A STUDY ON PROPAGATION CHARACTERISTICS AND INTERFERENCE OF SPREAD SPECTRUM CODE DIVISION MULTIPLE ACCESS CELLULAR RADIO SYSTEMS

By

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Abstract

Owing to the demand for the cellular radio services, people are looking for different ways to increase the capacity of a cellular radio system. Spread spectrum technique is proposed for the next generation system as a standard multiple access scheme. Theoretically, spread spectrum Code Division Multiple Access (CDMA) systems can provide much higher capacity than that of Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) systems.

In CDMA cellular radio systems, all users transmit on the same frequency spectrum. The signal received at the base station is distinguished by using one's dedicated code. By the orthogonality property of the codes, one's signal can be retrieved from a mixture of signal, which comprises signals from all the users. Consequently, the channel can be accessed simultaneously by a number of users. In reality, codes cannot be completely orthogonal to each other cyclically. Practical systems use Pseudo Random Bit Sequences (PRBS), which is near orthogonal but not completely orthogonal. Signals from different users would interfer each other according to the degree of correlation of the codes. This kind of interference is described as Multiple Access Interference (MAI) and would bound the capacity of a system. Furthermore, if users transmit at the same power level no matter where they are, signals from users close to the base station will overwhelm the signals of users away from the base station. This is called the near-far effect. For combating the near-far effect, users have to control their transmission power such that their signals arrive at the base station with the same power level. Nevertheless, the power of any users or base stations will be "leaked" to the other cells and causes the adjacent cell interference (ACI), which is unavoidable. Under different propagation characteristics, the adjacent cell interference would be different. In this thesis, the adjacent cell interference under different propagation characteristics would be analyzed. The objective of this thesis is to obtain some useful formula for the design of a CDMA cellular radio system. The cases in ideal circumstance, in the presence of long-term fading and short-term fading are studied. In addition, ACI in microcellular systems is also analyzed. A closed-form solution of the ACI is obtained. Further, since the capacity of a CDMA system would greatly depend on the accurate control of the transmission power of each user, the effect of the imperfection of power control on the system capacity is also investigated. A relationship between the standard deviation of the signal power and the system capacity is obtained. The result obtained in this thesis can be used for the system planning of a CDMA cellular radio system in different environment.

Keywords: Code Division Multiple Access (CDMA), Cellular Radio, Adjacent Cell Interference, Propagation, Imperfect Power Control and Microcell.

Contents

Chapter 1

Introduction

Cellular Radio Communications is one of the fastest developing technology in the telecommunication industry. Since the launch of the first cellular radio system in the mid '70, the development of cellular systems has already reached the third generation. It is just about twenty years for the first cellular radio system evolved into the most advanced cellular systems nowadays. Part of the challenging in planning future wireless systems is to determine the services that they will be required to support. People are now looking for an ubiquitous communications at any time in any form, which is called Personal Communications Services (PCS). This has been the major thrust of TG8/1 of the ITU-R (the International Telecommunication Union - Radio-communication sector, formerly CCIR), which is defining Future Public Land Mobile Telecommunication Systems (FPLMTS). Spectrum was allocated on an international basis to FPLMTS at the 1992 World Administrative Radio Conference (WARC '92) [1, 2].

Recently, wireless communication is mainly for providing telephone services. According to multiple access scheme, there are two kinds of cellular radio systems operating in Hong Kong. They are the Frequency Division Multiple Access (FDMA) systems, e.g. AMPS and TACS, and the Time Division Multiple Access (TDMA) systems, e.g. GSM. Owing to the high demand for the cellular radio services, people are looking for a more sophisticated system to provide a much higher capacity. People propose to deploy the technology of Code Division Multiple Access (CDMA) in cellular radio systems [3]. In theory, CDMA has a number of merits over FDMA and TDMA systems [4, 5, 6]. The advantages of CDMA are

1. High capacity
2. Reliable handoff algorithm (Soft handoff - Make before break)
3. Utilization of voice activity to reduce interference
4. Capacity increase by sectorization
5. Universal frequency reuse
6. Graceful degradation of system performance
7. Utilization of multipath signal is possible by RAKE receiver

Nevertheless, owing to the deployment of PRBS instead of completely orthogonal access codes of different users, multiple access interferece arises and bounds the system capacity. CDMA has the disadvantage that accurate power control is needed. Otherwise, the system will be broken down due to the near-far effect. That is signals from the users close to the base station will overwhelm the signals of users which are far away. When power control is deployed in CDMA systems, signals from mobile users have to be controlled such that all of the received signals at the base station will have the same power. On the other hand, even the power control is perfect, the power from any user will "leak" to the adjacent cells and affect the quality of the channels at the adjacent cells. The corresponding adjacent cell interference will bound the capacity of the system. In this thesis, the effect of adjacent cell interference on the system capacity under different circumstances are going to be studied. The cases in ideal circumstance, in the presence of log-normal fading and microcellular propagation environment will be analyzed. Lastly, the effect of imperfect power control on the system capacity will be analyzed.

The thesis will be organized as follows: the theory of cellular concept and spread spectrum CDMA will be presented in the subsections 1.1 and 1.2 of this chapter. The propagation characteristics of different environment will be presented in the subsection 1.3. The contributions of this thesis is presented in chapter 2. Based on the model presented, the adjacent cell interference will be analyzed in chapter 3, 4 and 5 for the environments of idea circumstance, in the presence of log-normal fading and of microcellular systems, respectively. The effect of imperfect power control on the system capacity will be discussed in chapter 6. Conclusions will be drawn in chapter 7. In the last chapter, two proposed cellular radio systems using CDMA are discussed.

1.1 Cellular Radio Systems

In 1958, AT & T Bell Laboratory proposed the Advanced Mobile Phone System (AMPS), which utilized the cellular concept. Before that, people did not have this concept and channels were supposed to be used once at a time in a service area.

The idea of cellular radio is to reuse the frequency channels by dividing the service area into small cells. All the channels of the system will be allocated to the cells repeatedly by following a certain manner. Channels will be allocated to more than one cell. Users can use any of the nominal channels in a particular cell. By the careful control of the transmission power, a channel can be used simultaneously at different cells without causing too much interference to the other users using the same channel. This is the cellular concept. An example is used to illustrate the idea. A service area is supposed to be divided into a number of cells[1]. Channels are supposed to be allocated to a cluster of 7 cells. The system is said to have a frequency reuse pattern of 7. Assuming there are totally 70 channels for the system, each cell will be allocated 10 channels. Each group of channels is represented as G_i, where $i = 1, 2, \cdots, 7$. The channels in each group may be

$$\begin{aligned}
G_1 &= \{C_1, C_8, \cdots, C_{64}\} \\
G_2 &= \{C_2, C_9, \cdots, C_{65}\} \\
G_3 &= \{C_3, C_{10}, \cdots, C_{66}\} \\
G_4 &= \{C_4, C_{11}, \cdots, C_{67}\} \\
G_5 &= \{C_5, C_{12}, \cdots, C_{68}\} \\
G_6 &= \{C_6, C_{13}, \cdots, C_{69}\} \\
G_7 &= \{C_7, C_{14}, \cdots, C_{70}\}
\end{aligned}$$

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[1] A hexagon will be used to represent a cell

where C_i is the i^{th} channels $i = 1, 2, \cdots, 70$.

In figure 1.1, hexagonal cells are grouped into 7-cell clusters. Each cell of each cluster is allocated a group of channels, which are repeatedly allocated to different cells in different clusters. As a result, assuming there are totally n cells in the system, the number of usable channels is $10n$. As n increases, the number of usable channels increases. Further, as long as $n > 7$, the utilization of the channels will be higher than that in traditional mobile communication systems.

Those cells assigned the same set of channels are called cochannel cells. In ideal circumstance, the distance between any cochannel cells is fixed. Referring to figure 1.1, starting from any cell in any direction, moving towards two cells, turning right by 60^o and moving one cell further, one will reach the cell, which has the same assigned channels of the starting cell.

The frequency reuse pattern K is defined as

$$K = u^2 + uv + v^2 \tag{1.1}$$

where (u, v) are the coordinates of the closest cochannel cell relative to the reference cell in the coordinate system as shown in figure 1.2.

The frequency reuse distance D, which is the distance between two cochannel cells, is given by $D = \sqrt{3K}R$ where R is called cell radius and is the distance from the cell center to any vertex. Reference [4] has a more detail description of cellular radio concept.

Owing to the demand for high capacity services, systems are designed to accommodate as many users as possible. One of the possible ways to increase capacity is to reduce cell size. For different size of cell, the system has different characteristics and advantages. Some of the cell classifications is listed in the following:

1. Macrocell

   Macrocell is used to describe cells used in traditional cellular systems, e.g., AMPS, TACS and GSM. The size of a cell is usually large, ranged from 1 to 20 km. The transmission power is about 1 to 10 W. The propagation delay of the signal is much higher when compared with the other smaller cell systems. Base station antenna is installed at the top of skyscraper.

2. Microcell

   Microcell is proposed to be deployed in the third generation cellular systems. In such systems, the size of each cell is much smaller, ranged from 100 m to 1 km. The transmission power is about 0.1 to 1 W. Since the cell size is small, for a given area, the number of cells would be large. As a result, the total capacity of the system would be much higher than that of macrocellular systems.

3. Picocell

   Picocell is proposed to be deployed in the indoor cellular radio systems. It is supposed to provide the services of wireless local loop or PABX in a building. Picocell are proposed to have base stations installed in each of the story of a building. The size of each cell may even smaller, ranged from 1 to 100 m.

1.2 Code Division Multiple Access (CDMA)

Multiple access scheme in a cellular radio system is the way of accessing a base station by a number of users simultaneously. Since the resources, frequency spectrum and time, are limited for radio communications, the way of sharing the resources is crucial to the efficiency and capacity of the system. In cellular radio systems, popular schemes are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

- Frequency Division Multiple Access

  In FDMA, a given spectrum is divided into frequency bands. Each channel corresponds to a pair of bands for transmission and receiving. When a user wants to make a call, it requests for a channel first. If there is available channel, it is assigned a channel for communications. When it finishes a call, it releases the channel.

- Time Division Multiple Access

  In TDMA, a given spectrum is divided into frequency carriers, usually, which are frequency bands much wider than that of FDMA. For each carrier, time is divided into frames, which correspond to a certain amount of time for transmission. Each frame is divided into a number of time slots. A channel corresponds to a time slot in each frame. When a user wants to make a call, it requests for a time slot. If there is available, it is assigned a time slot. It can transmit its data at that particular time slot in every frame. When it finishes a call, it releases the time slot.

For CDMA, neither the frequency spectrum is divided nor is the time divided. A channel corresponds to a code. When a user wants to make a call, it requests for an identification code. When the system performance is better than the predefined quality of service, the user will be assigned a code. It can communicate by using the code to process its data. The frequency time graph of different multiple access schemes is shown in figure 1.3. There are variants of CDMA. Some typical variants are listed in the followings [7]:

1.2.1 Direct Sequence CDMA (DS-CDMA)

Data from any user will be spread by using a code sequence. Simply, a PRBS with much higher bit rate to multiply with the data is used. Afterwards, the spread data will be modulated for transmission. At the receiver, data from different users are mixed. The dedicated code for a particular user is used to retrieve its signal. Figure 1.4 shows an example to illustrate the principle of CDMA. In the figure, the sets of data from different users are multiplied by different codes. When the bit sequence is transmitted through the channel, the signals are mixed. But, if the receiver signal is further multiplied by any code, the corresponding data can be retrieved even in the presence of other users signals.

Mathematically, for user 1, its data sequence $x_1(t)$ is generated at the transmitter at the rate of R bps.

$$x_1(t) = \sum_{i=0}^{\infty} b_{1,i} \mathrm{rect}\left(\frac{t - iT}{T}\right) \tag{1.2}$$

where $b_{1,i} \in \{1, -1\}$, $T = \frac{1}{R}$ and $\mathrm{rect}(\cdot)$ is the rectangular function

$$\mathrm{rect}(\frac{t}{T}) = \begin{cases} 1 & \text{if } 0 \leq t < T \\ 0 & \text{otherwise.} \end{cases} \tag{1.3}$$

The data sequence will be encoded by a PRBS $c_1(t)$ with chip rate R_s, where $R_s >> R$

$$c_1(t) = \sum_{j=0}^{\infty} c_{1,j} \mathrm{rect}\left(\frac{t - jT_c}{T_c}\right) \tag{1.4}$$

where $T_c = \frac{1}{R_c}$.

The correlation of the PRBS would be close to orthogonal, i.e.,

$$R_{i,j} = \frac{1}{T} \int_0^T c_i(t) c_j(t) dt = \begin{cases} \rho & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \tag{1.5}$$

where $\rho = \frac{R_c}{R}$ is defined as the processing gain of the system.

After modulation, the signal for transmission is then given by

$$s_1(t) = x_1(t) c_1(t) \cos \omega_c t \tag{1.6}$$

When this signal is transmitted through the channel, signals from different users will be mixed up and at the receiver, the received signal is

$$r(t) = \sum_{i=1}^{m} s_i(t) = \sum_{i=1}^{m} x_i(t - \tau_i) c_i(t - \tau_i) \cos \omega_c (t - \tau_i) + n(t) \tag{1.7}$$

where m is the number of users in the cell, τ_i is the delay of the transmission of signal i and $n(t)$ is the additive white gaussian noise term. The received signal will be passed to the correlation receiver matched to $s_i(t)$. The output will be

$$Z_{i,j} = \int_{(j-1)T}^{jT} r(t) c_i(t) \cos \omega_c t dt \tag{1.8}$$

where $Z_{i,j}$ is the decision threshold for deciding the received j^{th} bit of user i is 1 or 0. If it is larger than 0, it is decoded as an 1. Otherwise, it is decoded as a 0. By the quasi-orthogonal property of the PRBS, the signal strength of other users would be close to zero. As a result, the signal from any users can be retrieved by using its own code in the presence of other users' signals. The block diagram for a typical transmitter and receiver of a CDMA system is shown in figure 1.5. Pursley [8, 9] have studied the effect of the orthogonality of the code on the signal-to-interference ratio and obtained the equation relating the signal-to-interference ratio, the processing gain and the number of users per cell.

$$\frac{S}{I} = \sqrt{\frac{3N}{K-1}} \tag{1.9}$$

where N is the processing gain of the system and K is the number of users per cell. For BPSK, the probability of error will be given by

$$P_e = Q\left[\sqrt{\frac{3N}{K-1}}\right] \tag{1.10}$$

where

$$Q[x] = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-u^2/2}du \tag{1.11}$$

Holtzman [10] obtained a simple but accurate method to calculate the probability of error due to the capturing effect, i.e., the orthogonality of the codes.

$$\begin{aligned} \hat{P}_e &= \frac{2}{3}Q\left[\sqrt{\frac{3N}{K-1}}\right] + \frac{1}{6}Q\left[\frac{N}{((K-1)N/3+\sqrt{3}\sigma)^{0.5}}\right] \\ &\quad + \frac{1}{6}Q\left[\frac{N}{((K-1)N/3-\sqrt{3}\sigma)^{0.5}}\right] \end{aligned} \tag{1.12}$$

with

$$\sigma^2 = (K-1)\left[N^2\frac{23}{360} + N\left(\frac{1}{20} + \frac{K-2}{36}\right) - \frac{1}{20} - \frac{K-2}{36}\right] \tag{1.13}$$

Similar results on different circumstances are obtained in other papers [11, 12, 13, 14, 15].

Why is CDMA called as spread spectrum? The reason is simple. When the signals in different stages are analyzed from the frequency perspective. The spectrum of the original signal will be spread when it is multiplied by a chip sequence, which has a much higher rate. The spectra of the original data, the spread signal and the despread signal and interference are shown in figure 1.6. That is the reason why it is called spread spectrum. When the signal is despread by the code at the receiver, since the correlation between the codes are very small, only the signal encoded by the dedicated code will be retrieved out from the mixed signals. The other will be received as some background noise. As a result, their effect on the signal strength will be small.

For the rest of the thesis, the interference analysis will be based on DS-CDMA systems.

1.2.2 Frequency Hopping CDMA (FH-CDMA)

The frequency spectrum is divided into a number of narrower frequency bands. Users transmit signal by choosing different frequency band at different instant. For instance, if there are totally 100 frequency bands, a user may transmit data at the 48th band for the first second, at the 72nd band for the next second, etc. The other users would follow another pattern to transmit its data. If the sequences of transmission do not collide, the data can reach the destination without contaminated by other users' signals. The receiver can get the data by following the pattern to retrieve the data at the dedicated frequency bands.

1.2.3 Time Hopping CDMA (TH-CDMA)

At the transmitter, data generated at the rate R is transmitted at a much faster rate R_s, where $R_s >> R$. The duration of the transmitted bit will be much shorter. The duration of one data bit $\frac{1}{R}$ is divided into $\frac{R_s}{R}$ time slots. The slot for the bit to be transmitted is not fixed. Rather, it is controlled by a code sequence. For instance, if $\frac{R_s}{R} = 100$, i.e., the duration is only hundredth of the original data, the duration of one original data is divided into 100 time slots. It may be transmitted at the 15th time slot for the first bit, 67th for the second, 2nd for the third, etc. The other users will follow another sequence for transmitting the data bit. As long as the codes of different users are different, they will not transmit the bit at the same time slot. If the receiver knows the code, it can then receive the data by retrieving the data bits at the dedicated instant.

1.3 Propagation Characteristics

For mobile radio systems, propagation characteristics of signals affect the quality as well as the capacity of a system. If the characteristics can be well predicted, the planning of the system will be much easier. In this section, some propagation channel models will be discussed.

A mobile radio signal $r(t)$ can be characterized by

$$r(t) = m(t)r_0(t) \tag{1.14}$$

where $m(t)$ is called local mean and its variation is due to the terrain contour between the base station and the mobile unit. The factor r_0 is called multipath fading and its variation is due to the waves reflected from the surrounding buildings and other structures. $m(t)$ can be obtained by taking the local mean of the signal. The characterization of signals can be divided into two parts [16, 17, 18]:

- Signal Strength Prediction
- Signal Variability

Signal strength prediction is concerned with the mean value of the signal power strength in any small area. The main parameter of concern is the path loss L, which is defined as the diminution of received power with distance. Signal variability is concerned with the variations of the signal from the mean value. It is usually described by a probability distribution function. These variation would have detrimental effects on the systems. In the latter part of the thesis, the effect of Rayleigh fading on the system capacity will be studied.

1.3.1 Signal Strength Prediction – Path Loss

The path loss prediction of radio signal would be crucial to the planning of a radio system. The smaller the signal loss, the higher interference to the cochannel cells will be. If the path loss can be accurately predicted, the amount of interference leaked to the cochannel cell can be determined. Signal strength prediction can be categorized into narrowband and wideband channel characterization. Narrowband channel characterization is for the transmission systems with signal in the frequency band varies in the same way. Wideband channel characterization is for transmission systems with signals which are much wider. That is if the bandwidth is wider than the coherence bandwidth, which will be defined in subsection 1.3.4, it will be described as wideband system. Otherwise, it will be described as narrowband system. Signal amplitudes in the frequency band will not has the same variations.

