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POWER CONTROL IN CELLULAR CDMA SYSTEMS

by

Haiyan Li

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
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POWER CONTROL IN CELLULAR CDMA SYSTEMS

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Date: November 3, 1997

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to my family

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Abstract

Spurred by consumer interest in wireless communications, more efforts are currently devoted towards increasing system capacity. CDMA systems, a well-known technique in combating interference and multipath, is finding more and more applications in digital cellular radio communications and advanced wireless technologies such as PCN. It provides a platform for a graceful evolution into the future generations of wireless technologies.

This thesis considers the power control schemes which are of prime importance for the CDMA wireless system capacity. Since the same radio channel is shared by several system users, each using a specific spread-spectrum pseudo-noise (PN) code, the capacity of the system is maximized if each mobile transmitter's power is controlled so that its signal arrives at the receiver with minimum signal-to-interference ratio required for an acceptable performance. In reality, the wireless channel is a random process (Rayleigh distributed for example) and prediction on the channel variation can not be made accurately; the system capacity therefore will be affected by the power control errors due to inaccurate compensation of wireless channel variation. The aim of this work is to investigate methods which will reduce these errors.

The proposed power control scheme is a variable-step-sized closed-loop power control scheme where more than one control bit are used in the control command. The algorithm provides a kind of prediction on wireless channel variation by keeping records of previous transmitter power values. The positive peaks in the received signal power are efficiently suppressed. The simulation results show that the power control errors are lower when compared with the existing power control schemes under the same channel condition and same number of power control bits (1 bit). When a larger number of bits are used in power control command, the wireless channel variation can be estimated more accurately and the power control errors may be further decreased.

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List of Acronyms

Acronym	Meaning
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
dB	Decibels
DS-CDMA	Direct Sequence Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FH-CDMA	Frequency Hopping Code Division Multiple Access
MSTO	Mobile Switching Tele-communication Office
PCS	Personal Communication Services
PG	Processing Gain
PN	Pseudo Noise
RMS	Root of Mean Square
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SSMA	Spread Spectrum Multiple Access
TDMA	Time Division Multiple Access

1.1 Wireless Mobile Communication

A whole new world of interconnection requirements has been thrust upon the telecommunication industry in terms of technical capability and the availability of dramatic new services. Dr. D. Cox proposed a new communication system called Universal Personal Communications in 1987. Since then a lot of new ideals have come up to deal with the increasing popularity of wireless telecommunication and issue of capacity. In digital systems, there are three basic multiple access schemes, frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA).

When selecting a multiple access scheme, among other issues, perhaps the most important one is the number of admissible users per cell for a given available total bandwidth, for given radio propagation conditions, and for a required transmission quality. This number is termed the cellular radio capacity. It is found that there is a theoretical equivalence between the three considered multiple-access schemes [2]. In other words, independently of the selected multiple-access scheme, all reasonable well designed multiple access schemes are theoretically equivalent if only AWGN (additive white Gaussian noise) channels are considered. However, in the cellular system, we might find that one may be better than the another. In a fading multipath environment, which is typical for

mobile radio applications, multipath is often a fundamental limitation to system performance, there are significant differences between these multiple-access schemes [2].

CDMA is a well-known technique to combat multipath. A unique capability of direct sequence CDMA is the exploitation of multipath to provide path diversity.

CDMA is a modulation and multiple access scheme based on spread spectrum communications techniques, a well established technology that has been applied in military communication. The application of CDMA to cellular mobile communication was first presented by Qualcomm in February 1989. Now it finds more and more applications in digital cellular radio communications and advanced wireless technologies such as PCN. It solves the near-term capacity concerns of major markets and answers the industry's long-term need for a next generation technology for truly portable communications in the most economic and efficient manner providing a platform for a graceful evolution into the future generations of wireless technologies.

1.2 Objective of the Study

The surging demand for the wireless communication shows the need for technology to further increase the capacity of cellular communication system and improve the system performance. CDMA was developed to increase the capacity of cellular network. Unlike FDMA and TDMA whose capacities are primarily bandwidth limited, the capacity of CDMA is only interference limited, any reduction in interference converts directly and linearly into an increase in capacity [3]. It has been shown that for terrestrial cellular network, the interference suppression feature of CDMA can result in many-fold increase in the capacity of the cellular network. However the above conclusion is based on the assumption that all signals arriving at the receiver with the same power. So power control is crucial to cellular CDMA system.

Since the same radio channel can be reused by all users in the system, the capacity of the system is maximized if each mobile transmitter's power is controlled so that its signal arrives at the cell-site with the minimum required signal-to-interference ratio. If the received signal at the cell site from a mobile is too low, the bit-error-rate will be too high for that user. On the other hand, if the received signal from a mobile is too high, the performance for that user will be acceptable, but interference to all the other mobile transmitters in the area will be increased, lowering the performance for the other users. The ideal situa-

tion will be to receive the same nominal power level from each mobile operating within the cell. By controlling the power of each transmitter can the resources be shared equitably among users and the system capacity be maximized.

Many power control schemes have been proposed. Some algorithms which deal with near-far affect and shadowing problem only work on average power control basis [4][5]. Those schemes only adjust the transmitter power to compensate the variation of the local mean of the wireless channel. Therefore they are slow acting and can not follow variation due to fast Rayleigh fading. The power control schemes proposed in [6] and [7] which are known as strict power control, take the fast Rayleigh fading into account. In [6] and [7] the transmitter updates its power by a fixed step in a certain frequency which is high enough to track the fast fading. Further investigation [in Chapter 5] shows that the fixed step sized power control schemes can not provide a satisfactory tracking of the fast deep fading level. The objective of this thesis is to propose a power control scheme which achieves better power control result for CDMA mobile systems.

1.3 Organization of the Thesis

Some basic characteristics about cellular mobile system are described in Chapter 2, including the harsh wireless channel environment, the frequency selective fading. Three basic multiple access schemes are also described, with the emphasis on CDMA system and its uniqueness.

Chapter 3 gives the literature review of power control issues in wireless network. First of all, the general description of power control concept in wireless network and the relationship of CDMA system capacity and power control error is presented. Based on the algorithm used in existing power control schemes, power control is classified as open-loop power control vs. closed-loop power control, centralized power control vs. distributed power control, and average power control vs. strict power control. Each is described briefly with the emphasis placed on strict power control. Finally a practical power control example is provided.

The proposed power control model is described in Chapter 4. First of all, the theoretical consideration is described. Then the adaptive power control model and two improvement algorithms with the emphasis on the wireless channel estimation algorithm are proposed. Finally the implementation of the proposed scheme is presented.

Chapter 5 presents the simulation results based on the proposed model in Chapter 4. First of all, the effect of wireless channel prediction on power control error is discussed. Then the effect of quantization on the power control message is illustrated and the simulation results are discussed and compared with the existing power control schemes. The last two sections show the outage probability and the capacity improvement for the proposed power control scheme.

In Chapter 6 the conclusions are made and future research directions are proposed.

Overview of Cellular Mobile Systems

2.1 Wireless Mobile Channel

Wireless mobile communication system is one of the most complicated system among all the other kind of communication systems. Because of wireless feature in mobile communication, the communication channel is subjected to time variant conditions in which energy can travel from the transmitter to the receiver via more than one path resulting from the variant geometry of the objects surrounding the receiving and/or transmitting mobile antennas. In addition, the movement of the transmitter or the receiver introduces Doppler phenomenon. The frequency shift is determined by the mobile moving speed, carrier wavelength and the angle of signal path, i.e.

$$\omega_n = \frac{2\pi}{\lambda} v \cos \alpha_n \quad (2.1)$$

where

- ω_n – Doppler angular frequency shift
- λ – signal wavelength
- α_n – angle of nth arriving path
- v – vehicle moving speed.

2.1.1 Multipath Environment

In wireless communications, the “multipath” situation arises because of reflection, diffraction and scattering from buildings, trees and other obstacles along the path. Radio waves therefore arrive at a mobile receiver from different directions with different time delays. They combine vectorially at the receiver antenna to give a resultant signal which can be large or small depending upon whether the incoming waves combine constructively or destructively. A receiver at one location may experience a signal strength several tens of dB different from a similar receiver located only a short distance away. As a vehicle-borne receiver moves from one location to another, the phase relationship between the various incoming waves changes; hence there are substantial amplitude fluctuations and the signal is said to be subject to fast Rayleigh fading.

Analytically, the wireless signal can be expressed as [8]

$$E = E_0 \sum_n C_n \cos(\omega_c t + \theta_n) \quad (2.2)$$

where

$$\theta_n = \phi_n + \omega_n t \quad (2.3)$$

and

- E – field strength of electrical component,
- $E_0 C_n$ – the real amplitude of the n th wave
- ω_c – angular frequency of CW signal,
- ϕ_n – random phase angles uniformly distributed from 0 to 2π .
- ω_n – Doppler frequency shift which is related with the vehicle speed v and carrier wavelength as Equation (2.1).

Based on Eq. 2.2, a typical variation of wireless channel is shown in Figure 2.1, simulated using a model in [8] with a Doppler frequency spectrum corresponding to a uniform angle of arrival path distribution. The carrier frequency is 900 MHz and the mobile speed is 40 km/hr.

In cellular wireless communications, generally the mobile radio signal is extremely variable. The mean signal strength will be constant only over relatively small areas, and will vary slowly as the receiver is moved. The statistical behavior of the local mean is

FIGURE 2. 1

Typical received wireless signal variation.

described by log-normal fitting. Superimposed on this slowly varying mean is the fast fading, described by Rayleigh fading, which is caused by multipath propagation in the immediate vicinity of the receiver. The probability density function of local mean $l(t)$ in dB is denoted as:

$$p(l) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(l-l_m)^2}{2\sigma^2}} \quad (2.4)$$

where l - random variable standing for local mean $l(t)$, l_m - mean value of l , σ^2 - signal average power.

The probability density function of Rayleigh fading $r(t)$ can be expressed as following:

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \quad (2.5)$$

where r is the signal envelop magnitude and σ^2 is the signal average power.

2.1.2 Characterization of Wireless Fading Channels

In mobile radio environment, the multipath medium has two characteristics: one is that the time spread introduced in the signal which is transmitted through the channel; the other is that the nature of the multipath varies with time due to the time variations in the structure of the medium.

The autocorrelation function of the wireless channel impulse response $\phi_c(\tau)$ can be depicted in Fig. 2.2. $\phi_c(\tau)$ is also known as the multipath intensity profile, τ is the time delay. The average values of τ over which $\phi_c(\tau)$ is essentially nonzero is called the multipath spread T_m .

FIGURE 2. 2

Multipath Intensity Profile.

The reciprocal of T_m is a measure of the coherence bandwidth of the channel. That is [9]:

$$(\Delta f)_c = \frac{1}{T_m} \quad (2.6)$$

where $(\Delta f)_c$ – channel coherence bandwidth.

Thus two sinusoids with frequency separation greater than $(\Delta f)_c$ are affected approximately independently by the channel. When an information-bearing signal is transmitted through the channel, if $(\Delta f)_c$ is small in comparison to the bandwidth of the transmitted signal, the channel is said to be frequency-selective. On the other hand, if $(\Delta f)_c$ is large in comparison to the bandwidth of the transmitted signal the channel is said to be frequency-nonselective or flat fading channels.

For frequency selective channels, the frequency components in the signal transmitted undergo the different attenuations and phase shifts. This provide the case of frequency diversity [10]. The number of diversity branches M is determined as following:

$$M = \frac{W}{(\Delta f)_c} \quad (2.7)$$

where W is the bandwidth of the transmitting signal. The effective number of diversity varies with the environment. M is larger in the urban area than in the suburban area. In other words, the wideband signal would provide more diversity gain in the urban areas than in suburban areas.

This is the case in spread spectrum communications where the signal occupies a bandwidth in excess of the minimum necessary to send the information. One of the main benefits of spread spectrum in civil communication is introducing frequency diversity. The amount of spectrum spreading determines the system performance [11]. A commonly used model for frequency selective wireless channel is the three-ray model shown in Fig.2.3, in which there are three resolvable paths, each has a complex gain $h_i(t)$, $i = 1, 2, 3$, corresponding delay of τ_1 and τ_2 . The gain in each path is statistically independent which can be used for diversity in RAKE receiver [12].

FIGURE 2.3

A three-ray model used to characterizing wireless channel.

2.2 Code-division Multiple Access (CDMA) Digital Systems

2.2.1 An Overview of CDMA Systems in Wireless Communications

The development of the code division multiple access (CDMA) scheme is mainly for capacity reasons. CDMA is one of the techniques used in spread spectrum systems. Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery.

In CDMA users are allowed to transmit simultaneously in time and occupy the same RF bandwidth as well, each user is given its own code, which is approximately orthogonal (i.e., has low cross correlation) with the codes of the other users [18].

The essence of CDMA is the use of an additional dimension in signal space which enables transceivers which occupy the same bandwidth (in contrast to FDMA systems) and exist at the same time (in contrast to TDMA Systems) still to be separable. This is done by spreading the wanted transmission bandwidth, multiplying the wanted digital signal by a spreading code at a substantially higher bit rate. (The resulting bits are usefully referred to as “chips” to distinguish them from message bits.) If the spreading code has the spectral properties of a pseudo-random binary sequence, then the result of the multiplica-

tion is a noise-like signal, but when the spread spectrum signal is processed through a correlator, which has knowledge of the sequence used to perform the spreading in the transmitter, then the wanted signal is recovered. If many sequences can be identified which have low cross-correlation characteristics then an equivalent number of spread spectrum transmissions can co-exist but remain orthogonal or quasi-orthogonal.

In theory, it does not matter whether the spectrum is divided into frequencies, time slots, or codes, the capacity provided from these three multiple access schemes is the same. The differences between the three multiple-accessing techniques become apparent when various real-world constraints are imposed upon the ideal situation. For example, one attractive feature of CDMA is that it does not require the network synchronization that TDMA requires. However, in cellular system where multipath is one of the major concerns, CDMA exhibits the unique feature of anti-multipath[19]. In CDMA, the frequency selectivity of the radio channel, which severely impairs the system performance, can be averaged out. Hybrid combinations of these techniques are frequently used (as in frequency-hopping GSM system.)

Spread-spectrum communications with its inherent interference attenuation capability, has over the years become an increasingly popular technique for use in many different systems. Applications range from anti-jam systems as in military use [20], to code division multiple access systems, to systems designed to combat multipath in wireless communication [21] [7].

