CHAPTER 10

Soft Handoff and Power Control in IS-95 CDMA

10.1 Introduction

Soft handoff is different from the traditional hard-handoff process. With hard handoff, a definite decision is made on whether to hand off or not. The handoff is initiated and executed without the user attempting to have simultaneous traffic channel communications with the two base stations. With soft handoff, a *conditional* decision is made on whether to hand off. Depending on the changes in pilot signal strength from the two or more base stations involved, a hard decision will eventually be made to communicate with only one. This normally happens after it is evident that the signal from one base station is considerably stronger than those from the others. In the interim period, the user has simultaneous traffic channel communication with all candidate base stations.

It is desirable to implement soft handoff in power-controlled CDMA systems because implementing hard handoff is potentially difficult in such systems. A system with power control attempts to dynamically adjust transmitter power while in operation. Power control is closely related to soft handoff. IS-95 uses both power control and soft handoff as an interference-reduction mechanism. Power control is the main tool used in IS-95 to combat the near-far problem. It is theoretically unnecessary to have power control if one can successfully implement a more intelligent receiver than that used in IS-95, which is the subject of the field of multiuser detection (MUD), a feature being proposed for the 3G CDMA systems. Power control is necessary in order for a CDMA system to achieve a reasonable level of performance in practice. The use of power control in the CDMA system necessitates the use of soft handoff when the original and new channels occupy the same frequency band. For power control to work properly, the mobile must attempt to be linked at all times to the base station from which it receives the strongest signal. If this does not happen, a positive power control feedback loop could inadvertently occur, causing system problems. Soft handoff can guarantee that the mobile is indeed linked at all times to the base station from which it receives the strongest signal, whereas hard handoff cannot guarantee this.

The performance of CDMA systems is very sensitive to differences in received signal powers from various users on the reverse link. Due to the nonorthogonality of the spreading PN codes used by different users, a strong interfering signal may mask out a weak desired signal, causing unreliable detection of the latter. This is called the *near-far problem.*

This chapter first covers handoff strategy used in IS-95 CDMA and then focuses on power control schemes for the reverse and forward link.

10.2 Types of Handoff

There are four types of handoff:

1. **Intersector or softer handoff.** The mobile communicates with two sectors of the same cell (see Fig. 10-1). A RAKE receiver at the base station combines the best versions of the voice frame from the diversity antennas of the two sectors into a single traffic frame.
2. **Intercell or soft handoff.** The mobile communicates with two or three sectors of different cells (see Fig. 10-2). The base station that has the direct control of call processing

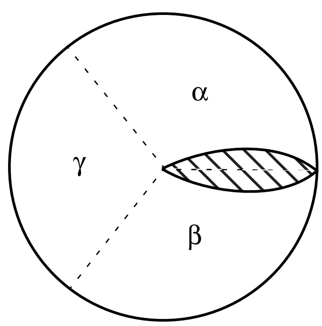
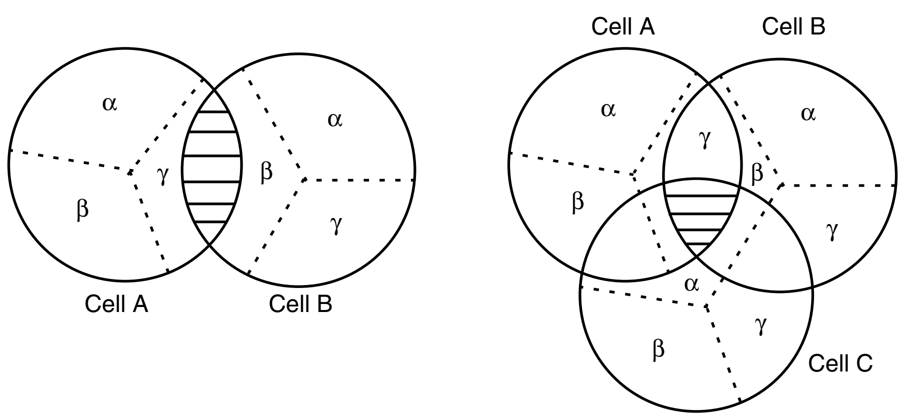


Figure 10-1 Softer Handoff



Two-Way Soft Handoff Three-Way Soft Handoff

Figure 10-2 Soft Handoff

during handoff is referred to as the *primary base station*. The primary base station can initiate the forward control message. Other base stations that do not have control over call processing are called the *secondary base stations*. Soft handoff ends when either the primary or secondary base station is dropped. If the primary base station is dropped, the secondary base station becomes the new primary for this call. A three-way soft handoff may end by first dropping one of the base stations and becoming a two-way soft handoff.

The base stations involved coordinate handoff by exchanging information via SS7 links. A soft handoff uses considerably more network resources than the softer handoff.

3. **Soft-softer handoff.** The mobile communicates with two sectors of one cell and one sector of another cell (see Fig. 10-3). Network resources required for this type of handoff include the resources for a two-way soft handoff between cell A and B plus the resources for a softer handoff at cell B.
4. **Hard handoff.** Hard handoffs are characterized by the *break-before-make* strategy. The connection with the old traffic channel is broken before the connection with the new traffic channel is established. Scenarios for hard handoff include

   - Handoff between base stations or sectors with different CDMA carriers
   - Change from one pilot to another pilot without first being in soft handoff with the new pilot (disjoint active sets)
   - Handoff from CDMA to analog, and analog to CDMA
   - Change of frame offset assignment—CDMA traffic frames are 20 ms long. The start of frames in a particular traffic channel can be at 0 time in reference to a system or it can be offset by up to 20 ms (allowed in IS-95). This is known as the *frame offset*. CDMA traffic channels are assigned different frame offset to avoid congestion. The frame offset for a particular traffic channel is communicated to the mobile. Both forward and reverse links use this offset. A change in offset

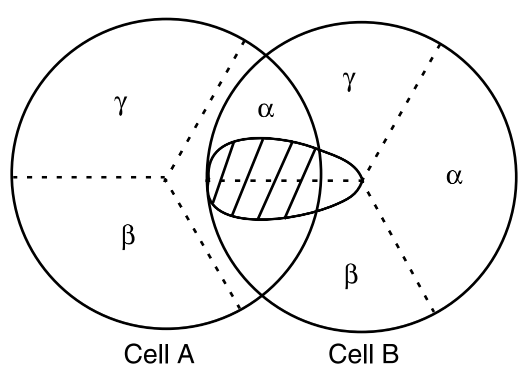


Figure 10-3 Soft-Softer Handoff

assignment will disrupt the link. During soft handoff the new base station must allocate the same frame offset to the mobile as assigned by the primary base station. If that particular frame offset is not available, a hard handoff may be required. Frame offset is a network resource and can be used up.

10.2.1 Soft Handoff (Forward Link)

In this case all traffic channels assigned to the mobile are associated with pilots in the active set and carry the same traffic information with the exception of power control subchannel. When the active set contains more than one pilot, the mobile provides diversity by combining its associated forward traffic channels.

10.2.2 Soft Handoff (Reverse Link)

During intercell handoff, the mobile sends the same information to both base stations. Each base station receives the signal from the mobile with appropriate propagation delay. Each base station then transmits the received signal to the vocoder/selector. In other words, two copies of the same frame are sent to the vocoder/selector. The vocoder/selector selects the better frame and discards the other.

10.2.3 Softer Handoff (Reverse Link)

During intersector handoff, the mobile sends the same information to both sectors. The channel card/element at the cell site receives the signals from both sectors. The channel card combines both inputs, and only one frame is sent to the vocoder/selector. It should be noted that extra channel cards are not required to support softer handoff as is the case for soft handoffs. The diversity gain from soft handoffs is more than the diversity gain from softer handoffs because signals from distinct cells are less correlated than signals from sectors of the same cell.

10.2.4 Benefit of Soft Handoff

A key benefit of soft handoff is the path diversity on the forward and reverse traffic channels. Diversity gain is obtained because less power is required on the forward and reverse links. This implies that total system interference is reduced. As a result, the average system capacity is improved. Also less transmit power from the mobile results in longer battery life and longer talk time.

In a soft handoff, if a mobile receives an *up* power control bit from one base station and a *down* control bit from the second base station, the mobile decreases its transmit power. The mobile obeys the *power down* command since a good communications link must have existed to warrant the command from the second base station.

10.3 Pilot Sets

The term *pilot* refers to a pilot channel identified by a pilot sequence offset and a frequency assignment. A pilot is associated with the forward traffic channels in the same forward CDMA link.

Each pilot is assigned a different offset of the same short PN code. The mobile search for pilots is facilitated by the fact that the offsets are the integer multiples of a known time delay (64 chips offset between adjacent pilots). All pilots in a pilot set have the same CDMA frequency assignment. The pilots identified by the mobile, as well as other pilots specified by the serving sectors (neighbors of the serving base stations/sectors), are continuously categorized by the mobile into four groups.

- **Active set.** It contains the pilots associated with the forward traffic channels (Walsh codes) assigned to the mobile. Because there are three fingers of the RAKE receiver in the mobile, the active set size is a maximum of three pilots. IS-95 allows up to six pilots in the active set, with two pilots sharing one RAKE finger.The base station informs the mobile about the contents of the active set by using the Channel Assignment message and/or the Handoff Direction message (HDM). An active pilot is a pilot whose paging or traffic channels are actually being monitored or used.
- **Candidate set.** This set contains the pilots that are not currently in the active set. However, these pilots have been received with sufficient signal strength to indicate that the associated forward traffic channels could be successfully demodulated. Maximum size of the candidate set is six pilots.
- **Neighbor set.** This set contains neighbor pilots that are not currently in the active or the candidate set and are likely candidates for handoff. Neighbors of a pilot are all the sectors/cells that are in its close vicinity. The initial neighbor list is sent to the mobile in the System Parameter message on the paging channel. The maximum size of the neighbor set is 20.
- **Remaining set.** This set contains all possible pilots in the current system, excluding pilots in the active, candidate, or neighbor sets.

