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Power Control

Roman Pichna
Nokia Telecommunications

Qiang Wang
Nikko Research Center

25.1 Introduction

The growing demand for mobile communications is pushing the technological barriers of wireless communications. The available spectrum is becoming crowded and the old analog **FDMA** (frequency division multiple access) cellular systems no longer meet the growing demand for new services, higher quality, and spectral efficiency. A second generation of digital cellular mobile communication systems are being deployed all around the world. The second generation systems are represented by three major standards: the **GSM,** IS-136, and IS-95. The first two are TDMA-based digital cellular systems and offer a significant increase in spectral efficiency and quality of service as compared to the first generation systems, e.g., **AMPS, NMT,** and **TACS.** IS-95 is based on **DS/CDMA** technology. The standardization of the third generation systems, IMT-2000, (formerly known as FPLMTS) is being pursued at ITU. Similar efforts are being conducted at regional standardization bodies.

The channel capacity of any cellular system is significantly influenced by the cochannel interference. To minimize the cochannel interference, several techniques are proposed: frequency reuse patterns, which ensure that the same frequencies are not used in adjacent cells; efficient **power control,** which minimizes the transmitted power; cochannel interference cancellation techniques; and orthogonal signalling (time, frequency, or code). All of these are being intensively researched, and some have already been implemented.

This chapter provides a short overview of power control. Since power control is a very broad topic, it is not possible to exhaustively cover all facets associated with power control. The interested reader can find additional information in the recommended reading that is appended at the end of this chapter.

The following section (Section 25.2) provides a brief introduction into cellular networks and demonstrates the necessity of power control. The various types of power control are presented in this section. The next section (Section 25.3) illustrates some applications of power control employed in various systems such as analog AMPS, GSM, DS/CDMA cellular standard IS-95, and digital cordless telephone standard **CT2**. A glossary of definitions is provided at the end of the chapter.

25.2 Cellular Systems and Power Control

In cellular communication systems, the service area is divided into cells, each covered by a single base station. If, in the **forward link** (base station to mobile), all users served by all base stations share the same frequency, each communication between a base station and a particular user would also reach all other users in the form of cochannel interference. However, the greater the distance between the mobile and the interfering transmitter, the weaker the interference becomes due to the propagation loss. To ensure a good quality of service throughout the cell, the received signal in the fringe area of the cell must be strong. Once the signal has crossed the boundary of a cell, however, it becomes interference and is required to be as weak as possible. Since this is difficult, the channel frequency is usually not reused in adjacent cells in most of the cellular systems. If the frequency is reused, the cochannel interference impairs the signal reception in the adjacent cell, and the quality of service severely degrades unless other measures are taken to mitigate the interference. Therefore, a typical reuse pattern reuses the frequency in every seventh cell (frequency reuse factor = 1/7). The only exception is for CDMA-based systems where the users are separated by codes, and the allocated frequency may be shared by all users in all cells.

Even if the frequency is reused in every seventh cell, there is still some cochannel interference arriving at the receiver. It is, therefore, very important to maintain a minimal transmitted level at the base station to keep the cochannel interference low, frequency reuse factor high, and therefore the capacity of the system and quality of service high.

The same principle applies in the **reverse link** (mobile to base station)—the power control maintains the minimum necessary transmitted power for reliable communication. Several additional benefits can be gained from this strategy. The lower transmitted power conserves the battery energy allowing the mobile terminal (the portable) to be lighter and stay on the air longer. Furthermore, recent concerns about health hazards caused by the portable's electromagnetic emissions are also alleviated.

In the reverse link, the power control also serves to alleviate the near–far effect. If all mobiles transmitted at the same power level, the signal from a near mobile would be received as the strongest. The difference between the received signal strength from the nearest and the farthest mobile can be in the range of 100 dB, which would cause saturation of the weaker signals' receivers or an excessive amount of adjacent channel interference. To avoid this, the transmitted power at the mobile must be adjusted inversely proportional to the effective distance from the base station. The term effective distance is used since a closely located user in a propagation shadow or in a deep fade may have a weaker signal than a more distant user having excellent propagation conditions.