2.2.2 A Basic Description of a CDMA System

The ways in which the spectrum is spread include “direct-sequence”, “frequency hopping” and “time hopping”. By “direct sequence” it means that a fast generated pseudo-random sequence causes phase transitions in the carrier containing data, and “frequency hopping,” in which the carrier is caused to shift frequency in a pseudorandom way, while in “time hopping,” a message transmitted with a data rate of R requiring a transmit time interval is now allocated at a longer transmission time interval in which the data are sent in bursts dictated by a hopping pattern. The time interval between bursts also can be varied. Among the three methods the first two spreading techniques are commonly used. Figure 2.4 shows a basic system used in spread spectrum technology. Spread spectrum technology can be thought of as a second modulation technique.

FIGURE 2.4

A Basic Spread Spectrum System.

In Fig. 2.4, $x(t)$ is the signal before modulation, f_o is carrier frequency, $c(t)$ is the pseudo random spreading code, τ is the propagation time the signal takes from transmitter TX to receiver RX. The information generated from Information Source is first encoded by the Channel Encoder to increase the Hamming distance between the code words so that at receiving end the bit error rate can be reduced after the Channel Decoder. The code word taking on the waveform of $x(t)$ is then modulated by a carrier frequency f_o . After spreading, the transmitted signal $s(t)$ can be expressed as

$$s(t) = x(t)c(t)\cos(2\pi f_o t) \quad (2.8)$$

where the pseudo random spreading code $c(t)$ occupies a much wider frequency range than the information signal $x(t)$. At the receiving end, a delayed version of $s(t)$ is first despread by the delayed version of spreading code $c(t)$:

$$s_1(t-\tau) = x(t-\tau)c(t-\tau)\cos(2\pi f_o t)c(t-\tau_1) \quad (2.9)$$

where τ_1 is the estimated propagation delay generated in the receiver. For a good estimation, $\tau = \tau_1$, then $c(t - \tau)c(t - \tau_1) = 1$, hence the spread signal is completely de-spread.

The extent at which the bandwidth is expanded is termed as processing gain (PG) and defined as

$$PG = \frac{W}{B} \quad (2.10)$$

where

- W = total bandwidth occupied by the spread spectrum signal.
- B = information signal bandwidth.

The despread signal is then demodulated and decoded. The function of Channel Encoder/Decoder is also referred as forward-error correction (FEC). Finally the recovered information is obtained.

In direct sequence, one starts with a standard digital modulation, such as BPSK or QPSK with a bit rate of R kb/s which needs an information bandwidth of B_s kHz. Then each of those information bits is spread over a large number of coded bits called chips by means of a second modulation process. If N chips are needed for each bit, then the chip rate is NR kb/s which needs a transmission bandwidth $B_{ss} = NB_s$ kHz. Despreading at the front end of the receiver then delivers the BPSK or QPSK signal to the standard processor for such signals. This is illustrated in Fig. 2.4.

In frequency hopping, a transceiver would be equipped with N frequency channels so that an active call would hop over those N frequencies with a predetermined hopping pattern. This would change the centre frequency of the transmitted signal. This could be done slowly (one hop per many symbols) or fast (many hops per symbol). The idea behind spread spectrum is to transform a signal with bandwidth B_s into a noise-like signal of much larger bandwidth B_{ss} . The PN code generation has been extensively studied [21] - [25]. The power of radiated spread spectrum signal is spread over B_{ss}/B_s times the original bandwidth, while its power spectral density is correspondingly reduced by the same amount, so that the signal becomes “noise like”. Each spread spectrum signal should

behave as if it were “uncorrelated” with every other spread signal using the same bandwidth shown in Fig. 2.5.

FIGURE 2. 5

Radiated Power Density in Spread spectrum. B_s – information bandwidth.
 B_{ss} – transmission bandwidth.

CDMA systems typically are asynchronous (i.e., the transition times of the data symbols of the different users do not have to coincide, actually it is impossible to synchronize the transmission in reverse link), hence the design problem is much more complicated. In addition to the synchronization issue, the self-interference due to the multipath nature in wireless situation also need to be considered. Partial-correlation within a sequence and between PN sequences lend itself directly to self-interference. The key parameters in a CDMA system are both the cross-correlation and the partial-correlation functions, and the design and optimization of code sets with good partial-correlation properties can be found in many references such as [26] - [29].

2.3 Uniqueness of CDMA Systems

CDMA permits all users to transmit using the same band of frequencies all the time. Each user uses a code which is as orthogonal to the codes of other users as possible. Thus CDMA technique provide great immunity to interference.

In wireless digital communications, multipath is the main cause of fast Rayleigh fading. Interferences arise both from others and self-interference because of multipath.

Transmitting signals over multipath fading channels causes distortions and variations at the receiver. For wide band signals, the effect of Rayleigh fading is mitigated [30] [31]. The study in [32] shows that the mitigation effect is a function of bandwidth spreading and chip rate. For multipath delay longer than a chip-time interval, CDMA can use RAKE receiver to take advantage of multipath. For indoor environment with lower data rate, such multipath delays are too small. Qualcomm invented a delay-line antenna system which artificially creates multipath of sufficient delays for the RAKE processor to work effectively [7]. Thus CDMA offers a great advantage in the capability of anti-multipath. The use of a large number of frequencies in each waveform results in a form of frequency diversity that significantly reduces the degradation in performance that normally arises from rapid fading.

In a cellular CDMA system, the same channel center frequency is used in all cells. The CDMA waveform properties that provide processing gain are used to discriminate between signals that occupy the same channel. When the mobile is handed-off from one cell to another, it does not switch frequencies. The new cell site assigns a modem, while the old cell site still continues to handle the call. While the mobile is located in the transition region between two cells, the call can be switched back and forth between them as signal strength dictates; at this time cell site diversity mode can be given to the mobile. Only when the mobile is well established in the new cell will the original cell site discontinue handling the call.

Any user can access the system at any time without waiting for a free channel. Thus there are no blocked calls in the usual sense. There is no hard limit on the number of active users that can be handled simultaneously by the system. When the number of active users exceeds the design value, the result is a degradation of performance for all users rather than denial of access. This is usually referred to as "graceful degradation."

Because each user retains his unique signal set permanently, there is no channel switching or address changes as the user moves from cell to cell. Hence, the particularly objectionable characteristic of FM systems known as "forced termination," which occurs when a mobile crosses a boundary into a cell in which no channel is available, will not occur in this system.

Since all users occupy the same band, all user hardware is identical except for the filters associated with the unique signal set. And each potential user of the system is assigned a unique signal set, message privacy is achieved as a fringe benefit.

Priority messages can be accommodated in the system, even in the presence of system overload, without assigning dedicated channels or denying other users access to the system. This can be done by increasing the power level, on an emergency bases.

In addition, there are many other attributes of CDMA that are of great benefit to cellular system. Among them are:

- using voice activity factor and sectorization for capacity. This will be elaborated in section 3.2.
- no guard time comparing with the case in TDMA.
- coexistence in the same frequency band as conventional narrowband systems. This also make the transition from existing communication system to digital CDMA system easier.
- good for microcell and in-building systems. Because of its spreading spectrum feature, CDMA is a nature waveform suitable for microcell network and in-building environment.
- no frequency management or assignment needed compared with FDMA system.

Some approaches to discuss cellular CDMA capacity have been presented [33][17] [34] [3]. For the capacity of multiple cells CDMA system considering frequency reuse factor, CDMA can reuse the same spectrum of all cells, thereby increasing system capacity. It is shown that [3] the capacity of CDMA over digital TDMA or FDMA is on the order of 4 to 6 and over current analog FM/FDMA it is nearly a factor of 20 due to the above features.

Literature Review of Power Control in Cellular Radio Systems

3.1 General Description of Power Control in Wireless Networks

The nature of wireless communication involves a distance dependent propagation loss when signal travels from transmitter to receiver. The mean power of a received wireless signal expressed in the following form is based on a propagation path loss model in [39]:

$$P = \frac{K}{r^\alpha \left(1 + \frac{r}{r_b}\right)^\beta} \quad (3.1)$$

where

- P – received signal power.
- K – a constant.
- r – the distance between transmitter and receiver.
- r_b – turning point of the path loss curve. The value of r_b is approximately 200m [40].
- α, β – attenuation rates. When r is greater than r_b , the path loss slope is $\alpha + \beta$. According to the measurements in [39]-[40], α and β are around 2. The path

loss slope agrees with the inverse fourth-power law with distance when distance is greater than turning point.

Based on the above equation, a more accurate prediction of the signal power at receiver can be obtained by modifying Equation (3.1) by the effects such as surface roughness, terrain obstacles etc. [38].

The actual received signal strength in mobile receiver can be depicted in Figure 3.1 considering fast Rayleigh fading, log-normal shadowing and Eq. 3.1.

FIGURE 3.1

Mobile received signal strength in propagation loss, log-normal shadowing and Rayleigh fading

Consider the situation in which a number of mobile terminals attempt to transmit messages over a commonly shared channel to a central base station as in the case of CDMA system. If all users transmit the same power value then according to Equation 3.1, the signal from the farther transmitter will arrive at the base station with less power than the signal

power from the nearer transmitter. Therefore, a strong signal received from a near-end mobile will mask the weak signal from a far-end mobile. The effect is so severe that it actually affects the capacity of the cellular network. Moreover, the situation is worsen by the factors of log normal shadowing and Rayleigh fading.

It is very desirable to maximize the capacity of the wireless communication system in terms of the simultaneous telephone calls that can be handled in a given system bandwidth. The objective of power control is to equalize the received signal power for each transmitter so that the capacity of the wireless system can be increased. In wireless cellular network, power control needs to be implemented in both directions: forward link (base station to mobile unit) and reverse link (mobile unit to base station). But for the forward link if there is only one cell in the area as shown in Fig. 3.2 (a), power control is not needed. Because all signals are transmitted from one single base station and therefore they are subject to the same channel variations when arrive at the mobile station, for each user any interference caused by other user's signal remains at the same level relative to the desired signal.

FIGURE 3.2

Forward links in a single cell and multiple cells.

In multiple-cell cellular systems, the situation is more complicated. Interference from other base stations vary independently of the given base station. The worst case, which is referred as “corner effect” shown in Fig. 3.2 (b), is that of the user moving near the boundary of the given cell and located equi-distant from its current base station and other two or more base stations. Power control is necessary for the forward link in multiple cell wireless system. The purpose of forward-link power-control is to reduce the amount of interference from neighboring cells by reducing the total amount of power transmitted. The decreased interference in a cell allows the larger number of users in the cell with a given performance level. Since the users at the cell boundary are the most susceptible to interference from other cells, power control takes the form of reducing the power transmitted for near-end users. At the base station power is adjusted depending on the needs of the individual mobile in the given cell.

For reverse link, power control is required even in single cell system because for each user the signal varies independently of the signal from other users due to the different propagation paths. As shown in Figure 3.3(a), since all users are typically geographically separated, a receiver trying to detect the j th signal may be swamped by the i th transmitter which is located at a much shorter distance, that is, if all users transmit with equal power, the signal from the i th transmitter will arrive at the cell site with a larger power than that of the j th signal.

The situation in multiple cell environment is more complicated than that in a single cell. Interference arrives not only from the users in the given cell, but also from the users from neighboring cell shown in Fig. 3.3 (b). In multiple cells, mobile j and interfering mobile i are in different cells. r is distance between mobile i and its own base station. r_i is distance of mobile i from the given base station of the cell where user j resides. The interference varies according both to the attenuation in the path to the given base station and inversely to the attenuation from the interfering user to his own base station. Referring to Figure 3.3(b), user j is interfered by user i , the larger the distance between the interfering user i and its own base station r is, or the smaller the distance between user i and the given

base station r_i is, the larger the interference the user i imposes on user j . The interfering user i is power controlled by his own base station.

FIGURE 3.3

Reverse links in a single cell and multiple cells.

3.2 Capacity of Cellular CDMA Systems and Power Control

In cellular CDMA several users can transmit messages simultaneously over the same radio bandwidth, each using a specific spread-spectrum pseudo-noise (PN) code. Since these codes can not be exactly orthogonal for a set of asynchronous users, in addition, in mobile environment the synchronization between the users in uplink is impractical, inter-user interference usually adds on the power basis and the radio link performance of any one user becomes poorer as the number of simultaneous users increases.

Section 3.2.1 describe why capacity is interference related. Section 3.2.2 discuss how the power variation can affect system capacity.

3.2.1 The Effect of interference on the Capacity of CDMA System

Here I will focus on the reverse link (user to cell site) capacity, because the forward link (cell site to user) employs coherent demodulation by pilot carrier, which is being

tracked, and since the multiple transmitted signals are synchronously combined, its performance in a single cell system is likely to be superior to that of the reverse link [3]. While in the reverse direction, the operation between all users is not coordinated, non-coherent reception and independent fading of all users is assumed. Thus, the emphasis is on the evaluation of reverse link capacity and we assume that the capacity in the forward link will be better than or at least equal to that found on the reverse link.

Assuming with power control, all reverse link signals are received at the same power level, i.e. for N users, the cell site processes the desired signal having power P and $(N-1)$ interfering signals each also having power P . Given the fact that bit energy E_b and the noise density N_0 can be expressed as:

$$E_b = \frac{P}{R} \quad (3.2)$$

$$N_0 = (N-1)\frac{P}{W} + \frac{\eta}{W} \quad (3.3)$$

where

- N – number of users per cell.
- R – information bit rate.
- W – total spread spectrum bandwidth.
- η – background noise (including thermal noise distributed over the total bandwidth W).
- P – received power from each user.

Then

$$\frac{E_b}{N_0} = \frac{W/R}{(N-1) + (\eta/P)} \quad (3.4)$$

where

- W/R – processing gain.
- E_b/N_0 – bit energy-to-noise density ratio, commonly called signal-to-noise ratio SNR, its value must ensure the adequate performance of the modem and decoder.

From Eq. 3.4, it is noticed that the number of users have to be reduced if the required SNR increases.

It was shown that the voice signals are intermittent with an activity factor of approximately 3/8 in [33]. It suggests that capacity can be increased by an amount inversely proportional to this factor by suppressing transmission during the quiet period of each speaker to reduce interference. Similarly any spatial isolation through the use of directional antennas (sectorization), which reduces interference, also provides a proportional increase in capacity. Sectorization means that directional antennas are used at the cell site both for receiving and transmitting. For example, with three antennas per site, each having 120° effective beam-widths, the interference sources seen by any antenna are approximately one-third of those seen by an omni-directional antenna. Henceforth, using three sectors, the number of users per cell can be increased three times as much capacity.

Taking the effect of voice duty and sectorization, the actual average SNR can be written as

$$\frac{\overline{E_b}}{N_o} = \frac{W/R}{(N_s - 1)\alpha + (\eta/P)} \quad (3.5)$$

where

- N_s – number of users per sector.
- α – voice duty factor.