While searching for a pilot, the mobile is not limited to the exact offset of the short PN code. The short PN offsets associated with various multipath components are located a few chips away from the direct path offset. In other words, the multipath components arrive a few chips later relative to the direct path component. The mobile uses the *search window* for each pilot of the active and candidate set, around the earliest arriving multipath component of the pilot. Search window sizes are defined in number of short PN chips. The mobile should center the search window for each pilot of the neighbor set and the remaining set around the pilot's PN offset using the mobile time reference.

10.4 Search Windows

The mobile uses the following three search windows to track the received pilot signals:

- SRCH_WIN_A: search window size for the active and candidate sets
- SRCH_WIN_N: search window size for the neighbor set
- SRCH_WIN_R: search window size for the remaining set

10.4.1 SRCH_WIN_A

SRCH_WIN_A is the search window that the mobile uses to track the active and candidate set pilots. This window is set according to the anticipated propagation environment—it should be large enough to capture all usable multipath signal components of a base station, and at the same time it should be as small as possible in order to maximize searcher performance.

EXAMPLE 10.1

Consider the propagation environment of a CDMA network, where the signal with a direct path travels 1 kilometer (km) to the mobile, whereas the multipath travels 5 km before reaching the mobile. What should be the size of SRCH_WIN_A?

$$\text{Direct path travels a distance of } \frac{1000}{244} = 4.1 \text{ chips}$$

$$\text{Multipath travels a distance of } \frac{5000}{244} = 20.5 \text{ chips}$$

The difference in distance traveled between the two paths = 20.5 – 4.1 = 16.4 chips
The window size ≥ 2 × 16.4 = 32.8 chips
Use window size = 33 chips

EXAMPLE 10.2

Consider cells A and B separated by a distance of 12 km. The mobile travels from cell A to cell B. The RF engineer wishes to contain the soft handoff area between points X and Y located at distance 6 and 10 km from cell A (see Fig. 10-4). What should be the search window size?

At point X the mobile is 6000/244 = 24.6 chips from cell A

At point X the mobile is 10,000/244 = 41.0 chips from cell B

Path difference = 41.0 – 24.6 = 16.4 chips

At point Y the mobile is 10,000/244 = 41.0 chips from cell A

At point Y the mobile is 6000/244 = 24.6 chips from cell B

Path difference = 41.0 – 26.4 = 16.4 chips

The SRCH_WIN_A > 2 × 16.4 > 32.8 chips

This way, as the mobile travels from cell A to cell B, the mobile can ensure that, beyond Y, the pilot from cell A drops out of the search window.

10.4.2 SRCH_WIN_N

SRCH_WIN_N is the search window that the mobile uses to monitor the neighbor set pilots. The size of this window is typically larger than that of SRCH_WIN_A. The window needs to be large enough not only to capture all usable multipath of the serving base station's signal, but also to capture the potential multipath of neighbors' signals. In this case, we need to take into account multipath and path differences between the serving base station and neighbor-

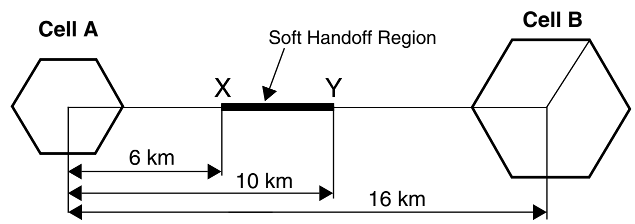


Figure 10-4 SRCH_WIN_A for Soft Handoff between X and Y

ing base stations. The maximum size of this search window is limited by the distance between two neighboring base stations. Let's consider two neighboring base stations located at a distance of 6 km. The mobile is located right next to base station 1, and, therefore, the propagation delay from base station 1 to the mobile is negligible. The distance between base station 2 and mobile is 6 km. The distance in chips is 6000/244 = 24.6 chips. The search window shows that the pilot from cell 2 arrives 24.6 chips later at the mobile. Thus, in order for a mobile (located within cells 1 and 2) to search pilots of potential neighbors, SRCH_WIN_N needs to be set according to the physical distances between the current base station and its neighboring base station. The actual size may not be this large, since this is an upper bound for SRCH_WIN_N.

10.4.3 SRCH_WIN_R

SRCH_WIN_R is the search window that the mobile uses to track the remaining set pilots. A typical requirement for the size of this window is that it is at least as large as SRCH_WIN_N.

10.5 Handoff Parameters

There are four handoff parameters. T_ADD, T_COMP, and T_DROP relate to the measurement of pilot E_c/I_t and T_TDROP is a timer. Whenever the strength of a pilot in the active set falls below a value of T_DROP, a timer is started by the mobile. If the pilot strength goes back above T_DROP, the timer is reset; otherwise the timer expires when a time T_TDROP has elapsed since the pilot strength has fallen below T_DROP. Mobile maintains a handoff drop timer for each pilot in the active set and in the candidate set.

10.5.1 Pilot Detection Threshold (T_ADD)

Any pilot that is strong but is not in the HDM is a source of interference. This pilot must be immediately moved to the active set for handoff to avoid voice degradation or a possible dropped call. T_ADD affects the percentage of mobiles in handoff. It should be low enough to quickly add useful pilots and high enough to avoid false alarms due to noise.

10.5.2 Comparison Threshold (T_COMP)

It has effect on handoff percentage similar to T_ADD. It should be low for faster handoff and should be high to avoid false alarms.

10.5.3 Pilot Drop Threshold (T_DROP)

It affects the percentage of mobiles in handoff. It should be low enough to avoid dropping a good pilot that goes into a short fade. It should be high enough not to quickly remove useful pilots in the active or candidate set. The value of T_DROP should be carefully selected by considering the values of T_ADD and T_TDROP.

10.5.4 Drop Timer Threshold (T_TDROP)

It should be greater than the time required to establish handoff. T_TDROP should be small enough not to quickly remove useful pilots. A large value of T_TDROP may be used to force a mobile to continue in soft handoff in a weak coverage area.

Table 10-1 provides typical values of the handoff parameters.

10.6 Handoff Messages

Handoff messages in IS-95 are Pilot Strength Measurement message (PSMM), Handoff Direction message (HDM), Handoff Completion message (HCM), and Neighbor List Update message (NLUM).

The mobile detects pilot strength (E_c/I_t) and sends the PSMM to the base station. The base station allocates the forward traffic channel and sends the HDM to the mobile. On receiving the HDM, the mobile starts demodulation of the new traffic channel and sends HCM to the base station.

The PSMM contains the following information for each of the pilot signals received by the mobile:

- Estimated E_c/I_t
- Arrival time
- Handoff drop timer

The HDM contains the following information:

- HDM sequence number
- CDMA channel frequency assignment
- Active set (now has old and new pilots [PN offsets])
- Walsh code associated with each pilot in the active set

Table 10-1 Handoff Parameter Values

Parameter	Range	Suggested Value
T_ADD	–31.5 to 0 dB	–13 dB
T_COMP	0 to 7.5 dB	2.5 dB
T_DROP	–31.5 to 0 dB	–15 dB
T_TDROP	0 to 15 seconds	2 seconds

- Window size for the active and candidate sets
- Handoff parameters (T_ADD, T_DROP, T_COMP, T_TDROP)

The HCM contains the following information:

- A positive acknowledgment
- PN offset of each pilot in the active set

The NLUM is sent by the base station. It contains the latest composite neighbor list for the pilots in the active set.

The mobile continuously tracks the signal strength for all pilots in the system. The signal strength of each pilot is compared with the various thresholds such as the pilot detection threshold, the pilot drop threshold, the comparison threshold, and the drop timer threshold.

A pilot is moved from one set to another depending on its signal strength relative to the thresholds. Fig. 10-5 shows a sequence on the threshold.

1. Pilot strength exceeds T_ADD. Mobile sends a PSMM and transfers pilot to the candidate set.
2. Base station sends an HDM to the mobile with the pilot to be added in active set.
3. Mobile receives HDM and acquires the new traffic channel. Pilot goes into the active set and mobile sends HCM to the base station.
4. Pilot strength drops below T_DROP; mobile starts the handoff drop timer.

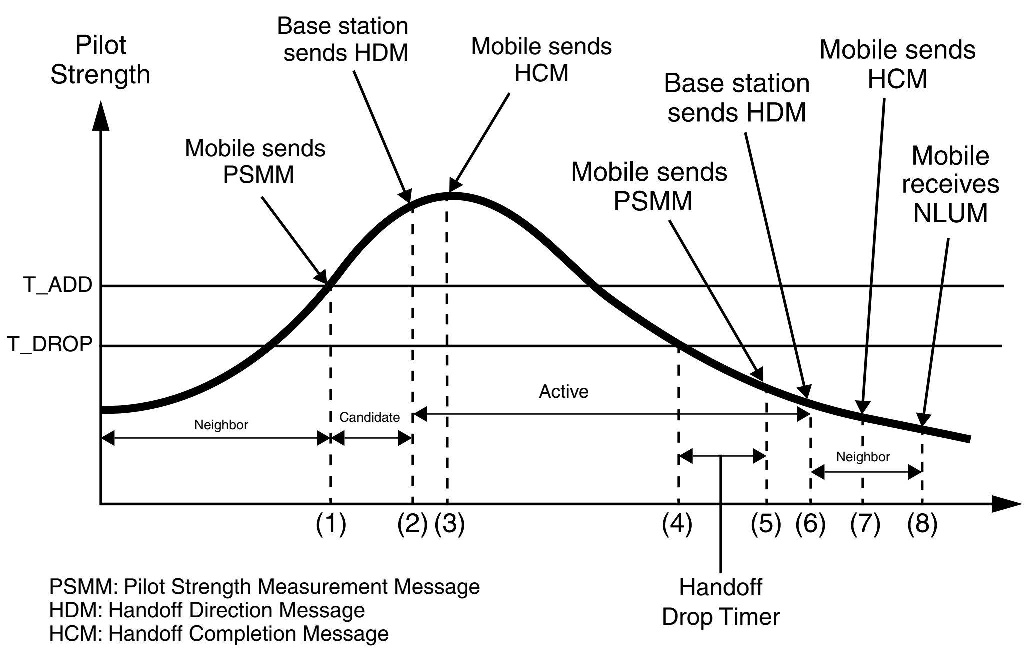


Figure 10-5 Handoff Threshold Example: Pilot Thresholds

5. Handoff drop timer expires. Mobile sends a PSMM to the base station.
6. Base station sends an HDM without related pilot to the mobile.
7. Mobile receives HDM. Pilot goes into the neighbor set and mobile sends HCM to the base station.
8. The mobile receives an NLUM which does not include the pilot. Pilot goes into the remaining set.

