thermal noise can be easily overcome by increasing the signal-to-noise ratio (SNR). Intra-cell interference, however, cannot be reduced by simply increasing the transmission power of the transmitter. This is because an increase in the power transmission increases the interference to the neighboring cells, i.e., raises the inter-cell interference.

For a narrowband cellular system like global system for mobile (GSM), several cells use the same set of frequencies in a given coverage area. Frequency planning is necessary to ensure that the adjacent cells do not use the same set of frequencies, as shown in Figure 2.2.

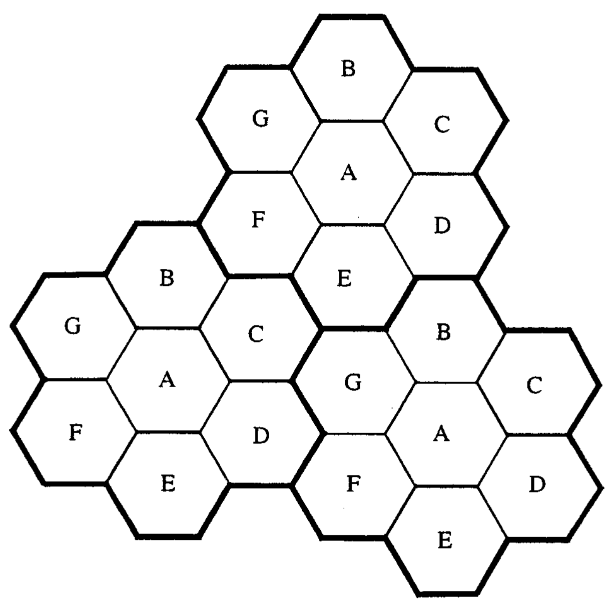

Figure 2.2 Cells with the Same Letter Use the Same Set of Frequencies (From Ref. [6].)

When the size of each cell is approximately the same and the base stations are transmitting with the same power, the co-channel interference ratio is independent of the transmitted power. It is however dependent on the radius of the cell, R, and the distance between the centers of the nearest co-channel cells, D. Increasing the ratio of D/R, extends the spatial separation between the co-channel cells relative to the coverage distance of a cell. Hence, the interference can be reduced by increasing the separation of the co-channel cells.

The signal-to-interference ratio (SIR) for a mobile receiver is given by [6]

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}. \tag{0.1}$$

where S is the desired signal power from the desired base station, I_i is the interference power caused by the i^{th} interfering co-channel cell base station, and i_0 is the number of interfering signals. If each base station transmits with equal power and, assuming that the path loss exponent is the same throughout the coverage area, S/I can be approximated as:

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_o} \left(D_i\right)^{-n}}. \tag{0.2}$$

where R is the radius of the cell, D_i is the distance of the i^{th} interferer from the mobile, and n is the path loss exponent.

If all the first tier interfering base stations are at distance D from the desired base station, Equation (0.2) simplifies to:

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0}. \tag{0.3}$$

where N is the number of cells per cluster. Hence, for a narrowband system, the SIR can be improved by increasing N. However, the second generation systems were optimized for voice. They cannot support high data rate applications. Simply increasing the bandwidths of the systems does not help. Instead, it severely degrades the quality and the reliability due to the frequency-selective fading.

A broadband system like CDMA reuses the whole frequency spectrum in all the cells. The system uses site diversity and exploits multipath fading through Rake combining. Considering only the first tier cells, the distance between the desired base station to the interfering station from the adjacent cells is fixed at $\sqrt{3}R$, where R is the radius of the hexagon cell. The geometry of a cell in a DS-CDMA system is shown in Figure 2.3.

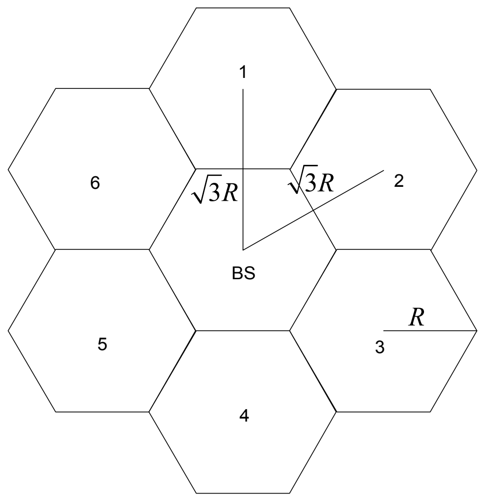

Figure 2.3 Third-Generation (CDMA) Cellular Network (From Ref. [4].)

C. TECHNIQUES TO IMPROVE COVERAGE AND CAPACITY

Techniques like cell sectoring to expand the capacity of the cellular system are commonly applied. With an antenna array and with proper array signal processing techniques, an adaptive antenna system can alleviate these problems by suppressing the interference and reducing the effect of multipath fading.

1. Cell Sectoring

Sectoring improves the capacity by reducing co-channel interference through strategic placement of the base station antenna. There is no change in the radius of the cell. Replacing the single omni-directional antenna at the base station with several directional antennas reduces the co-channel interference. Each of the directional antenna will be radiating within a specified sector. By using a directional antenna, a given cell will receive interference from a fraction of all the cells.

The factor by which the co-channel interference is reduced depends on the amount of sectoring used. A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in Figure 2.4 (a) and (b).

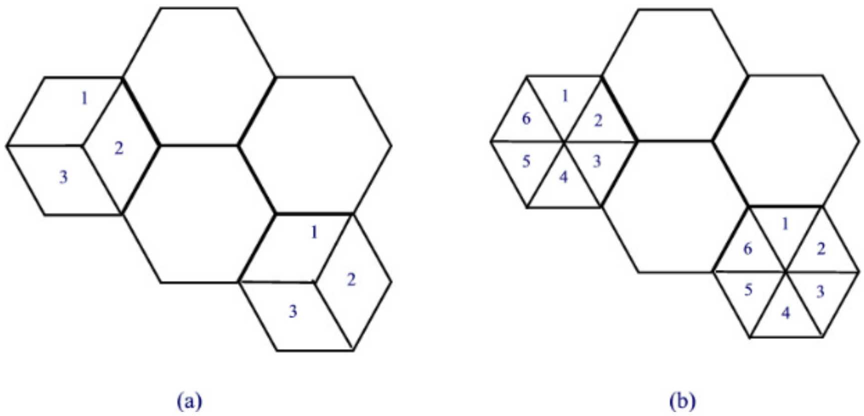

Figure 2.4 (a) 120° Sectoring; (b) 60° Sectoring (After Ref. [5].)

When sectoring is employed, the channels used in a particular cell are broken down into sectored groups and are used only within a particular sector as illustrated in Figure 2.4 (a) and (b). Assuming a seven-cell system, for the case of 120° sectoring, the number of interfering base stations is reduced from six to two. This is because only two of the six co-channel cells will cause interference to the desired base station as shown in Figure 2.5. If omni-directional antennas were used at each base station, all six co-channel cells would interfere with the reference cell.

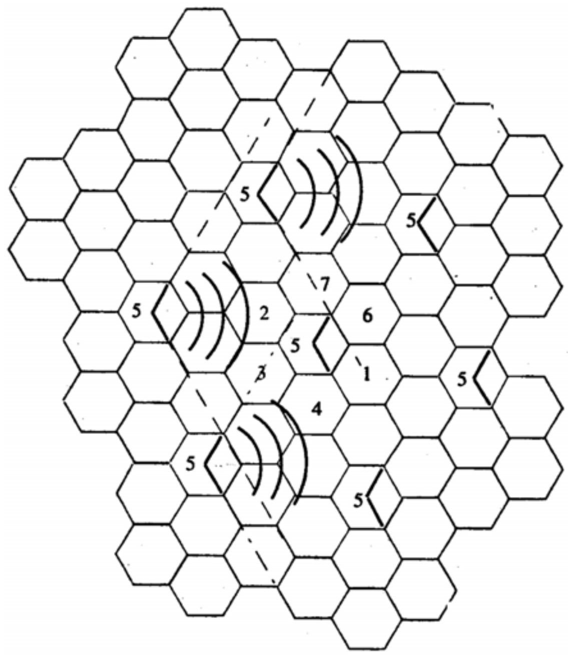

Figure 2.5 120° Sectoring Reduce Interference from Co-channel Cells (From Ref. [6].)

2. Adaptive Antenna Array

An adaptive antenna array is an antenna array arranged in a certain distributed configuration with a specialized signal processor. It can be deployed in the CDMA mobile communication system to improve the system's performance and capacity significantly by minimizing the undesired co-channel interference. Most of the adaptive antenna array systems can form beams directed to the desired signal and form nulls toward the undesired interferer, such as a co-channel base station. This will enhance the signal-to-interference (SIR) ratio because the received desired signal strength is maximized and the undesired interference is minimized.

Other benefits of an adaptive antenna array include:

- increase in range or coverage arising from an increased signal strength due to array gain,
- increase of capacity arising from interference rejection,
- rejection of multi-path interference arising from inherent spatial diversity of the array, and
- reduction of expense through lower transmission powers to the intended user.

An adaptive antenna array system is commonly classified into one of the three categories: switched beam antennas, dynamic phased arrays and adaptive antennas. Although a multiple antenna system is also commonly used at the receiver for L-fold diversity, which could mitigate the effects of fading by reducing the signal fluctuations when the signal is sufficiently de-correlated, the multiple antennas cannot distinguish a signal from a co-channel base station. This method of extracting the maximum signal power from the antennas is not appropriate because the method also enhances the co-channel interference together with the desired signal.

A switched-beam antenna system consists of an antenna array, each forming highly directive, pre-defined fixed beams. The system usually detects the maximum received signal strength from the antenna beams and chooses to transmit the output signal from one of the selected beams that gives the best performance. In some ways, a switched beam antenna system is very much like an extension of a sectoring directional antenna with multiple sub-sectors.

Without knowing the direction of arrival of the desired signal, the desired signal may not fall onto the chosen beam because the beams formed are fixed in direction. Hence switched beam antennas may not provide the optimum SIR. In fact, in cases in which a strong interfering signal is at or near the center of the chosen beam, while the desired user is away from the center of the chosen beam, the interfering signal can be enhanced far more than the desired signal, which results in poor SIR.

Dynamic phased arrays use the direction of arrival (DoA) information from the desired signal and steer a beam maximum toward the desired signal direction. This method when compared to a switch-beam antenna is more superior in performance because it tracks the desired user DoA continuously. It uses a tracking algorithm to steer the beam toward the desired user. The tracking of the DoA enables the system to offer an optimal gain for the desired signal, while simultaneously minimizing the reception of the interfering signal by directing the nulls to the interferer's direction. Thus, excellent SIR can be achieved.

In the adaptive array, the weights are continuously adjusted to maximize the signal-to-interference-plus-noise ratio (SINR) and to provide the maximum discrimination against undesired interfering signals. If the interferer is absent and if only noise is present, the adaptive antennas maximize the signal-to-noise ratio (SNR) and behave as a maximal ratio combiner (MRC).

With the use of various signal-processing algorithms at the receiver-adaptive antenna array system, this system can distinguish between the desired signal and the interfering signals and calculate their direction of arrival continuously. This is done to minimize interference dynamically by steering the nulls pattern toward these undesired sources and to form the maximum gain pattern toward the desired signal. Such algorithms are usually implemented by digital signal processing software, which is relatively easy to implement.

Using other algorithms for branch diversity techniques, the adaptive antenna array system can process and resolve separate multi-path signals. This technique can be combined with the adaptive antenna system to further maximize the SINR or SIR as shown in Figure 2.6.

An adaptive antenna array system may consist of *N* number of spatially distributed antennas with an adaptive signal processor that generates the weight vectors for optimum combination of the antenna array output as shown in Figure 2.6. This can also be regarded as an *N*-branch diversity scheme, providing more than the two diversity branches commonly used. The received RF signals from the *N*-antenna elements are coherently converted to a baseband frequency, which is sufficiently low enough for the adaptive array processor to digitize the signals effectively.

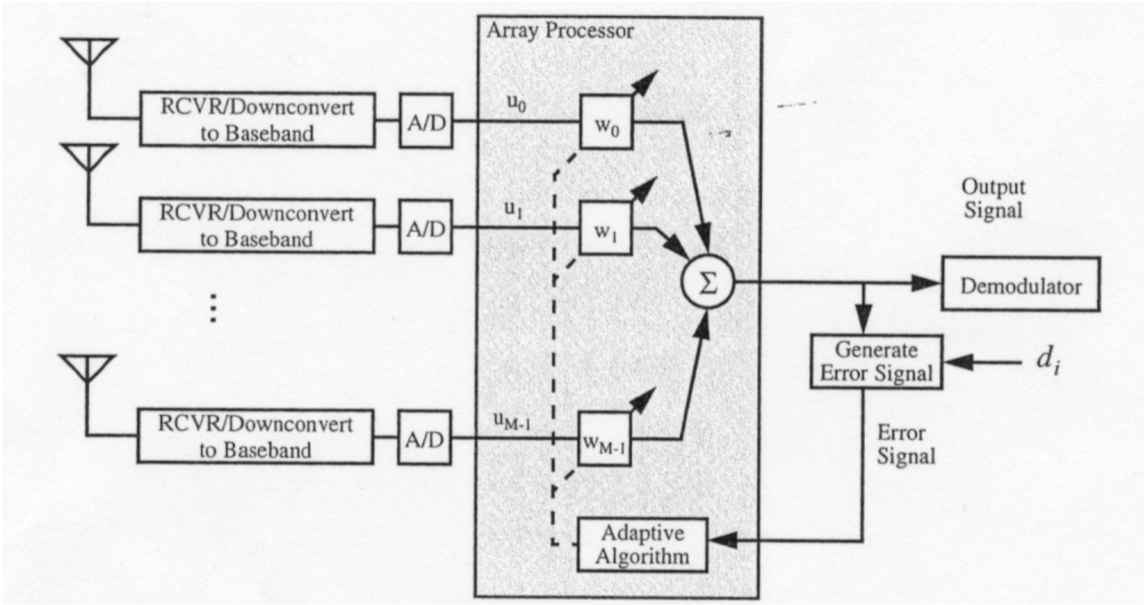

Figure 2.6 Block Diagram of an Adaptive Antenna System (From Ref. [1].)