It is shown in [3] that taking voice duty factor of 3/8 and sectorization of 120° into account, the average number of users per cell can be increased by a factor of 5 or 6. In CDMA the capacity is only interference limited, any reduction in interference converts directly into an increase in capacity.

For the capacity of multi-cell CDMA networks, the interference from neighboring and distant cells also need to be considered. Other issues, such as propagation path loss, shadowing effect directly relate to the capacity of the CDMA wireless networks.

Fig. 3.4 illustrates the reverse link capacity corresponding to four different surrounding cells load-conditions: (1) surrounding cells being full. (2) being half-full. (3) having 1/4 capacity, (4) surrounding cells being empty which applies to a single cell without other cell's interference. Fig. 3.4 is generated under the following condition [3]: (a) path loss is the product of the fourth power of the distance and a log-normal distributed variable whose standard deviation is 8 dB; (b) users in the system are uniformly distributed; (c) 120° sectorization; (d) voice factor is 3/8; and (e) spread bandwidth 1.25 MHz and data rate 8 kb/s. The x axis is the number of users per sector and the y axis is the probability of bit-error-rate being greater than 10^{-3} . It can be seen that the heavier the average load in surrounding cells, lower is the number of users the desired cell can support for a given bit-error-rate. The capacity of cellular CDMA system is very sensitive to the interference, i.e., the capacity is interference limited. Thus power control is one of the most important variables to govern.

FIGURE 3.4

The reverse link capacity per sector.

3.2.2 Susceptibility of CDMA Capacity to Power Control

The capacity of CDMA is closely related to the received power at the cell site. Power control is very important to CDMA system. CDMA system capacity is maximized if each mobile transmitter's power is controlled so that its signal arrives at the cell-site with the minimum required signal-to-interference ratio. If the received signal at the cell site from a mobile is too low, then the bit-error-rate will be too high. On the other hand, if the mobile's received signal is too high, its performance will be acceptable, but interference to all the other mobile transmitters will be increased, lowering the performance for the other users. The ideal situation will be to receive the same nominal power level from each mobile operating from the cell. If that were the case the total signal power received at the cell site would be equal to the nominal received power times the number of the mobiles. By controlling the transmitted power of each user the system resources can be shared equitably among users and system capacity can be maximized.

Power control schemes that deal with “near-far” and shadowing problems can only keep the received power almost equal. But the variation of the received power can still impact the system capacity. The loss in capacity of CDMA system due to imperfect power control has been studied in [36]. The system model used in [36] is the data signal modulated onto a phase-coded carrier. For example, the k th user's transmitted signal may takes the following form:

$$s_k(t - \tau_k) = (2P)^{1/2} b_k(t - \tau_k) a_k(t - \tau_k) \cos(\omega_c t + \phi_k) \quad (3.6)$$

where

- $a_k(t)$ – data signal,
- $b_k(t)$ – spreading signal, both $a_k(t)$ and $b_k(t)$ are assuming a sequence of unit-amplitude (positive and negative) rectangular pulses, but $b_k(t)$ is faster. For a processing gain of N , each data interval has N spreading chips.
- P – received signal power, here assumed equal power for all users.
- ω_c – carrier frequency.
- ϕ_k – phase shift.
- τ_k – propagation delay.

With the bit error rate calculation model in [37], the author made a comparison for equal power with the case of unequal power and the capacity reduction due to the unequal power is illustrated for uncoded transmission.

Table 3.1 shows how much capacity, in number of users for a given bit error rate must be reduced due to imperfect power control, process gain $N = 63$ chips/bit, objective bit error rate $P_e = 10^{-3}$. Column one is the standard deviation of power variation corresponding to uncoded cases. Column two is the dB conversion from column one. The capacity percentage reduction corresponding to the power variation is given in column 3. From Table 3.1, it can be seen that capacity reduction is quite sensitive to power variation because of imperfect power control.

TABLE 3.1

Reduction in number of users vs. power variation (after Holtzman [36])

RMS Power Var. (%)	RMS Power Var. (dB)	Reduction in Users (%)
0	0	0
10	-0.4, +0.4	2
20	-1, +0.8	10
30	-1.5, +1.1	25
40	-2.2, +1.5	50

3.3 Existing Power Control Schemes

It has been recognized that power control is important to the performance in wireless CDMA network. Power control issue has been studied by many authors so far. A variety of power control schemes have been put forward based on different criteria. The existing power control schemes can be classified as open loop power control and closed loop power control based on the principle of control theory, or be divided as centralized power control and distributed power control based on where the power control process is conducted, or be grouped as average power control and strict power control based on how frequently power control command is issued.

3.3.1 Open Loop Power Control and Closed Loop Power Control

- **Open loop power control**

In open loop power control, the transmitter attempts to estimate the path loss based on the measurement of the receiving power. Reception of a strong signal indicates that the transmitter and receiver are either very close or there is good propagation path between transmitter and receiver, thereby a relatively less power is needed for acceptable reception. As shown in Fig. 3.5 (a), A and B are the two ends of the communication link. Take end B as an example, channel 1 and channel 2 are incoming and outgoing channel respectively. P_r is the received power from the incoming channel 1. P_t is the transmitted signal power. The higher the received power P_r , the less the path loss of the communication link is, the lower power P_t the transmitter needs to transmit the signal.

FIGURE 3. 5

Open loop power control (a) and closed loop power control (b).

The open loop power control is based on the assumption that the pass losses on both forward link and reverse link are the same. However, due to the discrepancy between the carrier frequency bands for each link, although log-normal shadowing normally exhibit reciprocity, the Rayleigh fading is independent for the reverse link and forward link, the

path losses will not be the same for each link. The coarse adjustment of the transmitting power need to be further refined. This is accomplished by closed loop power control.

- **Closed loop power control**

In closed loop power control, the independence of the Rayleigh fading on Channel 1 and Channel 2 is considered. In Figure 3.5(b), the transmitter power P_t at end B is controlled by the power control command from end A. The demodulator at the end A measures the received signal power P_r from the end B. The measurement is then compared with the desired signal level and a power adjustment command C_p is sent to the end B to increase or to decrease the transmitting power by a predetermined amount.

In cellular system, taking reverse link power control as an example, the mobile transmitter power is controlled by a signal from the base station. The desired signal power for each base station is coordinated by a system controller where decision, based on overall system information available, is made. According to the power level assigned by system controller, each base station controller maintains the desired power level for each mobile that is active within that cell. In reality, it is often desired to combine the open loop and closed loop power control techniques [7]. The power control command is executed with the reference of transmitter's open loop estimation to obtain the final value of the power to transmit.

3.3.2 Centralized Power Control and Distributed Power Control

- **Centralized power control**

Based on centralized power control in cellular radio systems, all mobiles using the same channel will attain a common carrier-to-interference ratio. Centralized power control need a central controller that has knowledge about all the radio links in the network. In [41] a centralized power control scheme is proposed to achieve the same CIR (carrier to interference ratio) in all radio links for non-fading spread-spectrum system. The authors in [4] proposed a centralized power control scheme for no fading channel which is claimed to

have the optimum solution, where the scheme is aimed at maximizing the minimum of the CIR's and minimizing the maximum of the CIR's for all the mobile. The scheme adjusts transmitter power to maintain the CIR to a common value. The model used in [4] is shown in Figure 3.6.

FIGURE 3.6

System model used in [4].

Assuming M mobiles sharing a common channel, mobile i belongs to its home base i and mobile j is communicating through base station j . The gains in all communication links are greater than zero. The carrier to interference ratio of mobile i at its base i is then given by

$$\gamma_i = \frac{P_i G_{ii}}{\sum_{\substack{j=1 \\ j \neq i}}^M P_j G_{ij}} \quad 1 \leq M, \text{ and } 1 \leq i \leq M \quad (3.7)$$

where

- P_i — transmitter power of mobile i .

- G_{ij} —gain of the communication link between the i th base station and the j th mobile
- M —number of users sharing a common channel
- γ_i —CIR of mobile i .

Two quantities γ^- and γ^+ were defined in [4].

$$\gamma^- = \max_{P \geq 0} \left(\min_{1 \leq i \leq M} \{\gamma_i\} \right) \quad (3.8)$$

$$\gamma^+ = \min_{P \geq 0} \left(\max_{1 \leq i \leq M} \{\gamma_i\} \right) \quad (3.9)$$

Where P is a M dimensional vector denoting the transmitter power vector for the mobiles in the common channel. It was proved using matrix theorem in [4] that there is a unique Γ so that the following equation hold true.

$$\Gamma = \gamma^+ = \gamma^- \quad (3.10)$$

Equation (3.10) implies that all the mobiles in this case will have a common carrier to interference ratio if the transmitter powers were adjusted according to the proposed schemes. Centralized power control has the advantage that most of the complicated power control process is conducted on a central controller, therefore ease the power control burden on each mobile. The disadvantage is that it is not easy to implement because the central controller need to have the knowledge about all the radio links in the network. But it served as the foundation of distributed power control [4].

• Distributed power control

A distributed power control scheme has been studied early in 1974 for satellite systems in [42]. Based on [42] a distributed power control was proposed which was claimed to be able to balance the CIR's at the receivers in cellular systems [5]. Under this scheme the transmitter adjust its current power at each time instant by a factor which is inversely proportional to its CIR.

Specifically, with the definition of carrier to interference in Eq. 3.7, the mobiles adjust their transmitter powers in discrete time steps. The transmit power for the i th mobile at the n th time instant is adjusted as

$$P_i^{(n)} = \frac{k P_i^{(n-1)}}{\gamma_i^{(n-1)}} \quad 1 \leq i \leq M, n \geq 1 \quad (3.11)$$

where

- k — a constant value greater than zero
- $\gamma_i^{(n-1)}$ — the corresponding carrier to interference ratio of mobile i at previous time instant $n-1$
- $P_i^{(n)}$ — transmitter power at time instant n

So that the transmitter power at current time is increased or decreased based on the value of the CIR of previous time instant. After a number of adjustments, all the users converge to a common CIR.

$$\lim_{n \rightarrow \infty} \gamma_i^{(n)} = \gamma_c \quad i = 1, \dots, M \quad (3.12)$$

The rate of convergence depends on the value of γ_c : the larger the γ_c is, the faster the scheme converges.

Note that both centralized and distributed power control mentioned above are under the condition of no negative link gain in any link in the system concerned. Also as long as time factor is concerned, which is crucial in mobile wireless communication where Rayleigh fading is inevitable, how the number of iterations affects the performance was not discussed. While the proposed schemes in [5] may be good for satellite mobile communication, they may be not adequate for land mobile communication.

3.3.3 Average Power Control and Strict Power Control

- **Average power control**

For the case when only “near-far” effect is concerned, an average power control scheme is proposed in [19]. The transmitted power is adjusted based on its distance between transmitter and receiver, i.e.

$$P_i = P_R \left(\frac{r_i}{R} \right)^4, \quad (3.13)$$

where

- P_i — the transmitted power for the i th mobile.
- R — the cell radius.
- P_R — the power required from those mobile at the cell boundary R to reach the cell site for a given performance.
- r_i — the distance between the cell site and the i th mobile.

Then the signals received at the cell site from all the mobile within a cell would remain at the same level. Average power control proposed in [19] attempts to eliminate the slowly varying near-far effects. The power control schemes proposed by [4] and by [17] are examples of average power control, while [4] also concerns shadowing effects.

In the mobile cellular environment, the path loss variation is subject not only to the effect of shadowing, which is log normal distributed, but also the fast fading, which is Rayleigh distributed. The transmitted power required at the mobile must be adjusted dynamically and frequently enough to avoid obsolete power control commands. Average power control is not adequate to deal with fast multipath fading process even if every user moves at a constant speed [6]. This leads to strict power control.

- **Strict power control**

When time factor (power control latency) is more crucial, strict power control needs to be considered. Strict power control is a fast power control with tight power adjustments. Error or inaccuracy in average power control will cause slow fluctuations of the average signal and interference levels, the effects of which are difficult to correct by coding and interleaving [6]. Strict power control which decreases the slowly-varying power control

error is useful for the systems which rely on improved performance from coding and interleaving. In [6] a strict power control scheme combined with closed loop power control scheme is proposed for the reverse link. The power adjustment command is transmitted from the receiver to the transmitter at a relatively higher rate, i.e. high enough to permit the Rayleigh fading to be tracked. Figure 3.7 illustrated the power control model used in [6], $P(i)$ — transmitted power from user to base station. $x(i)$ — wireless channel variation (dB). $e(i)$ — power control error (dB) caused by power control latency. T_p — power control delay (milliseconds), also referred as power control sampling period. δ — a fixed step size in power adjustment.

FIGURE 3. 7

Power control model used in [6] for reverse link.

The power control in [6] is implemented as follows: the power control command is updated every T_p second. The power control command is one bit value, “+1” or “-1”. During the i th period, the received signal power at the base station is user transmitted power modified by the channel variation.

$$P_r(i) = P(i) + x(i) \quad (3.14)$$

where

- $P_r(i)$ — received power at base station
- $P(i)$ — the transmitter power from the mobile
- $x(i)$ — channel variation
- i — the notation of time instance

Every T_p second, the received power is compared with the desired power level. The difference is called power control error based on which a power control command is send.

$$e(i) = P_r(i) - P_d \quad (3.15)$$

If $e(i) > 0$, power control command of “+1” is sent form base station to user, the transmitted power from the user for next period will be decreased by δ dB; Otherwise if $e(i) < 0$, a “-1” will be sent and a δ dB will be added to the transmitted power. δ dB is the pre-determined power control step size. Figure 3.8 shows the simulation results in [6].

FIGURE 3. 8

Simulation results in [6]. (a) — the received signal power, (b) — the Rayleigh fading wireless channel variation and transmitter power under power control.

The base station receiver uses two-branch antenna diversity with equal gain combining and the fading on each branch is independently Rayleigh distributed. The fixed step size δ is 1 dB. Under the assumption that the vehicle user is moving at a speed of 50 km/hr and carrier frequency of 900 MHz, the power control latency or power control period T_p in Fig. 3.8 is 2.4 msec.

If power control were perfect, the power controlled transmitted signal should look identical to the inverse channel variation shown in Fig. 3.8 (a) and the received signal after power control would remain at a constant level. But because of power control delay T_p and the fixed step size the transmitter adjusting its power according each power control command, it is observed that the received signal still bear the resemblance to the wireless channel signal. For the deepest fade in wireless channel which is about -19 dB the received signal after power control is -15 dB with the improvement of 4 dB. Table 3.2 shows how the standard deviation of the received power and the average received power are affected by power control delay using the power control scheme in [6].

TABLE 3.2

Impact of power control delay on the received power variation [6]. Fixed step size $\delta = 1$ dB.