In a DS/CDMA system, power control is a vital necessity for system operation. The capacity of a DS/CDMA cellular system is interference limited since the channels are separated neither in frequency nor in time, and the cochannel interference is inherently strong. A single user exceeding the limit on transmitted power could inhibit the communication of all other users.

The power control systems have to compensate not only for signal strength variations due to the varying distance between base station and mobile but must also attempt to compensate for signal strength fluctuations typical of a wireless channel. These fluctuations are due to the changing propagation environment between the base station and the user as the user moves across the cell or as some elements in the cell move. There are two main groups of channel fluctuations: slow (i.e., **shadowing**) and fast **fading**.

As the user moves away from the base station, the received signal becomes weaker because of the growing propagation attenuation with the distance. As the mobile moves in uneven terrain, it often travels into a propagation shadow behind a building or a hill or other obstacle much larger than the wavelength of the frequency of the wireless channel. This phenomenon is called shadowing. Shadowing in a land-mobile channel is usually described as a stochastic process having log-normal distributed amplitude. For other types of channels other distributions are used, e.g., Nakagami.

Electromagnetic waves transmitted from the transmitter may follow multiple paths on the way from the transmitter to the receiver. The different paths have different delays and interfere at the antenna of the receiver. If two paths have the same propagation attenuation and their delay differs in an odd number of half-wavelengths (half-periods), the two waves may cancel each other at the antenna completely. If the delay is an even multiple of the half-wavelengths (half-periods), the two waves may constructively add, resulting in a signal of double amplitude. In all other cases (nonequal gains, delays not a multiple of half-wavelength), the resultant signal at the antenna of the receiver is between the two mentioned limiting cases. This fluctuation of the channel gain is called fading. Since the scattering and reflecting surfaces in the service area are randomly distributed (buildings, trees, furniture, walls, etc.), the amplitude of the resulting signal is also a random variable. The amplitude of fading is usually described by a Rayleigh, Rice, or Nakagami distributed random variable.

Since the mobile terminal may move at the velocity of a moving car or even of a fast train, the rate of channel fluctuations may be quite high and the power control has to react very quickly in order to compensate for it.

The performance of the **reverse link** of DS/CDMA systems is most affected by the near–far effect and, therefore, very sophisticated power control systems in the reverse link that attempt to alleviate the effects of channel fluctuations must be used. Together with other techniques, such as micro- and macrodiversity, interleaving and coding, interference cancellation, multiuser detection, and adaptive antennae, the DS/CDMA cellular system is able to cope with the wireless channel extremely well.

The effective use of the **power control** in DS/CDMA cellular system enables the frequency to be reused in every cell, which in turn enables features such as the soft hand-off and base station diversity. All together, these help enhance the capacity of the system.

In the **forward link** of a DS/CDMA system, power control may also be used. It may vary the transmitted power to the mobile, but the dynamic range is smaller due to the shared spectrum and, thus, shared interference.

We can distinguish between two kinds of power control, the open-loop power control and the closed-loop power control. The open-loop power control estimates the channel and adjusts the transmitted power accordingly but does not attempt to obtain feedback information on its effectiveness. Obviously, the open-loop power control is not very accurate, but since it does not have to wait for the feedback information it may be relatively fast. This can be advantageous in the case of a sudden channel fluctuation, such as a mobile driving from behind a big building or in case it should provide only the initial or rough transmitted power setting.

The principle operation of open-loop power control is shown in Fig. 25.1. The open-loop power control must base its action on the estimation of the channel state. In the reverse link it estimates the channel by measuring the received power level of the pilot from the base station in the forward link and sets the transmitted power level inversely proportional to it. Estimating the power of pilot is, in general, more reliable than estimating the power of the voice (or data) channel since the pilot is usually transmitted at higher power levels. Using the estimated value for setting the transmitted power ensures that the average power level received from the mobile at the base station remains constant irrespective of the channel variations. However, this approach assumes that the forward and the reverse link signal strengths are closely correlated. Although forward and reverse link may not share the same frequency and, therefore, the fading is significantly different, the long-term channel fluctuations due to shadowing and propagation loss are basically the same.