The processor processes each digitized input channel by multiplying the adjusted complex weights of each branch to form the beam and the nulls. This results in the beam and null steering, which can be viewed as a spatial filter having a pass and a stop band created for the direction of the desired signal and interference, respectively.

In general, it is possible to generate (N–1) nulls in the array system radiation pattern toward (N–1) interferer directions with N-antenna elements in the adaptive array system. This will reduce the total interferer signal significantly, thereby reducing the interferer-to-signal ratio. Reducing the interference in the interference limited system can improve the system's performance and capacity.

D. ASSUMPTIONS MADE

The following assumptions were made in this thesis:bullets .5 from left margin

- A standard two-dimensional hexagonal cell with base stations in the center of every cell is considered (Figure 2.3).
- A mobile station connects to the closest base station and is power-controlled by that base station.

- The distance from the center of the cell to any of the six vertices of the hexagon, known as the cell radius, is 1 unit. Hence, the distance between the base station to any first tier co-channel base station is $\sqrt{3}$ units.
- The base stations in each cell transmit with an equal amount of power.
- Only interference from the first tier cells is considered as the interference from the second and subsequent tier cells is negligible.
- The path loss exponent is the same throughout the coverage area.

E. SUMMARY

The honeycomb cell concept was able to solve the problem of limited frequency spectrum with rapid increase in the number of users. However, interference is still the major limiting factor in the performance of the cellular system.

Techniques like cell sectoring and implementation of adaptive antenna array can improve the system's coverage and capacity. Modeling of the UCA will be described in detail in Chapter III.

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III. UNIFORM CIRCULAR ADAPTIVE ARRAY

In wireless communications, the three types of propagation paths after the wave propagates through a physical medium are line-of-sight (LOS), non-LOS reflected or combined LOS and non-LOS reflected. The path taken is dependent on the type of environment. For LOS propagation, the wireless channel can be considered an additive white gaussian noise (AWGN) channel. Many non-LOS reflected propagation paths would result in a Rayleigh (without LOS path) or a Rician (with LOS path) fading channel. This chapter describes the modeling of both the channel and the equally spaced circular adaptive array system.

A. CHANNEL DESCRIPTION

The non-LOS reflected propagation paths would have delay, angle and Doppler spreads in the fading channels. These propagation effects can be modeled with the vector channel model developed in Ref. [1]. In this thesis, only the impact of the angular spread on the bit error rate (BER) performance of the uniform circular array (UCA) is studied.

The vector channel model for an *N*-element uniform linear array (ULA) developed in Ref. [1] is as shown:

$$v(\theta)=\begin{bmatrix} 1 \\ e^{-j2\pi\frac{d}{\lambda}\sin(\theta)} \\ \vdots \\ e^{-j2\pi\frac{(k-1)d}{\lambda}\sin(\theta)} \end{bmatrix} \qquad k=1,\ 2,\ \cdots,\ N. \tag{0.4}$$

where d is the separation distance between the array elements, λ is the wavelength of the desired signal and θ is the angle of arrival of the signal. This vector channel model has also been widely used to evaluate the performance of an adaptive antenna array in the mobile radio environment. The vector channel developed for the UCA is also based on the same principle used to develop the ULA Ref. [8]. The array manifold vector $v(\theta)$ for an *N*-element UCA is as follows:

$$v(\theta) = \begin{bmatrix} e^{-j2\pi\frac{R}{\lambda}\sin(\phi)\cos(\theta)} \\ e^{-j2\pi\frac{R}{\lambda}\sin(\phi)\cos\left(\theta-\frac{2\pi}{N}\right)} \\ \vdots \\ e^{-j2\pi\frac{R}{\lambda}\sin(\phi)\cos\left(\theta-\frac{2\pi(m-1)}{N}\right)} \end{bmatrix} \qquad m = 1, 2, \cdots, N. \tag{0.5}$$

where R is the circular radius of the antenna array. The azimuth angle which is also known as the angle of arrival (AOA), θ, is on the horizontal plane where the sensors are situated. It measures from a reference imaginary axis on this horizontal plane. The elevation angle, ϕ, is measured from a reference imaginary axis perpendicular to the horizontal plane as shown in Figure 3.1.

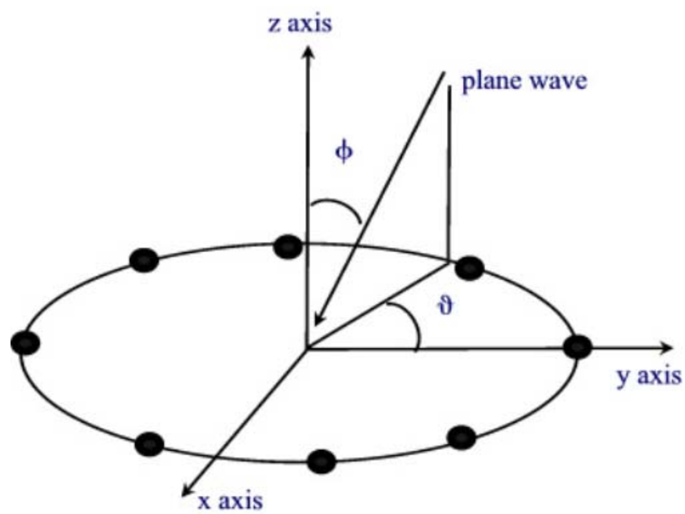


Figure 3.1 Uniform Circular Array (After Ref. [2].)

The generalization of the model will not be lost by setting the elevation angle, ϕ, to 90^0. Hence, only the azimuth angles are considered in the propagation geometry in this thesis. The array vector $v(\theta)$ for the N-element UCA becomes:

$$v(\theta)=\begin{bmatrix} e^{-j\frac{2\pi R}{\lambda}\cos(\theta)} \\ e^{-j\frac{2\pi R}{\lambda}\cos\left(\theta-\frac{2\pi}{N}\right)} \\ \vdots \\ e^{-j\frac{2\pi R}{\lambda}\cos\left(\theta-\frac{2\pi(m-1)}{N}\right)} \end{bmatrix} \qquad m=1,2,\cdots,N. \tag{0.6}$$

B. ADAPTIVE ANTENNA

Unlike a switched-beam antenna with fixed directional beams, an adaptive antenna usually consists of an array with appropriate inter-element spacing. The weights of each element of the antenna array are changed dynamically to maximize the signal-to-interference and noise ratio (SINR). Traditional adaptive antenna systems used in the military for radar and satellite applications employ the well-defined AOA of the desired and interfering signals to determine the weights.

Basically, the weights are chosen so that the resulting antenna pattern will have nulls and beam in the directions of the interfering and the desired signals, respectively. An *N*-element array has *N*–1 degrees of freedom. It can “null out” up to *N*–1 interfering signals. Hence, an adaptive antenna can increase the system’s capacity by overcoming the fading effect and the co-channel interference.

Figure 3.2 shows an adaptive antenna array having *N*-elements with *L* interfering signals. The received signal at the *k-th* antenna element output, x_k(t), will be calculated as:

$$x_k(t)=s_k(t)+n_k(t), \qquad k=1,2,\ldots,N. \tag{0.7}$$

where $s_k(t)$ is the complex envelope of the signal and $n_k(t)$ is the noise received by the *k-th* antenna element. From Equation (3.3), the complex signal envelope for the *N*-element UCA is calculated as:

$$s_k(t)=s(t)\,e^{j\frac{2\pi R}{\lambda}\cos\left(\theta-\frac{2\pi(k-1)}{N}\right)} \qquad k=1,2,\ldots,N, \tag{0.8}$$

where *s(t)* is the complex envelope of the transmitted desired signal.

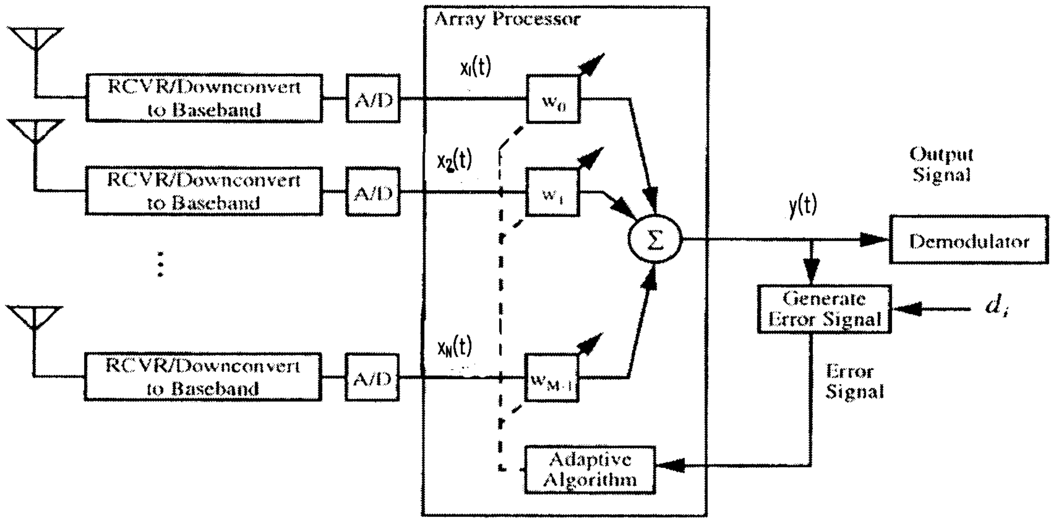


Figure 3.2 Block Diagram of an Adaptive Antenna System (From Ref. [1].)

Finally, the array output signal *y(t),* which is the weighted sum of all the digitized input signals, $x_k(t)$, will be determined from Equation (0.9):

$$y(t) = \sum_{k=1}^{N} w_k x_k(t) = W^T X = X^T, \tag{0.9}$$

where

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix}, \qquad X = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{bmatrix}. \tag{0.10}$$

The adaptive array system continuously adjusts the weights vector *W* using an optimum control algorithm with criterion such as minimum mean square error (MMSE) [1].

C. OPTIMAL WEIGHTS

In this thesis, the algorithm computes the optimum weight for the adaptive antenna system by minimizing the interference-to-signal ratio (ISR). The performance analysis will be based on an UCA with 3- or 4-elements which are uniformly placed in a circle of the radius *R*.

For the case of a 4-element array, the amplitudes of the received signals are A_1, A_2, A_3 and A_4, and their respective phase differences are φ_1, φ_2, φ_3 and φ_4. Considering only the azimuth angles in the propagation geometry, the far-field antenna factor F_{array} is calculated as follows:

$$F_{array} = A_1 e^{j\psi_1} e^{-j\frac{2\pi R}{\lambda}\cos(\theta)} + A_2 e^{j\psi_2} e^{-j\frac{2\pi R}{\lambda}\cos\left(\theta - \frac{2\pi}{4}\right)} + A_3 e^{j\psi_3} e^{-j\frac{2\pi R}{\lambda}\cos\left(\theta - \frac{4\pi}{4}\right)} + A_4 e^{j\psi_4} e^{-j\frac{2\pi R}{\lambda}\cos\left(\theta - \frac{6\pi}{4}\right)}.$$

(0.11)

The operating frequency and the circular radius, R, are set to be 2 GHz and $\lambda/2$, respectively. The total gain is normalized to be equal to 1 by setting the following condition:

$$A_{12} + A_{22} + A_{32} + A_{42} = 1. \tag{0.12}$$

The complex gains of the array in the direction of the desired signal $\left(F_{array_b}\right)$ and the three interferers $\left(F_{array_{i1}}, F_{array_{i2}}, F_{array_{i3}}\right)$ are calculated with the following equations:

$$F_{array_b} = A_1 e^{-i\frac{2\pi R}{\lambda}\cos(\theta_b)} + A_2 e^{i\psi_1} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_b - \frac{2\pi}{4}\right)} + A_3 e^{i\psi_2} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_b - \frac{4\pi}{4}\right)} + A_4 e^{i\psi_3} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_b - \frac{6\pi}{4}\right)}, \tag{0.13}$$

$$F_{array_{i1}} = A_1 e^{-i\frac{2\pi R}{\lambda}\cos(\theta_{i1})} + A_2 e^{i\psi_1} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i1} - \frac{2\pi}{4}\right)} + A_3 e^{i\psi_2} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i1} - \frac{4\pi}{4}\right)} + A_4 e^{i\psi_3} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i1} - \frac{6\pi}{4}\right)}, \tag{0.14}$$

$$F_{array_{i2}} = A_1 e^{-i\frac{2\pi R}{\lambda}\cos(\theta_{i2})} + A_2 e^{i\psi_1} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i2} - \frac{2\pi}{4}\right)} + A_3 e^{i\psi_2} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i2} - \frac{4\pi}{4}\right)} + A_4 e^{i\psi_3} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i2} - \frac{6\pi}{4}\right)}, \tag{0.15}$$

$$F_{array_{i3}} = A_1 e^{-i\frac{2\pi R}{\lambda}\cos(\theta_{i3})} + A_2 e^{i\psi_1} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i3} - \frac{2\pi}{4}\right)} + A_3 e^{i\psi_2} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i3} - \frac{4\pi}{4}\right)} + A_4 e^{i\psi_3} e^{-i\frac{2\pi R}{\lambda}\cos\left(\theta_{i3} - \frac{6\pi}{4}\right)}. \tag{0.16}$$

The amplitude of the received signal is calculated as:

$$A_4 = \sqrt{A_1^{\,2} + A_2^{\,2} + A_3^{\,2}}. \tag{0.17}$$

The ISR is then calculated as follows:

$$ISR = \frac{\sqrt{\left|F_{array_{i1}}\right|^2 + \left|F_{array_{i2}}\right|^2 + \left|F_{array_{i3}}\right|^2}}{\left|F_{array_b}\right|}. \tag{0.18}$$

Using MATLAB as the simulation software, the complex-valued weights were optimized after iterations and the ISR was minimized. However, some initial guessing in the values of the variables was required to start the simulation. In the case of the 4-element array, six initial values $\left(A_1, A_2, A_3, \psi_1, \psi_2, \psi_3\right)$ had to be guessed before the simulation could begin.