T_p (msec)	Diversity Order M	Standard Deviation	Average Power dB
2.4	2	2.3	0.53
1.2	2	1.9	0.41
0.48	2	0.9	0.13
2.4	4	1.6	0.30
1.2	4	1.2	0.13
0.48	4	0.6	0.15

With the increasing demand of wireless communication, the capacity of wireless networks is one of the most key issues need to be further studied. The power control schemes proposed in [6] still leave some room for improvement as shown in Chapter 5.

According to the linear feedback control theory, the author in [36] suggests a theoretical measure about how well can power control be done. It is expressed as follows:

$$\frac{\text{rms-in-controlled-power}}{\text{rms-deviation-in-uncontrolled-power}} \geq \sqrt{1 - R^2(\tau)} \quad (3.16)$$

where

- τ - the time lag, i.e. power control implemented at time t is based on a perfect measurement of the power at time τ seconds earlier.
- $R(\tau)$ - the autocorrelation of channel variation for a Rayleigh fading channel.

It is clear that the key factor in closed loop power control is the power measurement interval. It is important that the latency in determining the power control signal and in transmission process be kept small so that the channel conditions will not change significantly before the control command can be received and acted upon.

3.4 A Practical Example of Power Control

The power control scheme implemented in Qualcomm [7] can be served as an example in the application of power control in wireless CDMA system.

3.4.1 Reverse Link

The power control in reverse link is carried out in two steps: open loop power control and closed loop power control.

In open loop, each mobile unit attempts to estimate the path loss from base station to mobile unit by measuring the power level of the “pilot” signal. In Qualcomm CDMA system, all base stations transmit a “pilot” signal on the same frequency, this signal is used by all mobiles for initial synchronization and demodulation of the digital signal. The estimation of the path loss is used to adjust the transmitter power. The lower the path loss in the channel, the lower power will be used by the mobiles’s transmitter. Also, the rate of increase of mobile transmitter power must generally be limited to the rate of power control command issued by base station in closed loop power control to reduce mobile transmitter power. This approach is implemented so that it would rather tolerate a temporary degradation in one mobile than incur a degradation of all other mobile units.

Closed loop power control is a second step in power control in Qualcomm CDMA system. To account to the independence of fast Rayleigh fading on the forward link and reverse link, which the mobile can not estimate, the mobile transmitter power is also controlled by the command from the base station. At the base station, the received signal power from each mobile is compared to the nominal level for that mobile and a power adjustment command is sent to the mobile to increase or decrease its transmitter power by a predetermined step size, usually about 1dB. This power adjustment command is combined with the mobile's open loop estimation to obtain the final value of the mobile transmit power.

The rate at which the power adjustment command is issued must be high enough to allow the Rayleigh fading on the inbound path to be tracked. In [7], every millisecond a power command is sent from a base station to a mobile terminal for a vehicle speed up to 25-50 miles per hour communicating in 850 MHz band.

3.4.2 Forward Link

In forward link, the power control is also implemented in open loop and closed loop power control. But compared with reverse link, the dynamic range of the adjustment in open loop is smaller with the value around plus or minus 6 dB around the normal power. Whereas in reverse link the dynamic range could be 80 dB or more in case of a sudden improvement in reverse channel.

As for closed loop power control in forward link, the mobile has the capability to measure the signal-to-interference ratio. This is performed by comparing the desired signal power to the total interference and noise power. Based on this measurement the mobile requests the cell site to adjust its transmitting power. If the received signal is weak, as in the case where the mobile is moving in the shadow of a big building where there is excessive path loss, or CIR for the mobile is small as mobile is around the location where the path loss to one or two neighboring cells is almost the same as the path loss to its own base station, the mobile asks the cell site to increase its transmitting power. And if the signal is

too high, as the mobile moves out of the shadow of a large building, it asks for a reduction of transmitting power from base station. When the cell site receives the request to adjust its transmitting power from each mobile, it responds by adjusting the corresponding transmitting signal power by a predetermined amount, usually 0.5 dB (1 dB in reverse link). And the base station changes its power also at a slower rate than in the case of reverse link. The base station consider the power demands being made on it by all the mobiles in deciding whether to comply with the request from any particular mobile as well.

Power Control Model and Implementation

4.1 Theoretical Consideration

The mobile radio signal consists of a local mean value which remains nearly constant over a small area, but varies slowly as the receiver moves, superimposed upon which is the fast Rayleigh fading. The slow varying shadowing is caused by terrain irregularities and the man made surroundings intervening receiver and transmitter. The rapid fading resulting from multipath is usually observed over distances of about half a wavelength. This thesis considers the fast fading, proposes a scheme to maintain the received power at a level as constant as possible, i.e. strict power control.

Power control is essential in the use of direct sequence multiple access (CDMA) techniques over radio channels. In CDMA mobile systems, power control in reverse link (mobile to base) is more important than that in forward link (base to mobile) due to non-synchronized operation. Because of the separation of the operation frequencies in the two channels reverse link and forward link are two independently fading channels in CDMA system. Hence closed-loop power control scheme must be used. The objective of power control process is to regulate the transmitted power of all users to maintain equal received powers from all the mobile users, or equal signal to interference ratio CIR for all users. This condition is essential in order to optimize the system capacity. This is particularly

important in CDMA system where system capacity is vulnerable to short term received power variation at the receiving end (see Table 3.1 in Chapter 3).

In an ideal case, if the channel is perfectly predictable, then the transmitter power can be controlled exactly by set to be the inverse of the channel variation. So that at the receiving end, a desired constant received signal power can be obtained as shown in Fig. 4.1.

FIGURE 4.1

Strict power control in ideal case. (a) - wireless channel variation. (b) - transmitter power. (c) - received signal power.

In reality, the wireless channel exhibits random Rayleigh fading, it is not possible to predict the channel variations accurately. On the other hand, in a real system, there is a time lag between the time when the power control command is issued in the receiver and the time when the power control command is acted upon in the transmitter. Therefore power control errors due to time lag are unavoidable. In order to avoid excessive positive peaks and negative peaks in the received signal, the excess power control latency should be limited.

The power control command period can be estimated using Fig. 4.2, t_{prop} is the propagation delay between transmitter and receiver, t_{ave} is received signal average time in receiver. According to IS-95 standards [7], for reverse link power control, the mobile transmits signal in reverse link and power control command is sent in forward link. Due to propagation delay, t_{prop} seconds later (see the notation in Fig. 4.2), the transmitter signal which is modified by channel variation, arrives at the receiver. The receiver will take t_{ave} seconds to average the received signal power. After comparing with the desired received power, a power control command will be embedded in the data communication channel to be sent to transmitter through forward link.

FIGURE 4. 2

Illustration of power control period in a closed-loop power control scheme.

For a cell with radius R , in reverse link power control, the propagation delay from transmitter (i.e. the user) to receiver (i.e. the base station) is R/C at the maximum, where C is the electro-magnetic wave propagation speed. Referring to Fig. 4.2, the power control period can be expressed as following:

$$T_{pc} = t_{ave} + 2t_{prop} \quad (4.1)$$

Where

- T_{pc} – power control period in seconds.
- t_{ave} – signal average time at the receiver (sec).
- t_{prop} – signal propagation time between two ends (one way), $t_{prop} = R/C$ (sec)

Substituting $R = 10\text{km}$ (typical size), $C = 3.0 \times 10^8\text{m/sec}$, $T_{pc} = t_{ave} + 0.067$ (msec). Microcell can support data rate higher than that is possible in macrocell due to relatively small delay spread in microcell. For a microcell of radius, say $R = 1\text{km}$, then $T_{pc} = t_{ave} + 0.0067$ (msec). One observes that the propagation time is negligible comparing with averaging time. The smaller the cell radius, the smaller the signal propagation time. Power control time can be thought of approximately equal to t_{ave} for microcell wireless system. The time delay involved in generating, transmitting and executing a power control command is also considered to be negligible when compared with signal average time.

4.2 Description of the Adaptive Power Control Algorithm

When designing an adaptive control system, a performance index must be chosen and measured [43]. The designed system is considered an optimum control system when the system parameters are adjusted so that the performance index reaches a minimum value. This thesis uses the standard deviation in the received signal power as the performance index. The aim is to propose a power control scheme which minimizes this performance index.

So far, the schemes proposed for strict power control [6] [7] deal only with a fixed step size algorithm which is not suitable for fast deep fade. The received signal power is compared to a desired level at the receiver, and a hard quantized power command bit is transmitted back to the transmitter. The transmitter adjusts its transmitting power by a pre-determined fixed step size according to the command bit. In such case, only one power command bit is sent. Although it uses less channel capacity in this case, the effect of power control commands is too slow to take place, i.e. it does not give a quick response to deep fades. After all, it is the deep fades that significantly affect the quality of wireless communication. A detailed observation of the channel variation shows that dramatic changes to the performance often occur around deep fades.

This thesis provides a power control scheme which addresses the shortcoming related to fixed step size power control. The scenario of close loop power control proposed in this study is shown in Fig. 4.3, where TX — transmitter, RX — receiver, i — time index. $t_i = iT_{pc}$, T_{pc} — power control update or command period as shown in Eq. 4.1, $P_t(i)$ — the transmitter power at instant i , which is adjusted by a variable step size corresponding channel variation, $P_r(i)$ — received signal power at time index i .

The proposed power control works in this manner. The receiver at the base station for reverse link power control sends the control signal to the transmitter by comparing the received signal power with the desired signal power. The desired power level at the receiver is determined by a system controller residing at the MSTO based on the overall system information available. In cellular network, the communication environment of each cell is different from that of other cells. Therefore the desired received power for each base station is also different. The receiver at the base station maintains the desired signal strength information for each mobile that is active within that cell. The changes in the value of desired signal power are much slower compared with the fast Rayleigh fading, for strict power control it can be assumed to be constant [6]. Based on these measurements, the link path loss is estimated at the transmitter, which is used by the transmitter to adjust its transmitting power.

FIGURE 4.3

Closed-loop power control process for variable step size. $P_t(i)$ and $P_r(i)$ are the transmitter power and received power at instant i .

The relationship between the received power and transmitter power is as follows.

$$P_r(t) = P_t(t) + P_{ch}(t) \quad (4.2)$$

where

- $P_r(t)$ – the received signal power (in dB).
- $P_t(t)$ – the transmitter power (in dB).
- $P_{ch}(t)$ – the channel variation at time t (in dB), which is Rayleigh distributed random process with the characteristics shown in Fig. 2.1.

Since at every T_{pc} seconds, the transmitter updates its power by a dynamic amount (instead of fixed step) according to the feedback value from the receiver, which reflects the variation of the wireless channel, the transmitter power can compensate the channel variation better than in the case of fixed step size. One can see that power control period is critical in strict power control schemes. The strict power control scheme is investigated based on the assumption that the power control latency be short enough to allow the efficient tracking of fast Rayleigh fading of the wireless channel, which is reasonable referring to Eq. 4.1. The smaller T_{pc} is, the more accurate the channel variation can be compensated.

4.3 Simulation Model

4.3.1 Description of the Basic Power Control Model

Figure 4.4 shows the power control model used in this thesis. During each power control period, the transmitter transmits signal with a certain power in channel 1. The power control error is estimated in the receiver and the power control command is sent back from the receiver to the transmitter through channel 2. Channel 1 and channel 2 are reverse link and forward link respectively for reverse link power control. In CDMA due to the frequency separation between forward link and reverse link, the statistical characteristics for channel 1 (reverse link) and channel 2 (forward link) are identical but independent.

In Fig. 4.4, $P_t(i-1)$ and $P_t(i)$ are transmitter power for time period $t_{i-1} \sim t_i$ and $t_i \sim t_{i+1}$ respectively. i is time index, $t_i = iT_{pc}$, T_{pc} is power control period. $P_r(t)$ is the actual received signal power. $\overline{P_r(t_{i-1}, t_i)}$ is the measured received power. P_d is desired received signal power. $e(i)$ is power control error for the previous power control period $t_{i-1} \sim t_i$.

The transmitter power $P_t(i)$ at time instant t_i is adjusted by the power control command from receiver. In order to decide $P_t(i)$, the power control error for power control period from t_{i-1} to t_i must be calculated. The following steps are followed in Fig. 4.4.

(1) At the receiving end, the received signal power during power control period $t_{i-1} \sim t_i$ is the transmitter power $P_t(i-1)$ undergoing through channel variation, i.e.,

$$P_r(t) = P_t(i-1) + P_{ch}(t) \quad t_{i-1} \leq t < t_i \quad (4.3)$$

where

- $P_r(t)$ – received signal power during period $t_{i-1} \sim t_i$.
- $P_t(i-1)$ – transmitter power during period $t_{i-1} \sim t_i$.
- $p_{ch}(t)$ – Rayleigh fading channel variation.

FIGURE 4. 4

The proposed strict power control model for variable step size.

(2) The measured received signal power is compared with the desired received power P_d . The power control error $e(i)$ resulted from previous transmitter power $P_t(i-1)$ is calculated as follows.

$$e(i) = \overline{P_r(t_{i-1}, t_i)} - P_d \quad (4.4)$$

where

- $e(i)$ – power control error from previous transmitter power $P_t(i-1)$.

- $\overline{P_r(t_{i-1}, t_i)}$ – measured received signal power.
- P_d – desired received signal power. For strict power control, P_d can be assumed to be a constant[6].

In Eq. 4.4, the measured received signal power is obtained by averaging $P_r(t)$ over the power control period $t_{i-1} \sim t_i$.

$$\overline{P_r(t_{i-1}, t_i)} = \text{mean}(P_r(t)), \quad t_{i-1} \leq t < t_i \quad (4.5)$$

where $P_r(t)$ is given in Eq. 4.3.

Encoded power control error $e(i)$ is used as power control command. It is sent back to transmitter through channel 2 to adjust the transmitter power for time instant t_i .

(3) At the transmitter end, the transmitter keeps the power $P_t(i-1)$ transmitted during period from t_{i-1} to t_i . Upon receiving the power control command $e(i)$ from the receiver, the transmitter adjusts its power for the next period according to the following equation,

$$P_t(i) = P_t(i-1) - e(i) \quad (4.6)$$

where

- $P_t(i), P_t(i-1)$ – transmitter powers during period from t_i to t_{i+1} and period from t_{i-1} to t_i respectively.
- $e(i)$ – power control error for the previous period from t_{i-1} to t_i .
- i – time instant. $t_i = iT_{pc}$ and T_{pc} is power control delay.

With the same approach the transmitter power $P_t(i+1)$ for the next period from t_{i+1} to t_{i+2} can be determined, and so on.