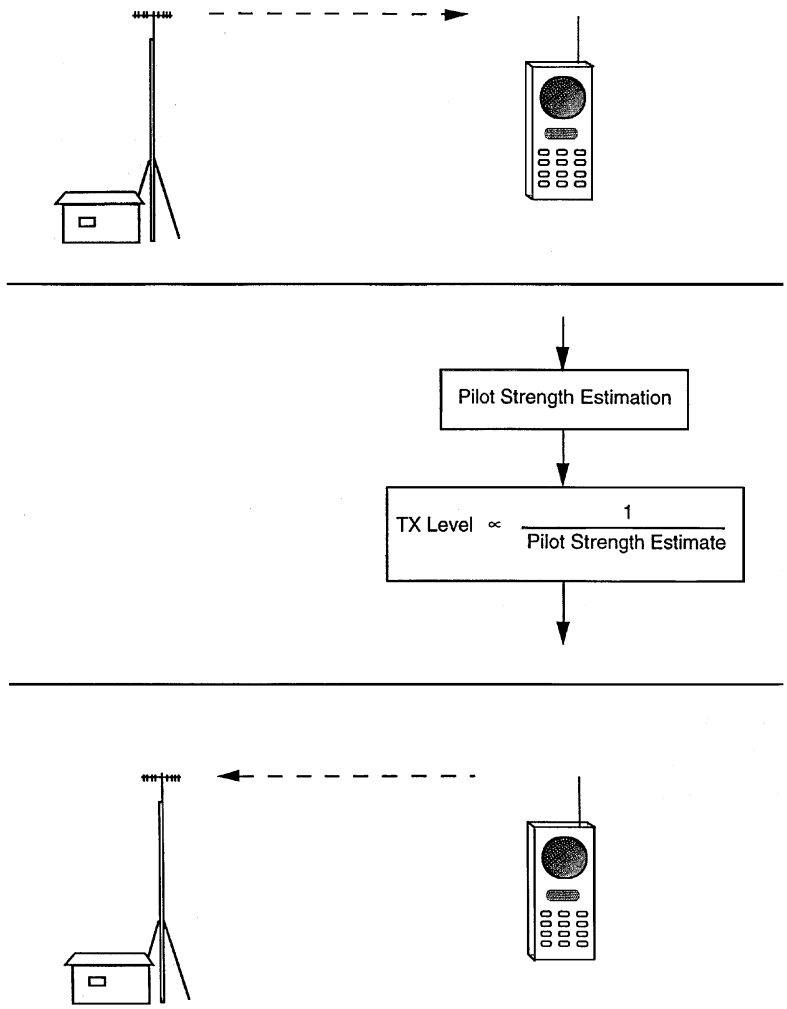

FIGURE 25.1: Reverse link open-loop power control.

The closed-loop power control system (Fig. 25.2a) may base its decision on an actual communication link performance metric, e.g., received signal power level, received signal-to-noise ratio, received bit-error rate, or received frame-error rate, or a combination of them. In the case of the reverse link power control, this metric may be forwarded to the mobile as a base for an autonomous power control decision, or the metric may be evaluated at the base station and only a power control adjustment command is transmitted to the mobile. If the reverse link power control decision is made at the base station, it may be based on the additional knowledge of the particular mobile's performance and/or a group of mobiles' performance (such as mobiles in a sector, cell, or even in a cluster of cells). If the power control decision for a particular mobile is made at the base station or at the switching office for all mobiles and is based on the knowledge of all other mobile's performance, it is called a centralized power control system. A centralized power control system may be more accurate than a distributed power control system, but it is much more complex in design, more costly, and technologically challenging.