For CDMA systems, suppose that a transmitted power P_t is used to send a wideband signal with a bandwidth B along a mobile radio path r. The power spectrum over the bandwidth B is $S_t(f)$, then the P_t can be expressed as

$$P_t = G_t \int_{f_0-\frac{B}{2}}^{f_0+\frac{B}{2}} S_t(f)df \tag{1.15}$$

The received power

$$P_r = \frac{P_t}{4\pi r^2} \cdot C(r,f) \cdot A_e(f) \tag{1.16}$$

where $C(r,f) = \frac{k}{r^2 f}$ is the median characteristic and $A_e(f) = \frac{c^2 G_r}{4\pi f^2}$ is the effective aperture of the receiving antenna. k is a constant factor, c is the speed of light, G_t and G_r are the gains of the transmitting and receiving antennas, respectively. Substituting the values of $C(r,f)$, $A_e(f)$ and (1.15) into (1.16),

$$P_r = \frac{kc^2 G_r G_t}{(4\pi r^2)^2} \int_{f_0-\frac{B}{2}}^{f_0+\frac{B}{2}} \frac{S_t(f)}{f^3} df \tag{1.17}$$

The value of $S_r(f)$ is assumed to be constant for $f_0 - B/2 \leq f \leq f_0 + B/2$, for simplicity and without losing much generality. Then (1.17) becomes

$$P_r = \frac{kc^2 G_t G_r}{(4\pi r^2)^2 f_0^3} \left[1 - \left(\frac{B}{2f_0}\right)^2\right]^{-2} \tag{1.18}$$

From (1.18), the B/f_0 ratio for the case of 1-dB difference in path loss between narrowband and wideband may be found. That means by solving the denominator of (1.18) as follows:

$$10\log\left[1-\left(\frac{B}{2f_0}\right)^2\right]^2 = -1 \text{ dB} \tag{1.19}$$

$B = 0.66f_0$ is obtained. In most wideband applications, B will not be wider than $f_0/2$. Therefore, the narrowband propagation path loss should be applied to the wideband propagation path loss. In the following, the path loss models are obtained by the narrowband signal analysis and measurement.

1. Friis equation for Free-Space Transmission [19]

   $$P_r = P_t\left(\frac{\lambda}{4\pi d}\right)^2 G_tG_r \tag{1.20}$$

   where P_r is the received power, P_t is the transmitted power, λ is the wavelength, d is the distance between the transmitter and receiver, G_t and G_r are the antenna gain at the transmitter and at the receiver, respectively. From the equation, the path loss $L = \frac{P_t}{P_r}$ is proportional to the square of the distance between the transmitter and receiver in free-space transmission.

2. Two-path model for propagation over a plane earth [20, 21, 4, 17]

   The complex analytical results for propagation over a plane earth is simplified by Bullington [22] by considering the direct, reflected, and surface waves. Referring to figure 1.7, the power received at the receiver is

   $$P_r = P_t\left(\frac{\lambda}{4\pi d}\right)^2 G_tG_r\left|1+Re^{j\Delta}+(1-R)Ae^{j\Delta}+\cdots\right|^2 \tag{1.21}$$

where R is the ground reflection coefficient

$$R = \frac{\cos\theta - a\sqrt{\epsilon - \sin^2\theta}}{\cos\theta + a\sqrt{\epsilon - \sin^2\theta}}$$

where $a = 1/\epsilon$ for vertical polarization and $a = 1$ for horizontal polarization, θ is the angle of incidence. For typical ground parameters $\epsilon = 15 - j90/F$, where F is the frequency in megahertz. The quantity Δ is the phase difference between the reflected and the directed paths between transmitting and receiving antennas. Let h_t and h_r be the heights of the transmitter and receiver antennas, then Δ is given by

$$\begin{aligned} \Delta &= \frac{2\pi}{\lambda}\left[\left(\frac{h_t + h_r}{d}\right)^2 + 1\right]^{1/2} - \frac{2\pi d}{\lambda}\left[\left(\frac{h_t - h_r}{d}\right)^2 + 1\right]^{1/2} && (1.22) \\ &\approx \frac{4\pi h_t h_r}{\lambda d} \qquad \text{for } d \text{ greater than } 5h_t h_r && (1.23) \end{aligned}$$

Since the earth is not a perfect conductor, some energy is transmitted into the ground, setting up ground currents that distort the field distribution relative to what it would have been over a perfectly reflecting surface. The surface wave attenuation factor A depends on frequency, polarization and the ground constants. An approximate expression for A is given by

$$A \approx \frac{-1}{1 + j(2\pi d/\lambda)(\sin\theta + a\sqrt{\epsilon - \sin^2\theta})^2} \qquad (1.24)$$

For large distances, $\theta \approx 90^o$, $R \approx -1$ and A can be neglected. Equation (1.21) can be reduced to

$$P_r = P_t\left(\frac{\lambda}{4\pi d}\right)^2 G_t G_r \sin^2\left(\frac{4\pi h_t h_r}{\lambda d}\right) \approx P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \qquad (1.25)$$

This is the two-path model equation. From the equation, the path loss is proportional to the fourth power of the distance d. The measurements at different cities [23] confirm that the path loss is approximately four.

There are other models for characterizing the propagation of radio signal in different terrains. References [23, 16, 17] have more models for signal strength predictions.

1.3.2 Signal Variability

Radio propagation environment is time-variant and depends on the surroundings, e.g., vehicles, people, buildings and landscape. Since there are too much factors needed to be considered, probability function is used to model the characteristics of the signal variations. The variation of signal strength can be classified into two parts: long-term and short-term. The long-term fading is the variation of the local mean of the signal strength. The long-term fading statistics can be obtained by taking the local mean of the received signal, i.e., taking the average of the received signal power for a period of 20 to 40 wavelengths. The short-term fading is the fast fluctuation of the signal strength. The statistics of short-term fading can be obtained by simply subtracting the received signal by the local mean.

Long-term fading

In radio propagation environment, there is usually no LOS path between the transmitter and receiver. The received signal is then the result of multiple reflections or diffractions. By considering the receiver signal arrived to the receiver by a multiple of reflections, the path loss can be expressed as the product of several reflection attenuations and free-space losses. [24]

Let Y be the random variable representing the path loss. According to our model of multiple reflections, Y is a product of N independent, positive random variables, X_i, $i = 1, 2, \cdots, N$.

$$Y = X_1 X_2 \cdots X_N$$

A new random variable Z is defined as

$$Z = 10 \log_{10} Y = 10(\log_{10} X_1 + \log_{10} X_2 + \cdots + \log_{10} X_N)$$

By the central limit theorem, the distribution of Z approaches the Gaussian distribution as $N \to \infty$. If Z is Gaussian, then the distribution of Y is log-normally distributed.

$$f_Y(y) = \frac{1}{\sqrt{2\pi}\sigma y} e^{-\frac{(10 \log_{10} y - \mu)^2}{2\sigma^2}} \qquad 0 \leq y < \infty \qquad (1.26)$$

Besides, Chrysanthou and Bertoni [25] investigated the source of the variability of signal mean from the diffraction point of view. They studied the two features which might cause the long-term fluctuation of the signal. One feature they considered was random variations in building height. The second included variations in building design, construction materials, and the presence of trees. By simulations, they obtained satisfactory results in predicting the log-term variations of the signal mean with log-normal distribution. As a result, the signal mean fluctuation is probably due to the two features they considered.

Extensive empirical data indicates that the distribution of the mean path loss is well approximated by log-normal distributions. The standard deviation σ is observed to be in the range of 4 dB to 12 dB.

Short-term Fading

In the followings, some typical channel models for short-term fading are discussed.

1. Gaussian Channel

   When signal variation is due to the additive white gaussian noise (AWGN) generated in the receiver, the channel is modeled as Gaussian channel. The received signal amplitude R_r is simply given by the constant signal amplitude R plus a noise term N, i.e., $R_r = R + N$. The probability density function of the noise term N is simply given by

   $$f_N(n) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{n}{2\sigma^2}} \qquad \text{for } -\infty \leq n \leq \infty \tag{1.27}$$

   The Gaussian channel is usually for microcellular radio systems with line-of-sight (LOS) communications and no multipath.

2. Rayleigh Fading Channel

   In a Rayleigh fading channel, the received signal is the resultant of N plane waves. The received electric field can be expressed as

   $$E(t) = I(t)\cos\omega_c t - Q(t)\sin\omega_c t \tag{1.28}$$

   where $I(t)$ and $Q(t)$ are the in-phase and quadrature components that would be detected by a suitable receiver, i.e.,

   $$I(t) \;=\; \sum_{n=1}^{N} C_n \cos(\omega_n t + \theta_n) \tag{1.29}$$

$$Q(t) = \sum_{n=1}^{N} C_n \sin(\omega_n t + \theta_n) \tag{1.30}$$

and

$$\omega_n = \frac{2\pi v}{\lambda} \cos(\gamma - \alpha_n) \cos\beta_n \tag{1.31}$$

$$\theta_n = \frac{2\pi z_0}{\lambda} \sin\beta_n + \phi_n \tag{1.32}$$

where C_n, ϕ_n, α_n and β_n are the amplitude, phase difference and spatial angles, respectively, of the n^{th} incoming wave with respect to an arbitrary reference. Please refer to figure 1.8 for the definition of the spatial angles, α_n and β_n. The receiving point is assumed to move with a velocity v in the $x - y$ plane in a direction making an angle γ to the x-axis. In these equations, ω_n represents the Doppler shift experienced by the n^{th} component wave. If N is sufficiently large, the in-phase and quadrature components can be modeled as two gaussian random variables with zero mean and variance $\sigma^2 = E[C_n^2]$. For those practical radio receivers which do not normally have the ability to detect the components $I(t)$ and $Q(t)$, they respond to the envelope and phase of the complex signal $E(t)$. The envelope $R(t)$ of the complex signal $E(t)$ is given by

$$R(t) = \sqrt{I^2(t) + Q^2(t)} \tag{1.33}$$

The probability density function of R can be shown to be Rayleigh, i.e.,

$$f_R(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{1.34}$$

where σ^2 is the mean power and $r^2/2$ is the short-term signal power.

The Rayleigh fading channel is usually for modeling the short-term signal variation in most of circumstances of non-LOS communications.

3. Rician Fading Channel

   In Rician fading channel, the received signal consists of a dominant path with many scattered paths. Referring to figure 1.9, the scattered paths are modeled as a two-dimensional Gaussian random variable. In addition to the dominant component, the received signal envelope R is modeled as a Rician probability density function

$$f_R(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + \bar{r}^2}{2\sigma^2}\right) I_0\left(\frac{r\bar{r}}{\sigma^2}\right) \tag{1.35}$$

   where $\bar{r}$ is the amplitude of the dominant component and σ is the standard deviation of the scattered components. Rician distribution is often described in terms of a parameter K defined as

$$K = 10 \log \frac{\bar{r}^2}{2\sigma^2} \mathrm{dB} \tag{1.36}$$

   It is interesting to know that as $K \to 0$, the PDF tends to be a Rayleigh distribution while as $K \to \infty$, the PDF tends to be a Gaussian distribution with mean value $\bar{r}$. As a result, Rayleigh channel and Gaussian Channel may be treated as the special cases of Rician channel.

   The Rician fading channel is used to model the signal variations in LOS radio communications and microcellular mobile radio systems.

4. Others

The received signal is well-described by Rayleigh statistics over a relatively small distance, with local mean over a somewhat larger area being log-normally distributed. When the area of interest is between these two areas, it will be expected to be described by distribution which is a mixture of Rayleigh and log-normal. The following distributions, which are such mixtures, are of our interest.

- Nakagami-m distribution

$$p_m(x) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m x^{2m-1}\exp\left(-\frac{m}{\Omega}x^2\right) \qquad x \geq 0 \text{ and } m \geq \frac{1}{2} \tag{1.37}$$

  where m and Ω are parameters (Ω being the mean square value) and $\Gamma(\cdot)$ is the Gamma function.

- Weibull distribution

$$p_w(x) = \begin{cases} \alpha w x^{w-1}\exp(-\alpha x^w) & x > 0 \\ 0 & x < 0 \end{cases} \tag{1.38}$$

  where $w > 0$ and $\alpha > 0$.

- Suzuki distribution

$$p_s(x) = \int_0^\infty \frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2}\right)\frac{M}{\sigma\alpha\sqrt{2\pi}}\exp\left[-\frac{\log(\sigma/\sigma_0)}{2\alpha^2}\right]d\sigma \tag{1.39}$$

  where σ is the mode of the Rayleigh distribution, α is the shape parameter of the lognormal distribution and $M = \log e = 0.434$.

1.3.3 Delay Spread

Owing to the multipath phenomenon, for a narrow pulse transmitted through the channel, the received signal will no longer be a pulse with negligible width but with a finite spread width. The mean spread width of the received signal by transmitting a very narrow pulse is defined as the delay spread. The higher the delay spread, the longer the duration of a bit at the receiver, which will result to the intersymbol interference (ISI). One way of combating ISI is by equalization. Chuang and more recent simulation studies [26, 27] have confirmed that a good rule-of-thumb for determining the need of equalization for a digital radio system is as follows: if a digital signal has a symbol duration which is more than ten times the root-mean-square (rms) delay spread σ_τ, then an equalization is not required for bit error rates better than 10^{-3}.

Furthermore, delay spread is also related to the path loss. Feuerstein *et al* [28] has proposed the overbound model. An overbound on the path loss can be obtained by using a simple exponential model of the form $\sigma_d = e^{0.065L_d}$, where σ_d is the rms delay spread in nanoseconds and L_d is the path loss in decibels, when the transmitter and receiver separation is d.

1.3.4 Coherence Bandwidth

The coherence bandwidth is defined as the bandwidth in which either the amplitudes or the phase of two received signals have a high degree of similarity. The delay spread is a natural phenomenon, and the coherence bandwidth is a defined creation related to the delay spread. Coherence bandwidth W_c can be approximated by the reciprocal of the delay spread σ_d

$$W_C \approx \frac{1}{\sigma_d}$$

If the bandwidth of the transmitted signal is sufficiently narrow, then all the transmitted frequency components will receive about the same amount of attenuation, and the signal will be passed undistorted. The channel is called frequency non-selective fading channel. Otherwise, the transmitted spectrum will start to be attenuated by different amounts. For the rest of the thesis, the propagation channel is assumed to be frequency non-selective.

1.4 Power Control in Cellular Radio Systems

Power control is an important issue in the design of cellular radio systems, especially for CDMA systems. Some of the result obtained in this issue will be discussed.

1.4.1 Centralized Power Control

Centralized power control means the cellular system would have a centralized controller to control the transmission power of different units in the system.

- Aein [29] proposed the idea of Power Balancing in frequency reuse system. He considered that for a radio receiver in the system, the received signal P_R from a mobile i would be interfered by other users and given by

$$P_R = G_{ii}P_i + \sum_{j=1,j\neq i}^{N} G_{ij}P_j, \qquad \forall i \in [1, N]$$

where G_{ij} is the link gain from mobile j to base i and P_i is the power transmitted at the transmitter of mobile i. By these N equations, a matrix equation can be obtained. By finding the eigenvalues and eigenvectors of the link gain matrix $\mathbf{Z} = [Z_{ij}]$, which is defined by

$$Z_{ij} = \begin{cases} G_{ij}/G_{ii} & \text{if } i \neq j \\ 0 & \text{if } i = j \end{cases}$$

the optimum transmitting power of different mobiles can be obtained such that the C/I of them are maximized.

- Zander [30] based on the idea of Aein and proposed a centralized power control scheme called the *Stepwise Removal Algorithm* (SRA) to control the power transmitted by each mobile in the system.
- Grandhi *et al* [31] modified the algorithm of Zander [30] such that the C/I of each mobiles are equal after power adjustment.
- Chuah *et al* [32] simulated different channel assignment schemes based on different criteria of power balancing.

1.4.2 Distributed Power Control

When each mobile unit or base station adjusts its power according to its information obtained, it is called distributed power control. Distributed power control schemes would be more practical for cellular radio systems.

- Zander [33] proposed a distributed algorithm – *Distributed Balancing Algorithm*, which adjusts the power transmitted by different mobiles such that the carrier-to-interference ratios of each mobiles converge.

The Distributed Balancing Algorithm (DB Algorithm)

$$P^{(0)} = P_0, \qquad P_0 > 0$$

$$P_i^{(\nu+1)} = \beta P_i^{(\nu)} \left(1 + \frac{1}{\Gamma_i^{(\nu)}}\right), \qquad \beta > 0.$$

where $P_i^{(\nu)}$ is the power transmitted by mobile i at the ν iteration, β is some positive constant and $\Gamma_i^{(\nu)}$ is the carrier-to-interference ratio of mobile i at the base station at the ν iteration.

Zander has also proposed an algorithm of how each mobiles adjust its power based on its own information from its base. He called it as *Limited Information SRA-Algorithm (LI-SRA)*. On the other hand, he has stated that there is a practical problem that the transmitter power in the DB algorithm are all increasing, unless the parameter β is chosen in a proper way. Ideally, selecting

$$\beta = \beta(\nu) = \frac{1}{[P^{(\nu)}]}$$

would ensure a "constant" average power level. However, calculating this quantity may not be possible in a completely distributed system since it would require knowledge about the power levels in all links. This would be a topic for further research.

- Grandhi *et al* [34] modified the DB algorithm of Zander [33]. The power adjustment made by the i^{th} mobile at the n^{th} time instant is given by

  $$P_i^{(n)} = \frac{cP_i^{(n-1)}}{\gamma_i^{(n-1)}}, \qquad 1 \le i \le M, \qquad n \ge 1,$$

  where $P_i^{(n)}$ is the power transmitted by the i^{th} mobile at the n^{th} iteration, $\gamma_i^{(n)}$ is its resulting CIR, and c is some positive constant. They have shown that the new algorithm converges faster than Zander's algorithm.

- Mitra [35] investigated an asynchronous cellular radio system. He gave an asynchronous adaptive algorithm for power control in cellular radio systems, which relaxes the demands of coordination and synchrony between various mobiles and base stations.

- Foschini and Miljanic [36] investigated a simple distributed autonomous power control algorithm and its convergence. First, if the i^{th} user evolves his signal-to-interference ratio, $\rho_i(t)$, to drive it towards the desired amount ρ by an amount proportional to the offset from ρ. Expressing this dynamic using β to denote the (necessarily positive) proportionality constant, they have

  $$\dot{\rho}_i(t) = -\beta[\rho_i(t) - \rho],$$

  They have found the condition of convergence.

  Proposition: If there is a power vector p^*, for which the desired ρ_i values are attained, then no matter what the initial $p_i(0)$, each of the $p_i(t)$ evolving according to

  $$\dot{p}_i(t) = -\beta \left[p_i(t) - (\rho/G_{ii}) \left[\nu + \sum_{j \neq i} G_{ij} p_j(t) \right] \right], \qquad (i = 1, 2, \cdots, J).$$

  will converge to p^*. In which, ν is the power of the additive receiver noise at the user sites.