The initially guessed values of the six variables were

$$A_1 = A_2 = A_3 = \frac{1}{\sqrt{4}}; \quad \psi_1 = \psi_2 = \psi_3 = \frac{\pi}{4}. \tag{0.19}$$

The values of the weights' amplitude are constrained between 0 and 1 to normalize the gain power. The most optimum strategy is to steer the null toward the interfering signal first rather than trying to maximize the gain of the desired signal.

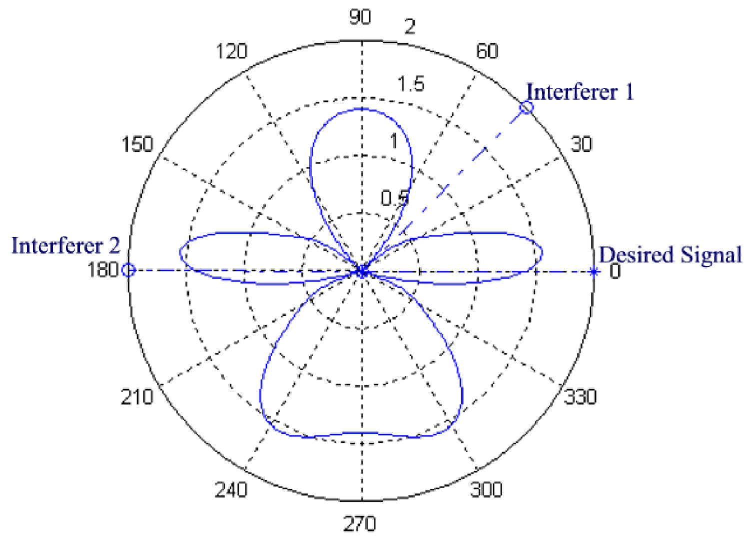
With the optimum weight values obtained after minimizing the ISR, these weights are substituted back into Equation (0.18) to compute the optimum ISR (ISR_{opt}) and to obtain the antenna factor values for all the directions.

D. ADVANTAGES OF UCA OVER ULA

1. Symmetry

If the DoA of the desired and the interfering signals fall on the opposite side, the algorithm for an ULA cannot minimize the ISR as desired. When the desired and the interfering signals are located in this symmetrical location and if the interfering signals are at equal distance and transmitting with equal power to the mobile as the desired signal, the ISR for an ULA will not be less than 0 dB. Fortunately, this situation can be overcome with an UCA due to its superior geometrical characteristics.

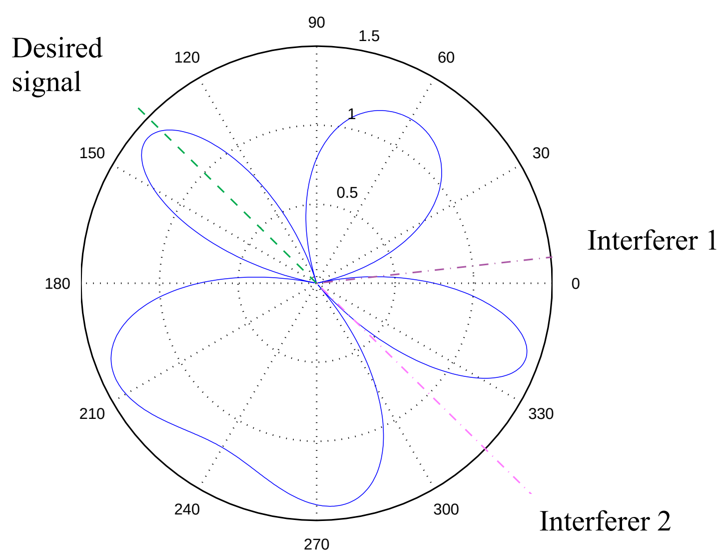
For a 3-element ULA, the computed ISR is 0 dB when one of the interfering signals is directly opposite the desired signal as shown in Figure 3.3:



ISR = 0 dB

Figure 3.3 A 3-Element ULA with an Interfering Signal Directly Opposite the Desired Signal (From Ref. [8].)

In an identical situation, the 3-element UCA is able to overcome this limitation by virtue of its superior geometry characteristics. The computed ISR is –18.8 dB when one of the interfering signals is directly opposite the desired signal as shown in Figure 3.4:



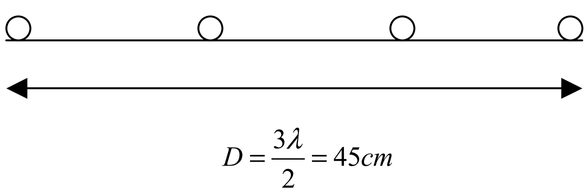
ISR = –18.8147 dB

Figure 3.4 A 3-Element UCA with an Interfering Signal Directly Opposite the Desired Signal

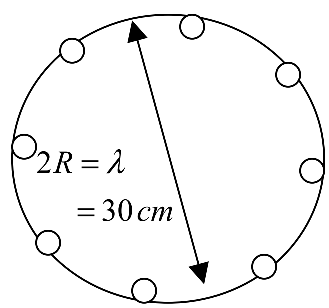
2. Antenna Separation

The space available to fit the antenna array in the mobile station such as a laptop is limited. A typical laptop has a diagonal space of only about 30 cm. Setting the operating frequency as 2 GHz and the element spacing as $\lambda/2(=15\text{ cm})$, the required space for a 4-element ULA is 45 cm as shown in Figure 3.5(a). Hence, there is insufficient space to place the antenna array linearly on the laptop.

On the other hand, a 4- or more element UCA will only require a fixed circular space of radius 15 cm as shown in Figure 3.5(b). Hence, it is possible to fit an UCA with more elements on the mobile stations as the space required is constant. An antenna array with more elements is able to "null up" more interfering signals, which thereby improves the system's performance and capacity significantly.



(a)



(b)

Figure 3.5 (a)4-Element ULA; (b) 8-Element UCA

E. SUMMARY

Chapter III described in details the vector channel model and the principles behind an *N*-element UCA. The advantages of the UCA over the ULA were also presented. Next, the forward channel propagation model in the coded DS-CDMA environment will be discussed in Chapter IV.

IV FORWARD CHANNEL PROPAGATION MODEL FOR CDMA SYSTEM

This chapter presents the forward channel propagation model of a coded direct sequence code division multiple access (DS-CDMA) mobile communication system in a slow, flat Rayleigh fading and log-normal shadowing environment. The forward channel is being studied because most data services are asymmetric, with the downstream requiring a higher data rate.

A. MEDIUM PATH LOSS

In practice, a mobile station can be located anywhere within a cell, with two degrees of freedom. Its position can be at a distance *R* from its base station and can be at a particular angle to the base station. Unlike an omni-directional antenna, the uniformly circular array (UCA) has an orientation, which must be considered. This directional effect of the UCA array increases the definition of the mobile station's position within the cell to a third-order problem since the mobile user can be randomly orientated in any direction.

In order to account for the co-channel interference, both the distances from the mobile station to all the six first-tier co-channel base stations and their relative antenna array to the base station angle must be estimated.

The distance from the base station in the center cell to the mobile station is represented as *R*, while the distance from the mobile station to the first-tier co-channel base stations is D_i. The cell radius is set as *D* and the angle of the mobile station from the base station is *A* radians as shown in Figure 4.1.

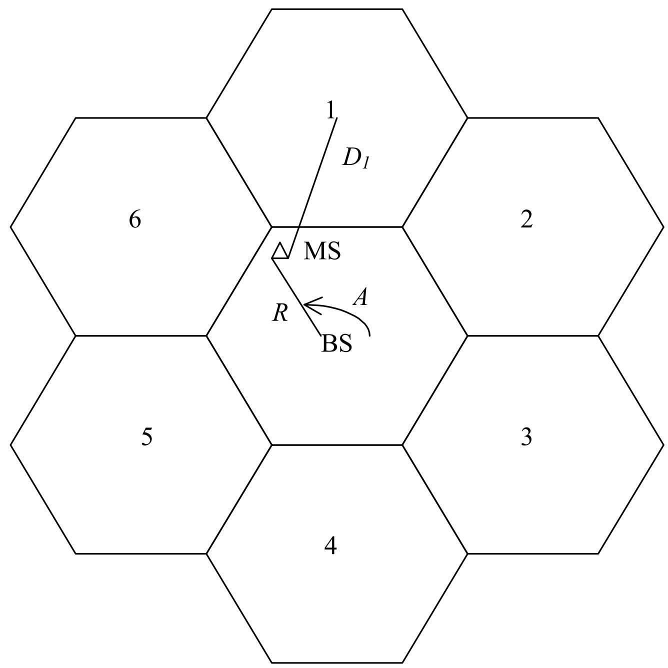


Figure 4.1 Basic Geometry of the Base Station with Six Co-channel Base Stations (After Ref. [4].)

With the center of the six first-tier hexagonal cells geometry fixed as their base station, all the seven angles and distances from the mobile station (MS) to all the seven base stations (BS) can be determined. Any position (*R, A*) in the center cell is defined as a phasor representation of the mobile station, i.e.,

$$MS = Re^{iA} \quad \text{where } (0 < R < 1) \text{ and } (0 < A < 2\pi). \tag{0.20}$$

The distance D_i and the direction of arrival of the co-channel *i-th* base station, θ_i, can be determined by using vector algebra.

With a normalized cell radius of $D = 1$, the distance between the center of each adjacent base station is $\sqrt{3}$ and the angle from the center origin to each adjacent base station, θ_{BS_i}, is at $(0, \pi/3, 2\pi/3, \pi, 4\pi/3, 5\pi/3, 2\pi)$ radians. All the distance and the look angles from the mobile-station to all adjacent base stations can then be determined as

$$D_i = \mathrm{Re}\left|\sqrt{3}e^{i\theta_{BS_i}} - Re^{iA}\right|, \tag{0.21}$$

$$\theta_{BS_i} = \left(0, \frac{\pi}{3}, \frac{2\pi}{3}, \pi, \frac{4\pi}{3}, \frac{5\pi}{3}, 2\pi\right), \tag{0.22}$$

$$\theta_i = \angle\left(\sqrt{3}e^{i\theta_{BS_i}} - Re^{iA}\right). \tag{0.23}$$

The azimuth angle and the distance toward the desired center base station are

$$\theta_{BS} = \pi + A. \tag{0.24}$$

$$D_{BS} = R. \tag{0.25}$$

These distances and angles are used to calculate the path loss for the desired signal and the co-channel interference using the Hata model, which is equivalent to an average path loss, $L_n(D)$, with a path loss exponent of $n = 4$ [6], i.e.,

$$L_n(D) \propto \left(\frac{D}{d_o}\right)^4. \tag{0.26}$$

where d_0 is the reference distance.

1. Hata Model

The Hata model is one of the simplest and most accurate empirical models for representing path loss of cellular systems as presented in [6]. It is based on Okumura model's graphical path loss data using a standard formula for an urban operating area and modified equations for other areas. The original Hata model matches the Okumura model closely for distances greater than 1 km, and the extended model further extends to cover higher frequency ranges with distances of about 1 km. In this thesis, the extended model was used as it better represents the operating environment of a third-generation cellular system.

The extended Hata model, which predict the median path loss L_H in dB as defined in [6] by

$$\begin{aligned} L_H &= 46.3 + 33.9\log\left(f_c\right) - 13.92\log\left(h_{base}\right) - a\left(h_{mobile}\right) \\ &\quad + \left[44.9 - 6.55\log\left(h_{base}\right)\right]\log\left(d\right) + C_M. \end{aligned} \tag{0.27}$$

where

$$a\left(h_{mobile}\right)=\left[1.1\log\left(f_c\right)-0.7\right]h_{mobile}-\left[1.56\log\left(f_c\right)\right]. \qquad \text{(dB)} \qquad (0.28)$$

and

$$C_M = \begin{cases} \text{0 dB for medium sized city and suburban areas} \\ \text{3 dB for metropolitan areas.} \end{cases}$$

Note that

f_c : carrier frequency in MHz,

h_{base} : base station antenna height in meters (m),

h_{mobile} : mobile-station antenna height in meters (m), and

d : separation distance is measured in kilometers (km).

The extended Hata model is restricted to the following range of parameters:

f_c	:	1500 MHz to 2000 MHz,
h_{base}	:	30 m to 200 m,
h_{mobile}	:	1 m to 10 m, and
d	:	1 km to 20 km.

In this thesis, the heights of both the mobile station and the base stations were set as 1 m and 30 m, respectively. The operating carrier frequency was chosen as 2000 MHz.

2. Log-normal Shadowing

For a given distance, the log-normal shadowing accounts for the variations in the average large-scale propagation fading environment. The actual path loss for a mobile station in different locations but with the same distance from the base station varies due to the type of the medium. This happens because the terrain variations in a particular path can be significantly different from the predicted average path loss. A Gaussian random variable χ with zero-mean and σ_{dB} standard deviation can be used to represent the shadowing of the average path loss value. The path loss with shadowing accounted for is modeled by

$$L_X(D) = L_H(\mathrm{d}) + \chi. \quad \text{(dB)} \tag{0.29}$$

where $L_H(D)$ is the average path loss at distance D km.

The above equation can be converted to a log-normal random variable L_X as defined in [4],

$$L_X = L_H X. \tag{0.30}$$

The above log-normal random variable L_X, now also accounts for the effect of log-normal shadowing. Together with the Hata model, they can be used accurately to simulate the propagation effects in the forward channel of the coded DS-CDMA cellular system in a Rayleigh slow-flat fading environment.

B. FORWARD CHANNEL MODEL

In Ref. [7], both the large-scale and small-scale propagation effects are combined into a single model. This combined Rayleigh log-normal channel fading model characterized the mobile radio channel accurately in a single unified model, which can be more completely analyzed.

The Rayleigh log-normal channel model is then applied to a typical DS-CDMA cellular system consisting of traffic from a cell's base station to the mobile station in the cell. This received signal includes the traffic intended for the mobile station from the signal base station (SBS), traffic from other users in the cell (intra-cell interference), traffic for users in adjacent cells (inter-cell interference) and additive white noise. The signal-to-noise plus interference ratio (SNIR) and bit error rate (BER) for the DS-CDMA forward channel in the Rayleigh log-normal fading channel were derived in [4].