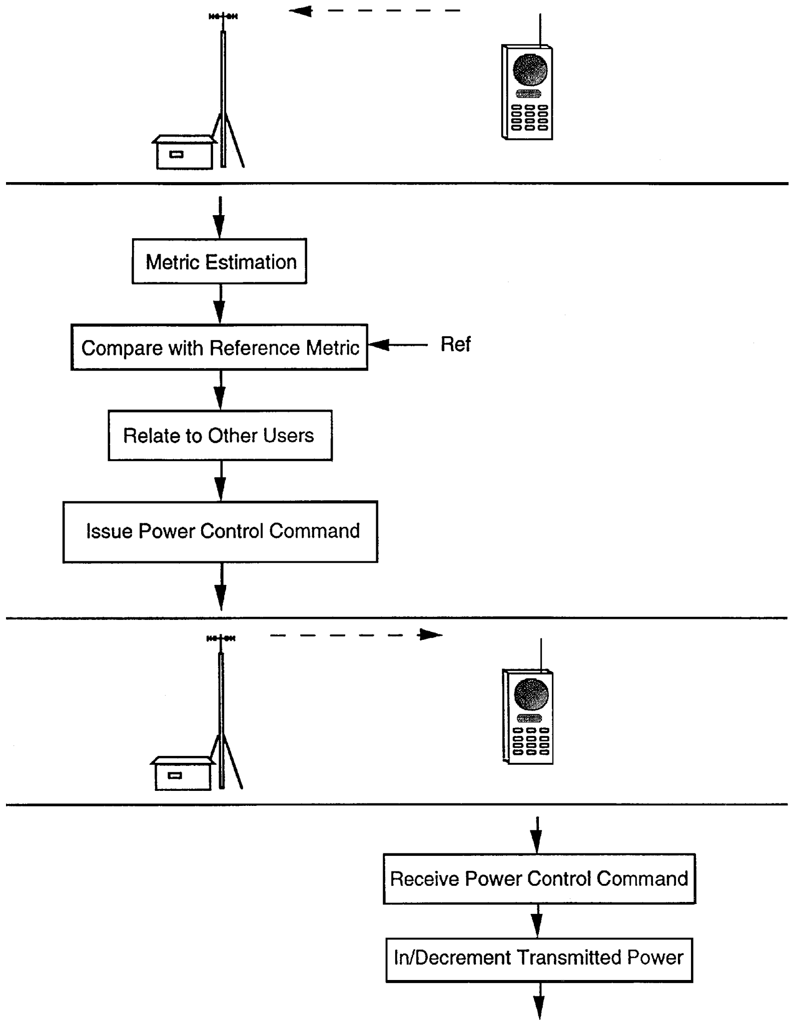

Figure 25.2a Reverse link closed-loop power control.

In principle, the same categorization may be used for the power control in the forward link (Fig. 25.2b) except that in the reverse link pilots from the mobiles are usually unavailable and only closed-loop power control is applied.

A special case for the design of power control are **TDD**-based systems [3]. In TDD systems, the forward and reverse link are highly correlated, and therefore a very good estimate of the channel gain in the forward link can be obtained from the estimate of the reverse link gain and vice versa. An open-loop power control then performs with the precision of a closed-loop power control but much