  Furthermore, in more precise difference equation form of algorithm, the power vector $P(k)$ of the mobiles is adjusted iteratively with

  $$\mathbf{P(k+1) = R_0 P(k)} + \eta$$

where R_0 has $\rho G_{ij}/G_{ii}$ in each nondiagonal $(i,j)^{th}$ position and zero along the diagonal, while the generic (i^{th}) component of ν is $\rho\nu/G_{ii}$ and

$$\eta = \rho[(\nu/G_{11}), (\nu/G_{22}), \cdots, (\nu/G_{JJ})]'$$

- Wong and Lam [37] proposed a new distributed power control scheme for cellular radio systems – *The Cooperative Algorithm*, which bases on limited information links between cochannel cells and adjusts the power transmitted by the mobiles in the systems such that maximizes the carrier to interference ratio in the system. The new algorithm is defined by the following set of equations:

  The Cooperative Algorithm

  $$\begin{aligned} P_i^{(0)} &= P_M && (1.40) \\ P_i^{(n+1)} &= \alpha_i^n P_i^{(n)} && (1.41) \end{aligned}$$

  $$\alpha_i^n = \left[\frac{\min(\Gamma_i^{(n)}, \max(\min_{j\in N_i} \Gamma_j^{(n)}, \gamma_0))}{\Gamma_i^{(n)}}\right]^{1/m}$$

  where N_i is the set of indices of base stations that send control data information to base station i according to the control data flow structure, γ_0 is minimum C/I ratio for transmission with acceptable quality, P_M is the maximum transmission power level of the mobile unit, and $m \geq 1$ is a parameter of the algorithm that control the rate of convergence.

  They have shown that the rate of convergence is much faster than the algorithm proposed by Zander in [33].

- Yates and Huang [38] related the problem of power control with base station assignment. They proposed a distributed algorithm for a mobile to adjust its power according to the carrier-to-interference ratios of different base stations. In case the C/I of one base is larger than the host base, the mobile will be switched to that base station (i.e., Handoff). They have proved that their algorithm converges no matter what circumstance is.

1.4.3 CDMA Power Control

In CDMA systems, the power control issue would be much more crucial to system performance. If the control is not done well, the system capacity would be significantly reduced. The power control schemes for the reverse- and forward-link would be quite different.

Reverse-link Power Control

The power control for the reverse-link of CDMA cellular radio systems would be simply adjusting the transmission power of each mobile units such that the received power at its home base station is constant at any time. It is concerned with the estimation of the link gain between a mobile unit and its base station. The practical implementation of the estimation of link gain in the presence of fading will be discussed in chapter 8.

Moreover, Nettleton and Alavi [39] introduced the concept of power balancing to the power control of CDMA systems. They formulated the power control problem into an eigenvalue problem. The optimum transmission power vector for all the mobile units can be obtained by solving the eigenvector of the matrix equation. Their method can be applied to control the power transmission of the reverse- and forward-link.

Forward-link Power Control

For the forward-link, by the power balancing, the optimum transmission power of each base station can be obtained. Further, Gejji [40] proposed a novel forward-link power control scheme. He was concerned with the users on the two extreme positions. He formulated the power control problem into a maximin problem. The optimum transmitting power at different locations can be obtained.

Mathematically, the power control function $f(x)$ controls the amount of power transmitted according to the position of the user ($x = r/R$, $r =$ distance of the user from the cell center and R is the cell radius). It should be found by maximizing

$$\min_{x} \frac{f(x)}{h(x)\int_0^1 y f(y) dy} \tag{1.42}$$

subject to $f(x) \geq 0$, and $f(1) = 1$. In (1.42), $h(x)$ is the variation in received total power relative to home cell power and depends on the position of the user.

Moreover, Zorzi [41] has proposed a simplified forward-link power control law (PCL) in cellular CDMA. He proposed the floor power control law

$$\Lambda_f(r) = [\Lambda_f(1) - \Lambda_f(0)]r^n + \Lambda_f(0) \tag{1.43}$$

where $\Lambda(r) \triangleq \frac{3L}{M}\varphi(r)$, r is the the distance between the mobile unit and the base station and n is the parameter for optimizing the system utilization. In which, L, M and $\varphi(r)$ are the processing gain, the number of admitted users per cell and the power control law of the system when the user is at a distance r from the base station, respectively. $\Lambda_f(0)$ and $\Lambda_f(1)$ are some special values which are obtained in [41]. Zorzi has shown that the optimum value of n is between 5 and 6 in the paper.

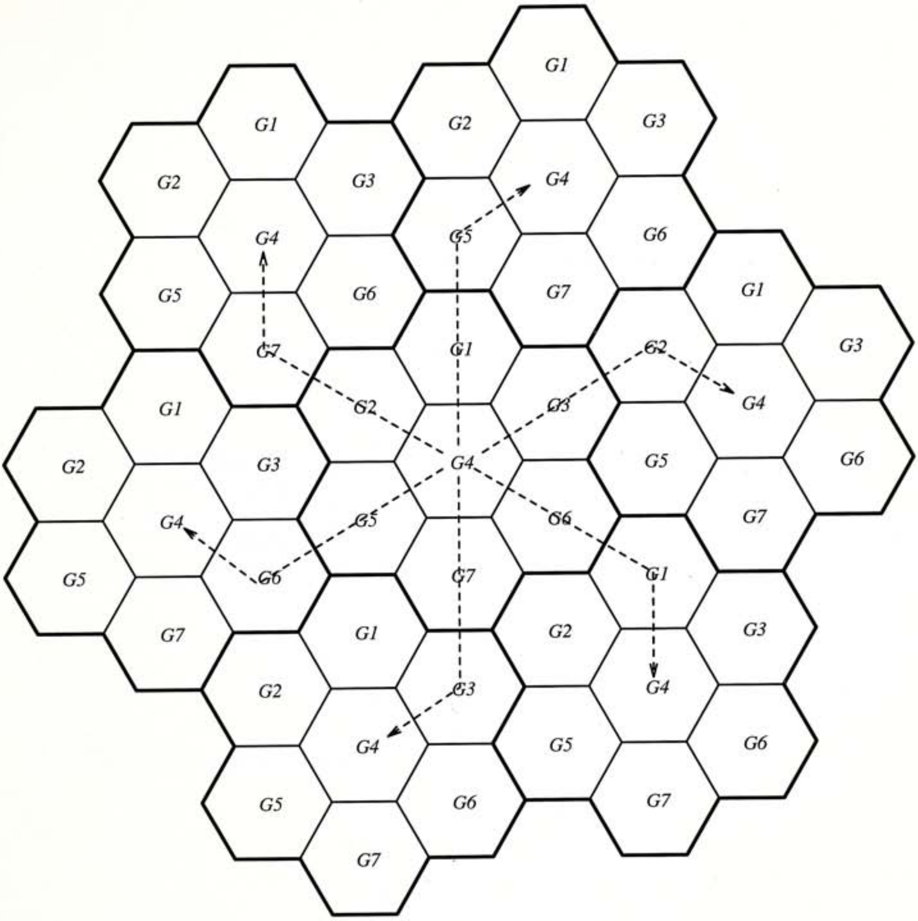

Figure 1.1: Channel Assignment of a cellular radio system

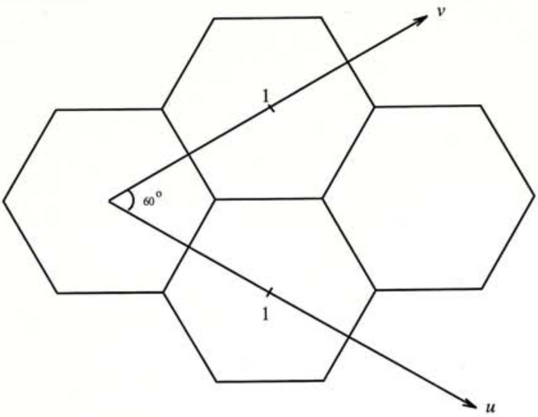

Figure 1.2: The (u, v) coordinates system

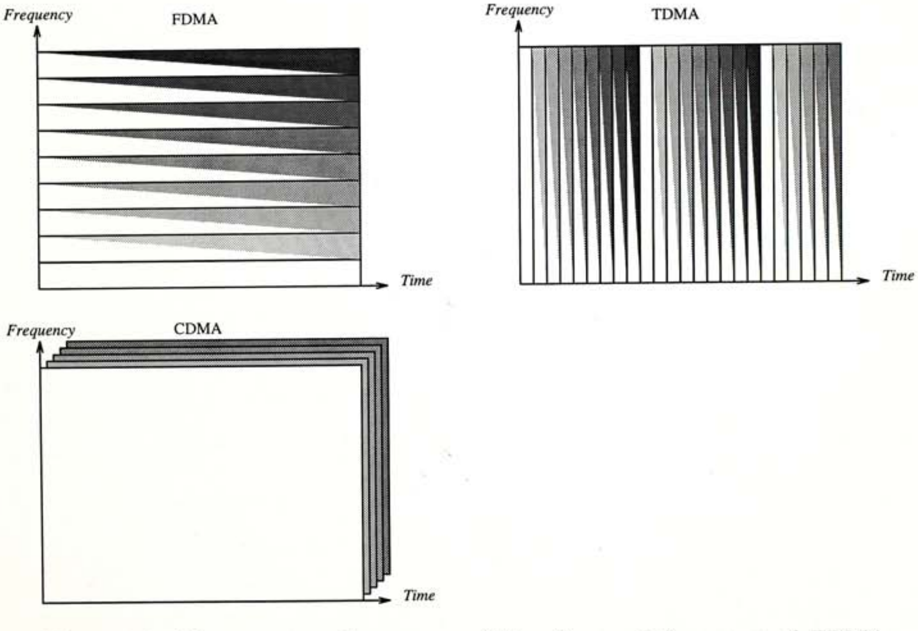

Figure 1.3: The corresponding access of the time and frequency of FDMA, TDMA and CDMA.

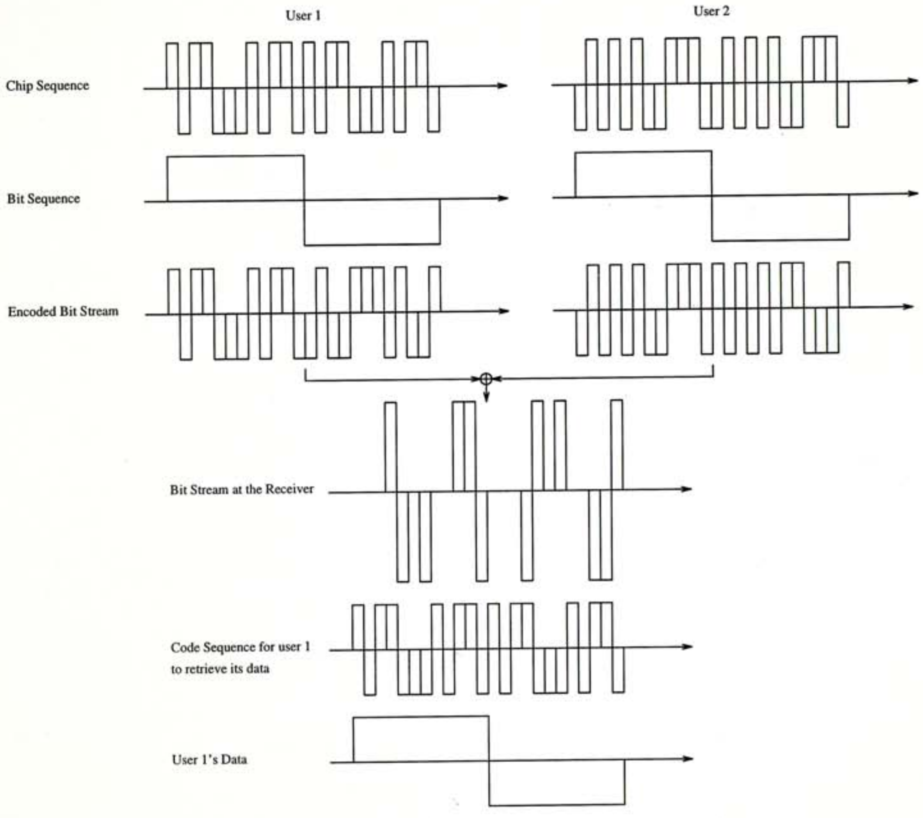

Figure 1.4: Figure to illustrate the principle of CDMA

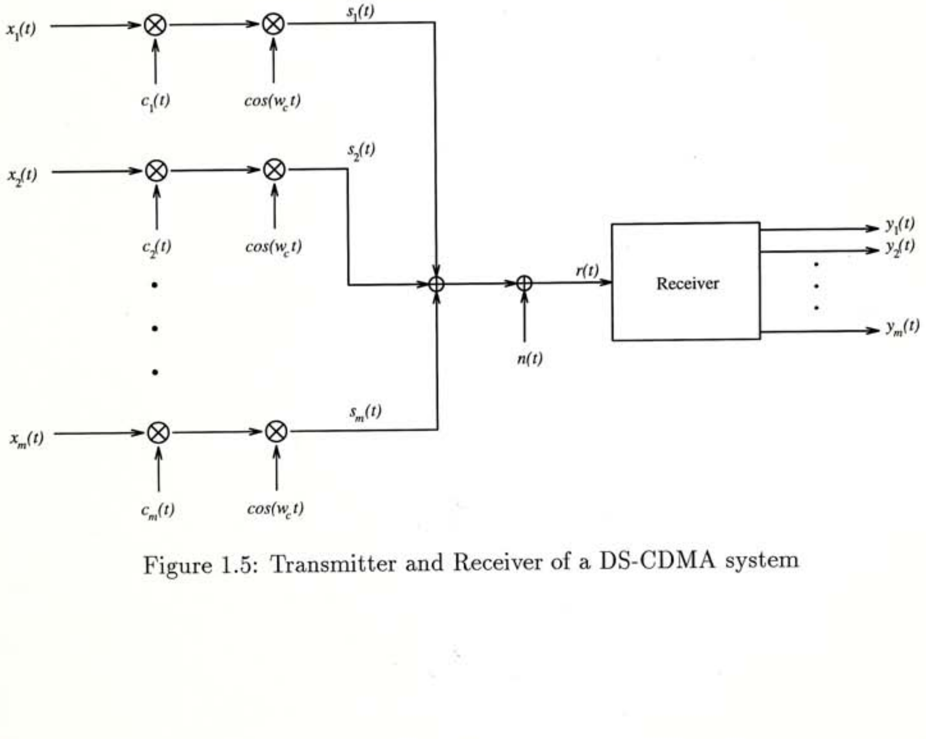

Figure 1.5: Transmitter and Receiver of a DS-CDMA system

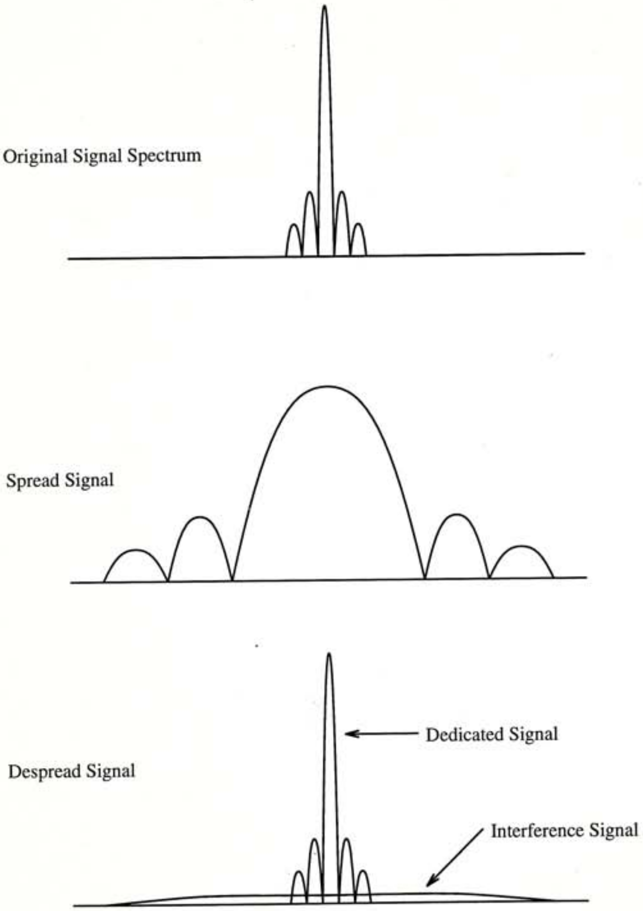

Figure 1.6: Spread Spectrum of Signals in CDMA systems

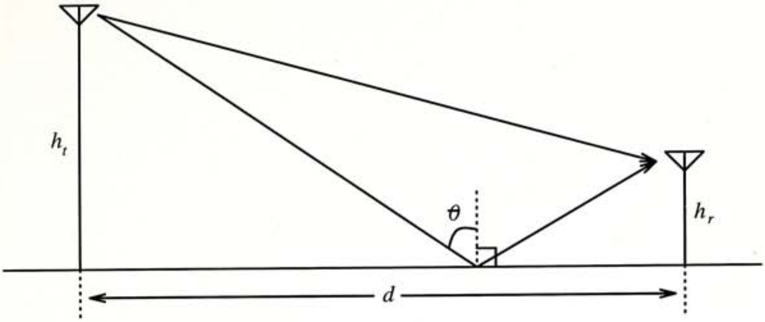

Figure 1.7: Two Ray model for propagation over a plane earth

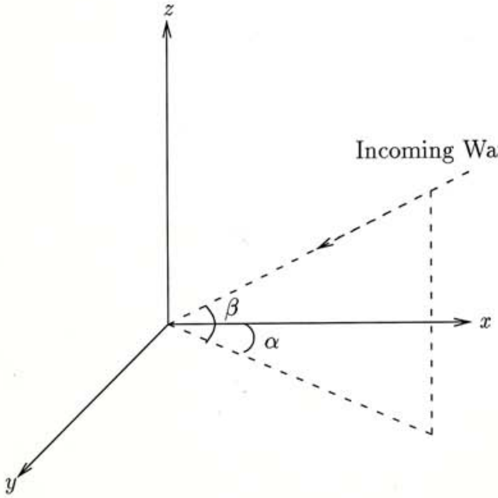

Figure 1.8: The definition of the spatial angles used for the n^{th} incoming wave.

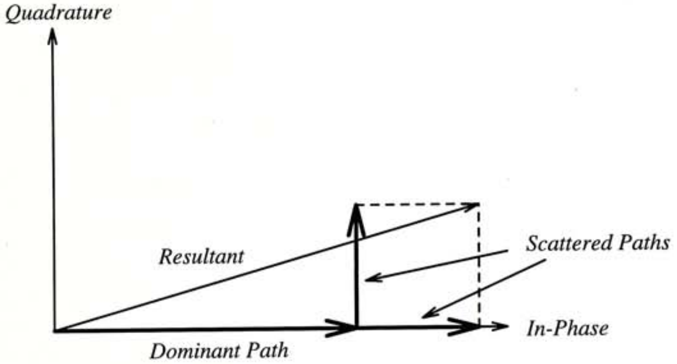

Figure 1.9: Phasor representation of the in-phase and quadrature components of Rician fading signal.

