2

The CDMA Concept

CDMA is a multiple-access scheme based on spread-spectrum communication techniques [1–3]. It spreads the message signal to a relatively wide bandwidth by using a unique code that reduces interference, enhances system processing, and differentiates users. CDMA does not require frequency or time division for multiple access; thus, it improves the capacity of the communication system.

This chapter introduces spread-spectrum modulation and CDMA concepts. It presents several design considerations tied to those concepts, including the structure of the spreading signal, the method for timing synchronization, and the requirements for power control. This chapter also points out CDMA IS95 [4] details to illustrate practical solutions to these design issues.

2.1 Direct-Sequence Spread-Spectrum Communications

Spread-spectrum communications is a secondary modulation technique. In a typical spread-spectrum communication system, the message signal is first modulated by traditional amplitude, frequency, or phase techniques. A pseudorandom noise (PN) signal is then applied to spread the modulated waveform over a relatively wide bandwidth. The PN signal can amplitude modulate the message waveform to generate direct-sequence spreading, or it can shift the carrier frequency of the message signal to produce frequency-hopped spreading, as shown in Figure 2.1.

The direct-sequence spread-spectrum signal is generated by multiplying the message signal $d(t)$ by a pseudorandom noise signal $pn(t)$:

$$g(t) = pn(t)d(t) \tag{2.1}$$

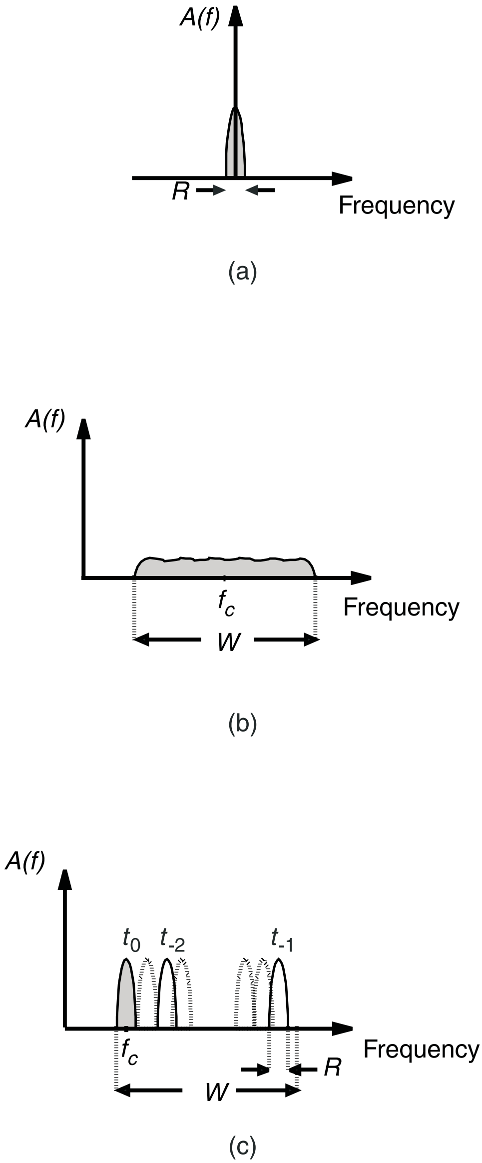

Figure 2.1 Spread-spectrum signals: (a) message signal, (b) direct-sequence signal, and (c) frequency-hopped signal.

In most cases, the PN signal is a very high rate, nonreturn-to-zero (NRZ) pseudorandom sequence that chops the modulated message waveform into chips, as shown in Figure 2.2. Hence, the rate of the secondary modulating waveform is called the chip rate, f_c, while the rate of the message signal is designated the bit rate, f_b. The two modulation processes produce different bandwidths, namely, R for the modulated message signal and W for the relatively wide spread-spectrum waveform. Note that the secondary modulation does not increase the overall power of the message signal but merely spreads it over a wider bandwidth.

The frequency-hopped spread-spectrum signal is formed by multiplying the message signal with a pseudorandom carrier frequency $\omega_{pn}(t)$:

$$g(t) = \cos[\omega_{pn}(t)t]d(t) \tag{2.2}$$

In this approach, the spectrum of the modulated message hops about a range of frequencies and produces a relatively wide bandwidth signal.