The mobile maintains a T_TDROP for each pilot in the active set and candidate set. The mobile starts the timer whenever the strength of the corresponding pilot becomes less than a preset threshold. The mobile resets and disables the timer if the strength of the corresponding pilot exceeds the threshold.

When a member of the neighbor or remaining set exceeds T_ADD, the mobile moves the pilot to candidate set (Fig. 10-6) and sends a PSMM to the base station. As the signal strength of candidate pilot P_c gradually increases, it rises above the active set pilot, P_a. A PSMM is sent to the base station only if

$$P_c - P_a > \text{T\_COMP x 0.5 dB}$$

where P_a and P_c are the strength of pilots in active and candidate sets.

10.7 Handoff Procedures

10.7.1 Mobile-Assisted Soft-Handoff (MASHO) Procedures

The mobile monitors the Forward Pilot Channel (FPICH) level received from neighboring base stations and reports to the network those FPICHs that cross a given set of thresholds. Two types of thresholds are used: the first to report FPICHs with sufficient power to be used for coher-

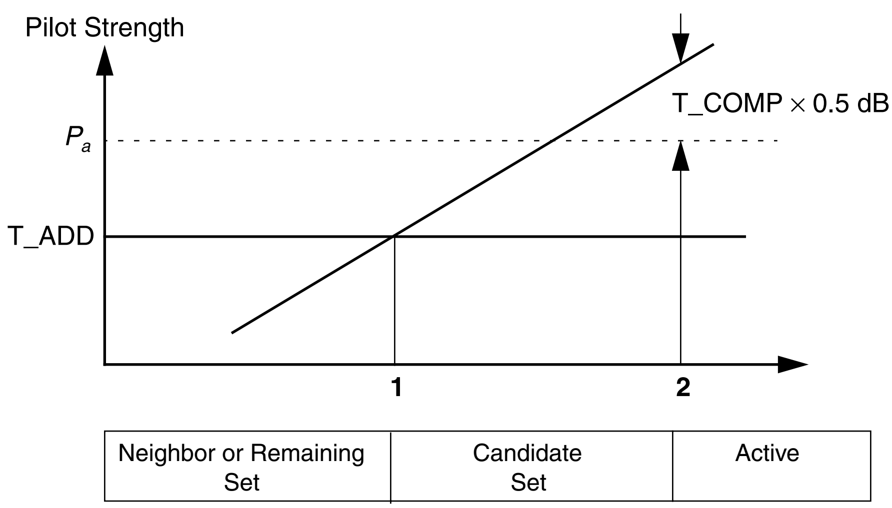


Figure 10-6 Pilot Movement from Neighbor or Remaining Set to Active Set

ent demodulation, and second to report those FPICHs whose power has dropped to a level where it is not beneficial to use them for coherent demodulation. The margin between the two thresholds provides a hysteresis to avoid a ping-pong effect due to variations in FPICH power. Based on this information, the network instructs the mobile to add or remove FPICHs from its active set.

The same user information, modulated by the appropriate base station code, is sent from multiple base stations. Coherent combining of different signals from different sectorized antennas, from different base stations, or from the same antennas but on different multiple path components is performed in the mobile using RAKE receivers. A mobile will typically place at least one RAKE receiver finger on the signal from each base station in the active set. If the signal from the base station is temporarily weak, then the mobile can assign the finger to a stronger base station.

The signal transmitted by a mobile is processed by base stations with which the mobile is in soft handoff. The received signal from different sectors of a base station is combined in the base station on a symbol-by-symbol basis. The received signal from different base stations can be selected in the infrastructure (on a frame-by-frame basis). Soft handoff results in increased coverage range and capacity on the reverse link.

10.7.2 Dynamic Soft-Handoff Thresholds

While soft handoff improves overall system performance, it may in some situations negatively impact system capacity and network resources. On the forward link, excessive handoff reduces system capacity whereas, on the reverse link, it costs more network resources (backhaul connections).

Adjusting the handoff parameters at the base stations will not necessarily solve the problem. Some locations in the cell receive only weak FPICHs (requiring lower handoff thresholds), and other locations receive a few strong and dominant FPICHs (requiring higher handoff thresholds). The principle of dynamic threshold for adding FPICHs is as follows:

- The mobile detects FPICHs that cross a given static threshold, T_1. The metric for the FPICH in this case is the ratio of FPICH energy per chip to total received power (E_c/I_t).
- On crossing the static threshold, the FPICH is moved to a candidate set. It is then searched more often and tested against a second dynamic threshold, T_2.
- Comparison with T_2 determines if the FPICH is worth adding to the active set. T_2 is a function of the total energy of FPICHs demodulated coherently (in the active set).
- The condition of an FPICH for crossing T_2 is expressed as

$$10\log(P_{cj}) \geq \mathrm{Max}\left\{\text{SOFT-SLOPE} \cdot 10\log\left(\sum_{i=1}^{N_A} P_{ai}\right) + \text{ADD-INTERCEPT}, T_1\right\} \tag{10.1}$$

where P_{cj} = strength of the jth FPICH in the coordinate set,
P_{ai} = strength of the ith FPICH in the active set,
N_A = number of FPICHs in the active set, and
SOFT-SLOPE and ADD-INTERCEPT = adjustable system parameters.

When FPICHs in the active set are weak, adding an additional FPICH (even weak) will improve performance. However, when there is one or more dominant FPICHs, adding an additional weaker FPICH above T_1 will not improve performance, but will use more network resources. The dynamic soft-handoff thresholds reduce and optimize the network resource utilization.

- After detecting an FPICH above T_2, the mobile reports it back to the network. The network then sets up the handoff resources and orders the mobile to coherently demodulate this additional FPICH. Pilot 2 is added to active set.
- When the FPICH (pilot 1) strength decreases below a dynamic threshold T_3, the handoff connection is removed. The FPICH is moved back to the candidate set. The threshold T_3 is a function of the total energy of FPICHs in the active set. FPICHs not contributing sufficiently to total FPICH energy are dropped. If it decreases below a static threshold T_4, an FPICH is removed from the candidate set.
- An FPICH dropping below a threshold (e.g., T_3 and T_4) is reported back to the network only after being below the threshold for a specific period of time. This timer allows for a fluctuating FPICH not to be prematurely reported.

Fig. 10-7 shows a time representation of soft handoff and associated events when the mobile station moves away from a serving base station (FPICH 1) toward a new base station (FPICH 2). The combination of static and dynamic thresholds (vs. static thresholds only) results in reduced soft-handoff regions (see Fig. 10-7). The major benefit of this is to limit soft handoff to areas and times when it is most beneficial.

1. When pilot 2 exceeds T_1, mobile moves it to the candidate set.
2. When pilot 2 exceeds T_2 (dynamic), mobile reports it back to the network.
3. Mobile receives an order to add pilot 2 to the active set.
4. Pilot 1 drops below T_3 (relative pilot 2).
5. Handoff timer expires on pilot 1. Mobile reports pilot strength to the network.
6. Mobile receives an order to remove pilot 1.
7. Handoff timer expires after pilot 1 drops below T_4.

10.8 Setup and End of Soft Handoff

10.8.1 Setup

One of the major benefits of a CDMA system is the ability of a mobile to communicate with more than one base station at one time during a call. This functionality allows the CDMA network to perform soft handoff. In soft handoff a controlling primary base station coordinates with other base stations as they are added or deleted for the call. This allows the base stations (up to three, total) to receive/transmit voice packets with a single mobile for a single call.

Each base station transmits the received mobile voice packets to the BSC/MSC. The BSC/MSC selects the best voice frame from one of the three base stations. This provides the PSTN party with the best-quality voice.

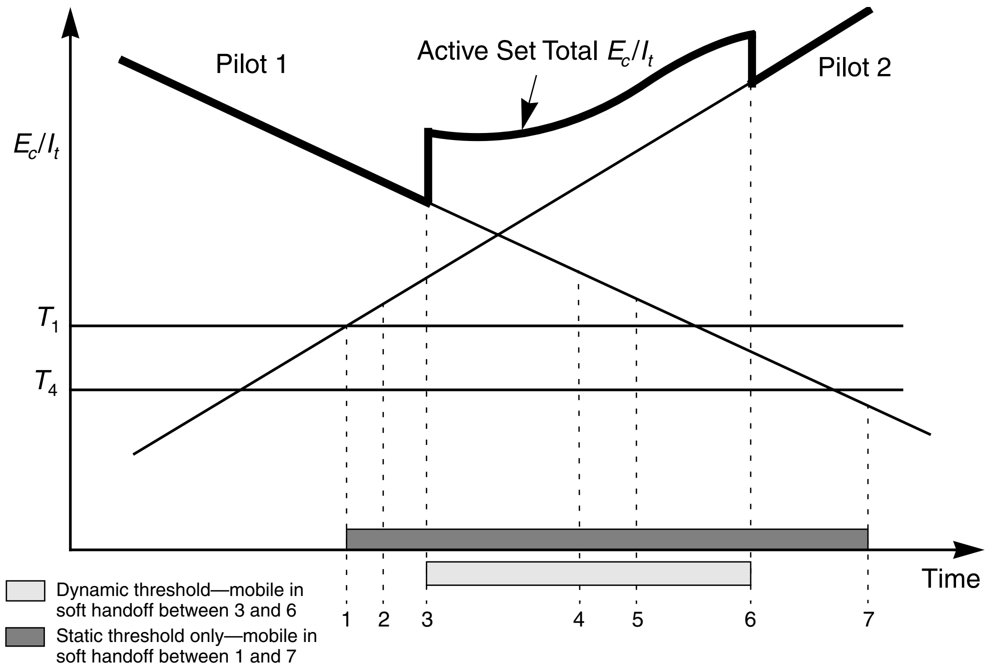


Figure 10-7 Dynamic Thresholds Handoff Procedure

Fig. 10-8 shows a mobile communicating with two base stations for one call. This is called a *two-way soft handoff*. Steps of soft handoff are

- The mobile detects a pilot signal from a new cell and informs primary base station A.
- A communications path from base station B to the original frame selector is established.
- The frame selector selects frames from both streams.
- The mobile detects that base station A's pilot is failing and requests that this path be dropped.
- The path from original base station A to the frame selector is dropped.