Chapter 2

Contributions

In this thesis, the adjacent cell interference analysis is performed. By using some mathematical models, closed-form solutions are obtained. In designing a CDMA cellular radio system, estimation of system capacity is a crucial issue to the successful implementation of the system. Based on the result obtained in this thesis, a general picture of what the system capacity would be can be obtained immediately. As a result, the overall number of base stations needed and thus the distance between neighbour base stations can be obtained just by substituting some parameters into the formulas derived in this thesis.

As radio propagation would depend greatly on the environment, different propagation environment would have different effect on the radio signal. In this thesis, the effects of adjacent cell interference on different propagation environments have been studied. The corresponding closed-form formulas are obtained accordingly. No similar result on microcell CDMA cellular radio system has been obtained before. As the demand of high capacity is getting higher and higher, the implementation of microcell would be getting more common. As a result, the estimation of microcellular radio system capacity is a concern to building a new high capacity CDMA microcellular radio system.

In this thesis, the effect of imperfect power control on the system capacity has been studied. From the analysis, this effect would impose another capacity degradation on the system. When considering this effect, a capacity margin of the system should be considered. This can be done by just plugging the required parameters into the formula obtained in this thesis. The corresponding number of capacity decrease can be obtained immediately.

The contribution of this thesis is to provide some tools for system design engineer in designing a CDMA cellular radio system. By using the tools supported in this thesis, the system capacity can be obtained immediately. The formulas in this thesis are derived based on some assumptions, which are general and being used by system design engineer. The approach is novel for the derivation of the formulas in this thesis.

Chapter 3

ACI Analysis of the Reverse-Link

In this chapter, the performance of the reverse-link in CDMA cellular radio systems will be analyzed. The effect of adjacent cell interference on the system capacity of a CDMA cellular radio system will be investigated. Hexagonal and circular cell structures are used for the investigation of the effect of adjacent cell interference on the system capacity. The amount of interference from the six adjacent cells of the first tier is obtained by numerical method in the hexagonal cell approach. Afterwards, a circle is used to approximate the hexagonal cell and a closed-form solution is obtained. Results show that the discrepancy between the two approaches is negligible. By the circular cell approach, the adjacent cell interference function is derived. The total adjacent cell interference is found by the adjacent cell interference function obtained. Generalization of the analysis to the irregular cell structure is also presented in this chapter.

3.1 Adjacent Cell Interference

In Code Division Multiple Access (CDMA) cellular radio systems, power control is a vital issue to the system capacity. Since different users occupy the same frequency band at the same time, signal of a user may be overwhelmed by strong signals from other users. As the frequency reuse pattern of CDMA system is proposed to be 1, i.e., universal frequency reuse, the same frequency band will be used at all cells. The signals are distinguished by the signature codes. As a result, signals leaked from a cell would interfere the cells around. For the forward-link of such system, Gejji [40] modeled the power control problem as a maximin problem. Based on the adjacent cell and co-cell interference, an optimum power control function is found by maximizing the objective function. The carrier-to-interference ratio will then be maximized and approximately equal at different places from the base.

For the reverse-link, in order to make all users obtain a stable carrier-to-interference ratio C/I, at the base station, a constant level of received power from different users has to be maintained. Lee [4] has investigated the effect of co-cell interference on the system capacity. Neglecting the interfering signals from adjacent cells, the C/I received from a mobile unit at the cell site is $(M-1)^{-1}$, where M is the total number of users that can be accommodated in a cell. In [42, 43], Cooper and Nettleton, and Gilhousen *et al* found the amount of interference caused by the adjacent cells numerically.

Mean value analysis approach will be deployed in this thesis. In the analysis, the mean system capacity will be obtained by using the carrier-to-mean interference ratio. The system with regular hexagonal cell structure will be studied first. Then, circular cells are used to approximate the hexagonal cells. The corresponding interference is obtained. In addition, a closed-form analytical solution for the problem is derived. By this solution, the amount of interference from adjacent cells can be obtained directly. System planner can approximate the amount of interference from the surrounding cells in an analytical way. Resource can be saved significantly in designing CDMA cellular radio systems.

The rest of the chapter will be organized as follows. In section 3.2, the numerical analysis of the hexagonal cell structure and functional analysis of the circular cell structure will be presented. The results obtained are compared and discussed. The interference function is derived in section 3.3. Generalization of the result to irregular cell structure will be presented in section 3.4. Conclusions are drawn in the last section.

3.2 Adjacent Cell Interference Analysis

3.2.1 Interference Analysis of Hexagonal Cells

In this section, the interference caused by the adjacent hexagonal cells will be considered. Referring to figure 3.1, for a user i in the hexagon ABCDEF, which is located at point N with coordinates (x_i, y_i), where the origin is at the center of its home cell, its distance from the center of the adjacent cell will then be given by

$$d(x_i, y_i) = \sqrt{(\sqrt{3}R_c - x_i)^2 + {y_i}^2} \tag{3.1}$$

where R_c is the cell radius, $-\frac{\sqrt{3}R_c}{2} \le x_i \le \frac{\sqrt{3}R_c}{2}$ and $-R_c + \frac{|x_i|}{\sqrt{3}} \le y_i \le R_c - \frac{|x_i|}{\sqrt{3}}$.

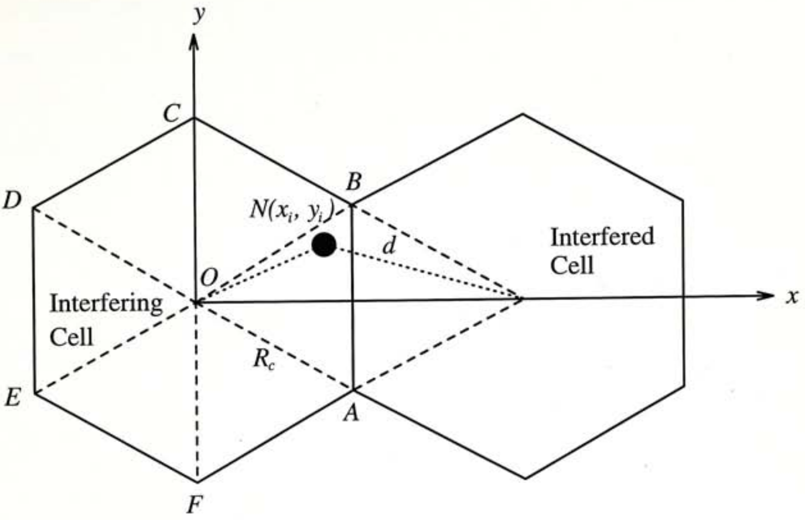

Figure 3.1: The interference caused by a mobile in region ABCDEF

If a power control scheme of ensuring equal received power at the base station is deployed, [1] received power at the base station is given by P_R and power transmitted at (x_i, y_i) is $P_R(\sqrt{x_i{}^2 + y_i{}^2})^\gamma$. The interference caused by the mobile to the adjacent cell will be given by

$$\begin{aligned} I(x_i, y_i) &= P_R(\frac{\sqrt{x_i{}^2 + y_i{}^2}}{d})^\gamma && (3.2) \\ &= P_R\frac{(x_i{}^2 + y_i{}^2)^{\gamma/2}}{[(\sqrt{3}R_c - x_i)^2 + y_i{}^2]^{\gamma/2}} && (3.3) \end{aligned}$$

where P_R is the constant received power at the base station and γ is the propagation exponent.

The mobiles are assumed to be evenly distributed over the hexagonal cell.

---

[1] The control of signal power is assumed to be done perfectly, i.e., the signal received at the base station is constant.

The probability distribution function of a user in the hexagon ABCDEF will be given by

$$f_{X,Y}(x,y)=\begin{cases}\frac{1}{\frac{3\sqrt{3}R_c{}^2}{2}} & \text{for} \begin{array}{l} -\frac{\sqrt{3}R_c}{2}\le x\le\frac{\sqrt{3}R_c}{2} \text{ and} \\ -R_c+\frac{|x|}{\sqrt{3}}\le y\le R_c-\frac{|x|}{\sqrt{3}} \end{array} \\ 0 & \text{otherwise}\end{cases} \tag{3.4}$$

The average interference from a mobile to the adjacent cell will be given by

$$\begin{aligned}
\bar{I}_{hex} &= E[I(X,Y)] && (3.5)\\
&= \iint I(x,y)f(x,y)dy\,dx && (3.6)\\
&= \int_{-\frac{\sqrt{3}R_c}{2}}^{\frac{\sqrt{3}R_c}{2}}\int_{-R_c+\frac{|x|}{\sqrt{3}}}^{R_c-\frac{|x|}{\sqrt{3}}}\frac{P_R(x^2+y^2)^{\gamma/2}}{[(\sqrt{3}R_c-x)^2+y^2]^{\gamma/2}}\cdot\frac{1}{\frac{3\sqrt{3}R_c{}^2}{2}}\,dy\,dx && (3.7)\\
&= \frac{P_R}{\frac{3\sqrt{3}R_c{}^2}{2}}\left[\int_0^{\frac{\sqrt{3}R_c}{2}}\int_{-R_c+\frac{x}{\sqrt{3}}}^{R_c-\frac{x}{\sqrt{3}}}\frac{(x^2+y^2)^{\gamma/2}\,dy\,dx}{[(\sqrt{3}R_c-x)^2+y^2]^{\gamma/2}}\right.\\
&\quad\left.+\int_{-\frac{\sqrt{3}R_c}{2}}^{0}\int_{-R_c-\frac{x}{\sqrt{3}}}^{R_c+\frac{x}{\sqrt{3}}}\frac{(x^2+y^2)^{\gamma/2}\,dy\,dx}{[(\sqrt{3}R_c-x)^2+y^2]^{\gamma/2}}\right] && (3.8)\\
&= \frac{P_R}{\frac{\sqrt{3}}{2}}\left[\int_0^{\frac{1}{2}}\int_{\frac{(-1+u)}{\sqrt{3}}}^{\frac{(1-u)}{\sqrt{3}}}\frac{(u^2+v^2)^{\gamma/2}}{[(1-u)^2+v^2]^{\gamma/2}}\,dv\,du\right.\\
&\quad\left.+\int_{-\frac{1}{2}}^{0}\int_{\frac{(-1-u)}{\sqrt{3}}}^{\frac{(1+u)}{\sqrt{3}}}\frac{(u^2+v^2)^{\gamma/2}}{[(1-u)^2+v^2]^{\gamma/2}}\,dv\,du\right] && (3.9)
\end{aligned}$$

The last equality is given by the substitution $u=\frac{x}{\sqrt{3}R_c}$ and $v=\frac{y}{\sqrt{3}R_c}$ for the normalization of the integral.

With γ equals to 4, equation (3.9) becomes

$$\begin{aligned}
\bar{I}_{hex} &= \frac{P_R}{\frac{\sqrt{3}}{2}}\left[\int_0^{\frac{1}{2}}\int_{\frac{(-1+u)}{\sqrt{3}}}^{\frac{(1-u)}{\sqrt{3}}}\frac{(u^2+v^2)^2}{[(1-u)^2+v^2]^2}\,dv\,du\right.\\
&\quad\left.+\int_{-\frac{1}{2}}^{0}\int_{\frac{(-1-u)}{\sqrt{3}}}^{\frac{(1+u)}{\sqrt{3}}}\frac{(u^2+v^2)^2}{[(1-u)^2+v^2]^2}\,dv\,du\right] && (3.10)
\end{aligned}$$

The integral in equation (3.10) cannot be solved analytically. By numerical method,

$$\bar{I}_{hex} = 0.06358 P_R \tag{3.11}$$

For a mobile in a cell communicating with the base station, it will exhibit interference to the other mobiles in the same cell. Assuming all M users are transmitting, for a particular user located at r_i from the base, its signal will be interfered by the other $M-1$ users. At the base station, the interference caused by the others to this user is

$$\sum_{j=1,\ j\neq i}^{M} P_R = (M-1)P_R$$

The total interference, from home cell and the first tier of adjacent cells, received at the base station will be

$$(M-1)P_R + 6M\bar{I}_{hex} \tag{3.12}$$

The carrier-to-interference ratio of this user is

$$\frac{C}{I} = \frac{P_R}{(M-1)P_R + 6M\bar{I}_{hex}} \tag{3.13}$$

With γ equals to 4, equation (3.13) becomes

$$\begin{aligned} \frac{C}{I} &= \frac{P_R}{(1.3815M-1)P_R} && (3.14) \\ &= \frac{1}{1.3815M-1} && (3.15) \end{aligned}$$

In cellular radio systems, the bit error rate should be less than 10^{-3} in order to provide an acceptable quality of service. With an efficient modem and a

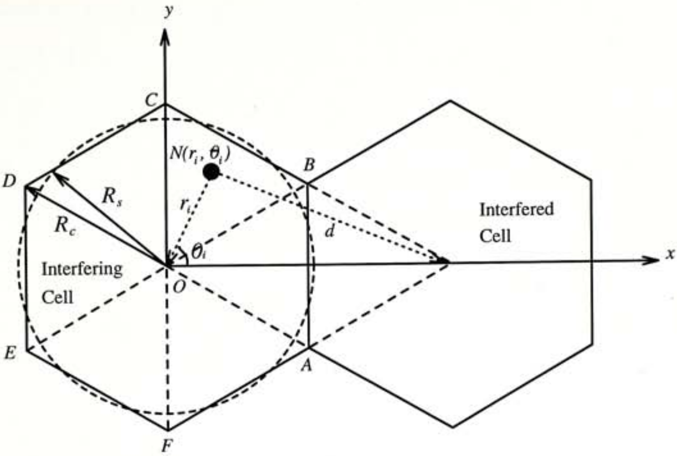

Figure 3.2: The interference caused by a mobile in a circular cell to its adjacent

powerful convolutional code (constraint length 9, rate 1/3) and two-antenna diversity, it corresponds to have $E_b/I_0 = 7$ dB, where E_b is the energy per bit and I_0 is the interference power per hertz [43]. In CDMA, C/I received at RF is closely related to the E_b/I_0 at the baseband.

$$C/I = (E_b/I_0)(R_b/B_c) \tag{3.16}$$

where R_b is the bit per second and B_c is the radio channel bandwidth in hertz. Assuming the vocoder rate R_b is 8 kbps and the total wide-band channel bandwidth $B_t = 1.25$ MHz, if $E_b/I_0 = 7$ dB, then $(C/I)_{req} = 0.032$. From equation (3.15), the maximum number of users that can be accommodated in a cell is $M_{max} = 23$

3.2.2 Interference Analysis of Circular Cell Structure

In this section, a circular region to approximate the hexagonal cell in the system will be used. The circle will have the same area as the hexagonal cell. Referring to figure 3.2, R_c and R_s are the cell radii of the circle circumscribing the hexagon and the circle that has the same area as the hexagon, respectively. The radius of the circle R_s will have the following relation with R_c

$$\begin{aligned} \pi {R_s}^2 &= \tfrac{3\sqrt{3}}{2} {R_c}^2 \\ \Rightarrow \quad R_s &= 0.9094 R_c \end{aligned} \tag{3.17}$$

For a mobile locating at a point N with polar coordinates $(r_i,\ \theta_i)$ [2] from its home base, its distance from the adjacent cell will be given by

$$d(r_i, \theta_i) = \sqrt{3{R_c}^2 + r_i^2 - 2\sqrt{3} R_c r_i \cos\theta_i} \tag{3.18}$$

where $0 \le r_i \le R_s$ and $0 \le \theta_i \le 2\pi$.

If a power control scheme of ensuring equal received power at the base station is deployed, the interference caused by the mobile to the adjacent cell would be given by

$$\begin{aligned} I(r_i, \theta_i) &= P_R \left(\frac{r_i}{d}\right)^{\gamma} && (3.19) \\ &= \frac{P_R r_i^{\gamma}}{[3{R_c}^2 + r_i^2 - 2\sqrt{3} R_c r_i \cos\theta_i]^{\gamma/2}} && (3.20) \end{aligned}$$

where P_R is the constant received power at the base station and γ is the propagation exponent.

---

[2] In this section, polar coordinates will be used to locate the users, since it will be more convenient in analyzing a circular region.

Same as the previous section, the mobiles are assumed to be evenly distributed over the circle. The probability distribution function of a user in the circle will be given by

$$f_{R,\Theta}(r,\theta) = \begin{cases} \frac{1}{\pi {R_s}^2} & \text{for } 0 \leq r \leq R_s \text{ and } 0 \leq \theta \leq 2\pi \\ 0 & \text{otherwise} \end{cases} \tag{3.21}$$

The average interference for a mobile caused to the adjacent cell will be given by

$$\begin{aligned} \bar{I}_{cir} &= E[I(R,\Theta)] && (3.22) \\ &= \iint I(r,\theta) f(r,\theta)\, r\, d\theta\, dr && (3.23) \\ &= \int_0^{R_s} \int_0^{2\pi} \frac{P_R r^{\gamma+1}}{[3{R_c}^2 + r^2 - 2\sqrt{3} R_c r \cos\theta]^{\gamma/2}} \cdot \frac{1}{\pi {R_s}^2}\, d\theta\, dr && (3.24) \\ &= \frac{P_R}{\pi {R_s}^2} \int_0^{R_s} \int_0^{2\pi} \frac{r^{\gamma+1}\, d\theta\, dr}{[3{R_c}^2 + r^2 - 2\sqrt{3} R_c r \cos\theta]^{\gamma/2}} && (3.25) \end{aligned}$$

Equation (3.25) is similar to the total interference equation in [42, page 272]. Here, only the adjacent six cells are considered. The generalized form of equation (3.25) is

$$I_{total} = \frac{P_R}{\pi {R_s}^2} \sum_{i=1}^{N} \int_0^{R_s} \int_0^{2\pi} \frac{r^{\gamma+1}\, d\theta\, dr}{[D_i^2 + r^2 - 2D_i r \cos\theta]^{\gamma/2}} \tag{3.26}$$

where N is the total number of cells in the service area and D_i is the distance between the interfering cell i and the interfered cell. D_i is related to R_c with the following expression

$$D_i = \sqrt{3K_i} R_c$$

where $K_i = u_i{}^2 + u_i v_i + v_i{}^2$ and (u_i, v_i) is the displacement in the u and v directions from the interfered cell to the interfering cell ($u_i, v_i \geq 0, u_i + v_i \geq 1$) [23].