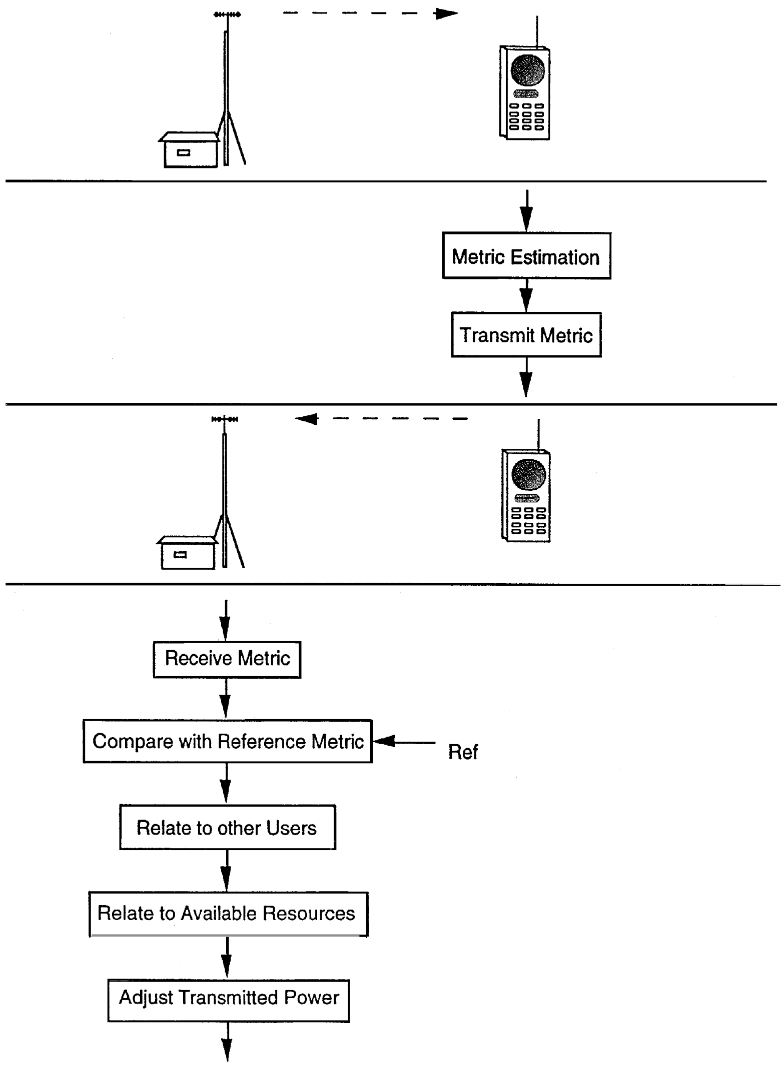

Figure 25.2b Forward link closed-loop power control.

faster since no feedback information has to be transmitted.

In the ideal case, power control compensates for the propagation loss, shadowing, and fast fading. However, there are many effects that prevent the power control from becoming ideal. Fast fading rate, finite delays of the power control system, nonideal channel estimation, error in the power control command transmission, limited dynamic range, etc., all contribute to degrading the performance of the power control system. It is very important to examine the performance of power control under nonideal conditions since the research done has shown that the power control system is quite sensitive to some of these conditions [11]. Kudoh [5] simulated a nonideal closed-loop power control system. Errors in the system were represented by a log-normal distributed control error with standard deviation σ_E (dB). Some results on capacity reduction are presented in Table 25.1.

The authors have also studied the effects of Doppler and delay and feedback errors in power control loop on power control [8].

TABLE 25.1 Capacity Reduction versus Power Control Error

	$\sigma_E = 0.5$ dB, %	$\sigma_E = 1$ dB, %	$\sigma_E = 2$ dB, %	$\sigma_E = 3$ dB, %
Forward link	10	29	64	83
Reverse link	10	31	61	81

Source: Kudoh, E., On the capacity of DS/CDMA cellular mobile radios under imperfect transmitter power control. *IEICE Trans. Commun.*, E76-B, 886–893, Apr. 1993.

25.3 Power Control Examples

In the following section, several applications of power control of analog and digital cellular systems are presented.

In the analog networks we may see power control implemented in both the reverse link and forward link [6]. Power control in the reverse link:

- reduces the chance of receiver saturation by a closely located mobile
- reduces the cochannel interference and thus increases the frequency-reuse factor and capacity, and
- reduces the average transmitted power at the mobile thus conserving battery energy at the mobile.

The power control in the forward link:

- reduces cochannel interference and thus increases the frequency reuse factor and capacity and
- reduces adjacent-channel interference and improves the quality of service.

One example of a power control system shown by Lee [7] was of an air-to-ground communication system. The relevant airspace is divided into six zones based on the aircraft altitude. The transmitted power at the aircraft is then varied in six steps based on the zone in which the aircraft is located. The power control system exhibits a total of approximately 28 dB of dynamic range. This reduces the cochannel interference and, due to the excellent propagation conditions in the free air, has a significant effect on the capacity of the system.

Another example of a power control system in an analog wireless network is in the analog part of the TIA standard IS-95 [10]. IS-95 standardizes a dual-mode FDMA/CDMA cellular system compatible with the present day AMPS analog FDMA cellular system.

The analog part of IS-95 divides the mobiles into three classes according to nominal **ERP** (effective radiated power with respect to half-wave dipole) at the mobile. For each class, the standard specifies eight power levels. Based on the propagation conditions, the mobile station may receive a power control command that specifies at what power level the mobile should transmit. The maximum change is 4 dB per step. (See Table 25.2).

IS-95 supports further discontinuous transmission. This feature allows the mobile to vary its transmitted power between two states: low and high. These two states must be at least 8 dB apart.