Using the forward error correction (FEC) the upper bound bit error probability P_e is defined in [7] as:

$$P_e \le \frac{1}{k} \sum_{d=d_{free}}^{\infty} \beta_d P_2(d), \tag{0.31}$$

with

$$P_2(d) = \int_{-\infty}^{\infty} Q\left(\sqrt{\frac{z_d}{\alpha}}\right) P_{z_d}(z_d)\, dz_d, \tag{0.32}$$

and [4, Eq. 4.60]

$$\alpha = \frac{e^{\left(\frac{\lambda^2 \sigma_{dB}^2}{2}\right)}}{3N} \sum_{i=1}^{6} \sum_{j=0}^{K_i - 1} \frac{L_H(D)}{L_H(D_i)} + \frac{N_o}{2E_c}. \tag{0.33}$$

where $E_c = kE_b / n$ is the coded bit energy and $\lambda = \ln 10/10 = 0.230$.

The first-event error probability of the random variable Z_d, $P_2(d)$, is the sum of d multiplicative chi-square (with two degrees of freedom) log-normal random variables. The details of the derivation and modeling of Z_d are elaborated in Ref. [7]. The total number of information bit errors that are associated with selecting a path of distance d from the all-zero path, β_d, can be calculated for a particular convolutional code. The log-normal shadowing random variable standard deviation, σ_{dB}, is in decibels (dB).

However, when incorporating an adaptive antenna, the above model must be modified to consider the antenna gain factors for all the six co-channel interference base stations (IBS). Hence the modified α becomes

$$\alpha' = \frac{e^{\left(\frac{\lambda^2 \sigma_{dB}^2}{2}\right)}}{3N} \sum_{i=1}^{6} \sum_{j=0}^{K_i - 1} \left[\left(\frac{L_H(D)}{L_H(D_i)}\right)\left(\frac{G_i}{g}\right)\right] + \frac{N_o}{2E_c} \tag{0.34}$$

where G_i and g are the antenna gain factor for the IBS_i and the SBS, respectively.

Optimization of the UCA array over a 360^0 orientation for any mobile station's positions within the center cell of a seven-cell cluster was carried out. Since the path loss from the various mobile stations' positions to the different IBSs, the SBS and the respective directions are different and an antenna array optimization constraint must be derived to account for all the above possible variations. A simple optimization using antenna factor interference-to-signal-ratio (ISR) may not be appropriate because it does not account for the different path loss values for the various interferers.

For simplicity, it was assumed that all the first-tier cells around the SBS's center cell have the same number of active users in each cell. The path loss ratio (*PLR*) was defined as the optimization factor for determining if the particular orientation of a particular position is the best or the worst in performance.

$$PLR = \sum_{i=1}^{6} \left(\frac{L_H(D)}{L_H(D_i)} \right) \left(\frac{G_i}{g} \right). \tag{0.35}$$

Note that α' is proportional to *PLR,* where the former is the denominator in the Q function of the first-event probability $P_2(d)$ in Equation (0.32). Thus, the value of $P_2(d)$ will decrease with the smaller value of *PLR.* Since the probability of error, P_e, is also proportional to $P_2(d)$ as defined in Equation (0.31), the value P_e will also decrease accordingly.

C. SUMMARY

After the optimization of the antenna array, the performance boundaries based on the *PLR* values were ready to be established. Due to the complexity of the forward channel model, an analytical solution could not be developed. Instead a Monte Carlo simulation was used to obtain the solutions for the performance analysis as described in Chapter V.

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V PERFORMANCE ANALYSIS OF THE ADAPTIVE CIRCULAR ARRAY ANTENNA SYSTEM

In this chapter, the performance of the uniform circular array (UCA) at the mobile station in the forward channel is analyzed. The results were also compared against the performance of the uniform linear array (ULA) developed in Ref. [8]. The coded direct sequence code division multiple access (DS-CDMA) forward channel model developed in Ref. [7] was used to represent the Rayleigh log-normal channel. The mobile station would be receiving the signals from the desired base station in this environment as discussed in Chapter IV.

A. PERFORMANCE BOUNDARY

The channel model is deemed to be too complex due to the following:

- It is a wireless channel,
- the position of the mobile station is random, and
- the orientation of the UCA array is also random.

Hence, no analytical solution could be developed and the bit error rate (BER) performance of the 3- and 4-element UCA was statistically simulated using Monte Carlo simulation. Obtaining a good representation of the result also was not an easy task because the BER performance at each location may deviate significantly with a different orientation. A 4-boundary approach was adopted in [4] to represent the adaptive ULA array system performance. Likewise, the same approach was also adopted for the adaptive UCA array system performance to obtain an "apple-to-apple" comparison.

The 4 boundaries are defined as:

1. Best of Best BER boundary (BB)
2. Worst of Best BER boundary (WB)
3. Worst of Worst BER boundary (WW)
4. Best of Worst BER boundary (BW)

First, the mobile station was randomly positioned and rotated 360^0 at each location within the cell. The optimization of the adaptive UCA for each random position at each orientation was performed with one-degree resolution. For each one-degree orientation, the optimized weights were obtained and were used to compute the antenna gain for all the antenna-array factors. The path loss ratio as defined in Equation (0.35) of Chapter IV, was then determined.

The whole process was repeated for the whole 360^0 orientation and the best and the worst path loss ratios that corresponded to the best and worst system performance for that single location were selected.

The whole optimization process was repeated to capture the best and the worst performance by positioning the mobile station randomly within the boundary of the cell. The performance analysis was restricted to only one of the 60^0 sectors of the cell because the result could apply to all parts of the cells without losing any generality. The furthest and the nearest distance from the desired base station are 1 km (normalized) and 0.1 km, respectively as shown in Figure 5.1:

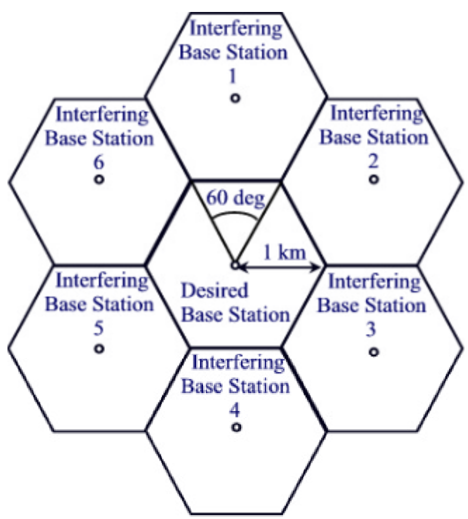

Figure 5.1 Area of Analysis within the Cell (After Ref. [4].)

For each location, the maximum and the minimum path loss ratio values were determined and sorted. Within each (the maximum and the minimum value) category, the largest and the smallest values were used to perform the Monte Carlo simulation on Equation (0.31) to obtain the BER performance boundaries as defined earlier.

The four performance boundaries for a system with 120 users per CDMA carrier per cell using a 3-element adaptive ULA versus an identical system using a 3-element adaptive UCA array were as shown in Figure 5.2. In both cases, the WW boundary is not visible as it is far above the chart of BER = 10^{-1}. The best of the best BER (BB) boundary, representing the very best performance, is the performance ceiling of the systems as the dominant co-channel interference had been successfully "nulled out." The locations of this point for both cases are within 10% of the normalized radius of the cell.

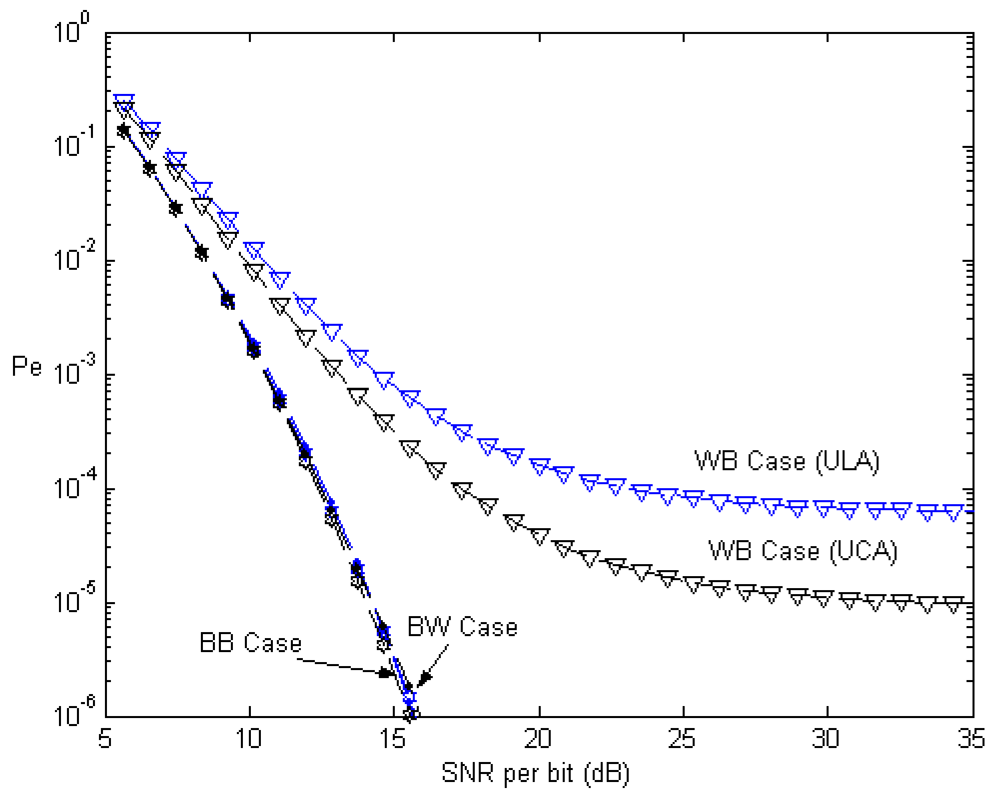

Figure 5.2 Forward Channel Performance Boundaries for the DS-CDMA System with a 3-Element Adaptive Array Systems $(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8)$ with 120 users per CDMA carrier per cell

Similarly, the four performance boundaries for a system with 120 users per CDMA carrier per cell using a 4-element ULA array versus an identical system using a 4-element UCA array were also plotted.

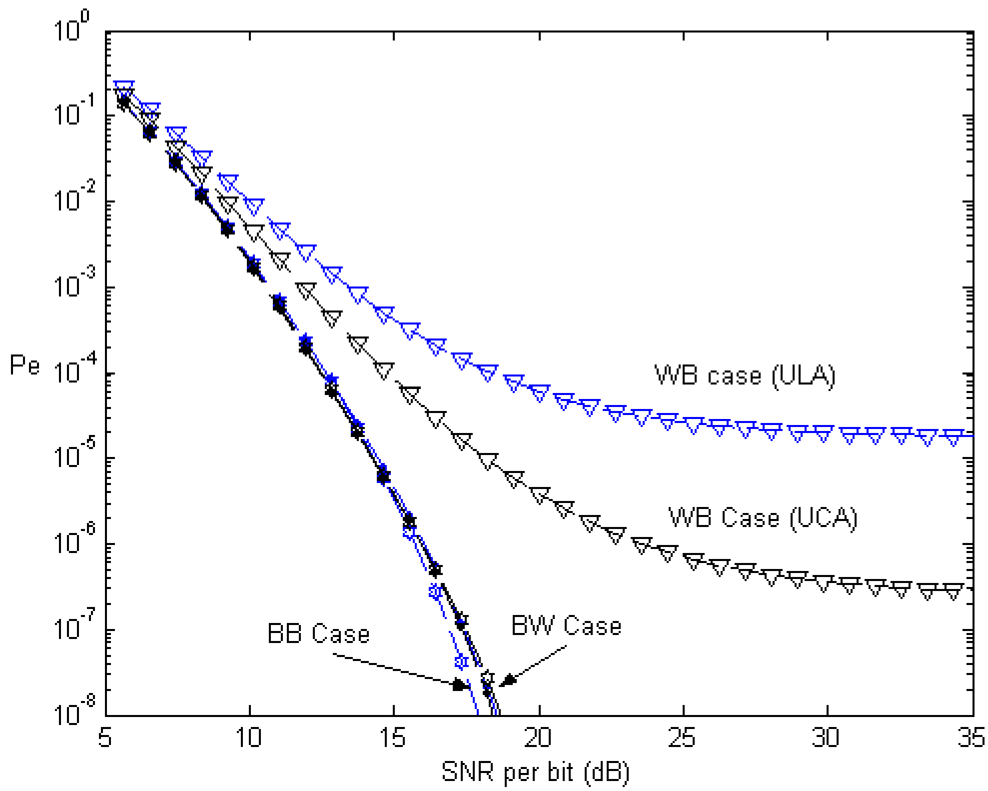

Figure 5.3 Forward Channel Performance Boundaries for the DS-CDMA System with a 4-Element Adaptive Array Systems $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$ with 120 users per CDMA carrier per cell

The effect of the log-normal shadowing is increased with higher values of σ_{dB}, which is the standard deviation of the Gaussian random variable that represents the shadowing of the average path loss, as discussed in Chapter IV. Increasing the value of σ_{dB} represents a hasher environment and will have a negative effect on the efficiency of the adaptive antenna. Hence, Figures 5.4, 5.5, 5.6 and 5.7 show that the performance decreased, as expected, in all four boundaries for systems using the adaptive antenna array.