Back to equation (3.25), with γ equals to 4, and using $\int_0^{2\pi} \frac{dx}{(a+b\cos x)^2} = \frac{2\pi a}{(a^2-b^2)^{3/2}}$, the equation becomes

$$\begin{aligned}\bar{I}_{cir} &= \frac{P_R}{\pi R_s{}^2} \int_0^{R_s} \frac{2\pi r^5 (3R_c{}^2 + r^2)}{(3R_c{}^2 - r^2)^3}\, dr & (3.27)\\ &= \frac{2P_R}{R_s{}^2} \int_0^{R_s} \frac{r^5 (3R_c{}^2 + r^2)}{(3R_c{}^2 - r^2)^3}\, dr & (3.28)\end{aligned}$$

Substituting $x = r/\sqrt{3}R_c$ for normalizing the integral,

$$\begin{aligned}\bar{I}_{cir} &= \frac{2P_R}{R_s{}^2} \int_0^{R_s} \frac{r^5 (3R_c{}^2 + r^2)}{(3R_c{}^2 - r^2)^3}\, dr & (3.29)\\ &= \frac{6R_c{}^2 P_R}{R_s{}^2} \int_0^{0.5250} \frac{x^5 (1 + x^2)}{(1 - x^2)^3}\, dx & (3.30)\end{aligned}$$

In general, for an interfering cell i away from the interfered cell by D_i, the average interference will be given by

$$\frac{2D_i^2 P_R}{R_s{}^2} \int_0^{\frac{0.9094}{\sqrt{3K_i}}} \frac{x^5 (1 + x^2)}{(1 - x^2)^3}\, dx \qquad (3.31)$$

The integral in equation (3.30) can be solved to obtain a closed-form solution. The corresponding result is

$$\bar{I}_{cir} = 0.06326 P_R \qquad (3.32)$$

Assuming that there are M users transmitting in the cell, the total interference from this interfering cell is given by

$$\bar{I}_{cir} = 0.06326 M P_R \tag{3.33}$$

Considering the six adjacent cells around, the total adjacent cell interference to a cell is

$$I_{total} = 0.37955 M P_R \tag{3.34}$$

The corresponding C/I is

$$\begin{aligned} \frac{C}{I} &= \frac{P_R}{(M-1)P_R + 0.37955 M P_R} && (3.35) \\ &= \frac{1}{(1.37955M - 1)} && (3.36) \end{aligned}$$

Comparing the result in equation (3.15) with equation (3.36), using a circle to approximate the adjacent cell interference in a hexagonal cell is acceptable.

3.3 Closed-form of Adjacent Cell Interference

Back to the general form of equation (3.31), using the substitution $u = \sqrt{1-x^2}$, the interference from cell i to the interfered cell which is away from cell i by D_i is

$$\begin{aligned} \bar{I}_{cir_i} &= \frac{2D_i^2 M P_R}{{R_s}^2} \int_0^{\frac{0.9094}{\sqrt{3K_i}}} \frac{x^5(1+x^2)}{(1-x^2)^3}\, dx && (3.37) \\ &= \frac{2MP_R}{0.9094^2} \left[-0.413504 + 6K_i + \frac{7.5{K_i}^2}{0.27567 - K_i} \right. \\ &\quad \left. + \frac{1.5{K_i}^3}{(0.27567 - K_i)^2} - 6K_i \ln\left|1 - \frac{0.27567}{K_i}\right| \right] && (3.38) \end{aligned}$$

$$
\begin{aligned}
&= MP_R\left[14.51016K_i \ln\left(\frac{K_i}{K_i - 0.27567}\right)\right. \\
&\qquad \left. - \frac{4(K_i - 0.360878)(K_i - 0.052649)}{(K_i - 0.27567)^2}\right] \qquad (3.39)
\end{aligned}
$$

The *Adjacent cell interference function* of K_i is defined as

$$
\begin{aligned}
\vartheta(K_i) &\triangleq 14.51016K_i \ln\left(\frac{K_i}{K_i - 0.27567}\right) \\
&\qquad - \frac{4(K_i - 0.360878)(K_i - 0.052649)}{(K_i - 0.27567)^2} \qquad (3.40)
\end{aligned}
$$

Then, the overall C/I ratio is given by

$$
\begin{aligned}
\frac{C}{I} &= \frac{P_R}{(M-1)P_R + \sum_{u=1}^{\infty}\sum_{v=0}^{\infty}\vartheta(u^2+uv+v^2)6MP_R} \qquad (3.41) \\
&= \left[(M-1) + 6M\sum_{u=1}^{\infty}\sum_{v=0}^{\infty}\vartheta(u^2+uv+v^2)\right]^{-1} \qquad (3.42)
\end{aligned}
$$

Figure 3.3 shows the graph of total interference from the surrounding cells against the number of tier of cells included. From the figure, the interference from the adjacent cells is mainly contributed from the first few tiers of cells. The interference from cells away from the tenth tier becomes insignificant and can be neglected. The total interference from all the adjacent cells is about 0.4321. Consequently, the number of tier of cells needed to be considered is ten.

Taking the total interference to be 0.4321 and $(C/I)_{req} = 0.032$ ($E_b/I_0 = 7$ dB), the number of users that can be accommodated in a cell is

$$
M = ((C/I)_{req}^{-1} + 1)/(1 + 0.4321) = (31.25 + 1)/(1.4321) \approx 22 \qquad (3.43)
$$

Adding voice activity cycle and sectorization, a nine fold of capacity can be obtained. The nine fold of system capacity would be an optimistic value.

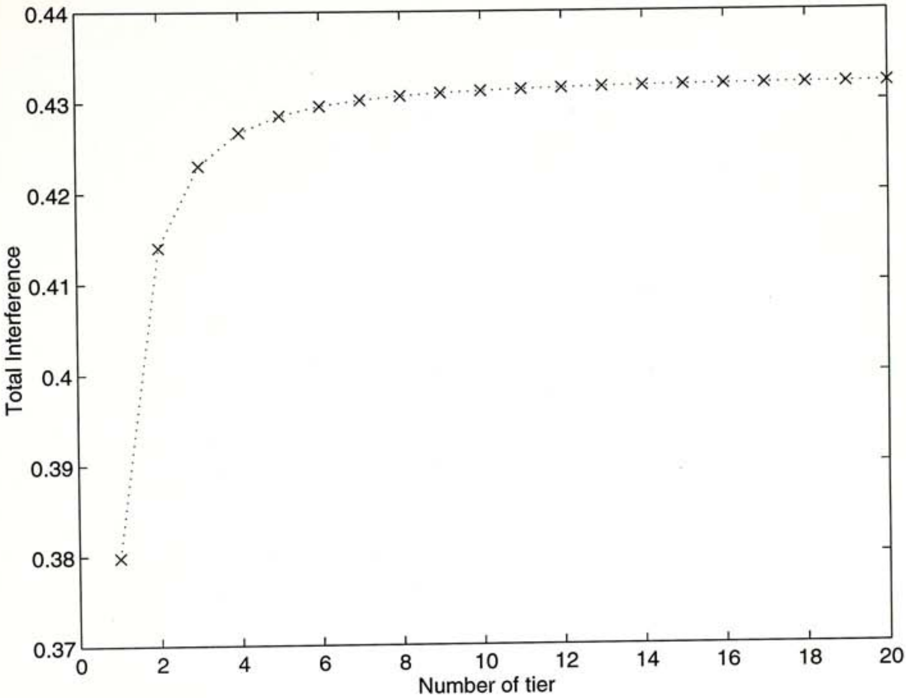

Figure 3.3: Total adjacent cell interference per user versus the number of tier of cells included

It is based on the assumptions that sectorization would reduce the amount of interference to one third of the original value in average and thus increase the capacity by three times. In addition, a person would use only 40

$$M = 22 \times 3 \times 2.5 = 165 \text{ channels/cell}$$

When the adjacent cell interference is considered, the capacity of CDMA cellular radio system still has higher capacity than other kind of systems, provided that the power control is done perfectly.

Furthermore, referring to equation (3.25), with γ equals to 2, the adjacent cell interference for path loss of 2 can be obtained. For a cell which is away from the interfered cell by D_i, the average interference from this cell will be

$$\begin{aligned}
\bar{I}_i &= \frac{P_R}{\pi {R_s}^2} \int_0^{R_s} \int_0^{2\pi} \frac{r^3 \, d\theta \, dr}{[D_i^2 + r^2 - 2D_i r \cos\theta]} && (3.44) \\
&= \frac{P_R}{\pi R_s^2} \int_0^{R_s} \frac{2\pi r^3}{D_i^2 - r^2} dr && (3.45) \\
&= P_R \left[-1 - \frac{1}{k_i^2} \ln\left(1 - k_i^2\right) \right] && (3.46)
\end{aligned}$$

where $k_i = \frac{R_s}{D_i}$ is the reciprocal of the cochannel interference reduction factor [23].

The adjacent cell interference function for path loss equals to 2 is

$$\vartheta_2(k_i) \triangleq \left[-1 - \frac{1}{k_i^2} \ln\left(1 - k_i^2\right) \right] \tag{3.47}$$

The curve of the value of adjacent cell interference versus the number of tier of cell is shown in figure 3.4. A much higher interference from the adjacent cells is observed and as a result, the higher the propagation path loss, the better the performance of CDMA cellular radio systems.

3.4 Generalization to Irregular Cell Structure

So far in the analysis, regular hexagonal and circular cell structure were used. Indeed, the analytical result can be generalized and applied to irregular cell shape, which is more realistic structure.

In a real cellular radio system, the cell layout may look as the one in figure 3.5. For a particular cell i away from an interfered cell by D_i, which is shown in

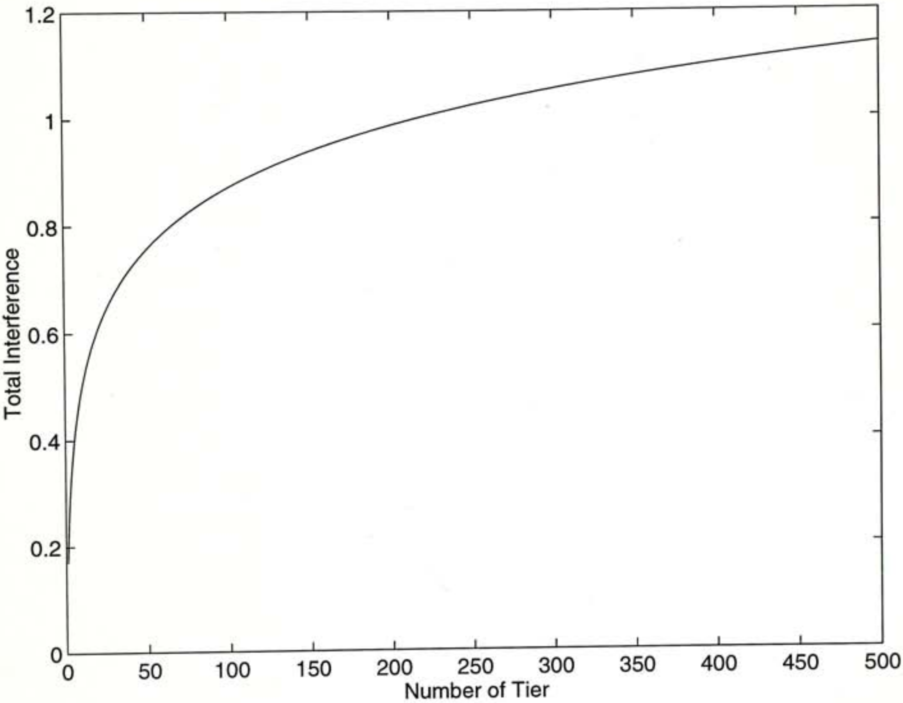

Figure 3.4: Total adjacent cell interference per user versus the number of tier of cells included, with propagation path loss equal to 2

figure 3.6, the interference from this cell can be approximated by using a circle with equal area and radius R_i to approximate this cell. Applying equation (3.31) to this cell with a minor change, the equation becomes

$$\begin{aligned} I_{irr} &= \frac{2MD_i^2 P_{R_i}}{{R_i}^2} \int_0^{\frac{R_i}{D_i}} \frac{x^5(1+x^2)}{(1-x^2)^3}\, dx && (3.48) \\ &= MP_{R_i}\left[-\frac{4-6k_i^2+k_i^4}{(1-k_i^2)^2} - \frac{4}{k_i^2}\ln\left(1-k_i^2\right)\right] && (3.49) \\ &= MP_{R_i}\vartheta'(k_i) && (3.50) \end{aligned}$$

where $k_i = \frac{R_i}{D_i}$ is the reciprocal of the cochannel interference reduction factor, which is given by the frequency reuse distance divided by the coverage radius [23, page 50], and $\vartheta'(k_i)$ is the modified adjacent cell interference function which is defined by

$$\vartheta'(k_i) \triangleq \left[-\frac{4-6k_i^2+k_i^4}{(1-k_i^2)^2} - \frac{4}{k_i^2}\ln\left(1-k_i^2\right)\right] \qquad (3.51)$$

The corresponding C/I equation becomes

$$\frac{C}{I} = \left[(M-1) + M\sum_i \vartheta'(k_i)\right]^{-1} \qquad (3.52)$$

By using equation (3.52), system planners just need to use the information of the distance between two base stations and the approximated area of each cell. The adjacent cell interference of a particular cell can be obtained immediately. As a result, the capacity for the reverse link of that cell can be estimated.

3.5 Conclusions

The adjacent cell interference function of CDMA cellular radio systems has been derived in this chapter. With this function, the interference from adjacent cells can be determined. Further, this adjacent cell interference function can be used for system planning. It provides a fast and simple way of estimating the interference from adjacent cells, and saves a lot of resources in designing CDMA cellular radio systems.

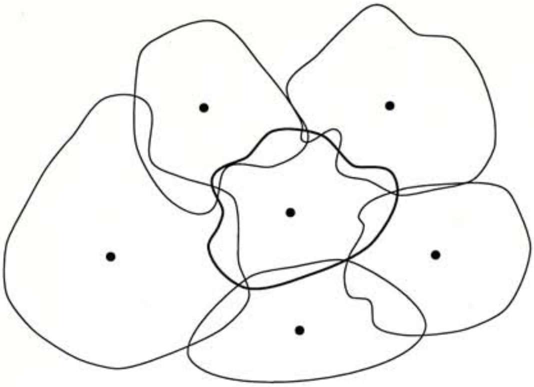

Figure 3.5: A real cell layout in a cellular radio system

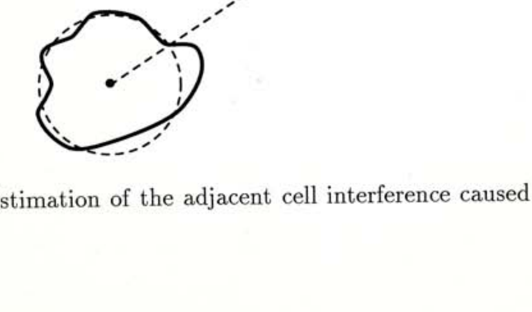

Figure 3.6: Estimation of the adjacent cell interference caused to a particular cell

Chapter 4

ACI Analysis of Reverse-Link with Log-normal Shadowing

4.1 Interference with Shadowing

In this chapter, the effect of shadowing and adjacent cell interference on the reverse-link capacity of a CDMA cellular radio system will be considered. Referring to [44], a widely accepted model for the signal transmission environment encountered in mobile communications systems indicates that the received signal power P_r averaged over fast fading should be expressed as,

$$P_r = P_t \cdot d^{-\gamma} \cdot 10^{\eta/10} \tag{4.1}$$

where P_t is the transmitted signal power, d is the distance between the transmitter and receiver, γ is the propagation constant, and η is a normally distributed random variable with zero mean and standard deviation σ in dB. Thus, the probability distribution of η is given by

$$f_H(\eta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\eta^2}{2\sigma^2}\right] \qquad \text{for } -\infty \leq \eta \leq \infty \tag{4.2}$$

By using the derivation in chapter 3, the amount of adjacent cell interference at the base station in the presence of shadowing can be obtained. As in chapter 3, the distribution of users in a cell is assumed to be uniform. The hexagonal cell will be approximated by a circular cell with equal area. The probability that a mobile is at the polar coordinates $(r,\ \theta)$ from its home base is

$$f_{R,\Theta}(r,\theta) = \begin{cases} \frac{1}{\pi R_s{}^2} & \text{for } 0 \leq r \leq R_s \text{ and } 0 \leq \theta \leq 2\pi \\ 0 & \text{otherwise} \end{cases} \tag{4.3}$$

where R_s is the radius of the circular cell.

The signal from the base station to the mobiles is assumed to be transmitted at a predetermined constant power P_{b_t}. Referring to figure 4.1, for a user situated at the polar coordinates (r_i, θ_i), the received signal power P_{m_r} at the mobile is

$$P_{m_r} = P_{b_t} \cdot r_i^{-\gamma} \cdot 10^{\eta/10}$$

At the mobile, it can calculate the corresponding signal attenuation due to path loss and shadowing, i.e., the factor $r_i^{-\gamma} 10^{\eta/10}$. Then, it will transmit its signal to the home base at the power P_{m_t} that can compensate the signal attenuation

$$P_{m_t} = P_R \cdot r_i^{\gamma} \cdot 10^{-\eta/10} \tag{4.4}$$

where P_R is the constant received power at the base station.

Assuming that the fading and path loss of the reverse-link and forward-link signals are the same at the home cell, its home base receives the signal at the level

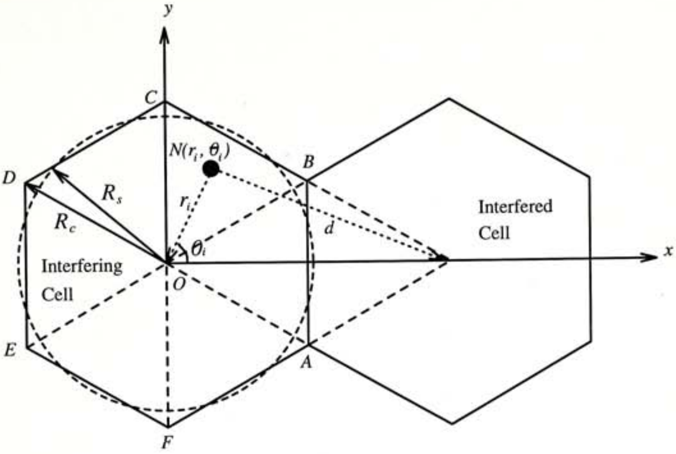

Figure 4.1: The interference caused by a mobile in a circular cell to its adjacent

$$\begin{aligned} P_{b_r} &= P_{m_t} \cdot r_i^{-\gamma} \cdot 10^{\eta/10} && (4.5)\\ &= P_R \cdot r_i^{\gamma} \cdot 10^{-\eta/10} \cdot r_i^{-\gamma} \cdot 10^{\eta/10} && (4.6)\\ &= P_R && (4.7) \end{aligned}$$

The power control is assumed to be done perfectly at one's home cell, i.e., the received signal power at one's home base station will be constant no matter where the mobile is. On the other hand, the signal from this mobile interferes the adjacent cell. Referring to figure 4.1, the interference from the mobile to its adjacent cell is given by

$$\begin{aligned} I(r_i, \theta_i, \eta, \eta') &= P_R(\frac{r_i}{d})^{\gamma} \frac{10^{\eta/10}}{10^{\eta'/10}} && (4.8)\\ &= \frac{P_R r_i^{\gamma} 10^{\eta/10}}{[3{R_c}^2 + r_i^2 - 2\sqrt{3}R_c r_i \cos\theta_i]^{\gamma/2} 10^{\eta'/10}} && (4.9) \end{aligned}$$

where η and η' are two independent and identically distributed (i. i. d.) random variables. They are normally distributed with zero mean and standard deviation σ.