Spread-spectrum modulation techniques provide powerful advantages to communication systems, such as a flexible multiple-access method and interference suppression. These advantages are examined here for direct-sequence spread-spectrum signals.

The direct-sequence spread-spectrum signal formed in a simple and ideal transmitter can be described by

$$s(t) = pn(t)Ad(t)\cos(\omega t + \theta) \tag{2.3}$$

where $pn(t)$ is the pseudorandom modulating waveform, A is the amplitude of the message waveform, $d(t)$ is the message signal with bipolar values ± 1,

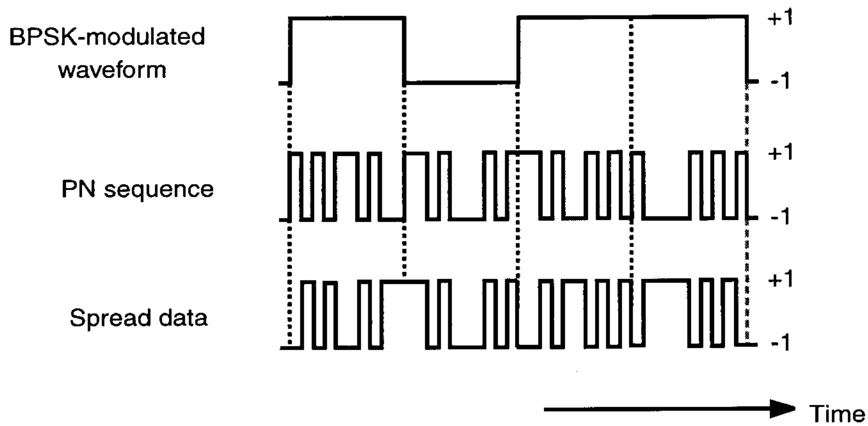

Figure 2.2 Direct-sequence spread-spectrum signals.

ω is the carrier frequency, and θ is a random phase. The signal is transmitted over the air interface and is received along with thermal noise $n(t)$ and interference $i(t)$, which are added by the channel. The received signal is[1]

$$r(t) = pn(t)Ad(t)\cos(\omega t + \theta) + n(t) + i(t) \tag{2.4}$$

To recover the message signal $d(t)$, the RF carrier, $\cos(\omega t + \theta)$, is removed, and the spread-spectrum signal is despread by a simple correlator. The correlator is synchronized to the transmitter's sequence, $pn(t)$, and its output is integrated over the bit period (T_b). The process is described by

$$\frac{1}{T_b}\int_0^{T_b} pn(t)r(t)dt = pn^2(t)Ad(t) + pn(t)[n'(t) + i'(t)] \approx Ad(t) \tag{2.5}$$

where $n'(t)$ and $i'(t)$ represent the down-converted thermal noise and interference. When the PN sequences at the transmitter and the receiver are synchronized, $pn^2(t) = 1$ and the bit energy is compressed back to its original bandwidth R. Any received interference, $i(t)$, is spread by the correlator to the relatively wide bandwidth W, and its effect is lowered.

The correlator affects the message signal $d(t)$ differently than it does the interference $i(t)$ and thereby improves the signal-to-noise ratio (SNR) of the received signal.[2] That powerful benefit is the *processing gain* of the system and is equal to the spreading factor W/R.

2.1.1 Spreading Codes

The spreading code is a critical component of spread-spectrum communications. It generates the pseudorandom signal used to spread the message signal. To be effective, the spreading code should produce values that resemble Gaussian noise and approximate a Gaussian random variable. In addition, these codes should be easily realizable at the transmitter and the receiver.

In general, the spreading signal is a binary waveform with values specified at the chip rate. The binary waveform allows easy implementation without sacrificing performance and enables synchronization of the transmitter to the received signal. It is possible to achieve a continuous-time waveform by passing the binary signal through a linear filter.

1. To illustrate the spread-spectrum concept, delay and scaling effects introduced by the channel are ignored here.
2. *Noise* refers to any unwanted energy and includes interference.

These characteristics are available from deterministic, pseudorandom sequences with the following classical properties:

- There are near-equal occurrences of +1 and −1 chips.
- Run lengths of r chips with the same sign occur approximately 2^{-r} times.
- Shifting by a nonzero number of chips produces a new sequence that has an equal number of agreements and disagreements with the original sequence [1].