As for the power control in a digital wireless system, three examples will be shown: GSM [1], CT2/CT2PLUS standard [2] for digital cordless telephones of second generation, and the IS-95 standard for digital cellular DS/CDMA system [10].

GSM is a Pan-European digital cellular system that was introduced in many countries during the 1992–1993 period. GSM is a digital TDMA system with a frequency hopping feature. The power

TABLE 25.2 Nominal ERP of the Mobile

	Nominal ERP (dBW) of mobile		
Power level	I	II	III
0	6	2	−2
1	2	2	−2
2	−2	−2	−2
3	−6	−6	−6
4	−10	−10	−10
5	−14	−14	−14
6	−18	−18	−18
7	−22	−22	−22

Source: Telecommunications Industry Association/Electronic Industries Association. Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System, *TIA/EIA/IS-95 Interim Standard,* Jul. 1993.

control in GSM ensures that the mobile station uses only the minimum power level necessary for reliable communication with the base station. GSM defines eight classes of base stations and five classes of mobiles according to their power output, as shown in Table 25.3.

TABLE 25.3 GSM Transmitter Classes

Power Class	Base Station Power (W)	Mobile Station power (W)
1	320	20
2	160	8
3	80	5
4	40	2
5	20	0.8
6	10	
7	5	
8	2.5	

Source: Balston, D.M. and Macario, R.C.V., *Cellular Radio Systems*, Artech House, Norwood, MA, 1993.

The transmitted power at the base station is controlled, nominally in 2-dB steps. The adjustment of the transmitted power reduces the intercell interference and, thus, increases the frequency reuse factor and capacity. The transmitted power at the base station may be decremented to a minimum of 13 dBm.

The power control of the mobile station is a closed-loop system controlled from the base station. The power control at the mobile sets the transmitted power to one of 15 transmission power levels spaced by 2 dB. Any change can be made only in steps of 2 dB during each time slot. Another task for the power control in GSM is to control graceful ramp-on and ramp-off of the TDMA bursts since too steep slopes would cause spurious frequency emissions.

The dynamic range of the received signal at the base station may be up to 116 dB [1] and, thus, the near–far problem may also by experienced, especially if the problem occurs in adjacent time slots. In addition to power control, a careful assignment of adjacent slots can also alleviate the near–far effect.

The CT2PLUS standard [2] is a Canadian enhancement of the **ETSI** CT2 standard. Both these standards allow power control in the forward and in the reverse link. Due to the expected small cell radius and relatively slow signal level fluctuation rate, given by the fact that the user of the portable is a pedestrian, the power control specifications are relatively simple. The transmission at the portable can have two levels: *normal* (full) and *low*. The low–normal difference is up to 20 dB.

The IS-95 standard represents a second generation digital wireless cellular system using direct-sequence code division multiple access (DS/CDMA). Since in a DS/CDMA system all users have the same frequency allocation, the cochannel interference is crucial for the performance of the system [4]. The near–far effect may cause the received signal level to change up to 100 dB [12]. This considerable dynamic range is disastrous for a DS/CDMA where the channels are separated by a finite correlation between spreading sequences. This is further aggravated by the shadowing and the fading. The fading may have a relatively high rate since the mobile terminal is expected to move at the speed of a car. Therefore, the power control system must be very sophisticated. Power control is employed in both the reverse link and in the forward link.

The reverse link power control serves to do the following:

- Equalizes the received power level from all mobiles at the base station. This function is vital for system operation. The better the power control performs, the more it reduces the cochannel interference and, thus, increases the capacity. The power control compensates for the near–far effect, shadowing, and partially for slow fading.
- Minimizes the necessary transmission power level to achieve good quality of service. This reduces the cochannel interference, which increases the system capacity and alleviates health concerns. In addition, it saves the battery power. Viterbi [12] has shown up to 20–30 dB average power reduction compared to the AMPS mobile user as measured in field trials.

The forward link power control serves to:

- Equalize the system performance over the service area (good quality signal coverage of the worst-case areas),
- Provide load shedding between unequally loaded cells in the service areas (e.g., along a busy highway) by controlling the intercell interference to the heavy loaded cells, and
- Minimize the necessary transmission power level to achieve good quality of service. This reduces the cochannel interference in other cells, which increases the system capacity and alleviates health concerns in the area around the base station.