Assuming the distribution of fading and the distribution of the user location are independent, the average interference from a mobile to the adjacent cell can be derived

$$
\begin{aligned}
& \bar{I}_{adj} && (4.10)\\
= \;& E[I(R,\Theta,H,H')] && (4.11)\\
= \;& \iiiint I(r,\theta,\eta,\eta')f(r,\theta)g(\eta)g(\eta')\,r\,d\eta'\,d\eta\,d\theta\,dr && (4.12)\\
= \;& \int_0^{R_s}\int_0^{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{P_R r^{\gamma+1}10^{\eta/10}}{[3{R_c}^2+r^2-2\sqrt{3}R_c r\cos\theta]^{\gamma/2}10^{\eta'/10}}\frac{1}{\pi {R_s}^2}\cdot\\
& \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\eta^2}{2\sigma^2}\right]\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{\eta'^2}{2\sigma^2}\right]d\eta' d\eta d\theta dr && (4.13)\\
= \;& \frac{P_R}{2\pi^2\sigma^2{R_s}^2}\int_0^{R_s}\int_0^{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{r^{\gamma+1}10^{(\eta-\eta')/10}}{[3{R_c}^2+r^2-2\sqrt{3}R_c r\cos\theta]^{\gamma/2}}\cdot\\
& \exp\left[-\frac{\eta^2+\eta'^2}{2\sigma^2}\right]d\eta'\,d\eta\,d\theta\,dr && (4.14)
\end{aligned}
$$

Since

$$
E\left[10^{\eta/10}\right]=\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty}10^{\eta/10}\exp\left[-\frac{\eta^2}{2\sigma^2}\right]d\eta=\exp\left[\frac{\sigma^2(\ln 10)^2}{200}\right]
$$

and the two fading random variables are assume to be i. i. d., $E[10^{(\eta-\eta')/10}] = E[10^{\eta/10}]^2$. As a result, equation (4.14) becomes

$$
\bar{I}_{adj}=\exp\left[\left(\frac{\sigma\ln 10}{10}\right)^2\right]\frac{P_R}{\pi {R_s}^2}\int_0^{R_s}\int_0^{2\pi}\frac{r^{\gamma+1}}{[3{R_c}^2+r^2-2\sqrt{3}R_c r\cos\theta]^{\gamma/2}}\,d\theta\,dr \tag{4.15}
$$

With γ equals to 4,

$$\bar{I}_{adj} = \exp\left[\left(\frac{\sigma \ln 10}{10}\right)^2\right] \frac{P_R}{\pi {R_s}^2} \int_0^{R_s} \int_0^{2\pi} \frac{r^5}{[3{R_c}^2 + r^2 - 2\sqrt{3} R_c r \cos\theta]^2} \, d\theta \, dr \quad (4.16)$$

Comparing equation (4.16) with the result obtained in chapter 3, when log-normal signal fading is considered in the analysis, the interference is increased by a factor which is called the *fading gain* in the system

$$G_f = \exp\left[\left(\frac{\sigma \ln 10}{10}\right)^2\right] \quad (4.17)$$

When the fading gain is considered in the closed-form solution of chapter 3, the following equation is obtained

$$\begin{aligned} \frac{C}{I} &= \frac{P_R}{(M-1)P_R + \sum_{u=1}^{\infty} \sum_{v=0}^{\infty} G_f \vartheta(u^2 + uv + v^2) 6 M P_R} && (4.18) \\ &= \left[(M-1) + 6 G_f M \sum_{u=1}^{\infty} \sum_{v=0}^{\infty} \vartheta(u^2 + uv + v^2)\right]^{-1} && (4.19) \end{aligned}$$

where M is the number of users that can be accommodated in a cell and $\vartheta(\cdot)$ is the adjacent cell interference function derived in the previous chapter.

$$\begin{aligned} \vartheta(K_i) \triangleq\ & 14.51016 K_i \ln\left(\frac{K_i}{K_i - 0.27567}\right) \\ & - \frac{4(K_i - 0.360878)(K_i - 0.052649)}{(K_i - 0.27567)^2} \end{aligned} \quad (4.20)$$

where $K_i = {u_i}^2 + u_i v_i + {v_i}^2$ and (u_i, v_i) is the displacement in the u and v directions from the interfered cell to the interfering cell ($u_i, v_i \geq 0, u_i + v_i \geq 1$).

Some typical values of G_f to the corresponding values of σ are shown in table 4.1. In the same table, the corresponding number of users M that can

σ (dB)	G_f	M
0	1	22
2	1.2362	21
4	2.3357	16
6	6.7442	8
8	29.7615	2

Table 4.1: Typical values of G_f and the corresponding number of users that can be accommodated in a cell

be accommodated in a cell, when shadowing is considered, is also shown. The dramatic effect with σ can be explained by the exponential variations of signal power by the log-normal fading. Increase of the standard deviation would induce to an exponential increase in the mean signal power. As a result, in the average, the amount of interference from the other users would be increased significantly.

What we have obtained above is the adjacent interference analysis with the consideration of log-normal shadowing. Gilhousen *et al* [43] considered similar circumstance but imposed a constraint that the signal a mobile within its cell is the strongest among all the signals from the other base stations. They modeled the received signal at the base station as a gaussian random variable. The constraint confined the received signal at home cell must be the strongest among the signals from the other cells.

$$
\begin{aligned}
d^{-\gamma} \cdot 10^{\eta/10} &\leq r_i^{-\gamma} \cdot 10^{\eta'/10} && (4.21)\\
10^{(\eta-\eta')/10} &\leq (\frac{d}{r_i})^{\gamma} && (4.22)\\
\eta - \eta' &\leq 40 \log_{10}(\frac{d}{r_i}) \qquad \text{(Take } \gamma = 4\text{)} && (4.23)
\end{aligned}
$$

Since $\eta - \eta'$ is a Gaussian random variable with zero mean and variance $2\sigma^2$, the expectation of $10^{(\eta-\eta')/10}$, (i.e., the fading gain) will be given by

$$\begin{aligned} G_f &= E\left[10^{(\eta-\eta')/10}\right] && (4.24)\\ &= \frac{1}{\sqrt{\pi}2\sigma}\int_{-\infty}^{40\log_{10}(\frac{d}{r_i})} 10^{\chi/10}\exp\left[-\frac{\chi^2}{4\sigma^2}\right]d\chi && (4.25)\\ &= \exp\left[\left(\frac{\sigma\ln 10}{10}\right)^2\right]\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\frac{40\log_{10}(\frac{d}{r_i})-\sigma^2\frac{\ln 10}{5}}{2\sigma}} e^{-u^2}du && (4.26)\\ &= \exp\left[\left(\frac{\sigma\ln 10}{10}\right)^2\right]\left\{1-\frac{1}{2}\mathrm{erfc}\left[\frac{20}{\sigma}\log_{10}\left(\frac{d}{r_i}\right)-\sigma\frac{\ln 10}{10}\right]\right\} && (4.27)\end{aligned}$$

The adjacent cell interference cannot be solved analytically when the maximum nominal power constraint is considered. Including equation 4.27 into equation 4.14,

$$\begin{aligned}\bar{I}_{adj} &= \exp\left[\left(\frac{\sigma\ln 10}{10}\right)^2\right]\frac{P_R}{\pi {R_s}^2}\int_0^{R_s}\int_0^{2\pi}\frac{r^5}{[3{R_c}^2+r^2-2\sqrt{3}R_c r\cos\theta]^2}\\ &\quad\cdot\left\{1-\frac{1}{2}\mathrm{erfc}\left[\frac{20}{\sigma}\log_{10}\left(\frac{\sqrt{3{R_c}^2+r^2-2\sqrt{3}R_c r\cos\theta}}{r}\right)-\sigma\frac{\ln 10}{10}\right]\right\}d\theta\, dr\end{aligned} \tag{4.28}$$

In general, if an interfering cell i is away from the interfered cell by D_i, the interference from this cell will be

$$\begin{aligned}\bar{I}_{adj} &= \exp\left[\left(\frac{\sigma\ln 10}{10}\right)^2\right]\frac{P_R}{\pi {R_s}^2}\int_0^{R_s}\int_0^{2\pi}\frac{r^5}{[D_i^2+r^2-2D_i r\cos\theta]^2}\\ &\quad\cdot\left\{1-\frac{1}{2}\mathrm{erfc}\left[\frac{20}{\sigma}\log_{10}\left(\frac{\sqrt{D_i^2+r^2-2D_i r\cos\theta}}{r}\right)-\sigma\frac{\ln 10}{10}\right]\right\}d\theta\, dr\end{aligned} \tag{4.29}$$

The numerical result of equation 4.29 for σ equals to 0 and 8 are obtained and shown in figure 4.2. The reason why the curves cross is that when only one tier of cell is considered, the effect of log-normal fading tends to diminish the interference power. It is due to the strongest nominal power constraint imposed on the signal power. As the separation between the interfering and interfered cells increases, i.e. the number of tier of cells increases, the constraint tends to be loosen. The corresponding interference power then increases significantly. The ACI in the presence of log-normal fading would be much higher than that without fading. Consequently, the capacity of the system in the presence of log-normal shadowing will be much lower than that in an ideal circumstance.

4.2 Conclusions

In this chapter, the adjacent cell interference in the presence of long-term shadowing have been derived. By the results obtained, the system capacity decreases exponentially as the standard deviation of the interfering signal increases. When maximum nominal power constraint is considered, the expression for the ACI is too complicated to be solved analytically. Instead, the ACI is obtained by using numerical method. In typical propagation environment, where $\sigma \approx 8$, the slow fading of adjacent cell interfering signal causes further significant reduction in system capacity.

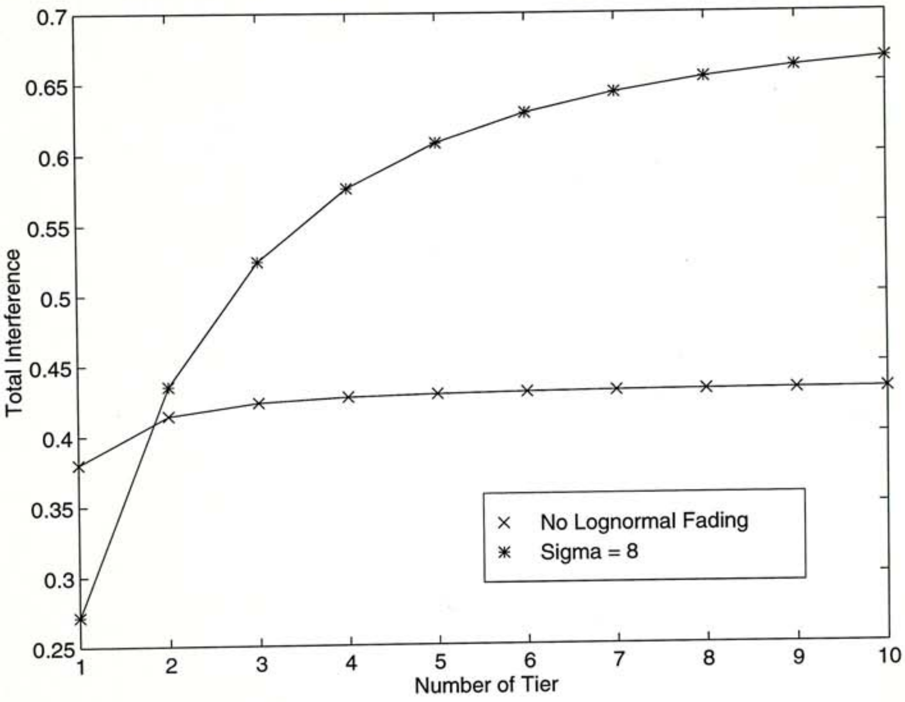

Figure 4.2: ACI per user with shadowing and maximum nominal power constraint versus the number of tier of cells included

Chapter 5

ACI Analysis of Microcell

Microcell concept is a way of increasing the capacity of traditional cellular radio systems. As the cell size decreases, the number of users accommodated per unit area increases at a rate inversely proportional to the square of the cell radius, provided that the number of users per cell is fixed. CDMA system is also a way of increasing the capacity of cellular radio systems. Theoretically, CDMA systems increase the capacity of a cell by three to ten times of the capacity of traditional systems. Nevertheless, the propagation characteristics in a microcell would affect the performance of CDMA microcellular radio systems. In this chapter, the line-of-sight (LOS) microcellular propagation model is used to analyze the adjacent cell interference (ACI) of a CDMA microcellular radio system. By using the model, the variation of interference versus the cell size is studied.

5.1 Propagation Characteristics of Microcellular Radio Systems

In traditional macrocellular radio systems, a propagation path loss of 4 is found to be applicable to most of the area [23]. This value can be derived analytically by using the simple two path model [20, 21, 4, 17]. A number of literatures has investigated the signal variation by using the two path model. On the other hand, when microcellular radio system is considered, the propagation characteristics would be different from the prediction by the macrocellular model. The macrocellular model assumes that the distance between the transmitter and receiver is long and the base station antenna height is high. Then the corresponding radio signal would attenuate proportional to d^4. In contrast, for microcellular radio systems, the distance between transmitter and receiver is short and the base station antenna is not placed at a very high position. A lot of researches has been done on investigating the propagation characteristics of microcellular radio systems. In the literatures [45, 28, 20, 46, 47, 48, 49], theory and measurements show that the signal propagation in microcell follows the two slope attenuation model with the break point at the first Fresnel zone clearance d_f

$$d_f = \frac{1}{\lambda}\sqrt{(\Sigma^2 - \Delta^2)^2 - 2(\Sigma^2 + \Delta^2)\left(\frac{\lambda}{2}\right)^2 + \left(\frac{\lambda}{2}\right)^4} \qquad (5.1)$$

where $\Sigma = h_t + h_r$ and $\Delta = h_t - h_r$, h_t is the height of the transmitting antenna, h_r is the height of the receiving antenna, and λ is the wavelength of the signal.

For the distance between the transmitting and receiving antennas $d < d_f$, the antenna pattern, variation of reflection coefficient with angle, and two ray interference conspire to give a regression slope of about 2, while interference between the two rays for $d > d_f$ leads to a regression slope near 4.

Referring to the chapter 3, the adjacent cell interference when the propagation loss equals to 2 is much higher than that when the propagation loss is 4 in a CDMA system. The adjacent cell interference of CDMA cellular radio systems limits the number of users that can be accommodated in a cell. As a consequence, in CDMA systems, the higher the propagation path loss, the larger the number of users that can be accommodated in a cell.

5.2 CDMA Microcellular Radio Systems

In order to be able to accommodate larger number of users, the microcellular concept is proposed [50] to increase the number of subscribers in a given area. On the other hand, the reduction of cell size will increase the probability that the distance between a subscriber and a base station is less than d_f (i.e., the propagation path loss approaches 2). Thus, this would increase the amount of interference to the adjacent cell. Therefore, the effect of cell size on the ACI in a CDMA system will be investigated.

The following assumptions have been made in the analysis.

- The propagation path loss for a mobile station away from the base station by d is 2 when $d \leq d_f$ and 4 when $d > d_f$. The path loss of a distance d between transmitter and receiver can be expressed by the following equation [28]

$$PL(d) = \begin{cases} 20\log_{10}(d) + p, & \text{for } d \leq d_f \\ 40\log_{10}(d/d_f) + 20\log_{10}(d_f) + p, & \text{for } d > d_f \end{cases} \tag{5.2}$$

where $p = PL(d_0)$ is the path loss in decibels at the reference distance $d_0 = 1$.

Thus, the power received P_r at the base station for a mobile which is away from it by d is

$$P_r = \begin{cases} A \cdot P_t \cdot d^{-2}, & \text{for } d \leq d_f \\ A \cdot P_t \cdot d^{-4} \cdot d_f^2, & \text{for } d > d_f \end{cases} \tag{5.3}$$

where A is a constant and P_t is the transmitted power.

- Power control is done perfectly, i.e., the signal of every users arrives at the base station with equal power P_R.
- Mobility is not considered. Once a mobile is connected to the base station, it will keep its position and transmit at its dedicated signal level.
- Mobiles are evenly distributed over the whole cell. Each cell is divided into two regions, i.e., the inner region with path loss equal to 2 and the outer region with path loss equal to 4. The probability that a mobile is located at (r, θ) is given by

$$f_{R,\Theta}(r,\theta) = \begin{cases} \frac{1}{\pi {R_s}^2} & \text{for } 0 \leq r \leq R_s \text{ and } 0 \leq \theta \leq 2\pi \\ 0 & \text{otherwise} \end{cases} \tag{5.4}$$

- The circular cell with the same area is used to approximate the hexagonal cell in the analysis.

In the analysis, the adjacent cell interference of the reverse link is considered since reverse link is generally accepted to be the limiting link of a CDMA cellular

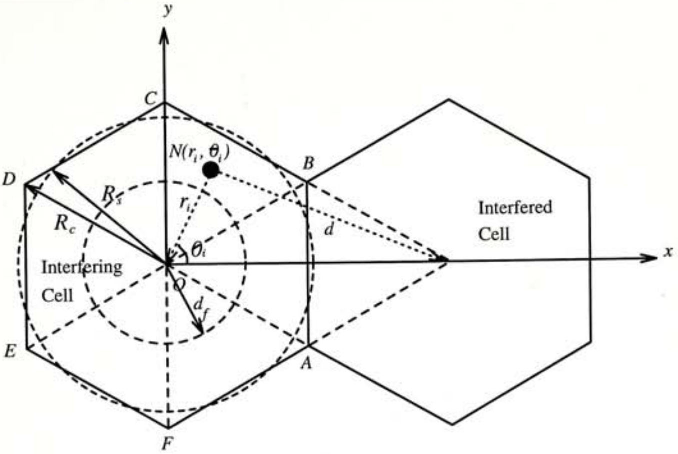

Figure 5.1: Interference from a mobile to the adjacent microcell

radio system [51]. For simplicity, shadowing is not considered in this analysis. Nevertheless, shadowing effect can be included in the analysis by using numerical method, while the closed-form expression derived in chapter 3 will be used.

Referring to figure 5.1, for a mobile at the coordinates $(r,\ \theta)$, it transmits signal to its home base station at the power P_{m_t} which is given by

$$P_{m_t} = \begin{cases} P_R \cdot r^2 & \text{for } r \leq d_f \\ P_R \cdot r^4 \cdot d_f^{-2} & \text{for } r > d_f \end{cases} \tag{5.5}$$

where P_R is the constant received power level at the base station.