Base station B gives base station A its assigned Walsh code. Base station A gives the mobile the Walsh code of B as part of the HDM. Now the mobile can listen to base station B.

Base station A gives the user's long-code mask to base station B. Now B can listen to the mobile. Both base stations A and B receive forward link power control information back from the mobile and act accordingly. The mobile receives independent puncture bits from both A and B. If directions conflict, the mobile decreases power; otherwise the mobile obeys directions.

10.8.2 End of Soft Handoff

Fig. 10-9 shows the process used by a mobile communicating with two base stations A and B to end handoff when the signal from base station A is not strong enough. When the mobile

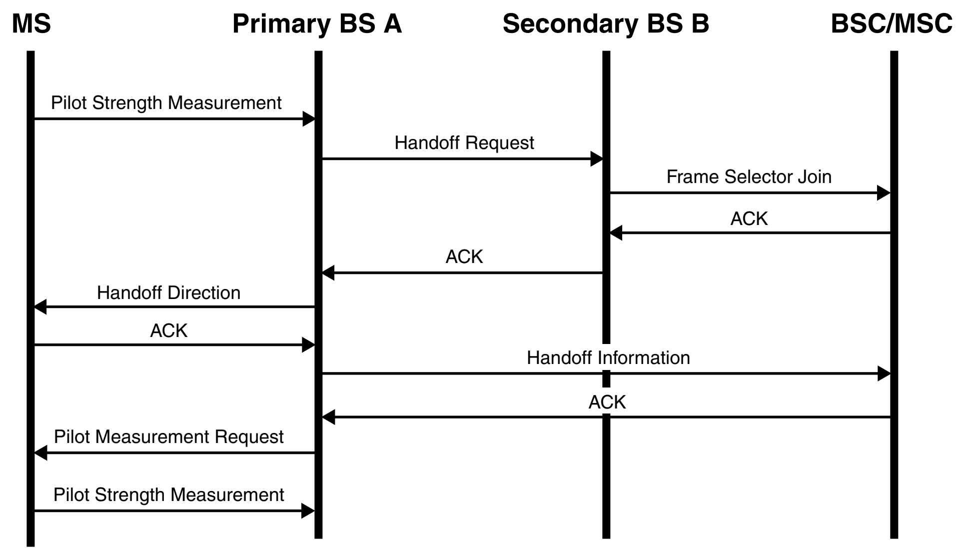


Figure 10-8 Soft Handoff Setup

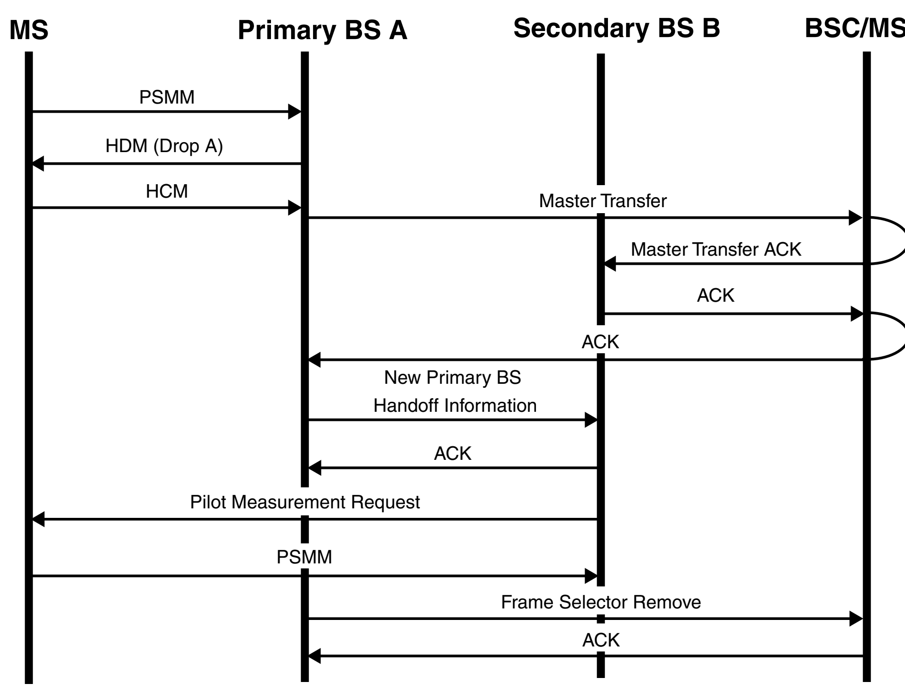


Figure 10-9 End of Soft Handoff

entered into soft handoff with base stations A and B, the primary base station was A. However, when the mobile drops A and starts communicating with base station B alone, B becomes the new primary base station.

10.9 Maintenance of Pilot Sets

10.9.1 Active Set Maintenance

The active set is initialized to contain only one pilot (e.g., the pilot associated with the assigned forward traffic channel). This occurs when the mobile is first assigned a forward traffic channel. As the mobile processes HDMs, it updates the active set with the pilots listed in the HDMs.

A pilot P_c from the candidate is added to the active set when P_c exceeds a member of the active set by T_COMP. A pilot P_a from the active set is removed when P_a has dropped below T_DROP and the drop timer (T_TDROP) has expired (see Fig. 10-10).

10.9.2 Candidate Set Maintenance

The candidate set is initialized to contain no pilot. This happens when the mobile is first assigned a forward traffic channel. A pilot P_n from the neighbor set is added to the candidate set when its strength exceeds T_ADD. Also, a pilot P_r from the remaining set is moved to the candidate set when its strength exceeds T_ADD. A pilot P_c is deleted from the candidate set when the handoff drop timer corresponding to P_c has expired. Also, when the candidate set size has been exceeded, the pilot P_c, whose handoff drop timer is close to expiring, is deleted from the candidate set (see Fig. 10-11).

10.9.3 Neighbor Set Maintenance

The neighbor set is initialized to contain the pilots specified in the most recently received Neighbor List message. This happens when the mobile is first assigned a forward traffic channel. The mobile maintains a counter—AGE—for each pilot in the neighbor set. If a pilot moves from the active set or candidate set to neighbor set, its counter is initialized to 0. However, if a pilot

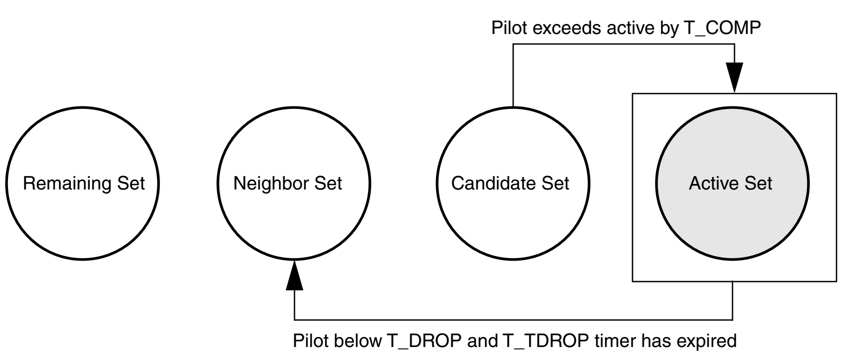


Figure 10-10 Active Set Maintenance

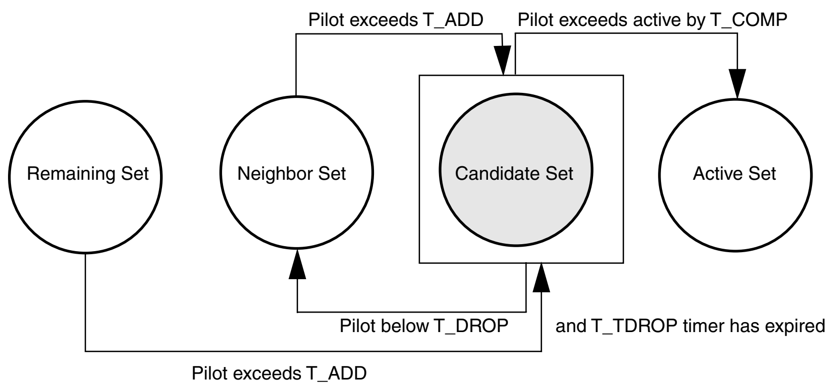


Figure 10-11 Candidate Set Maintenance

moves from the remaining set to the neighbor set, its counter is set to the maximum age value (see Fig. 10-12). The mobile adds a pilot in the neighbor set under the following conditions:

- A pilot in the active set is not contained in the HDM, and the corresponding handoff drop timer has expired.
- The handoff drop timer of a pilot in the candidate set has expired.
- A new pilot to the candidate set causes the candidate set size limit to be exceeded.
- The pilot is contained in the Neighbor List message and is not already a pilot of the candidate set or neighbor set.

The mobile deletes a pilot in the neighbor set under the following conditions:

- The HDM contains a pilot from the current neighbor set.
- The strength of a pilot in the neighbor set exceeds T_ADD.
- A new pilot to the neighbor set causes the size limit of the neighbor set to be exceeded.
- A neighbor set pilot's AGE exceeds the maximum value of the AGE counter.

10.10 The Need for Power Control

CDMA is an interference-limited system—since all mobiles transmit at the same frequency, internal interference generated within the system plays a critical role in determining system capacity and voice quality. The transmit power from each mobile must be controlled to limit interference. However, the power level should be adequate for satisfactory voice quality.

As the mobile moves around, the RF environment changes continuously due to fast and slow fading, shadowing, external interference, and other factors. The objective of power control is to limit transmitted power on the forward and reverse links while maintaining link quality under all conditions. Due to noncoherent detection at the base station, interference on the reverse link is more critical than it would be on the forward link. Reverse link power control is therefore essential for a CDMA system and is enforced by the IS-95 standard.