The reverse link power control system is composed of two subsystems: the closed-loop and the open-loop. The system operates as follows. Prior to the application to access, closed-loop power control is inactive. The mobile estimates the mean received power of the received pilot from the base station and the open-loop power control estimates the mean output power at the access channel [10]. The system then sets the closed-loop probing and estimates the mean output power,

$$\begin{aligned}\text{mean output power (dBm)} \quad = \quad & -\text{ mean input power (dBm)} \\ & - 73 \\ & + \text{ NOM\_PWR (dB)} \\ & + \text{ INIT\_PWR (dB)}\end{aligned} \tag{25.1}$$

where NOM_PWR and INIT_PWR are parameters obtained by the mobile prior to transmission. Subsequent probes are sent at increased power levels in steps until a response is obtained. The initial transmission on the reverse traffic channel is estimated as

$$\begin{aligned}\text{mean output power (dBm)} = & -\text{ mean input power (dBm)} \\ & -73 \\ & +\text{ NOM\_PWR (dB)} \\ & +\text{ INIT\_PWR (dB)} \\ & +\text{ the sum of all access probe} \\ & \quad\text{corrections (dB)}\end{aligned} \tag{25.2}$$

Once the first closed-loop power control bit is received the mean output power is estimated as

$$\begin{aligned}\text{mean output power (dBm)} = & -\text{ mean input power (dBm)} \\ & -73 \\ & +\text{ NOM\_PWR (dB)} \\ & +\text{ INIT\_PWR (dB)} \\ & +\text{ the sum of all access probe corrections (dB)} \\ & +\text{ the sum of all closed-loop power control} \\ & \quad\text{corrections (dB)}\end{aligned} \tag{25.3}$$

The ranges of the parameters NOM_PWR and INIT_PWR are shown in Table 25.4.

TABLE 25.4 NOM_PWR and INIT_PWR Parameters

	Nominal value, dB	Range, dB
NOM_PWR	0	–8–7
INIT_PWR	0	–16–15

Source: Telecommunications Industry Association/Electronic Industries Association. Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System. *TIA/EIA/IS-95 Interim Standard*, Jul. 1993.

The closed-loop power control command arrives at the mobile every 1.25 ms (i.e., 800 b/s). Therefore, the base station estimates the received power level for approximately 1.25 ms. A closed-loop power control command can have only two values: 0 to increase the power level and 1 to decrease the power level. The mobile must respond to the power control command by setting the required transmitted power level within 500 μs. The total range of the closed-loop power control system is $\pm$24 dB. The total supported range of power control (closed-loop and open-loop) must be at least $\pm$32 dB.

The behavior of the closed-loop power control system while the mobile receives base station diversity transmissions is straightforward. If all diversity transmitting base stations request the mobile to increase the transmitted power (all power control commands are 0), the mobile increases the power level. If at least one base station requests the mobile to decrease its power, the mobile decreases its power level.

The system also offers a feature of gated transmitted power for variable rate transmission mode. The gate-off state reduces the output power by at least 20 dB within 6 μs. This reduces the interference to the other users at the expense of transmitted bit rate. This feature may be used together with variable rate voice encoder or voice activated keying of the transmission.

The forward link power control works as follows. The mobile monitors the errors in the frames arriving from the base station. It reports the frame-error rate to the base station periodically. (Another mode of operation may report the error rate only if the error rate exceeds a preset threshold.) The base station evaluates the received frame-error rate reports and slightly adjusts its transmitting power. In this way, the base station may equalize the performance of the forward links in the cell or sector.

A system conforming with the standard has been field tested, and the results show that the power control is able to combat the channel fluctuation (together with other techniques such as RAKE reception) and achieve the bit energy to interference power density (E_b/I_0) necessary for a reliable service [12].

Power control together with soft handoff determines the feasibility of the DS/CDMA cellular system and is crucial to its performance. QUALCOMM, Inc. has shown on field trials that their system conforms with the theoretical predictions and surpasses the capacity of other currently proposed cellular systems [12].

25.4 Summary

We have shown the basic principles of power control in wireless cellular networks and have presented some examples of power control systems employed in some networks.