The interference caused to the adjacent cell which is D_i away from this interfering cell will be

$$I(r,\theta) = \frac{P_{m_t}}{d^4 \cdot d_f^{-2}} = \frac{P_{m_t} d_f^2}{[D_i^2 + r^2 - 2D_i r \cos\theta]^2} \tag{5.6}$$

The average interference for a mobile caused to the adjacent cell will be

$$
\begin{align}
\bar{I}_i &= E[I(R,\Theta)] \tag{5.7}\\
&= \iint I(r,\theta) f(r,\theta)\, r \, d\theta \, dr \tag{5.8}\\
&= \int_{d_f}^{R_s}\int_0^{2\pi} \frac{P_R r^5}{[D_i^2 + r^2 - 2D_i r\cos\theta]^2}\cdot\frac{1}{\pi R_s^2}\, d\theta\, dr \nonumber\\
&\quad + \int_0^{d_f}\int_0^{2\pi} \frac{P_R\, d_f^2\, r^3}{[D_i^2 + r^2 - 2D_i r\cos\theta]^2}\cdot\frac{1}{\pi R_s^2}\, d\theta\, dr \tag{5.9}\\
&= \frac{P_R}{\pi R_s^2}\left[\int_{d_f}^{R_s}\int_0^{2\pi} \frac{r^5}{[D_i^2 + r^2 - 2D_i r\cos\theta]^2}\, d\theta\, dr\right. \nonumber\\
&\quad \left. + \int_0^{d_f}\int_0^{2\pi} \frac{d_f^2 r^3}{[D_i^2 + r^2 - 2D_i r\cos\theta]^2}\, d\theta\, dr\right] \tag{5.10}\\
&= \frac{P_R}{\pi R_s^2}\left[\int_{d_f}^{R_s} \frac{2\pi r^5 (D_i^2 + r^2)}{(D_i^2 - r^2)^3}\, dr + \int_0^{d_f} \frac{2\pi d_f^2 r^3 (D_i^2 + r^2)}{(D_i^2 - r^2)^3}\, dr\right] \nonumber\\
&= \frac{2P_R}{R_s^2}\left[D_i^2 \int_{\frac{d_f}{D_i}}^{\frac{R_s}{D_i}} \frac{x^5(1+x^2)}{(1-x^2)^3}\, dx + d_f^2 \int_0^{\frac{d_f}{D_i}} \frac{x^3(1+x^2)}{(1-x^2)^3}\, dx\right] \tag{5.11}\\
&= P_R\left\{\left[-\frac{4 - 6k_r^2 + k_r^4}{(1-k_r^2)^2} - \frac{4}{k_r^2}\ln\left(1-k_r^2\right)\right]\right. \nonumber\\
&\quad \left. - \frac{1}{k_r^2}\left[-\frac{4k_d^2 - 6k_d^4 + k_d^6}{(1-k_d^2)^2} - 4\ln\left(1-k_d^2\right)\right] - \frac{k_d^2}{k_r^2}\left[\frac{k_d^2 - 2k_d^4}{(1-k_d^2)^2} + \ln\left(1-k_d^2\right)\right]\right\} \tag{5.12}
\end{align}
$$

where $k_d = \frac{d_f}{D_i}$ and $k_r = \frac{R_s}{D_i}$.

When M mobiles are transmitting to the base station, the total interference from this cell becomes

$$
\begin{align}
\bar{I}_i &= M P_R\left\{\left[-\frac{4 - 6k_r^2 + k_r^4}{(1-k_r^2)^2} - \frac{4}{k_r^2}\ln\left(1-k_r^2\right)\right]\right. \nonumber\\
&\quad \left. - \frac{1}{k_r^2}\left[-\frac{4k_d^2 - 6k_d^4 + k_d^6}{(1-k_d^2)^2} - 4\ln\left(1-k_d^2\right)\right] - \frac{k_d^2}{k_r^2}\left[\frac{k_d^2 - 2k_d^4}{(1-k_d^2)^2} + \ln\left(1-k_d^2\right)\right]\right\} \tag{5.13}\\
&= M P_R \vartheta_i(R_s) \tag{5.14}
\end{align}
$$

where $\vartheta_i(R_s)$ is the adjacent cell interference function, which is defined by

$$\begin{aligned}\vartheta_i(R_s) \triangleq{} & \left[-\frac{4-6k_r^2+k_r^4}{(1-k_r^2)^2}-\frac{4}{k_r^2}\ln\left(1-k_r^2\right)\right] \\ & -\frac{1}{k_r^2}\left[-\frac{4k_d^2-6k_d^4+k_d^6}{(1-k_d^2)^2}-4\ln\left(1-k_d^2\right)\right] \\ & -\frac{k_d^2}{k_r^2}\left[\frac{k_d^2-2k_d^4}{(1-k_d^2)^2}+\ln\left(1-k_d^2\right)\right] \qquad (5.15)\end{aligned}$$

The Carrier-to-Interference Ratio of the signal from a mobile at the base station is given by

$$\frac{C}{I}=\frac{P_R}{(M-1)P_R+\sum_i \bar{I}_i} \qquad (5.16)$$

The maximum number of mobiles that can be accommodated in a cell provided that all of them attain the required minimum Carrier-to-Interference ratio $(C/I)_{req}$ is

$$M=\frac{(C/I)_{req}^{-1}+1}{1+\sum_i \vartheta_i(R_s)} \qquad \text{users/cell} \qquad (5.17)$$

5.3 Results and Discussions

Figure 5.2 shows the change of the adjacent cell interference versus the radius R_s with $d_f = 100$ and 10 tiers of cells are considered. In the figure, as the radius of the cell increases from d_f, the adjacent cell interference decreases exponentially until reaching the limiting value (i.e., $\lim_{R_s\to\infty} 1+\sum_i \vartheta_i(R_s)$), which corresponds to the value of ACI with path loss equals to 4. This shows that as the cell size increases beyond d_f, the interference will significantly decrease. From the result,

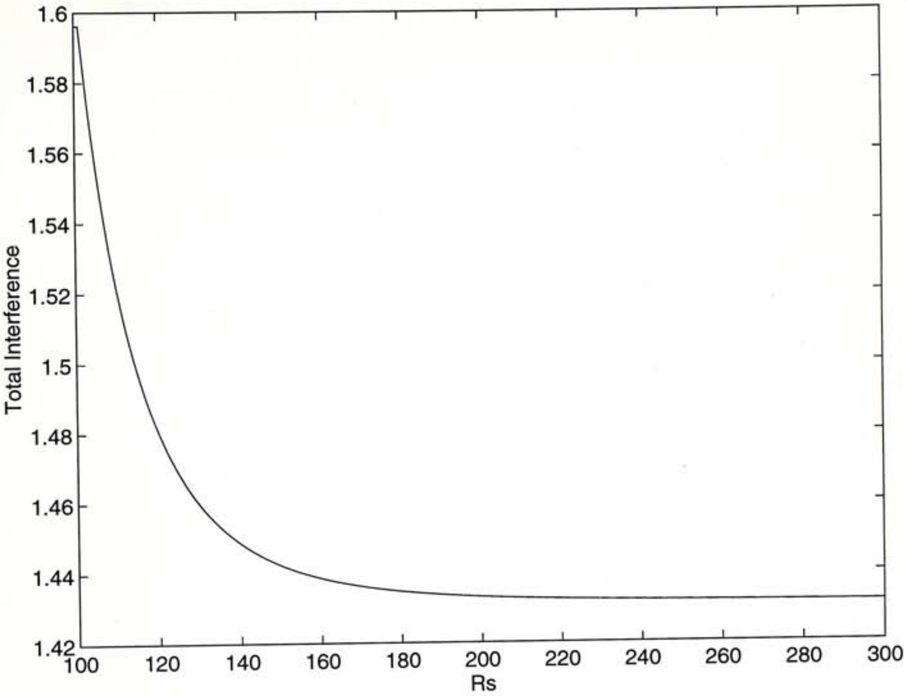

Figure 5.2: Total adjacent cell interference (ACI) per user versus the cell radius R_s with $d_f = 100$ and 10 tier of cells are considered.

when designing a CDMA system, the amount of adjacent cell interference from the adjacent cells can be determined when each cell size is fixed. For the case when all the cells are irregular and not with the same sizes, the value of ACI from any cell can still be estimated by knowing the values of D_i, R_s and d_f.

5.4 Conclusions

The amount of adjacent cell interference versus the cell radius is found. In this chapter, the ACI decreases as the cell radius increases beyond the first Fresnel zone clearance. That means the number of users per cell will increase as the cell radius increases.

Chapter 6

Outage Probability Analysis of Imperfect Power Control

In DS-CDMA cellular radio systems, power control is crucial to the system capacity. The more accurate the power controlled, the larger the number of users that can be accommodated in the system [52, 53]. Perfect power control is usually assumed in the analysis of the capacity of CDMA systems [42, 43, 4, 54, 39]. Nevertheless, in reality, power cannot be controlled such that the received power at the base station is constant for all the time. There must be some fluctuation of the value. The effect of log-normal shadowing on the system capacity has been investigated. Under real situation, the signal received at the base station is not only affected by the long-term fading but the short-term fading, which would impose another constraint on the system capacity. In this chapter, the effect of short-term signal fading and imperfect power control on the outage probability will be studied. The corresponding system capacity will be obtained.

6.1 Fast Fading of Signal

In this section, the effect of the short-term fading on the system capacity, when power control is not fast enough to combat the short-term fading will be investigated. The short-term signal fading is assumed to has a Rayleigh distribution. The long-term fading will not be considered in this chapter. Assuming the power control for combating the effect of propagation path loss is done perfectly, the received signal at the base station will be kept constant when the short-term signal fading is not included. Nevertheless, when the short-term fading effect is considered, the received signal of a particular user at the base station is

$$P_{b_r} = P_R \cdot \Psi \tag{6.1}$$

where Ψ is a random variable with probability distribution function $F_\Psi(\psi)$ [1]

$$F_\Psi(\psi) = 1 - \exp(-\psi) \tag{6.2}$$

On the other hand, the other users at the same cell would transmit signal to the base station. Since in CDMA system, users occupy the same channel. Assuming there are m users in each cell and they are transmitting to the base station simultaneously, the cochannel interference to the user would be

$$\begin{aligned} I_{b_r} &= \sum_{i=1}^{m-1} P_R \cdot \Psi_i & (6.3) \\ &= P_R X & (6.4) \end{aligned}$$

---

[1] The derivation is shown in appendix A.

where X is a random variable with the chi-square probability distribution function [2]

$$F_X^{(m-1)}(x) = \int_0^x \frac{y^{m-2}e^{-y}}{(m-2)!}dy \tag{6.5}$$

As a result, the Carrier-to-Interference ratio at the base station of the user is

$$\frac{C}{I} = \frac{P_R\Psi}{P_RX} = \Upsilon \tag{6.6}$$

where Υ is a random variable with distribution

$$\begin{aligned} F_\Upsilon(v) &= \Pr\{\Upsilon \le v\} = \Pr\{\frac{\Psi}{X} \le v\} = \Pr\{\Psi \le Xv\} && (6.7)\\ &= \int_0^\infty \Pr\{\Psi \le xv | X = x\}\Pr\{X = x\}dx && (6.8)\\ &= \int_0^\infty \int_0^{xv} f_\Psi(\psi)d\psi f_X(x)dx && (6.9)\\ &= \int_0^\infty \left[1 - e^{-xv}\right] \cdot \frac{x^{m-2}e^{-x}}{(m-2)!}dx && (6.10)\\ F_\Upsilon(v) &= 1 - \frac{1}{(v+1)^{m-1}} && (6.11) \end{aligned}$$

The probability density function is

$$f_\Upsilon(v) = \frac{d}{dv}F_\Upsilon(v) = \frac{m-1}{(v+1)^m} \tag{6.12}$$

When adjacent cell interference is included in the analysis, referring to the adjacent interference function derived in chapter 3, the C/I will become

---

[2] The superscript of the distribution function denotes that $F_X^{(m-1)}(x)$ corresponds to the summation of $m-1$ exponentially distributed random variables.

$$\frac{C}{I}=\frac{P_R\Psi}{P_RX+P_R\sum_i\vartheta_iX_i'}=\frac{\Psi}{X+\sum_i\vartheta_iX_i'} \tag{6.13}$$

where X and X_i' has probability distribution function $F_X^{(m-1)}(x)$ and $F_X^{(m)}(x)$ respectively.

The distribution of C/I can be solved by first finding the distribution of I/C.

$$\frac{I}{C}=\frac{X+\sum_i\vartheta_iX_i'}{\Psi}=\Xi \tag{6.14}$$

The distribution of the random variable Ξ is [55]

$$\begin{aligned}
F_\Xi(\xi) &= \Pr\{\Xi\le\xi\}=\Pr\left\{\frac{X+\sum_i\vartheta_iX_i'}{\Psi}\le\xi\right\} \\
&= \Pr\left\{\frac{\Psi}{X+\sum_i\vartheta_iX_i'}\ge\frac{1}{\xi}\right\} && (6.15) \\
&= \int_0^\infty dx\frac{x^{m-2}e^{-x}}{(m-2)!}\cdot\int_0^\infty dx_1'\frac{x_1'^{m-1}e^{-x_1'}}{(m-1)!}\cdots \\
&\quad \cdots\int_0^\infty dx_n'\frac{x_n'^{m-1}e^{-x_n'}}{(m-1)!}\cdot\exp\left\{-\left[\frac{(x+\sum_{i=1}^n\vartheta_ix_i')}{\xi}\right]\right\} && (6.16) \\
&= \left(\frac{\xi}{\xi+1}\right)^{m-1}\prod_{i=1}^n\left(\frac{\xi}{\xi+\vartheta_i}\right)^m && (6.17)
\end{aligned}$$

where n is the number of adjacent cells considered.

As a result, the distribution of the C/I is then given by

$$F_\Upsilon(\upsilon)=1-F_\Xi\left(\frac{1}{\upsilon}\right)=1-\left[\frac{1}{(\upsilon+1)^{m-1}}\prod_{i=1}^n\frac{1}{(1+\vartheta_i\upsilon)^m}\right] \tag{6.18}$$

In order to provide a satisfactory communication, an outage probability of less than 1% is required, i.e., $\Pr\{C/I\le 0.032\}<0.01$. Therefore,

$$1 - \left[\frac{1}{(\upsilon+1)^{m-1}} \prod_{i=1}^{n} \frac{1}{(1+\vartheta_i \upsilon)^m} \right] < 0.01 \tag{6.19}$$

$$\left[\frac{1}{(\upsilon+1)^{m-1}} \prod_{i=1}^{n} \frac{1}{(1+\vartheta_i \upsilon)^m} \right] \approx \prod_{i=0}^{n} \frac{1}{(1+\vartheta_i \upsilon)^m} > 0.99 \tag{6.20}$$

$$\Rightarrow \quad m < \frac{-\log 0.99}{\log \left[\prod_{i=0}^{n} (1+\vartheta_i \upsilon) \right]} < 1 \tag{6.21}$$

where $\vartheta_0 \triangleq 1$.

When power control is not fast enough to combat the effect of the short-term Rayleigh power fluctuation, interleaving and coding should be served to reduce the effect of power variations. Otherwise, its effect will break the system down. In addition, the closed-loop power control algorithm used in IS-95 is designed to combat the short-term fading. The corresponding controlled power received at the base station is shown in figure 6.1. The effect of the ripple of the controlled power on the system capacity will be discussed in the following section.

6.2 Imperfect Power Control in CDMA

In this section, the effect of imperfect power control on the system capacity will be studied. Although the transmitted power is adjusted for a user according to the environment, the power received at the base station will not be constant for all the time. There is some ripple of the received power, which will affect the signal of other users. The power control done by a particular user is assumed to be perfect [54] while the other users' signals received at the base station is given by $P_R + \Lambda$, where Λ is a gaussian random variable with zero mean and standard deviation equals to σ. Thus, the probability density function $f_\Lambda(\lambda)$ is

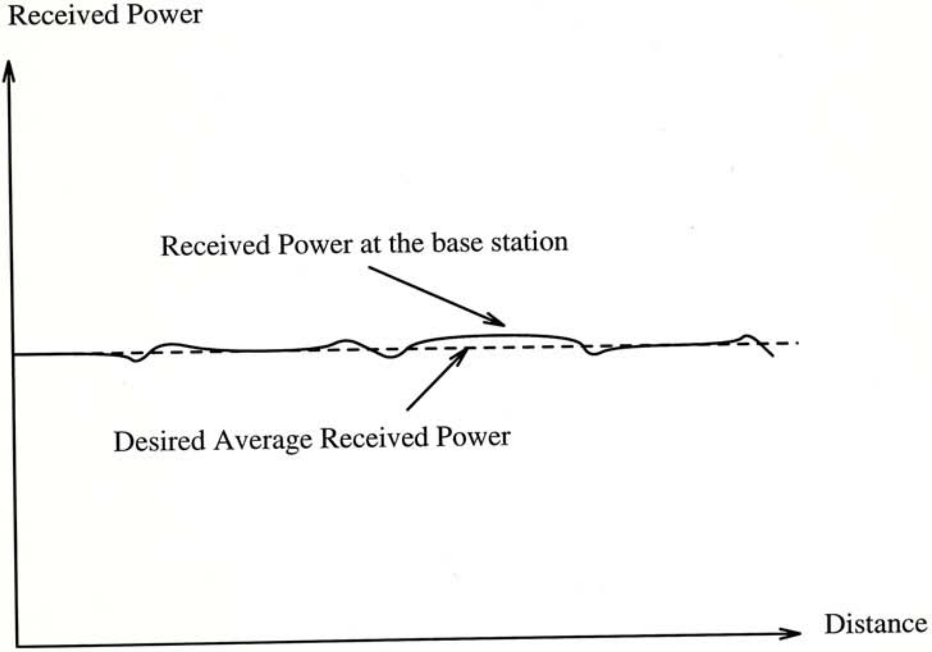

Figure 6.1: The signal received at the base station when open-loop and closed-loop power control algorithms are deployed

$$f_\Lambda(\lambda) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\lambda^2}{2\sigma^2}} \qquad -\infty \leq \lambda \leq \infty \tag{6.22}$$

The C/I is then given by

$$\begin{aligned}
\frac{C}{I} &= \frac{P_R}{\sum_{j=1}^{m-1}(P_R + \Lambda_j) + \sum_{i=1}^{n} \vartheta_i \sum_{j=1}^{m}(P_R + \Lambda_j)} && (6.23) \\
&= \frac{P_R}{(m-1)P_R + \Lambda_0^{(m-1)} + mP_R \sum_{i=1}^{n} \vartheta_i + \sum_{i=1}^{n} \vartheta_i \Lambda_i^{(m)}} && (6.24) \\
&= \frac{P_R}{(m-1)P_R + mP_R \sum_{i=1}^{n} + \Lambda_0^{(m-1)} \vartheta_i + \sum_{i=1}^{n} \vartheta_i \Lambda_i^{(m)}} && (6.25) \\
&\approx \frac{P_R}{mP_R \sum_{i=0}^{n} \vartheta_i + \sum_{i=0}^{n} \vartheta_i \Lambda_i^{(m)}} && (6.26) \\
&= \frac{1}{I_0 + I} && (6.27)
\end{aligned}$$

where $\Lambda^{(m)}$ represents the summation of m gaussian random variables, $\vartheta_0 = 1$, $I_0 \triangleq m \sum_{i=0}^{n} \vartheta_i$ and $I \triangleq \sum_{i=0}^{n} \frac{\vartheta_i}{P_R} \Lambda_i^{(m)}$.