In Fig. 4.4 power control period T_{pc} is very important in power control performance. Based on Section 4.1, the time delay effect in channel 1, encoder and channel 2 is ignored. T_{pc} is approximately equal to signal average time t_{ave} (see Eq. 4.1). At the time instant i , power control error $e(i)$ for the previous power control period from t_{i-1} to t_i is caused by power control latency T_{pc} .

The power control error $e(i)$ is returned as power control message in this chapter. In a real power control system, the encoder is used to quantize the power control message. The effect of encoder will be discussed in Chapter 5.

Note that in this model, the power control algorithm is performed in transmitter based on the returned power control error message $e(i)$ as shown in TX (transmitter) block. The transmitter also keeps a record of the power $P_t(i-1)$ transmitted one period, i.e., T_{pc} seconds earlier. With the knowledge of the received signal power fed back from the receiver, the transmitter can make direct estimation about the channel variation with a time lag T_{pc} seconds. From Eq. 4.3 and 4.5, the power control error for previous period can be expressed as

$$e(i) = P_t(i-1) + \overline{P_{ch}(t_{i-1}, t_i)} - P_d \quad (4.7)$$

with $\overline{P_{ch}(t_{i-1}, t_i)} = \text{mean}(P_{ch}(t)), t_{i-1} \leq t < t_i$

The transmitter power for period t_i to t_{i+1} in Eq. 4.6 can be rewritten as

$$P_t(i) = P_d - \overline{P_{ch}(t_{i-1}, t_i)} \quad (4.8)$$

where

- P_d – desired received signal power
- $P_t(i-1)$ – transmitter power from time instant t_{i-1} to t_i .
- $\overline{P_{ch}(t_{i-1}, t_i)}$ – averaged wireless channel variation during previous power control period $t_{i-1} \sim t_i$.

From Eq. 4.8, the transmitter power is actually the inverted value of averaged channel variation (in dB) of T_{pc} seconds ago based on the desired received power P_d . Therefore transmitter can track the channel variation quite well as long as T_{pc} is short enough. Also note that for a zero mean Rayleigh fading channel, the mean value of transmitter power is the desired received signal power.

Another aspect revealed from Eq. 4.8 is that the desired received power is embedded in the transmitter power. With the information of transmitted power T_{pc} seconds before $P_t(i-1)$ and the feed back message from the receiver about the power control error $e(i)$, the transmitter adjusts its power with the reference of desired received power P_d . Therefore it is legitimate to assume that if the desired received power P_d is a constant, the power control error will be the same. After all, the dynamic change in the transmitted power depends on the wireless channel variation T_{pc} seconds before.

In mobile communication realm, the wireless channel exhibits drastic variation characterized by Rayleigh fading, where a 30dB fade within a fraction of a second is not

uncommon. Figure 4.5 is the illustration of the simulation results obtained from the algorithm shown in Fig. 4.4 with the deepest fade of -28dB. The time axis is expanded for illustration. It is noted that using transmitter power as shown in Eq. 4.6 can compensate channel variation quite well. According to Eq. 4.8, the transmitter power is the delayed inverse version of channel variation in dB. Due to the power control delay T_{pc} , the wireless channel variation can not be compensated completely. The increased accuracy for scheme in Fig. 4.4 can be obtained by decreasing the power control latency T_{pc} .

FIGURE 4.5

Illustration of simulation result for basic power control model in Fig. 4.4

4.3.2 Analysis for the proposed scheme:

The simulation results shown in Fig. 4.5 can be better understood from analytical point of view. For analysis purpose, the averaging effect of the signal power is temporarily

ignored, which will be considered in implementation Section 4.5. The autocorrelation of the Rayleigh fading channel can be expressed as [8]:

$$\varphi(\tau) = \frac{\pi}{8} b_0 J_0^2(2\pi f_m \tau) \quad (4.9)$$

where

- b_0 — channel average power.
- $J_0(\bullet)$ — the Bessel function of first kind zero order.
- f_m — the maximum Doppler frequency shift.
- τ — time difference between the two channel samples.

The autocorrelation of channel variation $\varphi(\tau)$ is plotted in Fig. 4.6.

FIGURE 4. 6

The autocorrelation of Rayleigh fading channel

From Fig. 4.6. it can be observed that:

- (1) When $f_m \tau$ is between 0 and approximately 0.38, $\varphi(\tau)$ decrease monotonically. i.e., for $\Delta t > 0$,

$$\varphi(\tau) - \varphi(\tau + \Delta t) > 0 \quad (4.10)$$

(2) When $f_m\tau$ is large enough (greater than 1), $\phi(\tau)$ is negligible.

$$\lim_{\tau \rightarrow \infty} \phi(\tau) = 0 \quad (4.11)$$

For the power control scheme described in Eq. 4.3~4.6, the transmitter power is in fact the reversed value of channel variation averaged up to T_{pc} seconds ago according to Eq. 4.8. During the time period from t_i to t_{i+1} , with the transmitter power obtained in Eq. 4.8, the received signal power is

$$P_r(t) = P_t(i) + P_{ch}(t) \quad t_i \leq t < t_{i+1} \quad (4.12)$$

The power control error for time period $t_i \sim t_{i+1}$ is

$$e(i+1) = \overline{P_r(t_i, t_{i+1})} - P_d \quad (4.13)$$

where

$$\overline{P_r(t_i, t_{i+1})} = \text{mean}(P_r(t)), \quad t_i \leq t < t_{i+1} \quad (4.14)$$

Substituting Eq. 4.8 in Eq. 4.12, Eq. 4.13 can be rewritten as

$$e(i+1) = \overline{P_{ch}(t_i, t_{i+1})} - \overline{P_{ch}(t_{i-1}, t_i)} \quad (4.15)$$

From Eq. 4.15, it is observed that the power control error for the proposed scheme depends on the autocorrelation the wireless channel variation of two adjacent power control periods. The T_{pc} is small enough, power control error tends to be zero according to Eq. 4.15 and Eq. 4.11. When $T_{pc} = 0$, power control error is zero: the proposed power control scheme gives the power control results shown in Fig. 4.1 which is power control in ideal case. The shorter the power control period, the quicker the transmitter power tracks the channel variation, and the better the channel variation can be compensated. For example, for a vehicle speed of 100km/hr. and operating frequency $f = 900$ MHz, then the maximum Doppler shift is 84Hz (from Eq. 2.1). For $\tau = 0.6$ msec, $\phi(0.05) = 0.9516$. This means that the proposed algorithm approaches an ideal power control scheme when τ is small enough (as shown in Figure 4.1). The longer power control latency T_{pc} , the more the power control scheme shown in Fig. 4.4 deviates from the ideal case.

The main concern in power control is of deep channel fades where the communication link is most vulnerable to the interference from other users. The power control based on the proposed scheme adjusts the transmitter power in response to the fast channel vari-

ation. Fig. 4.7 shows a simulation result based on scheme in Fig. 4.4. In Fig. 4.7, the desired receiving power P_d is chosen to be 0dB here (in fact P_d can be set to be any constant value according to Eq. 4.8). The power control period is 0.6 milliseconds with the carrier frequency 900MHz and vehicle velocity 50 km/hr.

FIGURE 4.7

Simulation results based on scheme shown in Fig. 4.4. (a) – wireless channel variation, (b) – channel variation averaged over T_{pc} seconds, (c) – transmitter power, (d) – received power.

From Fig. 4.7 (d) it is noted that the received signal exhibits two nearly anti-symmetric peaks around the desired level. This is because of the fact that transmitter adjusts its power for next period to be the inverse of channel variation of previous period. Around the

deep fades, the channel changes so abruptly that the power control error near the deep fades will be much larger than that anywhere else.

In cellular wireless communications, it is important to control the transmitted power so that it will not increase the interference to other users. In other words, the high positive peaks caused by the power control algorithm, which pose excessive interference on other users, need to be eliminated. A detailed analysis of the channel variation around the deep fade shows that the high positive peaks result from the fact that the transmitted power is set to be the inverse of the channel variation. The dramatic changes in the received signal around the deep fade in the form of large peaks is due to over-adjusting and delayed correction due to power control latency. Those large peaks need to be minimized to bring down power control errors.

4.4 Improvements on the Basic Power Control Algorithm

4.4.1 Threshold Adjustment Algorithm

In order to suppress the positive peaks around deep fade, an improved power control scheme is proposed. As seen from Section 4.3, the transmitter power for time instant i is set to be the inverse value (in dB) of channel variation T_{pc} seconds ago. If at time t_i wireless channel recovers from a deep fade which occurred T_{pc} seconds ago, then over-adjustment is incurred due to excessive high value of transmitter power at time t_i .

The algorithm uses a threshold P_{th} as a upper delimiter. If the transmitter power

$$P_t(i) > P_{th} + P_d \quad (4.16)$$

then set

$$P_t(i) = P_{ad} + P_d \quad (4.17)$$

where

- P_{th} – threshold of the transmitter power with reference to the desired received signal power (in dB).
- P_{ad} – adjusted transmitter power with reference to the desired received signal power (in dB).
- P_d – desired received signal power (in dB).

Otherwise, the transmitter power will be the same as derived in Eq. 4.6.

Fig. 4.8 illustrates the implementation of the algorithm.

FIGURE 4.8

Threshold adjustment algorithm. (a) - channel variation, (b) - transmitter power, (c) - the received signal power

In Fig. 4.8, the wireless channel variation $P_{ch}(t)$ is shown in (a), transmitter power $P_t(i)$ during each power control period in (b) and the received signal power $P_r(t)$ in (c). The desired received signal power is 0dB. The value of P_{th} is set to be 17 dB and the adjusted transmitter power P_{ad} is 10 dB. Table 4.1 shows the value of power control error $e(i)$, transmitted power $P_t(i)$ and measured signal power $\overline{P_r(t_i, t_{i+1})}$ for Fig. 4.8. The transmitter power is derived by Eq. 4.6. Without the threshold adjustment, the result of adjustments is shown in brackets in Table 4.1.

TABLE 4. 1

Power control error, transmitted power and measured signal power in threshold adjustment algorithm (dB). Figures in bracket indicate the results without threshold adjustment

i	$[t_i, t_{i+1}]$	$e(i)$	$P_t(i)$	$\overline{P_r(t_i, t_{i+1})}$
0	$[t_0, t_1]$	0	0	-2
1	$[t_1, t_2]$	-2	2	-5
2	$[t_2, t_3]$	-5	7	-9
3	$[t_3, t_4]$	-9	16	-2
4	$[t_4, t_5]$	-2	10 (18)	0 (8)
5	$[t_5, t_6]$	0 (8)	10	5
6	$[t_6, t_7]$	5	5	3
7	$[t_7, t_8]$	3	2	3
8	$[t_8, t_9]$	3	-1	0.5

It can be seen that without threshold adjustment, the transmitter power for the time period $[t_4, t_5]$ is 18dB, the measured power control error is 8dB. With threshold adjustment, the transmitter power for period $[t_4, t_5]$ is adjusted to be 10dB according to Eq. 4.16 and Eq. 17, the resulting power control error is 0dB. From Fig. 4.8 (c), the positive peak in the received signal at time instant t_5 is brought down from 12dB to 4dB by using the threshold adjustment.

The simulation result for vehicle speed 50 km/hr, carrier frequency 900 MHz, power control period $T_{ps} = 0.6$ milliseconds is shown in Fig. 4.9. In the simulation P_{th} and P_{ad} are arbitrarily chosen to be 17dB and 10 dB respectively with respect to the desired received signal power. Comparing Fig. 4.7 and Fig. 4.9, the positive peak in Fig. 4.9 is smaller than that in Fig. 4.7 due to the threshold adjustment.

FIGURE 4.9

Improved power control scheme based on variable step size. (a) - wireless channel variation. (b) - transmitter power. (c) - received signal power.

It was observed that the simulation results are dependent on different values of P_{th} and P_{ad} . However, the selection of P_{th} and P_{ad} depends on the channel characteristics and the chosen quality criteria of communication. The higher the P_{th} or P_{ad} , the better performance the current user can achieve, but results in a greater interference to other users. On the other hand, the lower the P_{th} or P_{ad} , the poorer quality the current communication link become.

In order to determine the threshold and adjusted value for P_{th} and P_{ad} , the statistical characteristic of the deepest fade in the fading channels has been studied. An ensemble behavior of 100 wireless channel samples has been simulated. The simulation result is shown in Table 4.2 for vehicle speed 50 km/hr, carrier frequency 900 MHz. Each column is the statistical value of the deepest fades obtained from the simulation.

TABLE 4.2

Statistics of the deepest fades in the Rayleigh fading channel (dB), vehicle velocity $v = 50$ km/hr, carrier frequency $f = 900$ MHz.

Minimum	Maximum	Mean	Standard Deviation
-31.63	-1.20	-17.40	5.95

Table 4.3 illustrates the impact of selecting different P_{th}/P_{ad} values on variable step size power control error. It is seen that for the simulated wireless channel, when $P_{th} = 23$ and $P_{ad} = 14$, power control error is minimum. Table 4.3 is obtained based on 100 wireless channels.

TABLE 4.3

Impact of P_{th}/P_{ad} settings on strict power control of variable step size, $T_{pc} = 0.6$ msec. All the values are in dB.

P_{th}/P_{ad}	10/10	15/10	23/14	25/15	30/25
P.C. Error	0.62	0.60	0.59	0.59	0.6

It was found that the appropriate setting of P_{th}/P_{ad} should be chosen to be around $(|m|+\sigma)/(|m|-\sigma/2)$, where m is the mean value of the deepest fades in the wireless channel. σ is the standard variation of the deepest fade. For example, for a channel having the deepest fade with ensemble characteristics shown in Table 4.2, where $|m| = 17.40$ dB, $\sigma = 5.95$ dB, then P_{th}/P_{ad} can be set to be 23/14.

The reason $P_{ad} < P_{th}$ is that around deep fades, the channel changes so rapidly that at the time transmitter adjusts its power for the next period the wireless channel is already recovering compared with T_{pc} seconds ago. By introducing P_{th} and P_{ad} , the high positive peaks can be effectively limited so that over-adjustment is avoided.

4.4.2 Channel Prediction Algorithm

Fig. 4.10 shows a general example of power control results obtained from Eq. 4.3 ~ 4.6. For Rayleigh fading channel, channel changes abruptly around deep fade while elsewhere the channel variations are relatively smooth (see Fig. 4.10 (a)). The deep fade occurs at time instant t_8 . According to Eq. 4.8, the transmitter power at time instant t_9 is the inverse of previous channel variation, i.e., $P_t(t_9) = -P_{ch}(t_8)$. From time t_8 to t_{10} , the channel rises very fast. As $P_t(t_9)$ is much higher than $P_{ch}(t_9)$, the received power at t_9 has a positive peak. The similar situation happens at time instant t_{10} . The positive peaks at t_9 and t_{10} may cause excessive interference on other users. Therefore it is required to reduce those over-adjustment values.