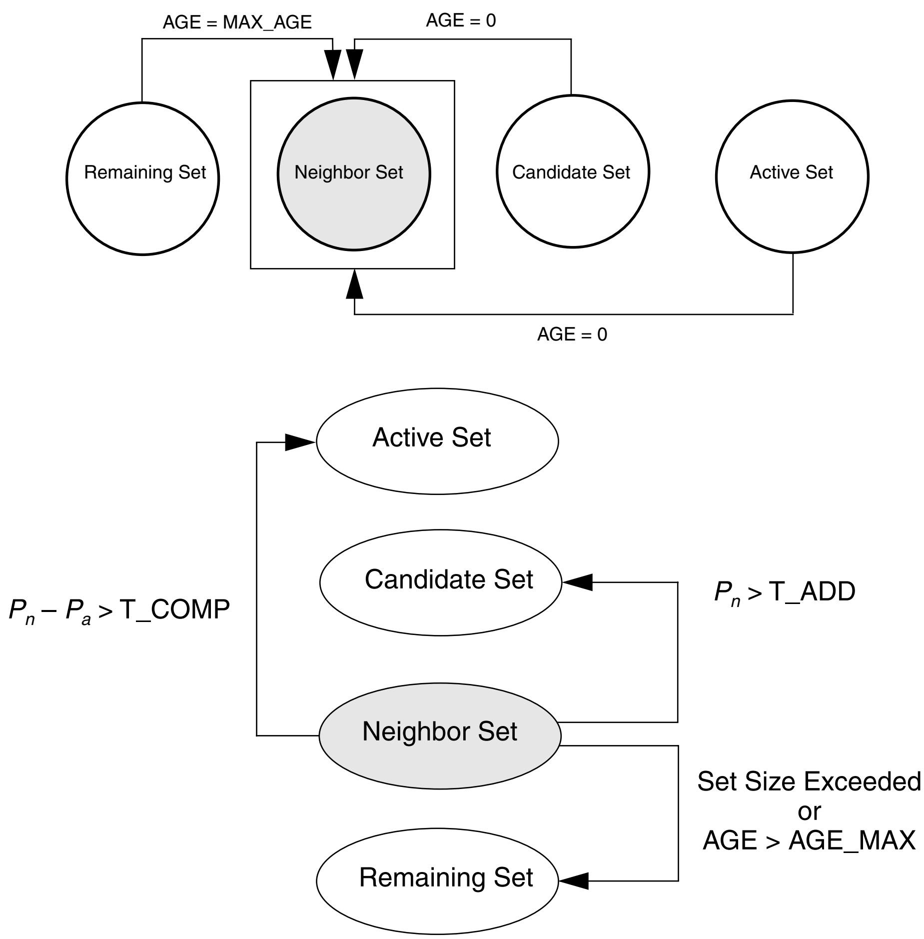


Figure 10-12 Neighborhood Set Maintenance

Power control is also needed in CDMA systems to resolve the near-far problem. To minimize the near-far problem, the goal in a CDMA system is to assure that all mobiles achieve the same received power levels at the base station. The target value for the received power level must be the minimum level possible that allows the link to meet user-defined performance objectives (BER, FER, capacity, dropped-call rate, and coverage). In order to implement such a strategy, the mobiles closer to the base station must transmit less power than those far away.

Voice quality is related to frame-error rate (FER) on both the forward and reverse link. The FERs are largely correlated to E_b/I_t. The FER also depends on vehicle speed, local propagation conditions, and distribution of other cochannel mobiles. Since the FER is a direct measure of signal quality, the voice quality performance in a CDMA system is measured in terms of FERs rather than E_b/I_t. Thus, to assure good signal quality, it is not sufficient to maintain a target E_b/I_t;

it is also necessary to respond to specific FERs as they occur. The recommended performance bounds are

- A typical recommended range for FER—0.2% to 3% (optimum power level is achieved when FER $\leq$ 1%)
- A maximum length of burst error—3 to 4 frames (optimum value of burst error $\approx$ 2 frames)

10.11 Reverse Link Power Control

The reverse link power control affects the access and reverse traffic channels. It is used for establishing the link while originating a call and reacting to large path-loss fluctuations. The reverse link power control includes the open-loop power control (also known as autonomous power control) and the closed-loop power control. The closed-loop power control involves the inner-loop power control and the outer-loop power control.

10.11.1 Reverse Link Open-Loop Power Control

The open-loop power control is based on the principle that a mobile closer to the base station needs to transmit less power as compared to a mobile that is farther away from the base station or is in fade. The mobile adjusts its transmit power based on total power received in the 1.23-MHz band (i.e., power in pilot, paging, sync, and traffic channels). This includes power received from all base stations on the forward link channels. If the received power is high, the mobile reduces its transmit power. On the other hand, if the power received is low, the mobile increases its transmit power.

In open-loop power control the base station is not involved. The mobile determines the initial power transmitted on the access channel and traffic channel through open-loop power control. A large dynamic range of 80 dB is allowed to provide an ability to guard against deep fades.

The mobile acquires the CDMA system by receiving and processing the pilot, sync, and paging channels. The paging channel provides the Access Parameters message which contains the parameters to be used by the mobile when transmitting to the base station on an access channel. The access parameters are

- The access channel number
- The nominal power offset (NOM_PWR)
- The initial power offset step size
- The incremental power step size
- The number of access probes per access probe sequence
- The time-out window between access probes
- The randomization time between access probe sequences

Based on the information received on the pilot, sync, and paging channels, the mobile attempts to access the system via one of several available access channels. During the access state, the mobile has not yet been assigned a forward link traffic channel (which contains the power control bits). Since the reverse link closed-loop power control is not active, the mobile initiates, on its own, any power adjustment required for a suitable operation.

The prime goal in CDMA systems is to transmit just enough power to meet the required performance objectives. If more power is transmitted than necessary, the mobile becomes a jammer to other mobiles. Therefore, the mobile tries to get the base station attention first by transmitting at very low power. The key rule is that the mobile transmits in inverse proportion to what it receives.

When receiving a strong pilot from the base station, the mobile transmits a weak signal back to the base station. A strong signal at the mobile implies a small propagation loss on the forward link. Assuming the same path loss on the reverse link, only a low transmit power is required from the mobile in order to compensate for the path loss.

When receiving a weak pilot from the base station, the mobile transmits back a strong signal. A weak received signal at the mobile indicates a high propagation loss on the forward link. Conversely, a high transmit power level is required from the mobile.

The mobile transmits the first access probe at a mean power level defined by

$$T_x = -R_x - K + (NOM\text{-}PWR - 16 \times NOM\text{-}PWR\text{-}EXT) + INIT\text{-}PWR \text{ (dBm)} \qquad (10.2)$$

where T_x = mean output transmit power (dBm),
R_x = mean input receive power (dBm),
NOM-PWR = nominal power (dB),
NOM-PWR-EXT = nominal power for extended handoff (dB),
INIT-PWR = initial adjustment (dB),
K = 73 for cellular (Band Class 0), and
K = 76 for PCS (Band Class 1).

If *INIT-PWR* were 0, then *NOM-PWR* – 16 × *NOM-PWR-EXT* would be the correction that should provide the correct received power at the base station. *NOM-PWR* – 16 × *NOM-PWR-EXT* allows the open-loop estimation process to be adjusted for different operating environment.

The values for *NOM-PWR*, *NOM-PWR-EXT*, *INIT-PWR*, and the step size of a single access probe correction *PWR-STEP* are system parameters specified in the Access Parameters message. These are obtained by the mobile station prior to transmitting. If, as the result of an Extended Handoff Direction message or a General Handoff Direction message, the *NOM-PWR* and *NOM-PWR-EXT* values change, the mobile uses the *NOM-PWR* and *NOM-PWR-EXT* values from the Extended Handoff Direction message or a General Handoff Direction message.

The total range of the *NOM-PWR* – 16 × *NOM-PWR-EXT* correction is –24 to 7 dB. While operating in Band Class 0, *NOM-PWR-EXT* is set to 0, making the total range of correction from –8 to 7 dB. The range of the *INIT-PWR* parameter is –16 to 15 dB, with a nominal value of 0 dB. The range of the *PWR-STEP* parameter is 0 to 7 dB. The accuracy of the adjustment to the mean output power due to *NOM-PWR*, *NOM-PWR-EXT*, *INIT-PWR*, or a single access probe correction of *PWR-STEP* should be ±0.5dB or ±20%, whichever is greater.

The major flaw with this criterion is that reverse link propagation statistics are estimated based on forward link propagation statistics. But, since the two links are not correlated, a significant error may result from this procedure. However, these errors will be corrected once the closed-loop power control mechanism becomes active as the mobile seizes a forward traffic channel and begins to process power control bits.

After the Acknowledgment time window (T_a) has expired, the mobile waits for an additional random time (RT) and increases its transmit power by a step size. The mobile tries again. The process is repeated until the mobile gets a response from the base station. However, there is a maximum number of probes per probe sequence and a maximum number of probe sequences per access attempt.

The entire process to send one message and receive an acknowledgment for the message is called an *access attempt*. Each transmission in the access attempt is referred to as an *access probe*. The mobile transmits the same message in each access probe in an access attempt. Each access probe contains an access channel preamble and an access channel capsule (see Fig. 10-13). Within an access attempt, access probes are grouped into access probe sequences. Each access probe sequence consists of up to 16 access probes, all transmitted on the same access channel.

There are two reasons that could prevent the mobile from getting an acknowledgment after the transmission of a probe.