Since the summation of gaussian random variables is still a gaussian random variable, I is a gaussian random variable with zero mean and standard deviation σ_I which is given by

$$\sigma_I = \sqrt{\sum_{i=0}^{n} \left(\frac{\vartheta_i}{P_R}\right)^2 \sum_{j=1}^{m} \sigma^2} = \frac{\sigma}{P_R} \sqrt{m \sum_{i=0}^{n} \vartheta_i^2} \tag{6.28}$$

One may observe that the interference power can be negative in our model. Nevertheless, the probability that the interference power is negative tends to zero. In appendix B, the mean-to-standard deviation of the interference power have been derived. The probability of negative interference power tends to zero for values interested. As a result, the negative interference power does not need to be considered.

In order to provide an outage probability less than 0.01, the corresponding number of users that can be accommodated in the system is

$$\Pr\left\{\frac{1}{I_0+I} \le 0.032\right\} = \Pr\{I \ge 31.25 - I_0\} < 0.01 \tag{6.29}$$

$$\begin{aligned}
\Pr\{I \ge 31.25 - I_0\} &= \int_{31.25-I_0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_I} e^{-\frac{u^2}{2\sigma_I^2}} du & (6.30)\\
&= \int_{\frac{31.25-I_0}{\sigma_I}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt & (6.31)\\
&= 1 - \int_{-\infty}^{\frac{31.25-I_0}{\sigma_I}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt & (6.32)\\
&= 1 - \Phi\left(\frac{31.25 - I_0}{\sigma_I}\right) < 0.01 & (6.33)\\
\Phi\left(\frac{31.25 - I_0}{\sigma_I}\right) &> 0.99 & (6.34)
\end{aligned}$$

where $\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{u^2}{2}} du$. By looking up the table of $\Phi(\cdot)$,

$$\begin{aligned}
\frac{31.25 - I_0}{\sigma_I} &= 2.33 & (6.35)\\
\frac{31.25 - m\sum_{i=0}^{n}\vartheta_i}{\frac{\sigma}{P_R}\sqrt{m\sum_{i=0}^{n}\vartheta_i^2}} &= 2.33 & (6.36)\\
31.25 &= 2.33\frac{\sigma}{P_R}\sqrt{m\sum_{i=0}^{n}\vartheta_i^2} + m\sum_{i=0}^{n}\vartheta_i & (6.37)\\
& & (6.38)
\end{aligned}$$

By the adjacent cell interference function derived in chapter 3, $\sum_{i=0}^{n}\vartheta_i = 1.4321$ and $\sum_{i=0}^{n}\vartheta_i^2 = 1.0242$ can be obtained,

$$31.25 = 2.33\hat{\sigma}\sqrt{1.0242m} + 1.4321m \tag{6.39}$$

where $\hat{\sigma} = \frac{\sigma}{P_R}$ is the normalized standard deviation, i.e., the deviation relative to the signal power. Thus,

$$m = \frac{(43.6422 + 2.7111\hat{\sigma}^2) - \hat{\sigma}\sqrt{15.0746\hat{\sigma}^2 + 485.3257}}{2} \tag{6.40}$$

An equation of m in terms of $\hat{\sigma}$ is obtained. Including the seven and a half times capacity increase given by voice activity and sectorization, figure 6.2 shows the change of m versus $\hat{\sigma}$. The capacity of the system decreases significantly with respect to $\hat{\sigma}$. As a result, a small deviation of the power from the dedicated value would severely reduce the capacity of the system.

For the specification of Qualcomm CDMA cellular radio system (IS-95) [3], an IS-95 channel occupies the same bandwidth of about 41 channels of the AMPS system and 123 channels of IS-54 Digital AMPS system. In order for the CDMA system provides a higher capacity than the other systems, from figure 6.2, $\hat{\sigma}$ should not be higher than 0.8. Otherwise, the capacity will be lower than that of the other systems.

6.3 Conclusions

In this chapter, the effect of short term fading on the system outage probability have been studied. In the presence of short-term fading, the Carrier-to-Interference ratio C/I varies significantly. As a result, the outage probability is high. Power control should be done fast enough to combat the effect of it. In the latter part, the effect of imperfect power control on the system capacity is studied. With the assumption that the received power at the base station derivates

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[3] The specifications of Qualcomm CDMA system will be discussed in chapter 8

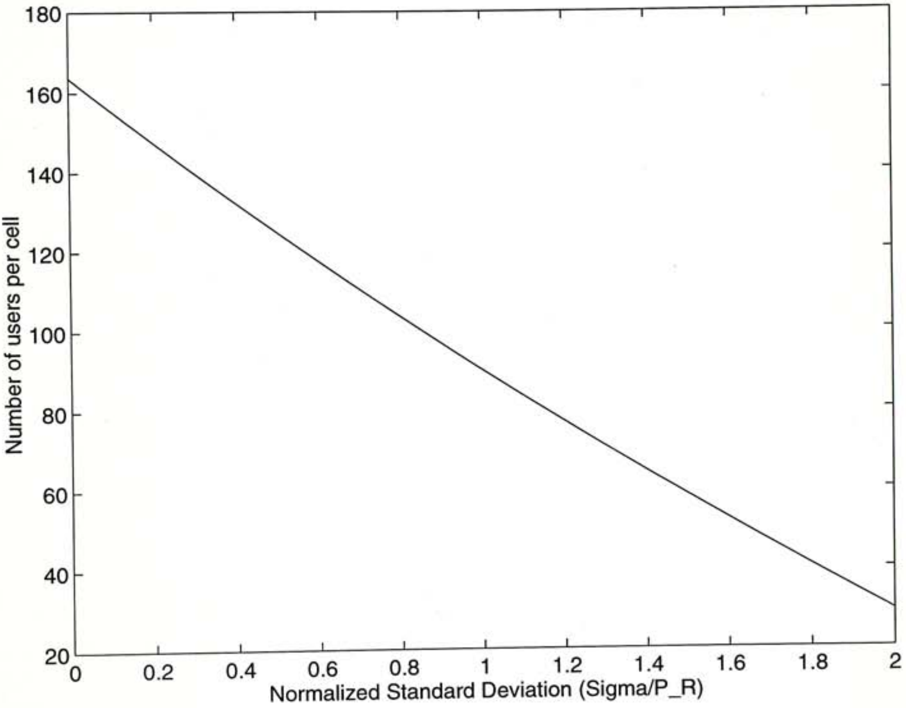

Figure 6.2: The system capacity (number of users per cell) versus the normalized standard deviation of the received power $\hat{\sigma}$.

from the nominal power with a gaussian distribution, the system capacity in number of users per cell can be expressed in terms of the standard deviation of the received power relative to the absolute received power $\hat{\sigma}$ at the base station. The capacity decreases significantly as $\hat{\sigma}$ increases. As a result, the deviation of received power from the nominal one should be kept within 0.8. Otherwise, the system capacity will no longer be higher than that of FDMA and TDMA systems. High capacity will no longer be the merit of CDMA.

Chapter 7

Conclusions

In this thesis, the effect of adjacent cell interference (ACI) on the capacity of a code division multiple access (CDMA) cellular radio system have been investigated. For the case of ideal circumstance, the adjacent cell interference function is derived. Closed-form solutions for the propagation exponent equals to 2 and 4 are obtained. The amount of ACI from different number of tier of cells are studied. From the equation, ten tiers of cells should be considered for the adjacent cell interference. The value of ACI is $0.4321M$ where M is the number of users in a cell.

When log-normal shadowing is considered, the ACI behaves differently from the ideal case. An equation for the ACI in terms of the variation of the signal in the presence of log-normal shadowing is obtained. The system capacity will be severely reduced. By considering the maximum nominal power constraint, i.e., the power received at the mobile from its home base is the strongest, an integral equation of the ACI is obtained. Unfortunately, the equation is too complicated to be solved. The amount of ACI for that is found by numerical intergration.

Results show that the ACI would behave much better than that without the constraint. In typical propagation environment, measurement shows that the standard deviation of the signal local mean in the presence of shadowing is about 8. For this value, the corresponding ACI with standard deviation equals to 8 would be much higher than that without fading, resulting to significant reduction of system capacity.

In microcellular radio system, the propagation characteristics would be quite different from what in macrocellular systems. The line-of-sight (LOS) two-slope regression model is used for characterizing the signal propagation in microcellular radio systems. With the model, a closed-form solution of ACI in terms of the radius of the cell is obtained. The formula can be used to determine the number of users that can be accommodated in a cell given that the size of each cell is fixed. As far as this thesis is concerned, no similar analytical result is obtained in other literature. By using the result in this part, the planning of a CDMA microcellular radio system would be much simplified. System capacity can be estimated by substituting the corresponding values into the closed form solution obtained.

The effect of imperfect power control is also investigated. The signal variation is modeled as a gaussian random variable with zero mean and standard deviation σ. An equation to describe the variation of BER with respect to the variance of the signal relative to the absolute signal power has been obtained.

The result obtained in this thesis can be applied to cellular radio system planning. By the simple form of ACI, the capacity of a cell can be estimated easily. For deploying a new CDMA cellular radio system, the estimation of the amount of interference from the surrounding cells would be crucial to the normal operation of a cell. When the interference from an adjacent cell is too high, the interference from that cell or the number of users that will be accommodated in the interfered cell should be reduced.

Chapter 8

Examples of CDMA Cellular Radio Systems

8.1 Qualcomm CDMA system

Qualcomm Incorporated in the USA is developing a CDMA cellular radio system. The specifications are as follows:

1. It operates at the top of the advanced mobile phone system (AMPS) band.
2. The bandwidth required for each forward- and reverse-link is 1.23 MHz, equivalent to 41 AMPS channels (41×30 kHz = 1.23MHz).
3. It operates in the 1.7 to 1.8 GHz band.
4. Quadrature Phase Shift Keying (QPSK) is used for modulating signal.
5. Universal frequency reuse and soft handoff are deployed.

The forward-link and reverse-link specifications are similar. In the following, the specifications of the forward-link are stated, followed by the specifications of the reverse-link.

8.1.1 Forward-link

1. There is one pilot channel, one synchronization channel, and 62 other channels. All of the 62 channels can used for traffic, but up to 7 can be used for paging.
2. All the channels are encoded with the 64 Walsh codes of length 64. The all-one code is for the pilot, the alternating polarity is used for the synchronization channel, while the paging and traffic channels use the other 62 codes.
3. The synchronization channel data at 1200 bps is convolutionally encoded to 2400 bps, repeated to 4800 bps and interleaved over the period of the pilot PRBS.
4. The speech is encoded by Qualcomm Codebook Excited Linear Predictive (QCELP) speech coding [56] at the rates of 1.2, 2.4, 4.8 or 9.6 kbps, depending on speaker activity.
5. The frame duration is fixed at 20 ms, the number of bits per frame varies according to the traffic rate.
6. Half rate convolutional encoding with a constraint length of 9 doubles the traffic rate to give rate from 2.4 to 19.2 k symbols/s. To ensure the rate is always 19.2 k symbols/s, data repetition is appropriately used at the lower

speech rates. Interleaving is performed over 20 ms, and the higher the data repetition used, the lower is the transmission power of the symbols.

7. A long code of $2^{42} - 1 (= 4.4 \times 10^{12})$ is generated containing the user's electronic serial number embedded in the mobile stations long code mask.
8. The scrambled data is multiplexed with the power control information which essentially steals bits from the scrambled data.
9. The 19.2 k symbols/s signal is spread to 1.2288 Mchip/s by the pilot quadrature PRBS signals.
10. The pilot signal provides the mobile units with system information and instructions, in addition to acknowledgement messages following access requests made on the mobile units' access channels.
11. The pilot signals from all the base stations use the same PRBS, but each BS is characterized by a unique time offset of its PRBS. These offsets are increments of 64 chips providing 511 unique offsets relative to the zero offset code.

8.1.2 Reverse-link

In general, the speech data of a mobile station is encoded and processed very similar to the forward-link data. The difference is stated as follows:

1. Speech is convolutionally coded at a rate 1/3 code of constraint length 9.
2. The Walsh coded signals at a mobile station are modulated by the long $2^{42} - 1$ PRBS with a specific time offset that is unique to a particular

mobile station, enabling the base station to distinguish signals arriving from different mobile stations.

3. The receiver at the base station has a tracking receiver and four receivers that each locks on to a significant path in the channel impulse response. The received signal is correlated with the 64 Walsh codes in each of the four receiver. The outputs of the four correlation receivers are combined and the correlator number having the maximum output selected to identify the recovered 6-bit symbol.

For more detail description of the Qualcomm CDMA system, please refer to [18].

The ways of controlling the transmission power of the Qualcomm CDMA system in reverse- and forward-link are different [57].

8.1.3 Reverse-Link Open-Loop Power Control

The open-loop power control in the reverse-link is mainly for combating the power fluctuation due to long-term fading or shadowing. Based on the strength of the pilot signal from the base station, each mobile units attempts to estimate the path loss from cell-site to the mobile unit. The reverse link path loss estimated at the mobile is used by the mobile to adjust its own transmitter power. The stronger the received signal, the lower will be the mobile's transmitter power. Reception of a strong signal from the cell-site or has an unusually good path to the cell-site from its mobile transmission. The rate of increase of mobile transmit power must generally be limited to the rate at which the closed-loop power control from the cell-site can reduce the power.

8.1.4 Reverse-Link Closed-Loop Power Control

The closed-loop power control in the reverse-link is mainly for combating the power fluctuation due to short-term fading. The path loss estimation used by open-loop power control cannot combat the effect of fast fading because the 45 MHz frequency separation greatly exceeds the coherence bandwidth of the channel. This means that a mobile unit cannot measure the path loss of a received signal and assume that the exactly the same path loss is present on its transmitted signal, particularly when the mobile is stationary. The above measurement technique provides the correct transmit power on the average, but additional provisions must be made for the effects of independent Rayleigh fading.

To account for the independence of the Rayleigh fading on the forward and the reverse link, each cell-site demodulator measures the received signal strength from each mobile. The measured signal strength is compared to the desired signal strength for that mobile and a power adjustment command is sent to the mobile in the outbound channel addressed to the mobile unit. This power adjustment command is combined with the mobiles' open loop estimate to obtain the final value of the mobile's transmit radiated power.

The cell-site power adjustment command signals the mobile unit to increase or to decrease the mobile power by a predetermined amount, nominally about 0.5-1 dB. The power adjustment command is transmitted at a relatively high rate, on the order of one command every millisecond, which is adequate to track fading processes for vehicle speeds up to 25-100 miles per hour for 850 MHz band mobile communications.

8.1.5 Forward-Link Power Control

The primary reason for providing forward-link power control is to accommodate the fact that in certain locations, the link from cell-site to mobile may be unusually disadvantaged. Unless the power being transmitted to this mobile is increased, the quality may become unacceptable. To achieve these objectives, the design includes a signal-to-interference measurement capability within the mobile receiver. This measurement is performed by comparing the desired signal power to the total interference and noise power. If the measured ratio is less than a predetermined value the mobile transmits a request for additional power to the cell-site. If the ratio exceeds the predetermined value, the mobile transmits a request for a reduction in power.

8.2 Interdigital Broadband CDMA System

The Interdigital Broadband CDMA system is not as mature as the Qualcomm CDMA system. The transmission frequency is proposed to be 800 MHz or 2 GHz. The signal is spread from an information bandwidth of 32 kHz to the spread spectrum bandwidth of 48 MHz. It is proposed to overlay on the spectrum, where other radio services are progressing, i.e., it shares with the existing cellular or paging spectrum. Notch filters are deployed for reducing the interference to the narrowband signals. The system is still at the preliminary stage and further specifications are going to be released.

Appendix A

Derivation of the PDF of the fast fading signal power

$$F_\Psi(\psi) = \Pr\{P \le \psi\} = \Pr\{\frac{A^2}{2} \le \psi\} = \Pr\{A \le \sqrt{2\psi}\} \tag{A.1}$$

$$= \int_0^{\sqrt{2\psi}} \frac{A}{\gamma^2} \exp\left(-\frac{A^2}{2\gamma^2}\right) dA \tag{A.2}$$

$$= 1 - \exp\left(-\frac{\psi}{\gamma^2}\right) \tag{A.3}$$

The result shows that when the distribution of the received signal envelope is Rayleigh, the short term power fluctuation of it will be exponentially distributed.

If Ψ is normalized, i.e., the received power is assumed to be given by $P_R\Psi$, then the pdf becomes

$$F_\Psi(\psi) = 1 - \exp(-\psi) \tag{A.4}$$

Appendix B

Derivation of the Mean-to-standard deviation ratio

Since the interference power should not be less than zero, in the range of values interested, the probability that $I < 0$ tends to zero. The mean and variance of the interference power are given by

$$E[I_0 + I] = I_0 = m \sum_{i=0}^{n} \vartheta_i \tag{B.1}$$

$$Var(I_0 + I) = E[(I_0 + I)^2] - I_0^2 = I_0^2 + E[I^2] - I_0^2 = E[I^2] = \left[\frac{\sigma}{P_R} \sqrt{m \sum_{i=0}^{n} \vartheta_i^2} \right]^2 \tag{B.2}$$

Therefore, the mean-to-standard deviation is

$$\frac{m\sum_{i=0}^{n}\vartheta_i}{\hat{\sigma}\sqrt{m\sum_{i=0}^{n}\vartheta_i^2}} \tag{B.3}$$

For values of interested, $m > 40$, $0 < \hat{\sigma} < 2$, $\sum_{i=0}^{n}\vartheta_i = 1.4321$ and $\sum_{i=0}^{n}\vartheta_i^2 = 1.0242$, it turns out that the ratio is greater than 3, i.e., the probability that the interference power less than zero tends to zero. As a result, the probability that the interference power is less than zero does not need to be considered.

Appendix C

Acronyms

ACI	Adjacent Cell Interference
AMPS	Advanced Mobile Phone System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CCIR	Comite Consultatif International de Radio (International Radio Consultative Committee)
CIR	Carrier-to-Interference Ratio
CDMA	Code Division Multiple Access
DS	Direct Sequence
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FPLMTS	Future Public Land Mobile Telecommunication Systems
GSM	Global System for Mobile Communications
i.i.d.	Independent and Identically Distributed

ISI	Inter-Symbol Interference
IS	Interim Standard
ITU-R	International Telecommunication Union - Radio-communication sector
LOS	Line-of-Sight
MAI	Multiple Access Interference
PABX	Private Automatic Branch Exchange
PCL	Power Control Law
PCS	Personal Communication Services
pdf	Probability Density Function
PDF	Probability Distribution Function
PRBS	Pseudo Random Bit Sequence
QCELP	Qualcomm Codebook Excited Linear Predictive
QPSK	Quadrature Phase Shift Keying
SRA	Stepwise Removal Algorithm
TACS	Total Access Communications System
TDMA	Time Division Multiple Access
TH	Time Hopping
WARC	World Administrative Radio Conference

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