FIGURE 4.10

Illustration of over-adjustment on rising side of the deep fade. (a) - channel variation, (b) - transmitter power. (c) - received signal power.

The positive peak around the each fade can be further suppressed by the following approach: while keeping track of the channel variation over the past two corrections, introduce a monitoring variable d :

$$d = \overline{P_{ch}(t_{i-1}, t_i)} - \overline{P_{ch}(t_{i-2}, t_{i-1})} \quad (4.18)$$

If $d > 0$, adjust transmitter power at time instant i from Eq. 4.8 as follows:

$$\begin{aligned} P_t(i) &= P_d - \overline{P_{ch}(t_{i-1}, t_i)} - \alpha \times d \\ &= P_d - (1 + \alpha) \overline{P_{ch}(t_{i-1}, t_i)} + \alpha \overline{P_{ch}(t_{i-2}, t_{i-1})} \end{aligned} \quad (4.19)$$

where

- d – monitoring variable for wireless channel
- $\overline{P_{ch}(t_{i-1}, t_i)}$, $\overline{P_{ch}(t_{i-2}, t_{i-1})}$ – averaged wireless channel variation during $t_{i-1} \sim t_i$ and $t_{i-2} \sim t_{i-1}$. These two parameters will be stored in transmitter (see Section 4.5)
- α – an adjustment coefficient; generally α takes a constant value between 1.0 ~ 3.0 for Rayleigh fading channel according to the simulation (see Chapter 5).

If $d < 0$, from Eq. 4.18, it means that the averaged channel variation decreased during period $t_{i-2} \sim t_i$. In this case over-adjustment will not occur (see Fig. 4.10 during period $t_6 \sim t_8$). No channel prediction will be done. In wireless communications, the positive peaks are more undesirable than the negative peaks; positive peaks will cause excessive interference to other users in the field.

The channel monitoring variable d reflects the channel changing history. For $d > 0$, it means the channel was rising relative to one T_{pc} seconds ago. But the channel variation for the present period $[t_i, t_{i+1}]$ is unknown at time instant t_i , t could be either rising or falling as shown in Fig. 4.11.

For the situations in Fig. 4.11 (a), it is seen that channel are rising monotonously during the period $t_{i-2} \sim t_{i+1}$, which is quite common around the rising end of deep fade (refer to Fig. 4.10). For Fig. 4.11(b), wireless channel was rising during t_{i-2} and t_i but falls during t_{i-1} and t_{i+1} , which is uncommon around deep fade.

FIGURE 4.11

Illustration of the two cases corresponding to $d > 0$ in wireless channel. d reflects channel variation history up to $2T_{pc}$ seconds ago.

Take Fig. 4.11 (a) for example. there could be five cases of channel variations within the range of t_{i-2} and t_i which satisfy the condition $\overline{P_{ch}(t_{i-1}, t_i)} > \overline{P_{ch}(t_{i-2}, t_{i-1})}$. These are shown in Fig. 4.12. For illustration reason, assume $\overline{P_{ch}(t_{i-2}, t_{i-1})}$ and $\overline{P_{ch}(t_i, t_{i+1})}$ are symmetric around $\overline{P_{ch}(t_{i-1}, t_i)}$ although the actual channel can be any value as long as it satisfies $\overline{P_{ch}(t_{i-1}, t_i)} > \overline{P_{ch}(t_{i-2}, t_{i-1})}$. Table 4.4 shows the effect of improvement described in this section for the five cases in Fig. 4.12.

In Table 4.4, parameter α is the adjustment coefficient shown in Eq. 4.19. Case number in the Table corresponding to that in Fig. 4.12. $\overline{P_{ch}(t_{i-2}, t_{i-1})}$, $\overline{P_{ch}(t_{i-1}, t_i)}$ and $\overline{P_{ch}(t_i, t_{i+1})}$ are the wireless channel variation at each time period $t_{i-2} \sim t_{i-1}$, $t_{i-1} \sim t_i$ and $t_i \sim t_{i+1}$. $P_t(i)$ and $\overline{P_r(t_i, t_{i+1})}$ are transmitter power and measured received signal power during time period $t_i \sim t_{i+1}$. The transmitter power and receiver power during time period $t_i \sim t_{i+1}$ are obtained by substituting the value in Fig. 4.12 into Eq. 4.19 and Eq. 4.3. In Table 4.4 the adjustment coefficient α is chosen to be 1 and 0 respectively. When $\alpha = 0$ it corresponds to the case of no channel prediction adjustment. It is seen from Table 4.4 that with the introduction of adjustment coefficient α and monitoring variable d , the positive peaks can be efficiently suppressed. The selection of α value will be discussed further in Chapter 5.

FIGURE 4. 12

Illustration of channel variation for the case (a) in Fig. 4.11

TABLE 4. 4

Illustration of channel prediction adjustment on the proposed power control scheme.

case	$\overline{P_{ch}(t_{i-2}, t_{i-1})}$	$\overline{P_{ch}(t_{i-1}, t_i)}$	$\overline{P_{ch}(t_i, t_{i+1})}$	$P_t(i)$		$\overline{P_r(t_i, t_{i+1})}$	
				$\alpha=0$	$\alpha=1$	$\alpha=0$	$\alpha=1$
1	-6	-4	-2	p_d+4	p_d+2	p_d+2	p_d
2	-3	-1	1	p_d+1	p_d-1	p_d+2	p_d
3	-2	0	2	p_d+2	p_d-2	p_d+2	p_d
4	-1	1	3	p_d-1	p_d-3	p_d+2	p_d
5	2	4	6	p_d-4	p_d-6	p_d+2	p_d

For the case in Fig. 4.11 (b), it is not commonly found around the deep fades although it occurs quite frequently for the channel near the desired level (refer to Fig. 4.10). And the side effect of this situation would not decrease the received power for the desired user excessively because there is no abrupt variations around this region. i.e., the monitoring variable d is negligibly small as compared with the monitoring variable near the deep fades. The algorithm described here is justified by the fact that the channel changes abruptly only around deep fade and it is smoother elsewhere. In Chapter 5 it will be seen that the power control error will be smaller with the improvement described in this section than that without using adjustment coefficient α and monitoring variable d .

4.5 Implementation of the Proposed Scheme

In transmitter, by keeping a record of transmitter power at the previous period, i.e., $P_t(i-1)$, and upon receiving the message from receiver about the power control error for previous period $e(i)$, the transmitter will adjust its power for the present period $t_i \sim t_{i+1}$ according to Eq. 4.6.

In order to determine the monitoring variable d , the channel variation of the previous two periods must be known. In real communication system, wireless channel variation is a random process. But channel variation for previous power control period T_{pc} seconds ago can be estimated based on the information of transmitted power and power control error T_{pc} seconds ago. From Eq. 4.7, the following two equations can be derived:

$$\overline{P_{ch}(t_{i-1}, t_i)} = e(i) - P_t(i-1) + P_d \quad (4.20)$$

and

$$\overline{P_{ch}(t_{i-2}, t_{i-1})} = e(i-1) - P_t(i-2) + P_d \quad (4.21)$$

where

- $\overline{P_{ch}(t_{i-1}, t_i)}$, $\overline{P_{ch}(t_{i-2}, t_{i-1})}$ – wireless channel variation during period $(t_{i-2} \sim t_{i-1})$ and $(t_{i-1} \sim t_i)$.
- $e(i)$ and $e(i-1)$ – power control errors for previous two periods $(t_{i-2} \sim t_{i-1})$ and $(t_{i-1} \sim t_i)$.
- $P_t(i-1)$ and $P_t(i-2)$ – transmitter power at time instant t_{i-2} and t_{i-1} .
- P_d – the desired received signal power assumed to be a constant[6].

The monitoring variable d is obtained using Eq. 4.18 by combining Eq. 4.20 and Eq. 4.21:

$$d = e(i) - P_t(i-1) - e(i-1) + P_t(i-2) \quad (4.22)$$

If $d > 0$, the value of transmitter power estimated by Eq. 4.6 need to be adjusted as

$$P_t(i) = P_t(i-1) - e(i) - \alpha \times d \quad (4.23)$$

where

- $P_t(i)$, $P_t(i-1)$ – transmitter power at time t_i and t_{i-1} .
- α – adjustment coefficient as defined in Eq. 4.19.
- d – monitoring variable defined in Eq. 4.18.

It can be seen that Eq. 4.23 provides a certain prediction about channel variation based on the information of channel variation T_{pc} seconds ago and $2T_{pc}$ seconds ago by introducing monitoring variable d and adjustment coefficient α . The simulation results in Chapter 5 will show that the power control errors based on Eq. 4.23 are much lower than those obtained without prediction.

Combining the algorithm in Section 4.4.1, if the transmitter power obtained in Eq. 4.23 satisfies the relationship $P_t(i) > P_d + P_{th}$, set the transmitter power as in Eq. 4.17, i.e., $P_t(i) = P_d + P_{ad}$.

The effect of the improvements described in Section 4.4.1 and 4.4.2 is shown in Fig. 4.13. The dashed lines in the transmitter power are the value without threshold adjustment and channel prediction. The solid lines is the actual transmitted power with the two adjustments. The same notation is used in the received signal power. It can be seen that the positive peaks in Fig. 4.13 are effectively suppressed by the two improvement algorithms: threshold adjustment and channel prediction.

Fig. 4.14 is the simulation result for a wireless channel with vehicle velocity $v = 50$ km/hr, carrier frequency $f = 900$ MHz. The threshold power $P_{th} = 17$, adjusted transmitter power $P_{ad} = 10$, adjustment coefficient $\alpha = 0.5$. Without power control, with a constant transmitter power, the received signal power would varies as shown in Fig. 4.14 (a) with the deepest fade around -20dB. Implementing the proposed power control scheme, the received signal power would vary as shown in Fig. 4.14(c) with the deepest fade around -10 dB.

FIGURE 4.13

Illustration of the improvements of channel prediction algorithm and threshold adjustment algorithm. (a) - wireless channel, (b) - transmitter power, (c) - received signal power. The dashed lines are for the cases without threshold and channel prediction.

Comparing Fig. 4.9 and Fig. 4.14, one can observe that the simulation result for the combined improvements (described in Section 4.4.1 and 4.4.2) converges more quickly than the one which only uses improvement in Section 4.4.1. Fig. 4.14 is obtained under the same simulation conditions as those in Fig. 4.9, and the adjustment coefficient α is arbitrarily chosen to be 0.5. The desired received power in both cases are 0dB. One can see that each positive peak in Fig. 4.14 is lower and narrower than that in Fig. 4.9, which mean the interference the user imposed on other users in Fig. 4.14 is less than that in Fig. 4.9.

FIGURE 4.14

Simulation result for the proposed power control scheme. (a) - channel variation. (b) - transmitter power using the improved scheme. (c) - received signal power.

Power Control Simulation and Results

5.1 Effect of Wireless Channel Prediction on Power Control Error

The proposed power control scheme in Chapter 4 adjusts the transmitter power based on the estimation of channel variation. It is achieved according to the history of transmitter power and power control command up to $2T_{pc}$ seconds before (T_{pc} is power control period). The simulation result (in Fig. Fig. 4.14) shows that the positive peaks in the received signal power can be effectively suppressed by introducing monitoring variable d for wireless channel and adjustment coefficient α (see Eq. 4.18 and Eq. 4.19).

The adjustment coefficient α is a fixed value in the proposed power control scheme. But channel monitoring variable d may change in different power control periods due to the wireless channel variation. Selecting different α values has different effects in the power control error.

In order to see the impact of value of α on power control error. Table 5.1 shows power control errors (reflected in standard deviation of received signal level) corresponding to different values of α with a power control period 0.6 milliseconds. Vehicle speed is 50km/hr, carrier frequency $f_c = 900$ MHz. Table 5.1 is obtained based on the simulation results of 100 wireless channels. The proposed power control algorithms, i.e., Eq. 4.3 ~

Eq. 4.6, and Eq. 4.16 ~ Eq. 4.19 have been used in the simulation. The threshold P_{th} and adjusted transmitter power P_{ad} are 23dB and 14dB respectively.

TABLE 5. 1

Power control errors averaged over 100 channels corresponding to different α values.

α	0.1	0.5	1.0	1.3	1.5	2.0
Power Control Error (dB)	0.75	0.59	0.45	0.43	0.45	0.57

From Table 5.1 it can be noted that when α is set to be 1.3, the power control error reaches its smallest value.

The purpose of introducing adjustment coefficient α is to mitigate the over-adjustment. The value of α reflects the wireless channel prediction used in the proposed power control scheme. If α is too small, over-adjustment can not be effectively suppressed. If α is too large, then less-adjustment may occur. In other words, the transmitter power adjusted using too large α value may not fully compensate the channel variation (refer to Eq. 4.19).

Fig. 5.1 and 5.2 illustrate the effect of different values of adjustment coefficient α on power control errors during power control process. Vehicle speed is 50km/hr. $f_c=900\text{MHz}$. The settings of P_{th}/P_{ad} are 23/14. The ensemble behavior of variable step size power control is obtained based on 100 samples.

Fig. 5.1 is for power control period of 0.6 milliseconds and Fig. 5.2 for 1 millisecond. For comparison α is chosen to be 0.5 and 1.3 respectively for each power control period. Here the value of $\alpha = 0.5$ is arbitrarily chosen to see the effect of optimum value of adjustment coefficient α on power control error in the power control process.

FIGURE 5.1

The ensemble behavior of power control error for power control period of 0.6msec with different adjustment coefficients (a) $\alpha = 0.5$, (b) $\alpha = 1.3$

It is observed that in both cases the fluctuation in the received power for $\alpha = 1.3$ is smaller than that for $\alpha = 0.5$. This agrees with the simulation results in Table 5.1. Comparing Fig. 5.1 with Fig. 5.2 it also shows that power control error with longer power control period is larger than that with shorter power control period. This is expected because of the fact that for the longer power control period, the channel estimation calculated in transmitter will make channel prediction less accurate.

FIGURE 5.2

The ensemble behavior of power control error for power control period $T_{pc} = 1$ msec with adjustment coefficients (a) $\alpha = 0.5$. (b) $\alpha = 1.3$

Table 5.2 listed power control errors (represented by standard deviation in the received signal power) for other power control periods using the proposed power control scheme for $\alpha = 1.3$ based on 100 channels. For illustration, simulation result for $\alpha = 0.5$ is also listed here. The simulation is done under the following conditions: vehicle speed $v = 50$ km/hr, carrier frequency $f = 900$ MHz. The power control period, T_{pc} , ranges from 0.1 milliseconds to 1 milliseconds. The standard deviation of the received power after power control vary with the value of T_{pc} . The shorter the power control period T_{pc} , the smaller the power control error (reflected in standard deviation of the received signal power).