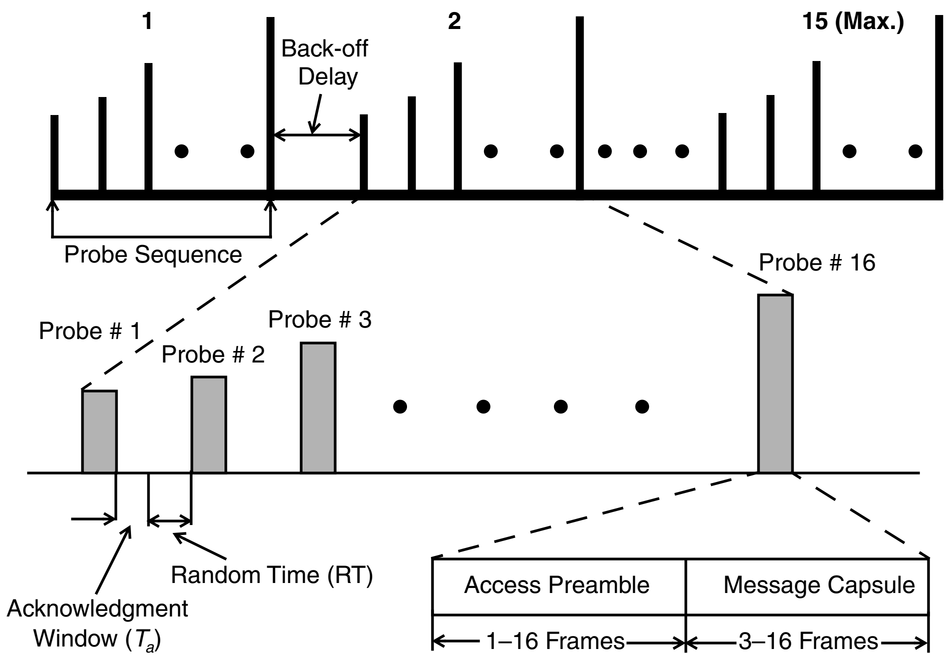


Figure 10-13 Access Attempt, Probe Sequence, and Probe in Open-Loop Power Control

1. The transmit power level might be insufficient. In this case, the incremental step power strategy helps to resolve the problem.
2. There might be a collision due to the random contention of the access channel by several mobiles. In this case, the random waiting time minimizes the probability of future collisions.

The process is shown by the access probe ladder in Fig. 10-14.

The transmit power is defined by

$$T_x = -R_x - K + (NOM\text{-}PWR - 16 \times NOM\text{-}PWR\text{-}EXT) + \text{Sum of Access Probe Corrections} \tag{10.3}$$

where the access probe correction is the sum of all the appropriate incremental power steps prior to receiving an acknowledgment at the mobile.

For every access probe sequence, a back-off delay is generated pseudorandomly. Timing between access probes of an access probe sequence is also generated pseudorandomly. After transmitting each access probe, the mobile waits for T_a. If an acknowledgment is received, the access attempt ends. If no acknowledgment is received, the next access probe is transmitted after an additional random time (see Fig. 10-13).

If the mobile does not receive an acknowledgment within an access attempt, the attempt is considered as a failure and the mobile tries to access the system at another time. If the mobile receives an acknowledgment from the base station, it proceeds with the registration and traffic channel assignment procedures. The initial transmission on the reverse traffic channel shall be at a mean output power defined by Eq. (10.3).

The mobile station supports a total combined range of initial offset parameters, closed *NOM-PWR*, and access probe corrections of at least ±32dB for mobile stations operating in Band Class 0 and ±40dB for mobile stations operating in Band Class 1.

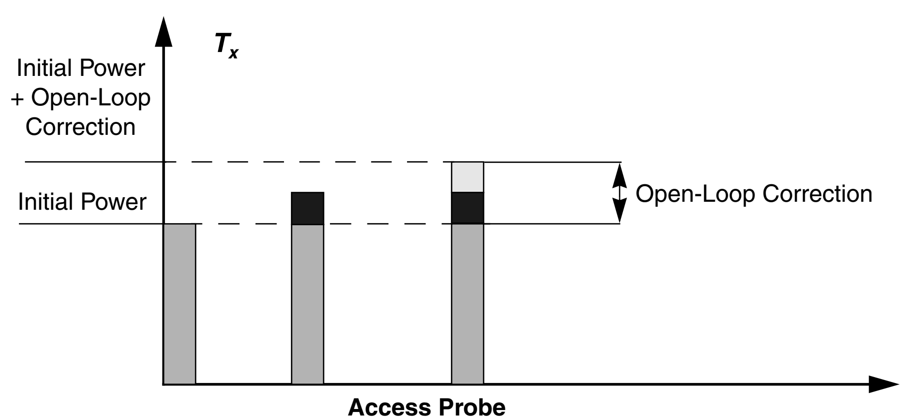


Figure 10-14 Access Probe Ladder

The sources of error in the open-loop power control are

- Assumption of reciprocity on the forward and reverse links
- Use of total received power including power from other base stations
- Slow response time ~ 30 ms to counter fast fading due to multipath

10.11.2 Reverse Link Closed-Loop Power Control

Fading sources in multipath require a much faster power control than the open-loop power control. The additional power adjustments required to compensate for fading losses are handled by the reverse link closed-loop power control mechanism, which has a response time of 1.25 ms for 1-dB steps and a dynamic range of 48 dB (covered in 3 frames). The quicker response time gives the closed-loop power control mechanism the ability to override the open-loop power control mechanism in practical applications. Together, two independent power control mechanisms cover a dynamic range of at least 80 dB. The closed-loop power control provides correction to the open-loop power control. Once on the traffic channel, the mobile and base stations engage in closed-loop power control.

The reverse link closed-loop power control mechanism consists of two parts—inner-loop power control and outer-loop power control. The inner-loop power control keeps the mobile as close to its target $(E_b/I_t)_{\text{setpoint}}$ as possible, whereas the outer-loop power control adjusts the base station target $(E_b/I_t)_{\text{setpoint}}$ for a given mobile.

To understand the operation of the closed-loop power control mechanism, let's review the structure of the forward traffic channel and its operation. The areas of focus are the output of the interleaver and the input to the MUX. A power control subchannel continuously transmits on the forward traffic channel. This subchannel runs at 800 power control bits per second. Therefore, a power control bit (0 or 1) is transmitted every 1.25 ms. A 0 bit indicates to the mobile that it should increase its mean output power level, whereas 1 indicates to the mobile to decrease its mean output power level.

A 20-ms frame is organized into 16 time intervals of equal duration (see Fig. 10-15). These time intervals, each of 1.25 ms, are called Power Control Groups (PCGs). Thus, a frame has 16 PCGs. Prior to transmission, the reverse traffic channel interleaver output data stream is gated with a time filter. The time filter allows transmission of some symbols and deletion of

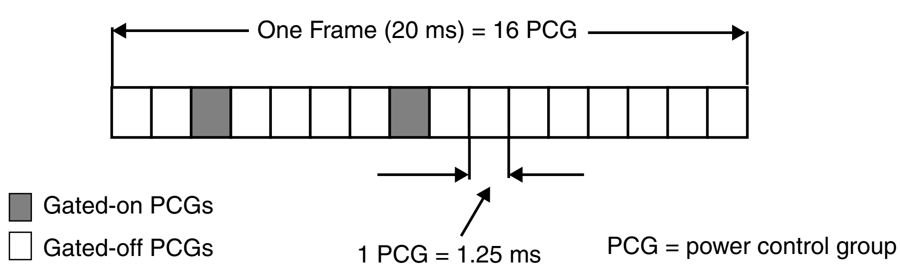


Figure 10-15 Power Control Groups

others. The duty cycle of the transmission gate varies with the transmit data rate, i.e., variable rate vocoder output, which, in turn, depends on the voice activity. Table 10-2 indicates the number of PCGs that are sent at different frame rates.

The assignment of the gated-on and gated-off groups is determined by the Data Burst Randomizer (DBR). At the base station, the reverse link receiver estimates the received signal strength by measuring E_b/I_t during each power group (1.25 ms).

- If the signal strength exceeds a target value, a power-down power control bit 1 is sent.
- Otherwise a power-up control bit 0 is transmitted to the mobile via the power control subchannel on the forward link.

Similar to the reverse link transmission, the forward link transmissions are organized in 20-ms frames. Each frame is subdivided into 16 PCGs. The transmission of a power control bit occurs on the forward traffic channel in the second PCG following the corresponding reverse link PCG in which the signal strength was estimated. For example, if the signal strength is estimated on PCG #2 of a reverse link frame, then the corresponding power control bit must be sent on PCG #4 of the forward link frame (see Fig. 10-16). Once the mobile receives and processes the forward link channel, it extracts the power control bits from the forward traffic channel. The power control bits then allow the mobile to fine-tune its transmit power on the reverse link.

Based on the power control bit received from the base station, the mobile either increases or decreases transmit power on the reverse traffic channel as needed to approach the target value of $(E_b/I_t)_{\text{nom}}$ or set point that controls the long-term FER. Each power bit produces a 1-dB change in mobile power, i.e., it attempts to bring the measured E_b/I_t value 1 dB closer to its target value. Note that it might not succeed because I_t is also always changing. Therefore, further adjustments

Table 10-2 Power Control Groups vs. Frame Rate

Frame Rate	Rate (kbps)	No. of PCGs Sent
Full	9.6	16
1/2	4.8	8
1/4	2.4	4
1/8	1.2	2

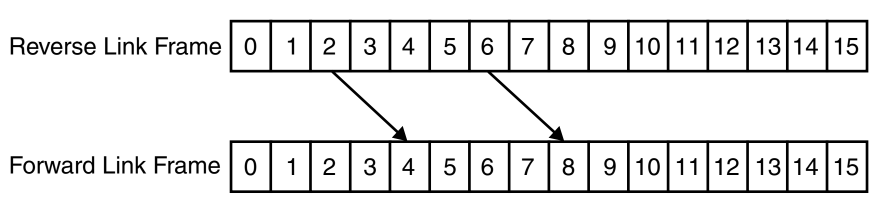


Figure 10-16 PCG Location in Reverse and Forward Link Frames

may be required to achieve the desired E_b/I_t. The base station, through the mobile, can directly change only E_b, not I_t, and the objective is the ratio of E_b to I_t, not any particular value for E_b or I_t.

The base station measures E_b/I_t 16 times in each 20-ms frame. If the measured E_b/I_t is greater than the current target value of E_b/I_t, the base station informs the mobile to decrease its power by 1 dB. Otherwise, the base station orders the mobile to increase its power by 1 dB (see Fig. 10-17).