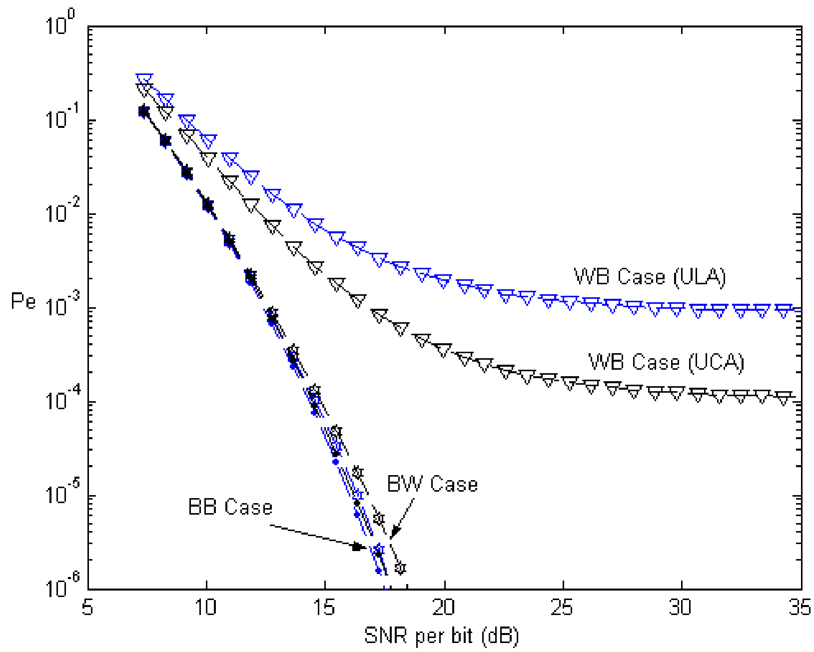

Figure 5.4 Forward Channel Performance Boundaries for the DS-CDMA System with a 3-Element Adaptive Array Systems $\left(\sigma_{dB}=8, Rcc=1/2, \nu=8\right)$ with 120 users per CDMA carrier per cell

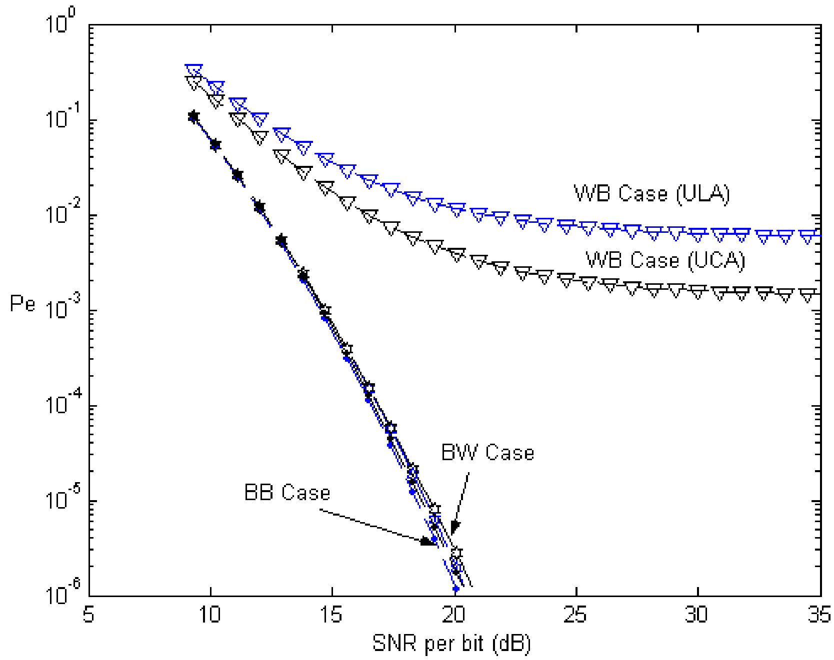

Figure 5.5 Forward Channel Performance Boundaries for the DS-CDMA System with a 3-Element Adaptive Array Systems $\left(\sigma_{dB}=9, Rcc=1/2, \nu=8\right)$ with 120 users per CDMA carrier per cell

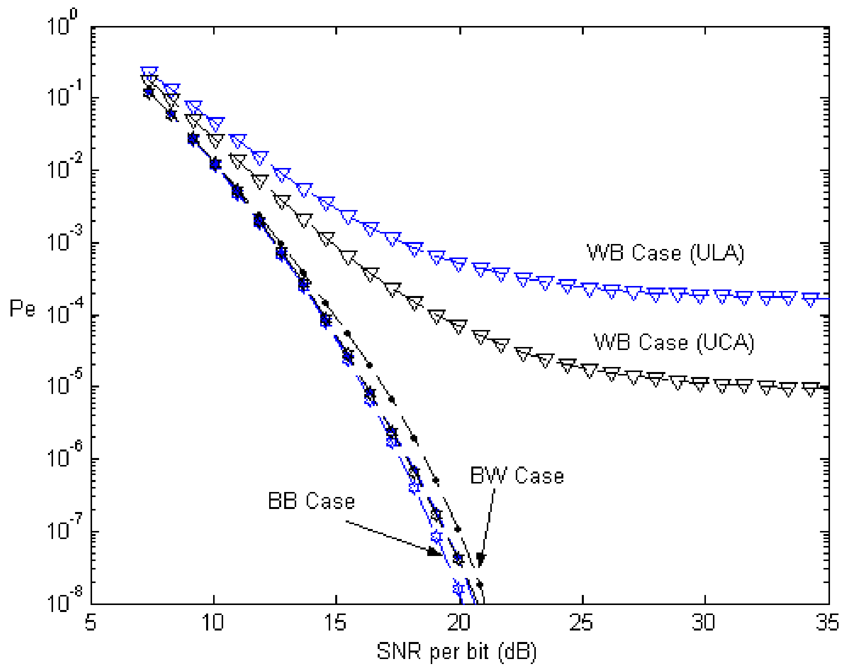

Figure 5.6 Forward Channel Performance Boundaries for the DS-CDMA System with a 4-Element Adaptive Array Systems $\left(\sigma_{dB} = 8, Rcc = 1/2, \nu = 8\right)$ with 120 users per CDMA carrier per cell

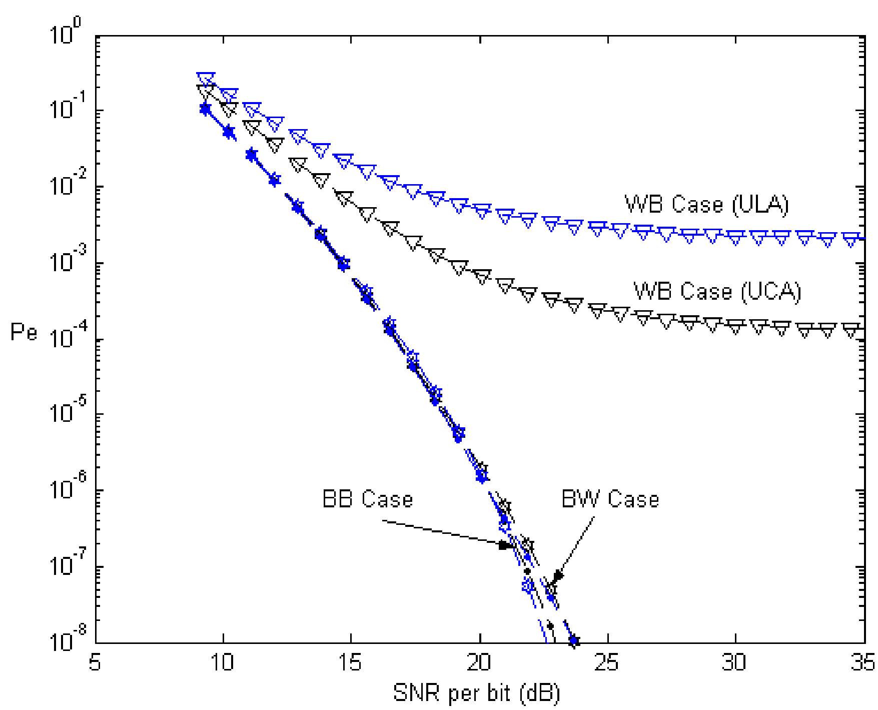

Figure 5.7 Forward Channel Performance Boundaries for the DS-CDMA System with a 4-Element Adaptive Array Systems $\left(\sigma_{dB} = 9, Rcc = 1/2, \nu = 8\right)$ with 120 users per CDMA carrier per cell

The WW case is a very pessimistic scenario in which the interferer is not being sufficiently suppressed. A poor initial guess for minimizing the interference-to-signal ratio (ISR), as discussed in Chapter III (Equation 3.14), could be the cause. The performance of this case is always above the usable limit of the BER for the 3- and 4-element adaptive array systems and therefore not plotted in the figures above. The location of this case is near the edge of the cell adjacent to the other co-channel cells. This boundary does not represent the performance of the systems adequately.

In all the figures above, the BW boundary is usually close to the ceiling performance boundary and is very much like the BB case. Likewise, both the BB and the BW boundaries do not give a "realistic" picture of the performance of the system because they are the optimistic scenarios in which the co-channel interferences have been effectively "nulled out."

The most representative boundary is the WB case because it provides a good indication of the performance of the system. The WB boundary provides the minimum assured performance of the communication system, which is useful in the design of a mobile communication system. This WB boundary indicates the worst case (the lowest limit) of the best performance achievable by the system with an adaptive array with a 360^0 of freedom.

It is noted that for all values of σ_{dB}, the UCA array system outperforms that of the ULA system, especially with a higher value of the signal-to-noise ratio (SNR). The ULA array is unable to minimize the ISR as desired when the DoA of the desired and the interfering signals fall on the opposite side. The UCA array can overcome this limitation and has a better performance by virtue of its superior geometry characteristics, as discussed in Chapter III.

B. WORST OF THE BEST PERFORMANCE BOUNDARY (WB)

Figures 5.8, 5.9, 5.10 and 5.11 illustrate the performance of the WB probability boundaries for a system using an adaptive ULA and a system using an adaptive UCA against the average SNR per bit for a different number of active mobile users per CDMA carrier per cell. For a given level of BER and a given number of active users, the corresponding average SNR per bit can be determined for each configuration.

An increase in the value of σ_{dB} will again undesirably decrease the performance of the systems as shown in Figure 5.12, 5.13, 5.14 and 5.15.

Likewise, the lognormal shadowing also has a negative effect on the system using the 4-element adaptive array as shown in Figures 5.16, 5.17, 5.18 and 5.19.

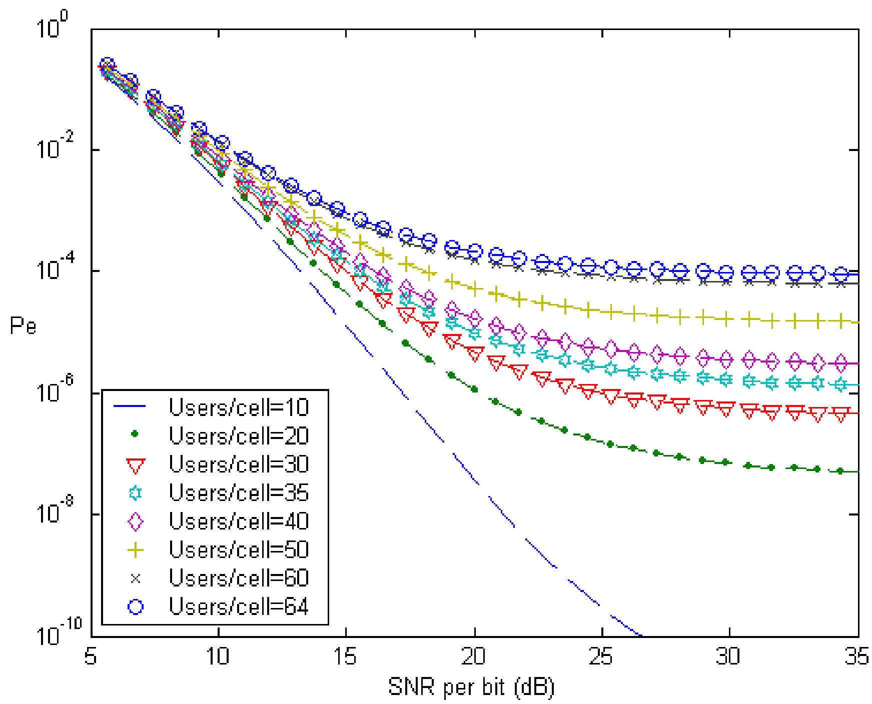

Figure 5.8 WB Performance Boundaries for the DS-CDMA System with a 3-Element ULA Array System $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

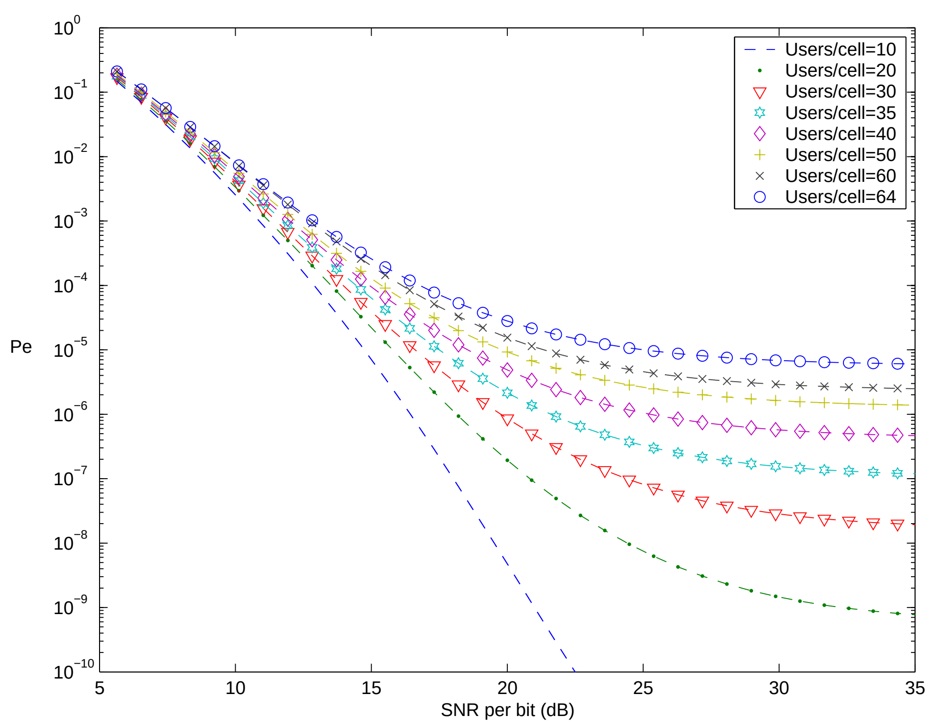

Figure 5.9 WB Performance Boundaries for the DS-CDMA System with a 3-Element UCA Array System $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