TABLE 5. 2

The power control errors using the improved scheme for different power control periods. $P_{th}/P_{ad} = 23/14$

T_{pc} (msec)	α	Standard Deviation(dB)
1	0.5	0.93
	1.3	0.59
0.6	0.5	0.59
	1.3	0.43
0.4	0.5	0.41
	1.3	0.34
0.2	0.5	0.26
	1.3	0.22
0.1	0.5	0.16
	1.3	0.12

In order to show the effects of the improvements described in Section 4.4, Table 5.3 shows the power control error for three cases: (1) basic scheme shown in Fig. 4.4, (2) with the improvement of introducing threshold and adjusted transmitter power by setting $P_{th}/P_{ad} = 23/14$ (refer Section 4.4.1), (3) with improvement of $P_{th}/P_{ad} = 23/14$ and channel prediction scheme with adjustment coefficient $\alpha = 1.3$ (see Section 4.4). The vehicle speed is 50km/hr, and the carrier frequency is 900MHz for all the cases. The power control periods varies from 0.2 milliseconds to 1 milliseconds.

TABLE 5. 3

Power control errors for different power control schemes. Case 1 – basic scheme (Fig. 4.4), Case 2 - threshold adjustment. Case 3 – channel prediction algorithm

T_{pc} (msec)	case		
	1	2	3
1	1.27	1.25	0.59
0.6	0.81	0.79	0.43
0.4	0.55	0.53	0.34
0.2	0.27	0.27	0.22

It is seen that by implementing the threshold adjustment algorithm and the channel prediction algorithm, the power control error decreases. The channel prediction algorithm reduces power control error more effectively than the threshold adjustment algorithm does. With the introduction of the adjustment coefficient α , power control error decreases by about 50 percent for power control period longer than 0.6 msec. The longer the power control period, the more obvious the improvements are. This is because of the fact that for

larger power control period, the channel estimation based on the previous transmitted power and the returned power control message is less related to current channel variation (refer to Eq. 4.15). Hence it is more important to use the improvements described in Section 4.4 for longer power control period.

5.2 Effect of Quantization on Power Control Error

5.2.1 Control Message Quantization Protocol

In reality, digital wireless communication requires that the feedback message from the receiver be discrete instead of continuum of real values. That means the power control message must be chosen to be one of the quantized levels according to the protocol between transmitter and receiver. Figure 5.3 shows an example of quantization of the samples of a power control message using a 3-bit quantizer, where δ is the quantization step, or resolution. The un-quantized samples are shown with solid dots and the quantized samples are shown with square dot.

FIGURE 5.3

An example of quantization with a 3-bit quantizer.

The quantization protocol between receiver and transmitter is described as following (here δ in dB stands for the power control unit and can be thought of power control resolution as shown in Fig. 5.3):

- For one bit, the adjustment is done with two levels, either 1δ dB or -1δ dB, depending on the value of the returning bit 1 or -1.
- For two bits, the four adjustment levels, 2δ dB, 1δ dB, -1δ dB and -2δ dB correspond to the returning bit pattern 11, 10, 01 and 00 respectively.
- For three bits, eight adjustment levels, 4δ dB, 3δ dB, 2δ dB, 1δ dB, -1δ dB, -2δ dB, -3δ dB and -4δ dB correspond to the returning bit patterns 111, 110, 101, 100, 011, 010, 001 and 000 respectively.

Take 2 bits as an example, for each power control command, transmitter power can jump to one of the four values shown in Table 5.4 for a power control resolution of 1dB from power level p_0 in dB or equivalent p_0^l in linear scale.

TABLE 5.4

Transmitter power adjustment levels from original power level P_0 in dB or P_0^l in linear scale according to power control message. Power control resolution is 1dB.

power control command	transmitter power	
	in dB	in linear scale
00	$p_0 - 2$	$p_0^l / 1.5$
01	$p_0 - 1$	$p_0^l / 1.26$
10	$p_0 + 1$	$1.26p_0^l$
11	$p_0 + 2$	$1.5p_0^l$

A summary of the protocol for 1, 2 and 3 bits used in returning channel is shown in Table 5.5 including feed back bit patterns, dynamic step sizes and maximum power adjustment ranges. For 4, 5 or more bits, the same rule will apply. Note that the number of adjustment power levels is 2^n , where n is the number of bits used in power control command. The dynamic adjustment step size varies with the number of bits and power control resolution δ dB. The maximum step size or the maximum power adjustment range can be expressed in the following manner:

$$\Delta = 2^{n-1} \times \delta \quad (\text{dB}) \quad (5.1)$$

where

- Δ - maximum power adjustment range or maximum step size in dB. The value of Δ reflects the maximum variation in the wireless channel the transmitter can compensate with one power control command in the proposed model shown in Fig. 4.4.
- n - number of bits used in power control command.
- δ - power control resolution in dB.

TABLE 5. 5

Example for the power control protocol between transmitter and receiver. δ is power control resolution in dB.

number of bits	bit patterns	dynamic step sizes (dB)	maximum power adjustment range (dB)
1	1	$+1\delta$	1δ
	0	-1δ	
2	11	$+2\delta$	2δ
	10	$+1\delta$	
	01	-1δ	
	00	-2δ	
3	111	$+4\delta$	4δ
	110	$+3\delta$	
	101	$+2\delta$	
	100	$+1\delta$	
	011	-1δ	
	010	-2δ	
	001	-3δ	
	000	-4δ	

Conceptually, following observations can be made, which will be verified in next section:

(1) with fixed power control resolution δ , the maximum power adjustment range increases with the number of power control command bits. This means the information about the deep fades in wireless channel variation can be feed back. Therefore the more command bits used, the less power control error with fixed power control resolution.

(2) when fixing maximum power adjustment range Δ , if more command bits are used the power control resolution δ decreases. This means that with each power control command, the transmitter can compensate channel variations more finely when more bits are used, resulting less power control error.

(3) for a fixed number of bits, when implementing the protocol shown in Table 5.5, fixing Δ or fixing δ is equivalent (refer to Eq. 5.1), the power adjustment step sizes vary with the power control resolution δ . In quantization case, wireless channel compensation involves two aspects: one is compensation precision and the other is compensation range. The compensation precision relates to the fineness the transmitter power compensate the channel variation. The compensation range is about how big the maximum step size could be, which is the main concern around deep fades. For a fixed number of power control bits, the smaller the power control resolution, the finer the wireless channel gets compensated, and the smaller the maximum step size or compensation range. On the other hand, the bigger the δ is, the bigger the compensation range, but the coarser the wireless channel gets compensated. So there is a trade off when selecting a power control resolution δ for a certain number of power control bits. And the optimum value of δ varies with the number of bits used in power control command. The effect of power control resolution δ , the maximum step size Δ and number of power control bits will be discussed in the next section.

5.2.2 Power Control Error for Quantized Command Message

In quantized power control system, the returned power control message sent by receiver will reflect the value of the received power with a certain error due to quantization. That implies the channel variation of T_{pc} seconds ago and $2T_{pc}$ seconds ago may not be estimated as precisely as in the continuum case. Therefore power control error in quantized system may be larger than those obtained without quantization.

In quantized case, the returned power control message representing power control error takes one of the value shown in Table 5.5 according to the power control protocol. Therefore the optimum value of adjustment coefficient α will be different from that in the continuum case.

In order to find out the optimum value of adjustment coefficient α in quantized case, Table 5.6 lists the power control errors using different values of adjustment coefficient α . This table is obtained with power control period 0.6 milliseconds, power control command 1 bit, and power control resolution 1dB. Here the optimum value of α is found to be around 2.0, while in continuum power control case the best value for α is 1.3.

The change in the optimum value of α is due to the fact that the channel varying estimation become less accurate due to quantization error. The power control error $e(i)$ is a

random variable related to the wireless channel variation. The fact that optimum value of α in quantized case is bigger than that in continuum case means that the mean value of power control message in quantized case is less than that in continuum case due to quantization (refer Eq. 4.23). This is because the power control error $e(i)$ is rounded to one of the quantized value shown in Fig. 5.3. The quantization error is even more significant around deep fades. It is also observed from Table 5.6 that the power control error is not very sensitive to the value of α as long as α falls between 1.3 ~ 2.5. For comparison, the power control error in no channel prediction case ($\alpha = 0$) is also listed in Table 5.6. It can be seen that the power control error decreases 0.5 dB using the optimum adjustment coefficient ($\alpha = 2.0$).

TABLE 5. 6

Power control errors (dB) corresponding to different α value in quantized case.

α	0	0.5	1.3	2.0	2.5	3.0
P.C.Error	1.67	1.29	1.17	1.16	1.19	1.21

Following simulations are to verify the observations made in Section 5.2.1:

(1) fixing the power control resolution δ

To show the effect of number of power control bits on power control error with fixed power control resolution δ , Fig. 5.4 shows the simulation results of the ensemble average of 100 samples over a power control period of 0.4 msec (a), 0.6 msec (b) and 1 msec (c) respectively with adjustment coefficient $\alpha = 2.0$. Four command bits have been used in the controlling message. The power control level resolution is 0.5dB. According to Eq. 5.1, the maximum power adjustment range is 4dB in Fig. 5.4. As can be seen that with same number of command bits (4 bits here), the longer power control period, the more fluctuant the received power becomes.

FIGURE 5.4

Power control errors in quantized cases. 4 bits control command. power control level resolution 0.5dB. (a) $T_{pc} = 0.4$ msec. (b) $T_{pc} = 0.6$ msec. (c) $T_{pc} = 1$ msec..

Fig. 5.5 is obtained under the same simulation conditions except using 2 bits in the power control command. And the maximum step size is 1dB in Fig. 5.5. Comparing with the same power control periods in Fig. 5.4 (a), (b) and (c), the variation in the received power in Fig. 5.5 is larger than that in Fig. 5.4 for each power control period. When more bits are used in control command, with the same power control resolution, i.e., the same compensation fineness, the maximum step size gets larger, the power control scheme responds to wireless channel variation better.

FIGURE 5.5

Power control errors in quantized cases, 2-bit control command. Power control resolution is 0.5dB. (a) $T_{pc} = 0.4$ msec. (b) $T_{pc} = 0.6$ msec. (c) $T_{pc} = 1$ msec

Table 5.7 lists power control errors of variable step size power control corresponding to continuum value power control, 4-bit control command and 2-bit control command. The simulation result shows that the power control error for 2 bits is the largest among the 3 groups, that for 4 bits comes next while that of continuum value power control is minimum. This is due to the fact that quantization in the controlling message causes the wireless channel variation imprecisely compensated. The lower number of bits used, the less accurate the channel variations are estimated. In the quantized cases here, since both cases use power control resolution 0.5dB, the number of power control bits can be translated

into Δ . In continuum case, there is no limitation on Δ , in 4 bits case, $\Delta = 4\text{dB}$ while in 2 bits case $\Delta = 1\text{dB}$.

TABLE 5. 7

Power control errors for 3 scenarios: (1) continuum value power control with $\alpha = 1.3$. (2) 4-bit control command and (3) 2-bit control command. In both quantized cases, $\delta = 0.5\text{ dB}$, $\alpha = 2.0$

T_{pc} (msec)	Power control error (dB)		
	Continuum	4-bit	2-bit
0.4	0.34	0.42	0.71
0.6	0.43	0.54	1.12
1.0	0.59	0.66	1.35

(2) fixing the maximum power adjustment range Δ

When the maximum power adjustment range Δ is fixed, the maximum step size the transmitter adjusts the power is fixed. When Δ is fixed, with the increase of number of power control bits, the power control resolution δ decreases, the estimation of channel variation becomes more accurate. And the transmitter power can get finer adjustment. Therefore power control error gets smaller.

Fig. 5.6 shows power control errors for different number of power control bits when the maximum power adjustment range is fixed. The relationship between power control resolution δ and number of command bits n is shown in Eq. 5.1.

The improvement between 1 bit and 2 bits is significantly larger than that between 2 bits and 3 bits. When the number of power control bits are further increased, power control error decreases at a lower rate. This means the information about channel variation embedded in 2 power control command bits is much more accurate than that in 1 command bit. And the estimation of channel variation using 2 bits is quite accurate comparing with the case of using more than 2 command bits.

FIGURE 5.6

Effect of number of power control bits on power control error when the maximum power adjustment range is fixed.

(3) fixing the number of power control bits

In order to see the relationship between the power control error and the power control resolution, the cases for different power control resolutions were simulated. Two bits are used in the control message in Fig. 5.7. $P_{th}/P_{ad} = 23/14$ (dB). The adjustment coefficient $\alpha = 2.0$. Power control period is 0.4 milliseconds. Power control resolution ranges from 0.1dB to 2.5dB. And according to Equation 5.1, the corresponding maximum dynamic range of power adjustment changes from 0.2dB to 5dB.

FIGURE 5.7

Power control errors (represented by standard deviation) versus power control resolution.

Based on Fig. 5.7, the following observations are made:

(1) Around the region of small resolution (0.1 ~ 0.8dB), the power control error represented by standard deviation, decreases significantly as power control resolution is increased. This is because with fixed number of power control bits, according to Eq. 5.1, the maximum power adjustment range increases when power control resolution gets larger. The channel variation get compensated more accurately when deep fades occur.

(2) Power control error reaches a minimum at around 0.9 dB resolution. When the resolution is further increased (>1.4dB), the curve of power control error goes up, i.e. the power control process will become unstable. This is caused by the fact that in wireless channel, if power control resolution is bigger than channel variation, over adjustment hap-

pens. Therefore the received signal power will bounce around the desired power level, rendering control system unstable.

Fig. 5.8 illustrates an example using power control resolution 0.9dB. Adjustment coefficient $\alpha = 2.0$. $P_{th}/P_{ad} = 23/14$, vehicle speed = 50 km/hr, carrier frequency = 900 MHz. Fig. 5.9 is obtained with the same simulation condition as that in Fig. 5.8 except that power control resolution is 2.5dB.

FIGURE 5.8

Simulation result with power control resolution $\delta = 0.9\text{dB}$. (a) - wireless channel variation. (b) - transmitter power. (c) - received signal power

FIGURE 5.9

Simulation result with power control resolution $\delta = 2.5\text{dB}$. (a) - channel variation. (b) - transmitter power. (c) - received signal power

Comparing Fig. 5.8 with Fig. 5.9, with the same channel variation shown in Fig. 5.8 (a), the transmitter power in Fig. 5.8 (b) tracks channel variation better than Fig. 5.9 (b) does. And the variation in the received signal power in Fig. 5.8 (c) is smaller than that in Fig. 5.9 (c).