The randomness of the signal $pn(t)$ is measured by the autocorrelation function $R_{pn}(\tau)$, given by

$$R_{pn}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} pn(t)pn(t + \tau)dt \tag{2.6}$$

Similarly, the autocorrelation for a sequence of M discrete values is written as

$$R_{pn}(\tau) = \frac{1}{M} \sum_{M} pn(t)pn(t + \tau) \tag{2.7}$$

and is plotted in Figure 2.3. A peak or peaks in the function indicate that the sequence contains subsequences that repeat. For a properly designed PN sequence, the autocorrelation function is very small and equal to $-1/M$ for every nonzero value of τ. Consequently, PN sequences also are useful for timing synchronization.

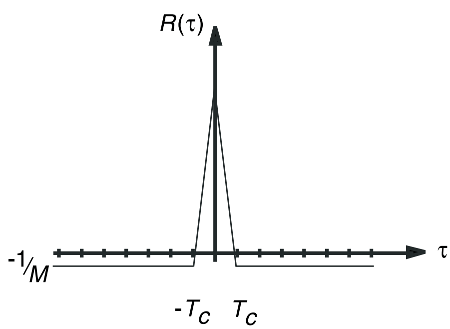

Figure 2.3 Autocorrelation of PN sequence.

The uniqueness of the signal $pn(t)$ is analyzed with the cross-correlation function, defined by

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)y(t + \tau)dt \tag{2.8}$$

or, alternatively, by

$$R_{xy}(\tau) = \frac{1}{M} \sum_{M} x(t)y(t + \tau) \tag{2.9}$$

where $x(t)$ and $y(t)$ are two different signals or sequences. In general, pseudorandom sequences demonstrate poorer cross-correlation attributes than deterministic sequences, as shown in Figure 2.4 [5]. That is because orthogonal sequences are designed to be dissimilar or orthogonal to each other. As a result, orthogonal codes are used in CDMA systems to differentiate users and to minimize interference.

The Hadamard code is a commonly used orthogonal code [6]. It is based on the rows of a square (n by n) matrix known as the Hadamard matrix. In the matrix, the first row consists of all 0s, while the remaining rows contain equal occurrences of 0s and 1s. Furthermore, each code differs from every other code in $n/2$ places.

The Hadamard matrix if formed by the following recursive procedure:

$$W_1 = [0] \qquad W_2 = \begin{bmatrix} W_1 & W_1 \\ W_1 & \overline{W}_1 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad W_{2n} = \begin{bmatrix} W_n & W_n \\ W_n & \overline{W}_n \end{bmatrix} \tag{2.10}$$

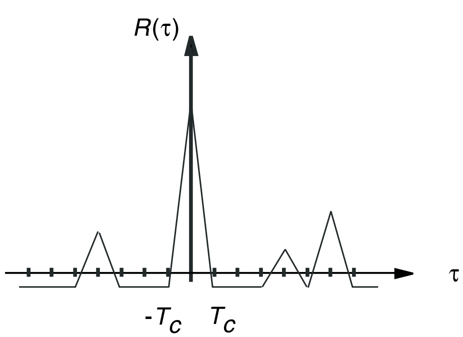

Figure 2.4 Cross-correlation of a PN sequence.

where $\overline{W}_n$ is derived from W_n by replacing all entries with their complements. The Hadamard matrix provides n orthogonal codes.

2.1.2 Spread-Spectrum Performance

Spread-spectrum modulation and CDMA techniques allow several users to share the radio interface; thus, the received waveform becomes the sum of k user signals and noise:

$$r(t) = \sum_{n=1}^{k} pn_n(t)A_n d_n(t)\cos(\omega t + \theta_n) + n(t) \tag{2.11}$$

The receiver retrieves the message signal by despreading the received signal. It does that by synchronizing its correlator to a specific spreading sequence, $pn(t)$, that is unique to the user and different from those of other users. As a result, the other user signals appear noiselike.