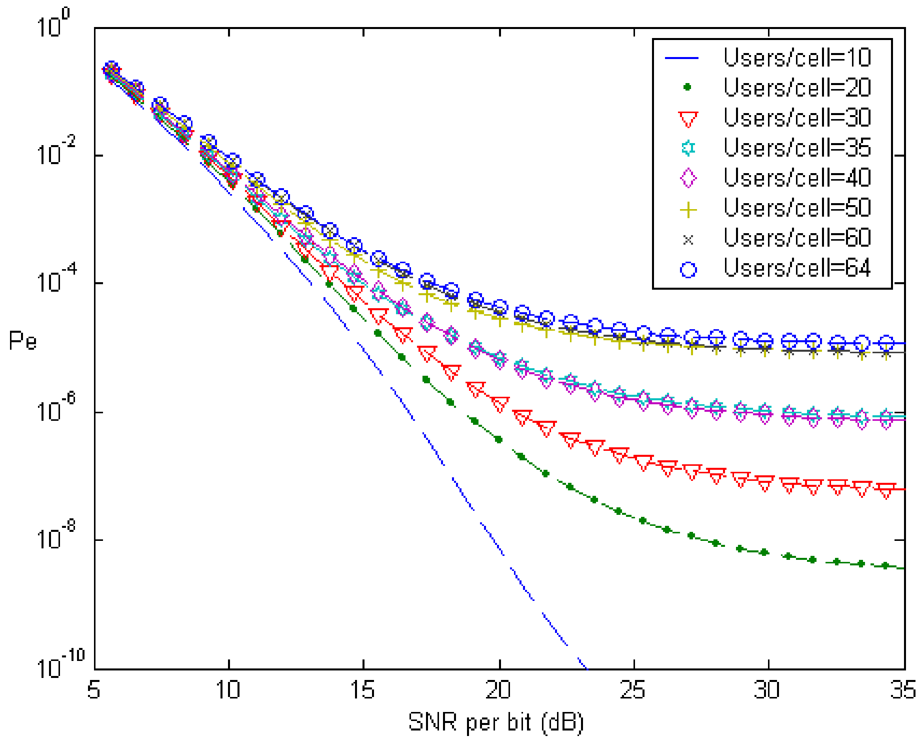

Figure 5.10 WB Performance Boundaries for the DS-CDMA System with a 4-Element ULA Array System $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

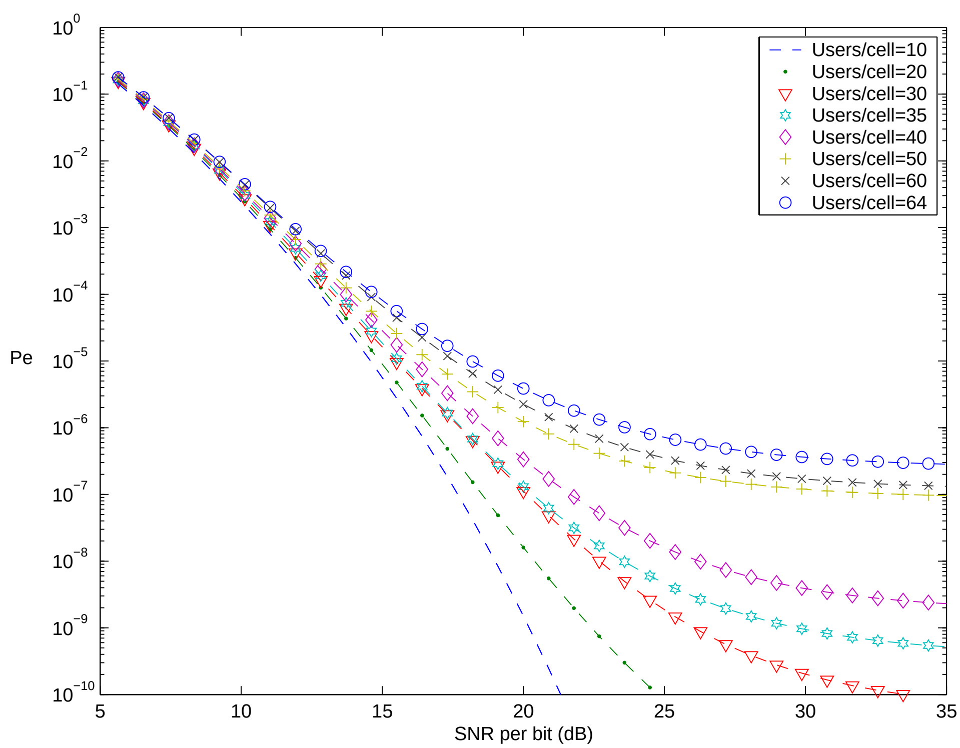

Figure 5.11 WB Performance Boundaries for the DS-CDMA System with a 4-Element UCA Array System $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

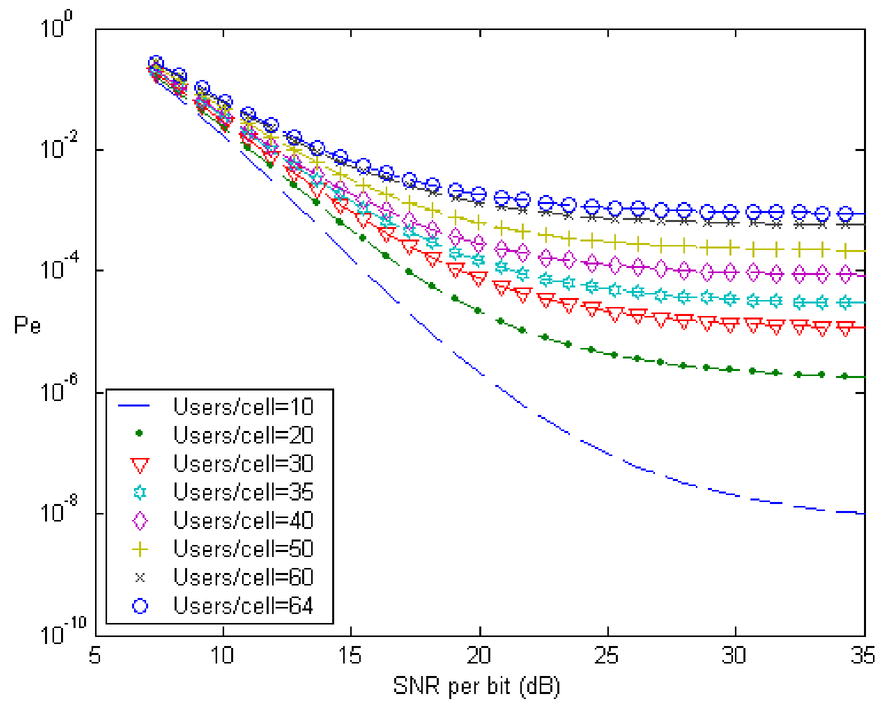

Figure 5.12 WB Performance Boundaries for the DS-CDMA System with a 3-Element ULA Array System $\left(\sigma_{dB}=8, Rcc=1/2, \nu=8\right)$

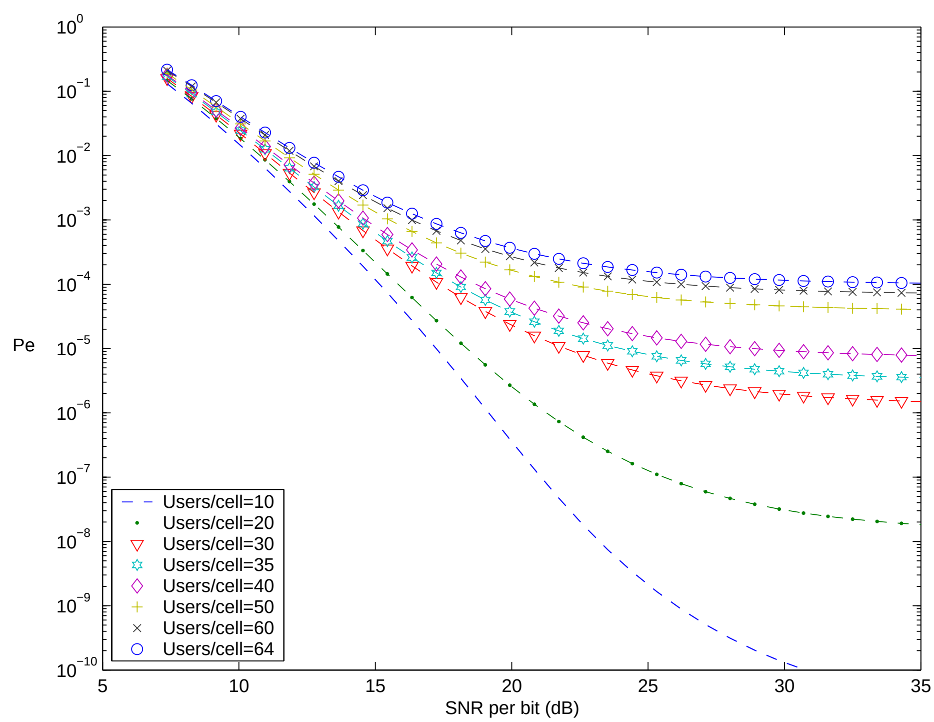

Figure 5.13 WB Performance Boundaries for the DS-CDMA System with a 3-Element UCA Array System $\left(\sigma_{dB}=8, Rcc=1/2, \nu=8\right)$

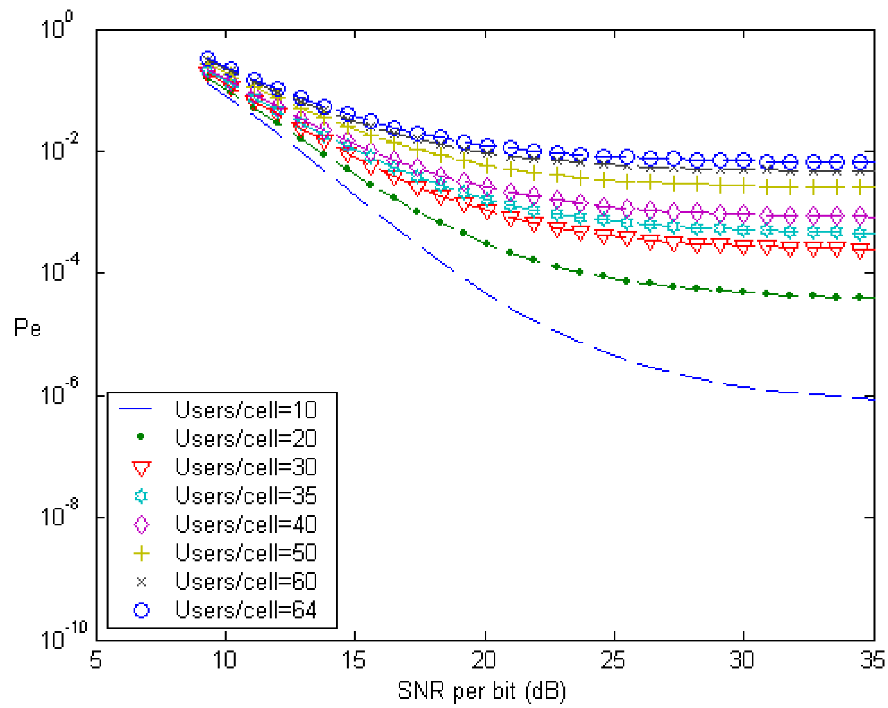

Figure 5.14 WB Performance Boundaries for the DS-CDMA System with a 3-Element ULA Array System $(\sigma_{dB}=9, Rcc=1/2, \nu=8)$

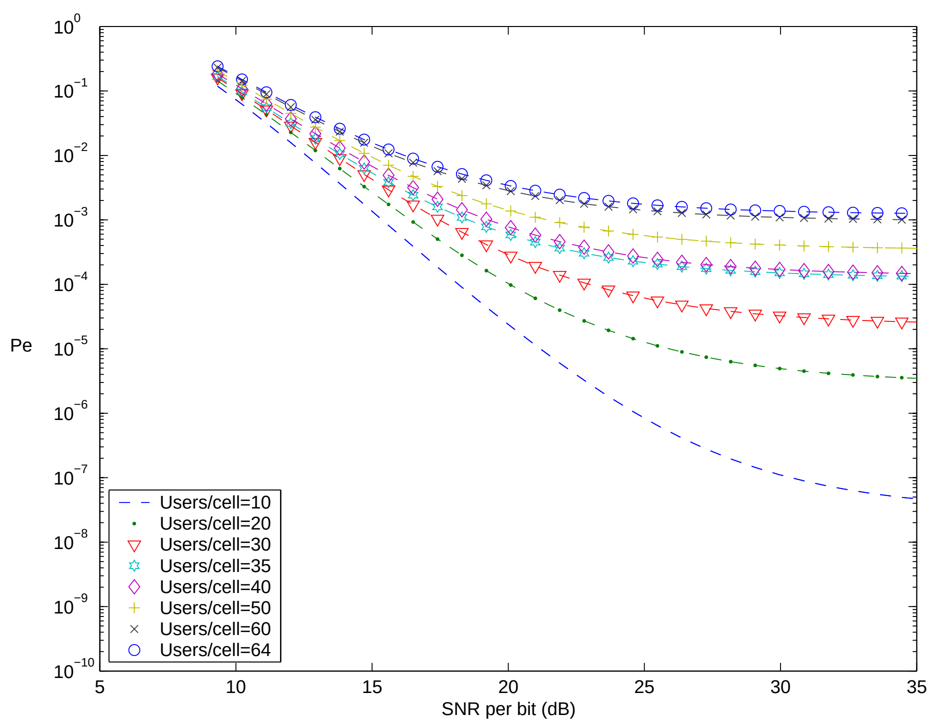

Figure 5.15 WB Performance Boundaries for the DS-CDMA System with a 3-Element UCA Array System $(\sigma_{dB}=9, Rcc=1/2, \nu=8)$