The relationship between E_b/I_t and the corresponding FER is nonlinear and varies with vehicle speed and RF environment. Performance deteriorates with increasing vehicle speed. The best performance corresponds to a stationary vehicle where additive white Gaussian noise dominates. Thus, a single value of E_b/I_t is not satisfactory for all conditions. The use of a single, fixed value for E_b/I_t could reduce channel capacity by 30% or more by transmitting excessive, unneeded power.

The value of the variable a is kept very small (see Fig. 10-18), so it may take 35 frames to reduce the E_b/I_t set point by 1 dB. Typically, the value of $100a$ is set at about 3 dB. The set point value is reduced by a for each consecutive frame until a frame error occurs. The set point is then increased by a relatively large amount and the process is repeated. The set point can range from 3 dB to 10 dB. A value of $E_b/I_t \geq 5$ dB corresponds to good voice quality.

Since FER is a direct measure of link quality, the system is controlled using the measured FERs rather than E_b/I_t. FER is the key parameter in controlling and assuring a satisfactory voice quality. It is not sufficient to maintain a target E_b/I_t, but it is necessary to control FERs as they occur. The objective of the Reverse Outer-Loop Power Control (ROLPC) is to balance the desired FER on the reverse link and system capacity. System capacity can be controlled with the

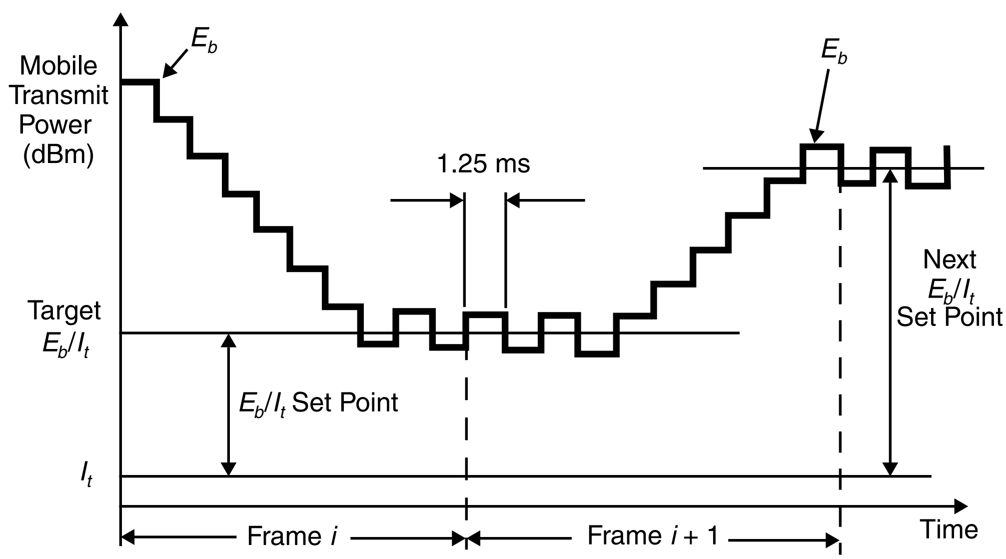


Figure 10-17 Target E_b/I_t

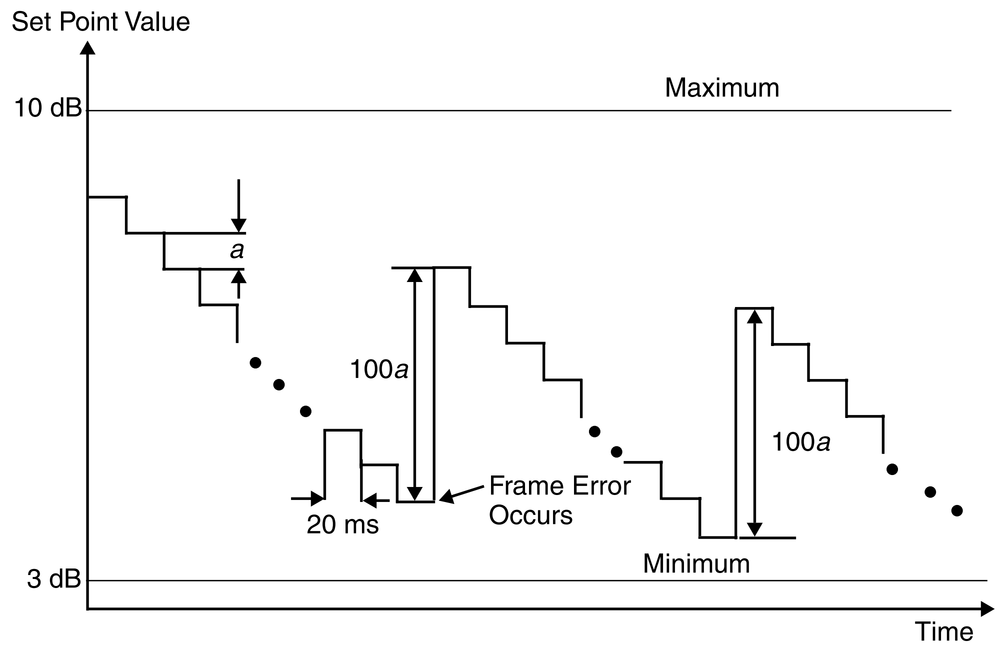


Figure 10-18 Set Point Value vs. Time

ROLPC parameters by increasing the acceptable FER. Changing FER can be accomplished by setting the ratio of *down_frr* to *up_frr*. The *down_frr* is calculated by the system by using the desired reverse FER (*rfer*) and *up_frr* as

$$down\_frr = (rfer \times up\_frr)/2 \qquad (10.4)$$

Based on simulations, the following values for *up_frr* are suggested:

If $(0.2\% \le rfer \le 0.4\%)$, $up\_frr = 6000$

If $(0.6\% \le rfer \le 1.0\%)$, $up\_frr = 5000$

If $(1.2\% \le rfer \le 2.0\%)$, $up\_frr = 3000$

If $(2.2\% \le rfer \le 3.0\%)$, $up\_frr = 1000$

Tables 10-3 and 10-4 lists the range and default values of different parameters for RS1 and RS2.

The inner-loop power control is also responsible for detecting the mobile that fails to respond to power control and that may be causing interference to other mobiles. The base station counts the number of consecutive power decrease commands, and, if the count exceeds the specified threshold value, the base station will send a Lock until Power Cycle message to the mobile. This message disables the mobile until the user turns the power off and on. Fig. 10-19 gives the flow chart for the reverse link closed-loop power control.

Table 10-3 ROLPC Parameters for RS1

Parameter	Range	Suggested Value	Description of Parameter
rfer 1	0.2–3.0%	1%	target reverse link FER (*rfer*)
$(E_b/I_t)_{\text{nom }1}$ (dB)	3.5–8.0%	6.5%	initial $(E_b/I_t)_{\text{set point}}$
$(E_b/I_t)_{\text{max }1}$ (dB)	5.5—9.5%	8.5%	maximum $(E_b/I_t)_{\text{set point}}$
$(E_b/I_t)_{\text{min }1}$ (dB)	3.0–5.8%	3.5%	minimum $(E_b/I_t)_{\text{set point}}$

Table 10-4 ROLPC Parameters for RS2

Parameter	Range	Suggested Value	Description of Parameter
rfer 2	0.2–6.0%	1%	target reverse link FER
$(E_b/I_t)_{\text{nom }2}$ (dB)	3.8–8.3%	6.8%	initial $(E_b/I_t)_{\text{set point}}$
$(E_b/I_t)_{\text{max }2}$ (dB)	5.8–9.8%	8.8%	maximum $(E_b/I_t)_{\text{set point}}$
$(E_b/I_t)_{\text{min }2}$ (dB)	3.0–5.8%	3.8%	minimum $(E_b/I_t)_{\text{set point}}$

The mobile power output with both open-loop and closed-loop power control is given as

$$\begin{aligned} T_x = -R_x - K + (NOM\text{-}PWR - 16 \times NOM\text{-}PWR\text{-}EXT) + INIT\text{-}PWR \\ + \text{Sum of Access Probe Corrections} \\ + \text{Sum of all Closed-Loop Power Control Corrections} \end{aligned} \tag{10.5}$$

10.12 Forward Link Power Control

Forward link power control (FLPC) aims at reducing interference on the forward link. The FLPC not only limits the in-cell interference, but it is especially effective in reducing other cell/sector interference.

The forward link power control attempts to set each traffic channel transmit power to the minimum required to maintain the desired FER at the mobile. The mobile continuously measures forward traffic channel FER. It reports this measurement to the base station on a periodic basis. After receiving the measurement report, the base station takes the appropriate action to increase or decrease power on the measured logical channel. The base station also restricts the power dynamic range so that the transmitter power never exceeds a maximum value that would cause excessive interference or so that it never falls below the minimum value required for adequate voice quality.

Since FERs are measured (not E_b/I_t as in the closed inner-loop strategy), this process is a direct reflection of voice quality. However, it is a much slower process. Because orthogonal Walsh codes are employed for the forward link instead of long PN codes, cochannel interference is not an urgent issue. Therefore, slow measurements do not add much degradation to system performance. Fig. 10-20 is a flow chart for the FLPC process.