In a wireless channel the channel transmission or channel gain is a random variable. If all transmitters in the system transmitted at equal and constant power levels, the received powers would be random.

In the reverse link (mobile to base station) each user has its own wireless channel, generally uncorrelated with all other users. The received signals at the base station are independent and random. Furthermore, since the users are randomly distributed over the cell, the distance between the mobiles and the base station may vary and so does the propagation loss. The differences between the strongest and the weakest received signal level may approach the order of 100 dB. This power level difference may cause saturation of the receivers at the base station even if they are allocated a different frequency or time slot. This phenomenon is called the near–far effect.

The near–far effect is especially detrimental for a DS/CDMA system where the frequency band is shared by all users and, for any given user, all other users' transmissions form the cochannel interference. Therefore, for the DS/CDMA system it is vitally important to efficiently mitigate the near–far effect.

The most natural way to mitigate the near–far effect is to power control the transmission in such a way that the transmitted power counterfollows the channel fluctuations and compensates for them. Then the received signal at the base station arrives at a constant amplitude.

The use of power control is not limited to the reverse link, but is also employed in the forward link. The controlled transmission maintaining the transmitted level at the minimum acceptable level reduces the cochannel interference, which translates into an increased capacity of the system.

Since the DS/CDMA systems are most vulnerable to the near–far effect they have a very sophisticated power control system. In giving examples, we have concentrated on the DS/CDMA cellular system. We have also shown the power control used in other systems such as GSM, AMPS, and CT2.

Although there are more techniques available for mitigation of the near–far effect, power control is the most efficacious. As such, power control forms the core in the effort in combatting the near–far effect and channel fluctuations in general [12].

Defining Terms

AMPS: Advanced Mobile Phone Service. Analog cellular system in North America.

CT2: Cordless Telephone, Second Generation. A digital FDMA/TDD system.

DS/CDMA: Direct Sequence Code Division Multiple Access.

DOC: Department of Communications.

ERP: Effective Radiated Power.

ETSI: European Telecommunications Standard Institute.

Fading: Fast varying fluctuations of the wireless channel mainly due to the interference of time-delayed multipaths.

FDMA: Frequency Division Multiple Access.

Forward link: Link from the base (fixed) station to the mobile (user, portable).

GSM: Groupe Spéciale Mobile, recently referred to as the **Global System for Mobility**. An ETSI standard for digital cellular and microcellular systems.

NMT: Nordic Mobile Telephone. A cellular telephony standard used mainly in Northern Europe.

Power control: Control system for controlling the transmission power. Used to reduce the cochannel interference and mitigate the near–far effect in the reverse link.

Reverse link: Link from the mobile (user, portable) to the base (fixed) station.

Shadowing: Slowly varying fluctuations of the wireless channel due mainly to the shades in propagation of electromagnetic waves. Often described by log-normal probability density function.

TACS: Total Access Communication System. An analogue cellular system used mainly in UK.

TDD: Time Division Duplex.

TDMA: Time Division Multiple Access.

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[12] Viterbi, A.J., The orthogonal-random waveform dichotomy for digital mobile personal communication. *IEEE Personal Comm.*, 1(1st qtr.), 18–24, 1994.

Further Information

For general information see the following overview books:

[1] Balston, D.M. and Macario, R.C.V., *Cellular Radio Systems*, Artech House, Norwood, MA, 1993.
[2] Simon, M.K., Omura, J.K., Scholtz, R.A., and Levitt, B.K., *Spread Spectrum Communication Handbook*, McGraw-Hill, New York, 1994.

For more details on power control in DS/CDMA systems consult the following:

[3] Gilhousen, K.S., Jacobs, I.S., Padovani, R., Viterbi, A.J., Weaver, L.A., and Wheatley C.E., III., On the capacity of cellular CDMA system. *IEEE Trans. Veh. Tech.*, 40, 303–312, May 1991.
or:
[4] Viterbi, A.J. and Zehavi, E., Performance of power-controlled wideband terrestrial digital communication. *IEEE Trans. Comm.*, 41, 559–569, Apr. 1993.

Readers deeply interested in power control are recommended the *IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology,* and relevant issues of *IEEE Journal on Selected Areas in Communications.*