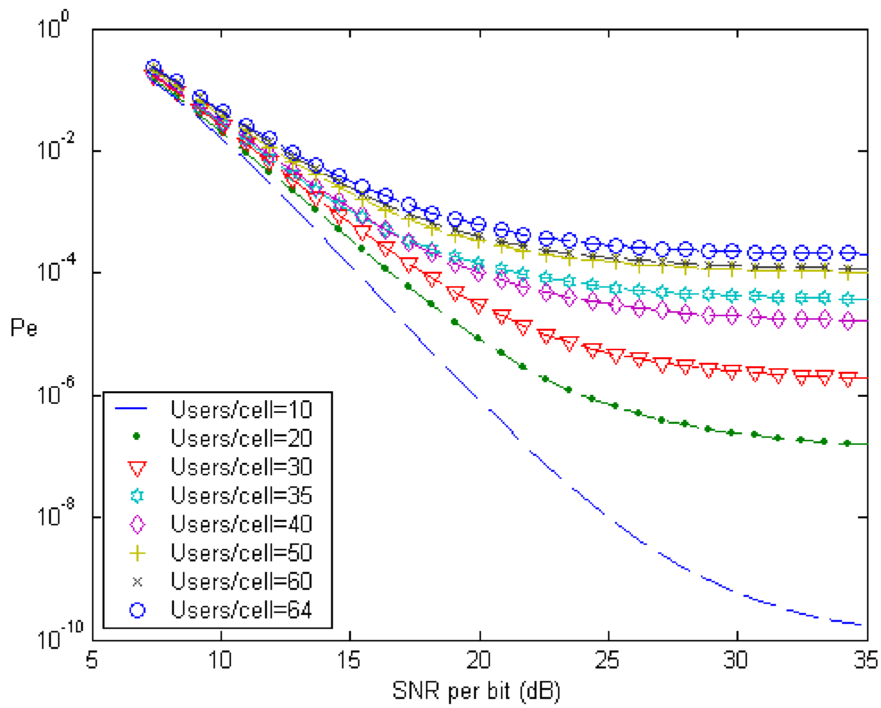

Figure 5.16 WB Performance Boundaries for the DS-CDMA System with a 4-Element ULA Array System $\left(\sigma_{dB} = 8, Rcc = 1/2, \nu = 8\right)$

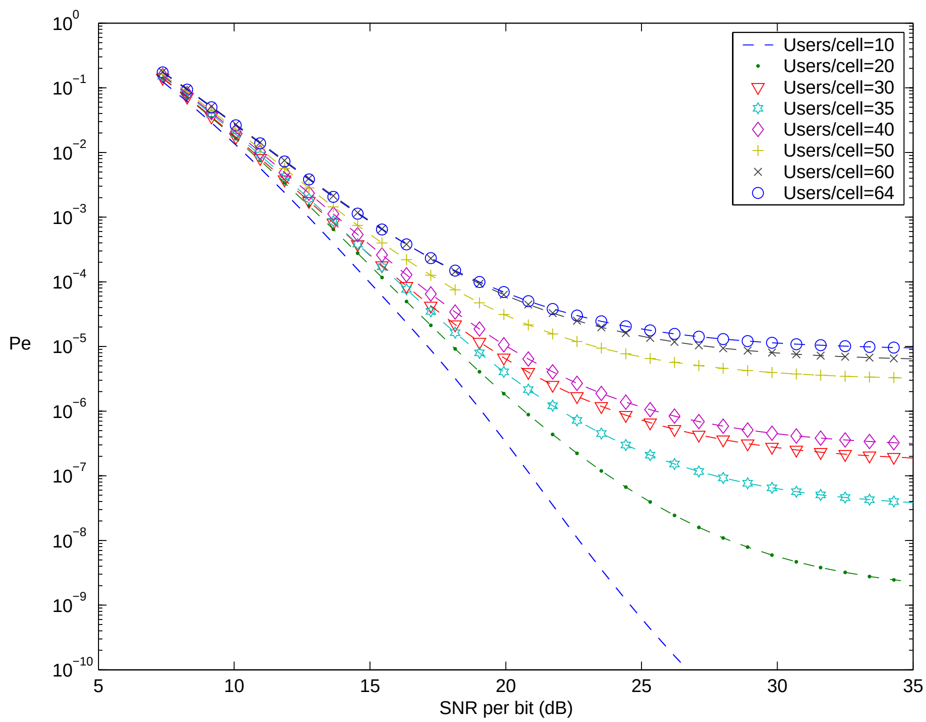

Figure 5.17 WB Performance Boundaries for the DS-CDMA System with a 4-Element UCA Array System $\left(\sigma_{dB} = 8, Rcc = 1/2, \nu = 8\right)$

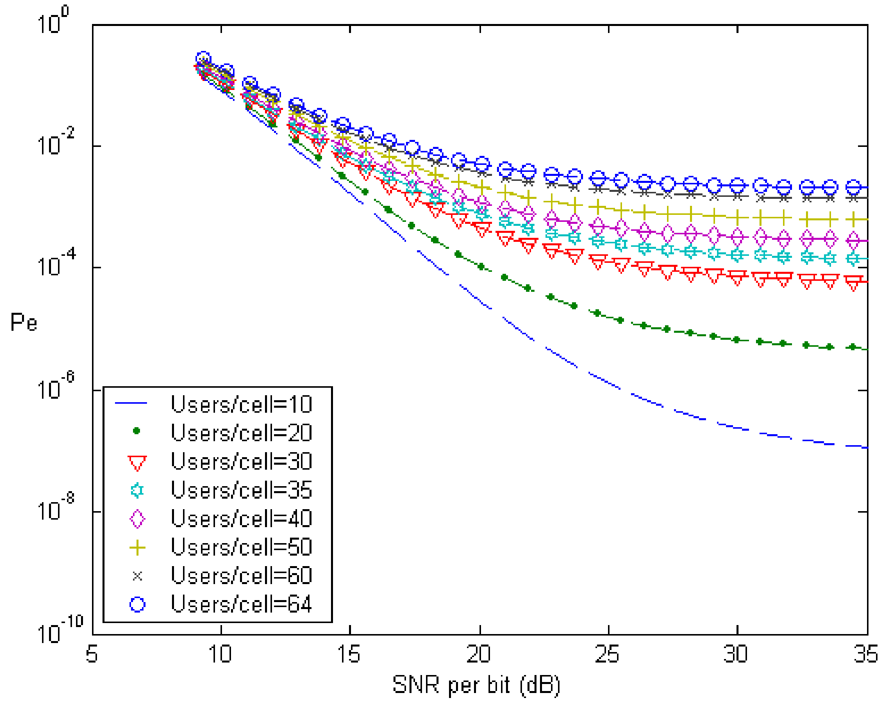

Figure 5.18 WB Performance Boundaries for the DS-CDMA System with a 4-Element ULA Array System $\left(\sigma_{dB}=9, Rcc=1/2, \nu=8\right)$

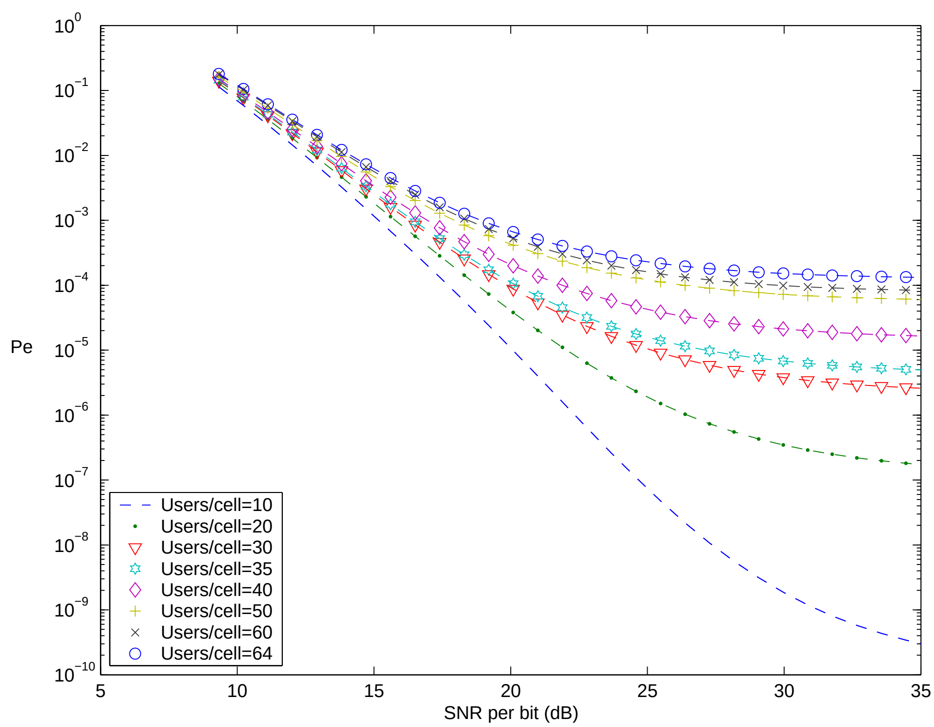

Figure 5.19 WB Performance Boundaries for the DS-CDMA System with a 4-Element UCA Array System $\left(\sigma_{dB}=9, Rcc=1/2, \nu=8\right)$

It is interesting to note from Figures 5.12, 5.13, 5.16 and 5.17 that there are cases in which the performance of the system with the adaptive ULA is as good as, or slightly better than that of the system with the adaptive UCA. This may be possibly due to the non-linear PLR optimization, which steers the different nulls toward different interferers. The optimized null depths, which depend on the initial guess values, the number of interferers, and the relative mobile and base stations' orientation, are very much algorithm dependent. This illustrates the complexity of analyzing a system that depends on multiple factors with each factor affecting the system's overall performance.

Furthermore, as the number of users per cell increases, the system with an adaptive UCA does not significantly improve the system when compared to the adaptive ULA. This is because the system with the adaptive UCA has reached its saturation level. Further improvement can only be achieved with better initial guess values, reducing the number of interfering signals, etc. Nevertheless, the antenna array with more elements generally can suppress more interfering signals and offer better overall system performance everywhere within the cell.

C. ADAPTIVE ARRAY WITH SECTORING

Sectoring, as discussed in Chapter II, is a technique to reduce the amount of intercell interference. This commonly employed technique was investigated to see whether further improvement could be achieved in conjunction with the adaptive array. The 120^0 and 60^0 sectoring techniques were implemented on the systems with the adaptive arrays. The results were plotted in Figures 5.20 and 5.21.

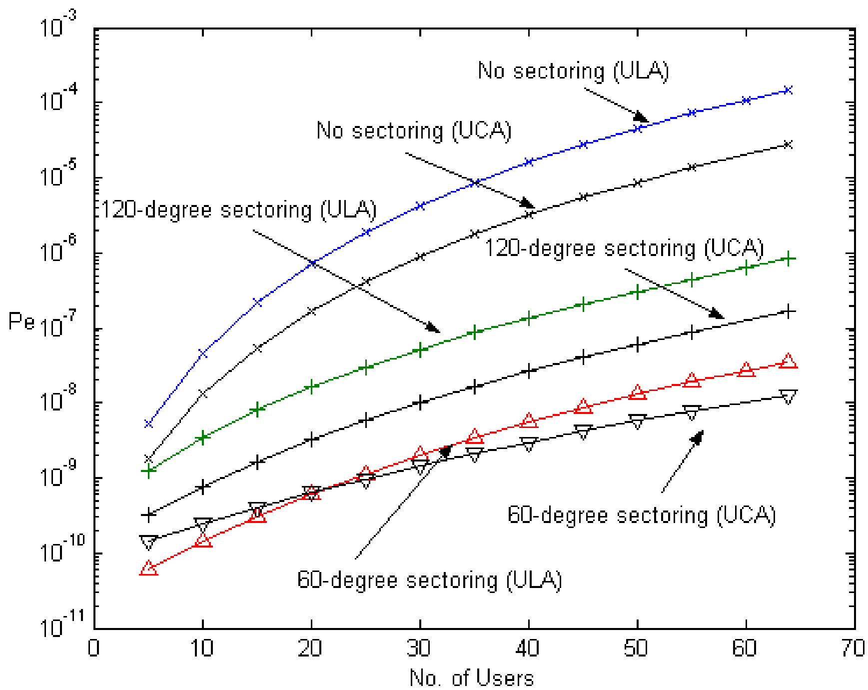

Figure 5.20 Probability of Bit Error for a 3-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15 dB $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

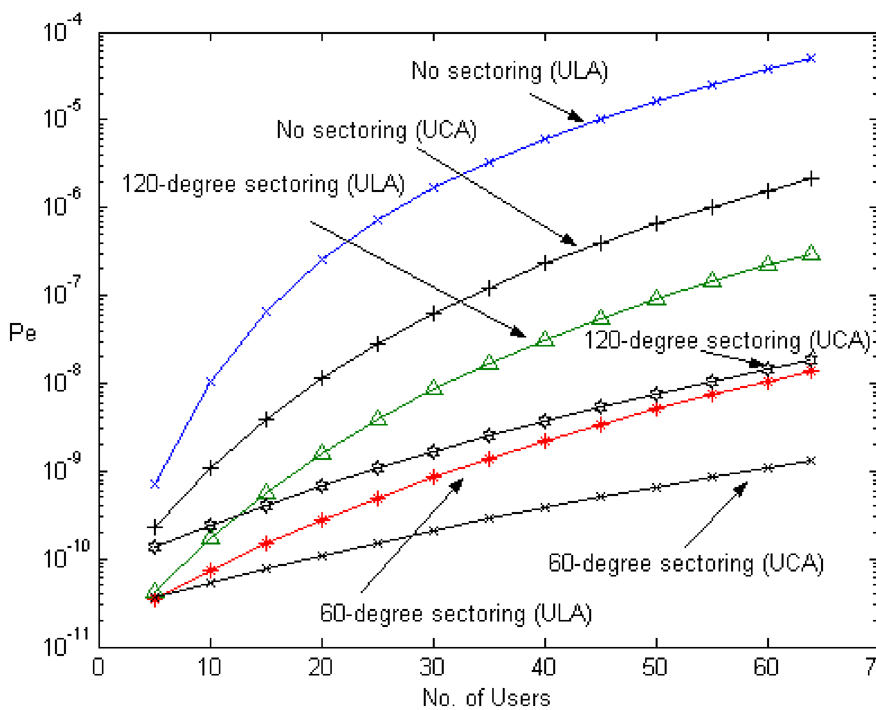

Figure 5.21 Probability of Bit Error for a 4-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15 dB $\left(\sigma_{dB} = 7, Rcc = 1/2, \nu = 8\right)$

The figures showed the BER versus the number of users for systems with a 3- and 4-element adaptive ULA and UCA in the coded DS-CDMA forward channel. The average SNR per bit and the fading parameter (σ_{dB}) are set at 15 dB and 7 dB, respectively. The mobile stations are assumed to be uniformly distributed within the cells.