The value of the power control errors are listed in Table 5.8 when the propagation model in Eq. 3.1 is incorporated in channel variation. The power control latency is 1 milli-second. Vehicle speed is 50 km/hr. Carrier frequency is 900 MHz. The transmitter power is adjusted with $\alpha = 2.0$, $P_{th}/P_{ad} = 23/14$. Power control resolution is 1dB. Channel labeled A represents Rayleigh channel as before. Channel labeled B is for Rayleigh chan-

nel imposed on the propagation loss model in Eq. 3.1 where the turning point is considered.

TABLE 5. 8

Power control error for the proposed scheme. (1) Channel A: Rayleigh fading channel; (2) Channel B: Rayleigh fading channel imposed on the propagation model in Eq. 3.1.

No.of bits	Channel	Power control error (dB)
1	A	1.5
	B	1.52
2	A	1.10
	B	1.11
3	A	0.84
	B	0.85

It can be seen that when propagation path loss with a breaking point is imposed on the Rayleigh fading channel, the power control error only increases by a negligible amount. During power control period of 1 msec, the vehicle with speed of 50 km/hr travels a distance $= v \times T_{pc} = 1.39 \times 10^{-2}$ m. The local mean is embedded in the fast Rayleigh fading signal.

5.2.3 Comparison of the Proposed Power Control Scheme with the Existing Scheme

The power control scheme proposed in this thesis using 1 bit control command and 1dB step size achieved less power control error than the existing fixed step-size power control does with the same channel condition. In Table 5.9, the proposed scheme is equivalent to the existing fixed step size scheme in the sense that both schemes use 1 bit control command and 1 millisecond power control period. But in transmitter two schemes behave differently. In existing scheme, transmitter adjusts its power by +1dB or -1dB according to the feedback message. In the proposed scheme, the value of transmitter power obtained above will be modified by an amount determined by the wireless channel variation history with adjustment coefficient $\alpha = 2.0$. And transmitter power threshold settings $P_{th}/P_{ad} = 23/14$.

TABLE 5. 9

Power control error (dB) in the fixed step size power control and variable step size power control. Both use 1 bit command and 1dB step size.

scheme	power control period (msec)		
	0.4	0.6	1.0
fixed step size	1.16	1.69	2.2
proposed	0.73	1.16	1.5

The comparison between the simulation results of fixed step size giving in [6] and that of variable step size giving in this thesis is shown in Table 5.10. In [6], a fixed step size of 1dB is used in power control. And the power control period is chosen to satisfy $f_d T_{pc} = k$, where f_d is the maximum doppler shift and k is a constant (chosen to be 0.02 and 0.05 respectively). Substituting vehicle speed 50 km/hr, carrier frequency 900 MHz into following equation:

$$T_{pc} = \frac{k \times c}{f \times v} \quad (5.2)$$

where

- T_{pc} – power control period
- k – a constant used in [6] selected to be 0.02 and 0.05.
- c – signal propagation speed. $c = 3 \times 10^8$ m/sec.
- f – carrier frequency.
- v – vehicle travelling speed.

the power control periods corresponding to $f_d T_{pc} = 0.02$ and 0.05 are 0.48 milliseconds and 1.2 milliseconds respectively.

TABLE 5. 10

Comparison between the fixed step size (1dB) power control [6] and variable step size power control with 1 bit command and 1dB step size.

Delay (msec)	schemes	Diversity	Standard Deviation (dB)
0.48	fixed	2	0.9
	step size	4	0.6
	variable step size	1	0.9
1.2	fixed	2	1.9
	step size	4	1.2
	variable step size	1	1.64

From Table 5.10 it is observed that power control scheme proposed in the thesis gives a smaller power control error than fixed step size power control for the same power control period, although the former uses no diversity and the latter uses diversity order of two and four respectively. The comparison is done based on the same power control period ($T_{pc} = 0.48$ msec or 1.2 msec) and same number of controlling bits (1 bit). The improvement is due to the fact that the proposed scheme introduced threshold P_{th} , adjusted transmitter power level p_{ad} (in Section 4.4.1) and adjustment coefficient α (in Section 4.4.2). Coefficient α decreases power control error more effectively than P_{th} and P_{ad} do (see Table 5.3), α brings down the positive peaks by efficiently mitigating the over-adjustment (refer to Fig. 4.8 and Fig. 4.11).

5.3 Outage Consideration in Real Application

In wireless CDMA system, the outage probability is an important measure of communication quality. When the received power is less than reception threshold value, the communication quality becomes so poor that the communication link could be jeopardized. The outage probability measure can also be used to evaluate the performance of power control algorithms. The outage probability can be defined as following:

$$P_{out} = \text{prob}(P_r < P_{thres}) \quad (\text{dB}) \quad (5.3)$$

with

$$P_{thres} = P_d - \Delta P \quad (\text{dB}) \quad (5.4)$$

where

- P_r – received signal power
- P_{thres} – power threshold
- P_d – desired received power
- ΔP – power threshold setting

Fig. 5.10 illustrates the outage probability for different number of control bits. Threshold setting $\Delta P = 2$ dB. Power control period is 1.25 msec. Adjustment coefficient $\alpha = 2$ and control resolution is 1 dB. The threshold setting $P_{th}/P_{ad} = 23/14$.

It is seen that with the increase in the number of power control bits, the outage probability decreases. The more bits used in controlling message, the more accurate channel estimation will be made, the less likely is the received power will to below the desired

received signal power, hence the smaller outage probability. But the improvement gets smaller when the number of power control bits reaches a certain value (4 bits).

FIGURE 5.10

Outage probability using different number of power control bits in the proposed adaptive step size power control scheme.

Table 5.11 shows how the outage probability in percentage is impacted by the power threshold setting ΔP for the proposed power control scheme in this thesis. In Table 5.11 the threshold setting ranges from 1dB to 3dB below the desired received power. The simulation is done with power control period = 1.25 msec, power control resolution = 1dB, adjustment coefficient = 2.

TABLE 5.11

Outage probability (%) for different power threshold settings.

no. of bits	ΔP (dB)				
	1	1.5	2	2.5	3
1	29	24	14	9	6

2	24	14	9	3	1
3	20	11	5	2	1
4	15	6	2	2	0
5	15	5	2	1	0

Note that for a certain number of command bits, the outage probability drops quickly when power threshold setting ΔP increases, which implies that with the proposed power control the received signal power falls mostly above the level which is 1.5 dB below the desired received signal power (see Fig.5.11).

FIGURE 5. 11

The impact of power threshold setting on outage probability.

5.4 Improvement on system capacity

The purpose of power control in wireless CDMA system is to increase capacity in terms of the number of users the system can support for a given bit error rate. When more bits are used in the power control message, the more accurate the wireless channel variation can be estimated, therefore smaller power control error can be obtained.

The capacity reduction due to unequal received power is studied in [36]. The author gives a numeric illustration of the relationship between bit error rate and the received signal variation regardless of what power control scheme was used, based on which the effect of standard deviation of the received signal power on the reduction of number of users is demonstrated. The system under consideration uses binary direct-sequence spread-spectrum multiple-access communications (BPSK) and a coherent correlation receiver. There are N users in the system. At the receiver end for user i , the received signal which is the sum of N spread-spectrum signals is multiplied by a synchronized replica of the original PN code for user i .

The multiple access interference (MAI) is approximately Gaussian, conditioned on the delays and phases of all the interfering signals and on the number of chip boundaries in the desired signal i at which a transition to a different value occurs. Assume the received power for each user is independent, identically distributed random variable. The MAI is a function of the received power from each user.

Fig. 5.12 is the numerical result given in [36] showing the relationship between the standard deviation in the received power and the system capacity for uncoded case. The simulation in [36] used the objective bit error rate of 10^{-3} and processing gain is 63.

It is seen that: (a) the larger the received power variation, the bigger reduction in the system capacity, i.e. the slope rises monotonously; (b) the reduction in capacity is more sensitive to the received power variation when power variation gets larger, i.e. the slope gets steeper when the power variation gets larger.

FIGURE 5.12

Relationship between the standard deviation (dB) in received signal power and reduction in system capacity for uncoded case.

In order to use the numerical result in [36], a curve fitting needs to be done for Fig. 5.12. By using Matlab tool, Fig. 5.12 can be expressed as

$$N_{act} = \left(1 - \frac{3.05x + 11.63x^2 - 42.89x^3 + 84.74x^4 - 59.23x^5 + 17.72x^6 - 1.94x^7}{100} \right) N \quad (5.5)$$

where

- N_{act} – the actual number of users in a system with a certain objective bit error rate for the case of unequal received power.
- x – standard deviation of received signal power in dB. The data fitting in Eq. 5.5 or Fig. 5.12 is valid for $x < 2.3$ dB.
- N – the number of users with equal received power for the same objective bit error rate.

In a power controlled system imperfect power control scheme results in power control error, so N_{act} is less than N due to the unequalled received signal power. The reduction factor is related to the value of the power control error.

According to the IS-95 standard, the power control sub-channel is continuously transmitted on the forward traffic channel at a rate of one bit every 1.25 msec (i.e., 800 bps).

Table 5.12 shows the capacity reduction in different scenarios: (1) using existing

TABLE 5. 12

The capacity reduction using different number of power control command bits.

power control scheme	No of bits	standard deviation in received power (dB)	capacity reduction (%)
no control	0	4.6	> 85
existing scheme [7]	1	2.2	66
proposed scheme	1	1.65	41
	2	1.30	25
	3	1.07	15
	4	0.91	10
	5	0.85	8

power control scheme [7], (2) using the proposed power control scheme proposed in this thesis with different number of control bits. Both power control schemes are implemented with power control period of 1.25 msec. Corresponding to each scenario, listed in Table 5.12 are standard deviation in received signal power, capacity reduction in percentage corresponding to power control errors reflected in the standard deviation of the received power variation.

For comparison, the standard deviation in the received power with no power control is also illustrated in Table 5.12. For a standard deviation of 4.6dB, a lower bound of 85% reduction is estimated according the results in [36].

It is noted that with 1 command bit and 1dB power control resolution, the capacity reduction for the proposed scheme in this thesis is less than that for existing fixed step-size power control scheme under the same condition. For example, if the system can support 100 users when there is no capacity reduction, then with existing power control the system

can only support 34 users, while with the proposed power control scheme in this thesis the system can support 59 users.

For the proposed power control scheme, the more bits used in the control message, the less power control error, and the less capacity reduction. The improvement for 2 bits compared with that of 1 bit is quite significant. When the number of bits is further increased, the capacity improves at a slower pace.

6.1 Conclusions

The proposed power control scheme with variable step size can track the fast Rayleigh fading more effectively than the existing scheme with fixed step size. The power control error can be further decreased with a variable step size closed loop power control scheme.

1. Literature review shows that the power control is crucial to the capacity of wireless CDMA system. Existing power control schemes have been classified into open loop power control and closed loop power control, average power control and strict power control, centralized power control and distributed power control, and fixed step size power control and variable step size power control strategies.

2. A closed loop strict power control model for variable step size is proposed in the thesis. In the proposed scheme, the power control error is used as power control command. The channel variation is estimated based on the transmitter power for the previous power control period and the resulting power control error. The theoretic analysis shows that the power control period is mainly the received signal averaging time. The smaller the power control period, the better the wireless channel can get compensated.

3. The simulation result based on the proposed power control model is shown in Fig. 4.7. The positive peaks are the result of over-adjustment and delayed correction due to power control period. In wireless communication, the principle of power control is to reduce the excessive interference imposed on other users while sacrificing the temporary degradation of individual user. The positive peaks in Fig. 4.7 are suppressed by the following algorithms:

(1) Setting the threshold P_{th} and adjusted transmitter power P_{ad} , if the transmitter power is greater than $(P_{th} + P_d)$, then use $(P_d + P_{ad})$ as the transmitter power, where P_d is the desired received signal power. P_{th} and P_{ad} are selected around the mean value of the deepest fades in the channel as discussed in Section 4.4.1.

(2) By introducing the adjustment coefficient α and channel monitoring variable d in Section 4.4.2, tracking channel variation $2 T_{pc}$ seconds back can efficiently predict the tendency of channel variation to further avoid channel over adjustment.

Fig. 4.14 in Chapter 4 shows that the positive peaks are successfully suppressed by using the two algorithms mentioned above.

4. The effect of quantization on power control message has been simulated. The protocol between the transmitter and the receiver is given in Table 5.5 for different number of command bits. The power control error in quantized case is bigger than that in continuum case. The relationship between power control error and the power control parameters (such as the number of command bits, power control resolution, and the maximum power adjustment range) is simulated. It is observed that:

- with fixed power control resolution, i.e., the power control accuracy is fixed, the more bits used in the power control command, the bigger the maximum power adjustment range (which is very important in tracking deep fades), the smaller power control error.
- When maximum power adjustment range is fixed, power control resolution decreases with the increase of the number of power control bits. The more bits are used in power control command, the more accurate channel variation information can be fed back, and the smaller is the power control error.
- with fixed number on power control bits, the maximum power adjustment range is related with power control resolution as shown in Eq. 5.1. There is a trade-off between selecting power control resolution and the maximum adjustment range. The smaller the power control resolution, the finer channel varia-

tion can be estimated, but the smaller the maximum power adjustment range. The larger the power control resolution, the bigger the maximum power adjustment range, but the coarser the wireless channel can be compensated. Thus there is an optimum value for the power control resolution at which power control error is minimum.

5. The power control error for the proposed model is compared with that in existing power control models. Under the same channel condition, with the same power control parameters, i.e., same power control periods, 1 bit power control command and 1dB step size, the power control error for the proposed power control model is smaller than that for the existing power control model (see Table 5.9). It is also shown that (Table 5.10) even with no diversity, the variable step size scheme gives nearly the same power control error as that in the fixed step size scheme with a diversity order of 2.

For the proposed variable step sized power control model. increasing the number of bits used in the control message, the outage probability decreases and system capacity increases (refer to Fig. 5.10 and Table 5.12).

6.2 Suggestion for Future Research

In a real wireless system using strict power control scheme, power control command for reverse link is imbedded in the logic forward CDMA channel transmitted by a base station[7] using the puncturing technique. Each power control bit shall replace two consecutive forward traffic channel modulation symbols (which is equivalent to 1 information bit for data rate of 9.6 kbps).

With puncturing technique, the more command bits are used in power control sub-channel, the smaller the power control error, but the more information bits will be punctured. Therefore to chose the appropriate number of power control bits for high system capacity and performance is a future research direction.

This thesis uses uniform quantization. A nonuniform quantization could be used in the proposed power control scheme. Also, different channel prediction techniques could be investigated to further decrease the power control error.

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