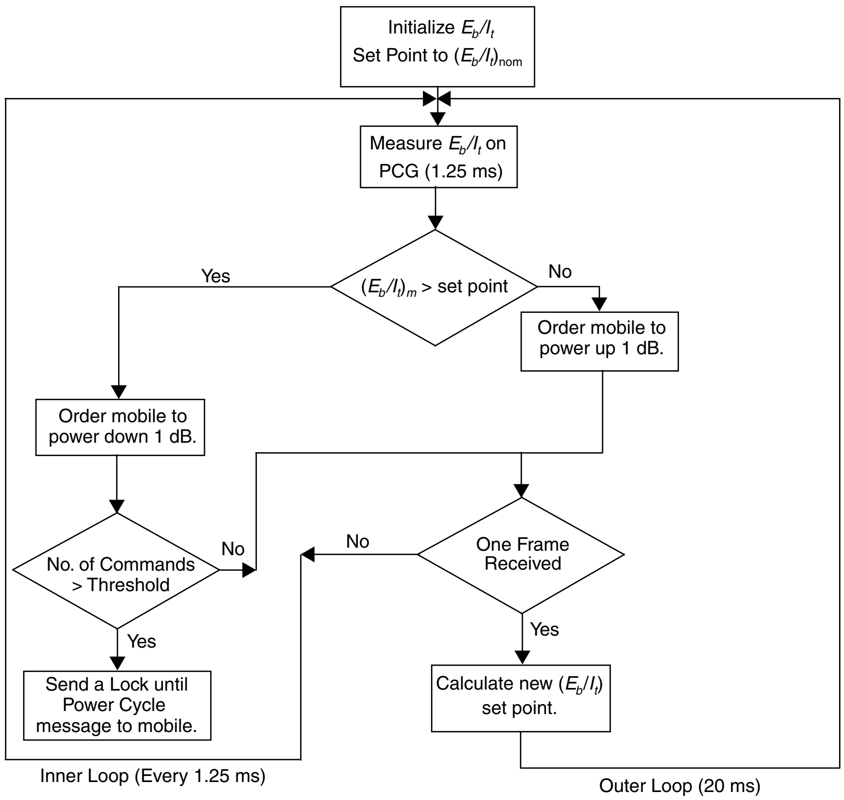


Figure 10-19 Flow Chart for Reverse Link Closed-Loop Power Control

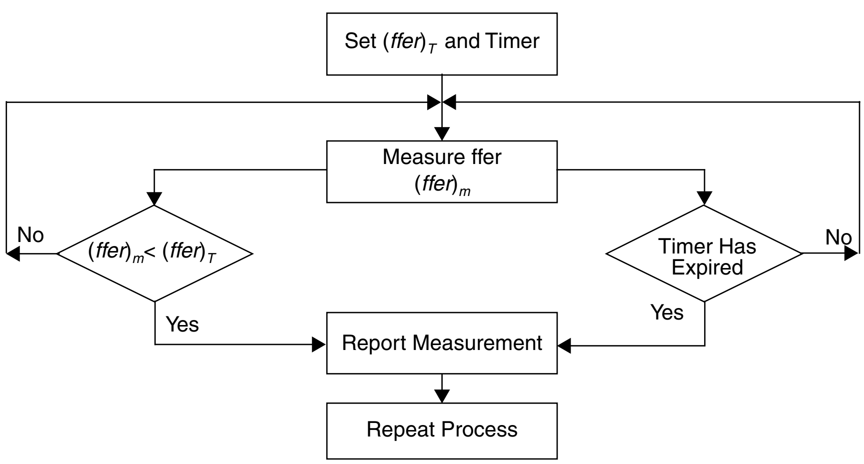


Figure 10-20 Flow Chart for Forward Link Power Control

Forward link power control is expressed in terms of parameters *N*, *D*, *U*, and *V* (see Fig. 10-21), which may be adjusted to various values for the operation of an actual system.

For RS1, the Power Measurement Report message (PMRM) contains the number of error frames received and the total number of frames received during the interval covered by the report (frame counters then are reset for the next report interval). The FER is equal to the number of error frames divided by the total number of frames received in the reporting interval. The following are the steps for forward link power control for RS1 (see Fig. 10-21).

Action by Mobile

- Mobile keeps track of the number of error frames in a period of length *pwr_rep_frame*.
- If error frames > a specified number, the mobile sends a PMRM containing:
  - Total number of frames in *pwr_rep_frame*
  - Number of error frames in *pwr_rep_frame*
  - FER
- If error frames < a specified number, a PMRM is not sent.
- After sending a PMRM, the mobile waits for a period—*pwr_rep_delay*—before starting a new period.

Action by Base Station

- On receiving the PMRM, the base station compares the reported FER as follows and adjusts traffic channel power.
  - FER < *fer_small* → reduce power by *D*
  - *fer_small* < FER < *fer_big* → increase power by *U*
  - FER > *fer_big* → increase power by *V*

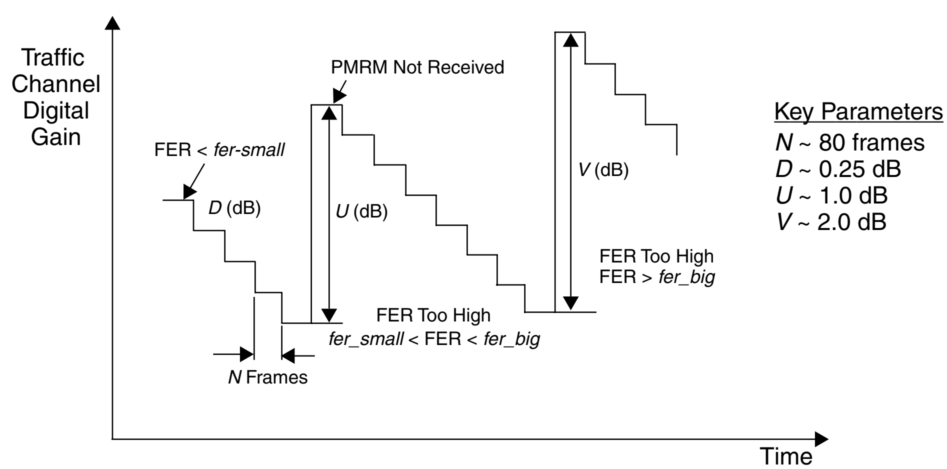


Figure 10-21 Forward Link Power Control for RS1

- If no PMRM is received
  - Base station starts a timer *fpc_step*.
  - When timer expires, power level is reduced by *D*.
  - The timer resets after it expires or after receipt of a PMRM.
- Digital gain is never set below *min_gain* or above *max_gain*.
- If *flpc_enable* = 0, digital gain is set to *nom_gain*.

For RS2, 1 bit per reverse link frame (the E or erasure bit) is dedicated to inform the base station whether or not the last forward link frame was received without error at the mobile. This allows more rapid and precise control of forward link power than the scheme used for RS1. The following are the steps for forward link power control for RS2 (see Fig. 10-22).

Forward Link Power Control with RS2

- Uses erasure indicator bit instead of PMRM
- Much faster than RS1 implementation
  - Forward link power control could change every 2 frames; thus, its response is very fast.
- Process
  - In each frame, the mobile sends an erasure indicator bit showing whether the previous forward frame had an erasure bit or not.
  - If an erasure is indicated by the mobile, the base station increases traffic channel digital gain by *dn_adj*.

Tables 10-5 and 10-6 list the values of the parameters for forward link power control for RS1 and RS2, respectively.

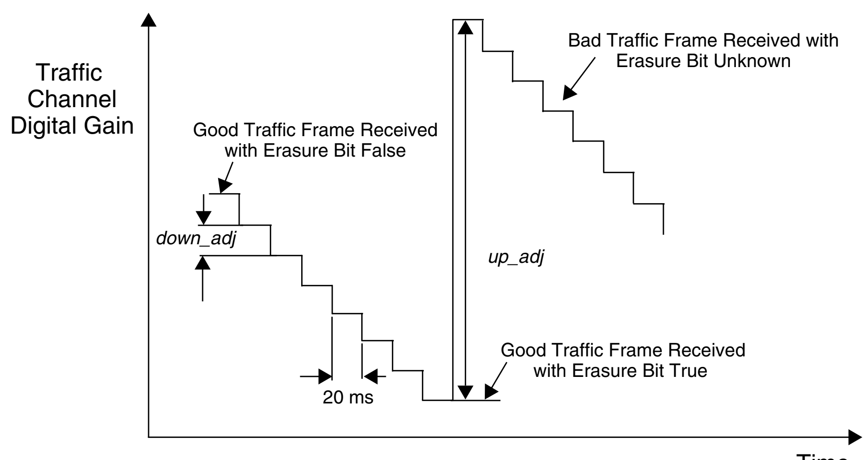


Figure 10-22 Forward Link Power Control for RS2

Table 10-5 Forward Link Power Control Parameters for RS1

Parameters	Range	Suggested Value	Description
FER	0.2–3%	1%	target forward FER
fer_small	0.2–5%	2%	lower forward link FER threshold minimum PMRM FER required to increase gain by *U*
fer_big	2–10%	6%	upper forward link FER threshold minimum PMRM FER required to increase gain by *V*
min_gain	34–50	40	minimum traffic channel digital gain
max_gain	50–108	80	maximum traffic channel digital gain
nom_gain	34–108	57	nominal traffic channel digital gain
fpc_step	20–5000 ms	1600 ms	forward power control timer value which determines when gain is decreased by *D*

Table 10-6 Forward Link Power Control Parameters for RS2

Parameter	Range	Suggested Value	Description
FER	0.2–6%	1%	target forward FER
up_adj	1–50	15	gain increase when forward erasure is observed
dn_adj	—	N/A	gain decrease when no forward erasure is observed
min_gain	30–50	30	minimum traffic channel digital gain
max_gain	50–127	127	maximum traffic channel digital gain
nom_gain	40–108	80	nominal traffic channel digital gain

where $dn\_adj = (up\_adj \times \text{FER})/100$

10.13 Summary

This chapter covered soft handoff and power control in IS-95 CDMA. Soft handoff provides path diversity on the forward and reverse links. Diversity gains are achieved because less power is required on the forward and reverse links. This results in the reduction of total system interference and an increase in system capacity.

Since the RF environment changes continuously due to fast and slow fading, shadowing, external interference, and other factors, the aim of power control is to adjust the transmitted power on the forward and reverse link while maintaining link quality under all operating conditions. Power control in the CDMA system is required to resolve the near-far problem. To minimize the near-far problem, the goal in a CDMA system is to assure that all mobile stations achieve the same received power levels at the base station.

The reverse link power control includes the open-loop power control and the closed-loop power control. The open-loop power control is too slow to counter fast fading due to multipath. The closed-loop power control provides correction to the open-loop power control. It begins after acquiring the traffic channel and is directed by the base station. The closed-loop power control occurs every 1.25 ms and is much faster and more effective than the open-loop power control. With the closed-loop power control, power can change ±16 dB per 20-ms frame.

10.14 References

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