The results proved that sectoring significantly improves the system's performance and accommodates more mobile stations within the cell. With the BER set at 10^{-8}, the capacity of the system with the 3-element adaptive UCA jumped from 9 mobile stations to 61 mobile stations (6.8 times more) when 60^0 sectoring was employed as shown in Figure 5.20.

Similarly, with the BER set as 10^{-8}, the capacity of the system with a 4-element adaptive UCA jumped from 19 mobile stations to 54 mobile stations (2.8 times more) when 120^0 sectoring was employed as shown in Figure 5.21. The improvement would be larger with 60^0 sectoring.

From the figures above, it is interesting to note that in most cases, though the adaptive UCA outperforms the adaptive ULA, there are cases in which the system with the adaptive ULA array performs better. This could be due to the non-linear ISR optimization algorithm, which depends heavily on the initial guess values, as discussed in Chapter III.

Increasing the shadowing parameter σ_{dB} corresponds to an environment with a deeper fading variation. With the BER still set as 10^{-8}, the 3-element adaptive UCA array system's capacity with 60^0 sectoring will reduce from 61 $(\sigma_{dB} = 7 \text{ dB})$ to 26 $(\sigma_{dB} = 8 \text{ dB})$ and 9 $(\sigma_{dB} = 9 \text{ dB})$ mobile stations, as shown in Figures 5.22 and 5.23.

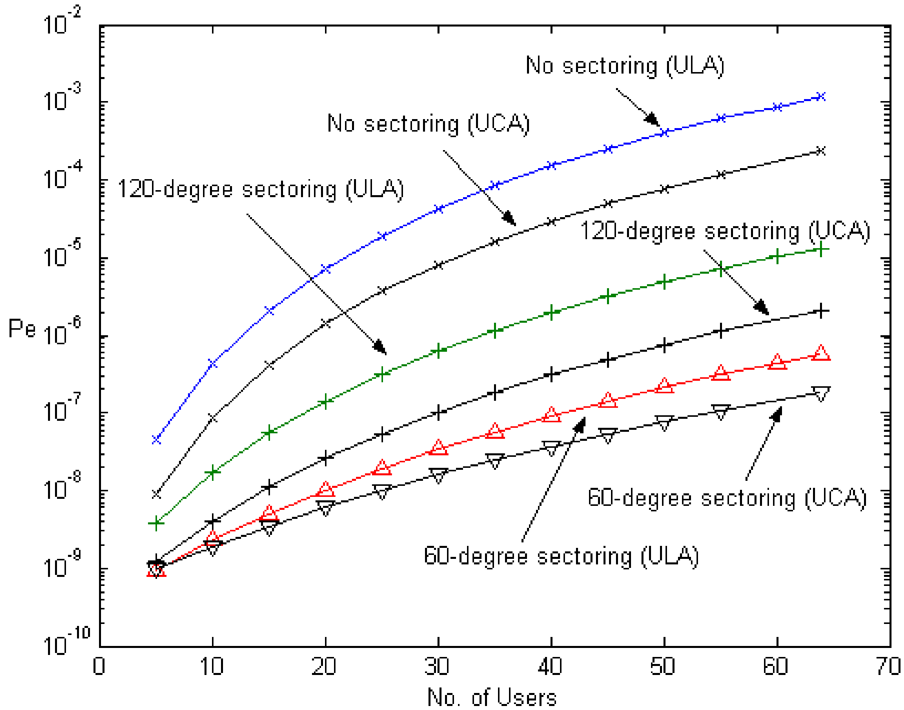

Figure 5.22 Probability of Bit Error for a 3-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15 dB $\left(\sigma_{dB}=8, Rcc=1/2, \nu=8\right)$

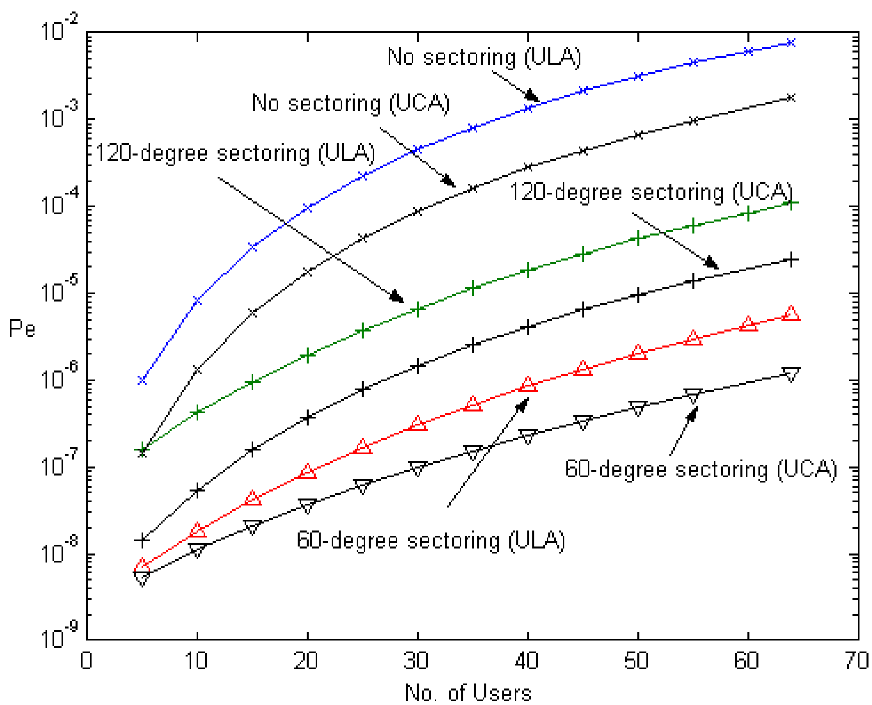

Figure 5.23 Probability of Bit Error for a 3-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15dB $\left(\sigma_{dB}=9, Rcc=1/2, \nu=8\right)$

Similarly, increasing the shadowing parameter σ_{dB} will decrease the performance of the 4-element adaptive array.

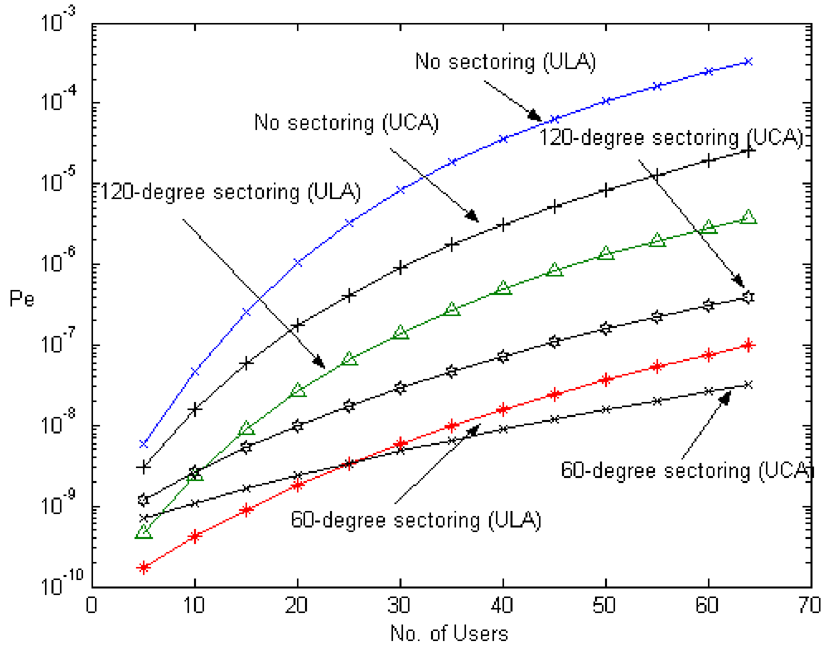

Figure 5.24 Probability of Bit Error for a 4-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15 dB $\left(\sigma_{dB} = 8, Rcc = 1/2, \nu = 8\right)$

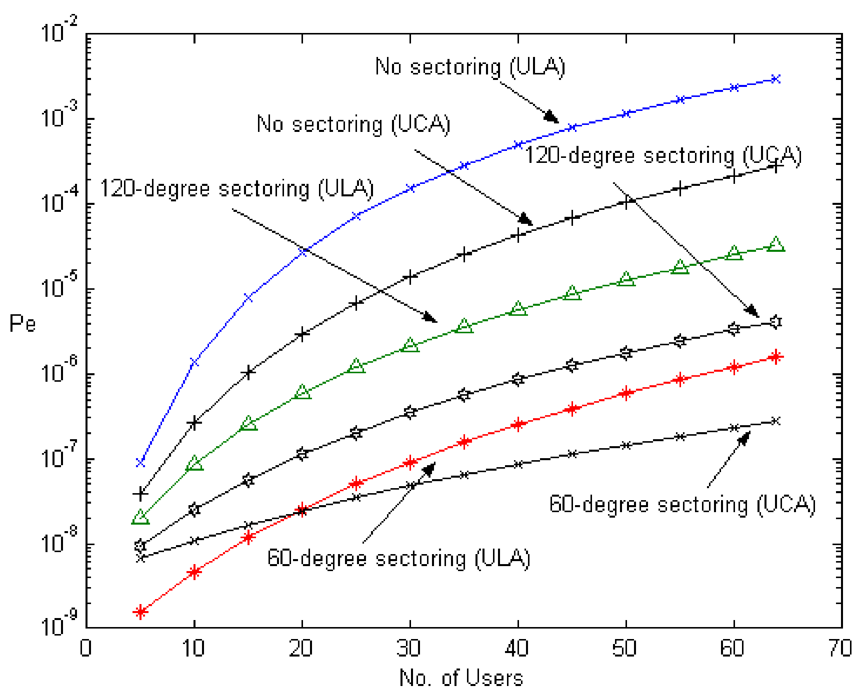

Figure 5.25 Probability of Bit Error for a 4-Element Adaptive Array DS-CDMA System Using Sectoring with a SNR per Bit of 15 dB $\left(\sigma_{dB} = 9, Rcc = 1/2, \nu = 8\right)$

D. SUMMARY

Four performance boundaries were obtained from the simulation results. The most representative boundary is the worst of the best BER (WB) case as it gave a good indication of the performance of the system.

From the simulation results, it can be seen that generally, the adaptive UCA performs better than the adaptive ULA. The interference from adjacent cells can be reduced with the sectoring technique (Chapter II). Both the 60^0 and 120^0 sectoring techniques were performed on the systems. The capacity of the system with the 3-element adaptive UCA was increased by 5.8 times with 60^0 sectoring while the capacity of the 4-element adaptive UCA was increased by 2.8 times with 120^0 sectoring.

On the other hand, increasing the shadowing parameter σ_{dB}, which corresponds to an environment with a deeper fading variation, degrades the performance of the systems regardless of the type of the adaptive array used. Further improvement may be achieved with a better initial guessed value for the algorithm or a better defined relative orientation between the mobile and base stations.

VI CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

The performance of the forward channel (base station to mobile station) of a coded direct sequence code division multiple access (DS-CDMA) system in a slow, flat Rayleigh fading and log-normal shadowing environment was analyzed in this thesis. An equally spaced circular antenna array with a 3- and 4-element was implemented on the mobile station.

The optimized 3- and 4-element uniform circular array (UCA) in the coded DS-CDMA forward-channel received signal model was developed. Four performance boundaries were established from the Monte Carlo simulations. The worst of the best (WB) boundary was selected as the performance reference because it was the most representative boundary.

The capacity and performance of the adaptive uniform linear array (ULA) and the adaptive UCA, under a range of shadowing conditions, with and without antenna sectoring at the base station and for various user capacities, were compared.

From the simulation results, generally, the performance of the system with the adaptive UCA is better than or at least on par with the system with the adaptive ULA. However, there are cases whereby the path-loss ratio obtained from the optimization of the 3-element adaptive array is slightly better than that from the 4-element adaptive array. This may be possibly due to the non-linear interference-to-signal ratio (ISR) optimization algorithm that depends heavily on the initial guess values, the number of interferers and the relative mobile and base stations' orientation.

Sectoring techniques significantly reduced the amount of inter-cell interference and improved the system's performance and hence increased the number of mobile stations allowed within the cell. The capacity of the system with the 3- and 4-element adaptive UCA was increased by 5.8 times (with 60^0 sectoring) and 2.8 times (with 120^0), respectively.

On the other hand, increasing the shadowing parameter σ_{dB}, which corresponds to an environment with a deeper fading variation, degrades the performance of the systems regardless of the type of adaptive array used. Further improvement may be achieved with a better initial guessed value for the algorithm or a better defined relative orientation between the mobile and base stations.

In conclusion, the application of the adaptive antenna technology at the mobile station for the third-generation DS-CDMA cellular system can be extended to the military mobile communication systems. Implementing the adaptive UCA on the mobile stations will help to increase the military mobile communication system's capacity and maximum data rates.

B. FUTURE WORK

This thesis uses the classical approach where the null pattern is steered toward the interfering signals based on the estimated direction of arrival (DoA) of the signals. The weights of the antenna are continuously adjusted to maximize the signal-to-interference-plus-noise ratio (SINR) and to provide the maximum discrimination against the undesired interfering signals.

If none of the interfering signals are correlated with the desired signal, then the adaptive array will set the null in the DoA of the interfering signals and a maximum SINR is achieved. However, if one of the interfering signal is highly correlated with the desired signal, which may happen in a multipath environment, then the adaptive array will also attenuate the desired signal.

This can be overcome by using an adaptive array with a steering vector that exploits the Vandermonde structure [2] to decorrelate the correlated signals. This approach will divide the adaptive array into a number of equal size overlapping sub-arrays. The decorrelated covariance matrix is obtained by averaging the covariance matrices of the subarrays.

Unlike the adaptive ULA, the steering vector of the adaptive UCA does not have the Vandermonde structure. As a future research subject, the DS-CDMA system performance analysis with the adaptive UCA in a Rayleigh fading and log-normal slow fading environment can be extended to a system that combines the advantages of the adaptive ULA with the inherent superior geometry characteristics of the adaptive UCA.

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