The noise (N_t) seen by the correlator is the signal energy received from the $k - 1$ users and thermal noise, that is,

$$N_t = \sum_{n=1}^{k-1} S_n + WN_o \tag{2.12}$$

where S_n is the received power from the nth user, N_o is the thermal noise power spectral density (psd), and W is the channel bandwidth. If the received power from each user is assumed equal[3] and k is large, such that $k - 1$ can be approximated by k, then

$$N_t \approx kS + WN_o \tag{2.13}$$

Furthermore, the interference generally is much larger than the integrated thermal noise ($kS >> WN_o$), so that

$$N_t \approx I = kS \tag{2.14}$$

From this result, two important observations are made. First, the interference of the spread-spectrum system increases linearly as the number of users is added. Second, the performance of the system suffers when any user transmits extra power, a problem known as the near-far effect [3].

3. This assumption is valid because in CDMA systems the power received from each user is strictly controlled.

The SNR is a key consideration in all communication systems. In digital communication systems, the SNR is characterized by a related figure of merit, the bit energy per noise density ratio (E_b/N_o). That parameter takes into account the processing gain of the communication system, a vital consideration in spread-spectrum communications. The parameter normalizes the desired signal power to the bit rate R to determine the bit energy and the noise or interference signal power to the spreading bandwidth W to determine the noise spectral density. Recall that the correlator

- Despreads or integrates the desired signal to the narrow bandwidth of the original message signal (R);
- Spreads the interference to a wider bandwidth;
- Leaves the uncorrelated noise unaltered.

Therefore,

$$\frac{E_b}{N_o} = \frac{S/R}{N/W} \approx \frac{S}{kS(R/W)} \tag{2.15}$$

Amazingly, the interference from other users (i.e., self-interface) is reduced by the processing gain (W/R) of the system.

A simple expression for the capacity of a CDMA system is developed from (2.15) and is given by

$$k \approx \frac{W/R}{(E_b/N_o)_{min}} \tag{2.16}$$

where $(E_b/N_o)_{min}$ is the minimum value needed to achieve an acceptable level of receiver performance, typically measured as the bit error rate (BER). The expression shows that the capacity of CDMA communication systems depends heavily on the spreading factor and the receiver's performance. The capacity is tied to a flexible resource—power—and is said to be *soft-limited*. In other words, if the required E_b/N_o is lowered, the transmit signal power allocated to each user is reduced, and the number of users can be increased. In contrast, the capacity of systems that employ other multiple-access methods like FDMA and TDMA are hard-limited. That is because their capacity is fixed by system design.

2.2 Overview of the CDMA IS95 Air Interface

Spread-spectrum communications using CDMA techniques originally were developed for military use [7]. The systems provided vital anti-jamming and low probability of intercept (undetectable) properties. Later, it was realized that those techniques also benefited cellular communications over dispersive channels. That led to operational (CDMA IS95) and planned (next-generation CDMA) networks based on spread-spectrum communications.

CDMA IS95 is a recent 2G wireless protocol. It and other 2G wireless protocols provide increased capacity, more robust service, and better voice quality by introducing digital methods. The CDMA IS95 standard [4] describes implementation details of the network, including the air interface, the protocol stack, the base station and mobile radio transmitters, the spreading codes, and the power control requirements.

2.2.1 Forward Link

The base station transmits radio signals to the mobile radio and forms the forward link, or downlink.[4] It relies on the forward-link modulator to protect the message signal against radio propagation impairments, to perform spread-spectrum modulation, and to provide multiple access by code division. The forward-link modulator is shown in Figure 2.5, and its operation is outlined below.

The input to the modulator is digital data from the voice coder (vocoder) or an application. The signal is protected using a forward error correction code (convolutional code) and repeated as needed to fill the frame buffer. Each frame buffer is then time interleaved to protect against burst errors. The time-interleaved data stream is scrambled by the long PN sequence, which has been slowed to match the bit rate. Power control information is then added. The resulting data is spread using an orthogonal Walsh code and randomized by the short in-phase (I) and quadrature-phase (Q) PN sequences. The signal then is applied to an RF carrier and transmitted.

The interleaving process scatters the bit order of each frame so that if a segment of data is lost during fading, its bits are dispersed throughout the reorganized frame, as illustrated in Figure 2.6. The missing bits are often recovered during the decoding process. Interleaving provides effective protection against rapidly changing channels but hinders performance in slow-changing environments.

The long code provides privacy by scrambling the message data. The short PN sequences distribute the energy of the transmit waveform so it appears

4. The term *downlink* is a carryover from satellite communications.

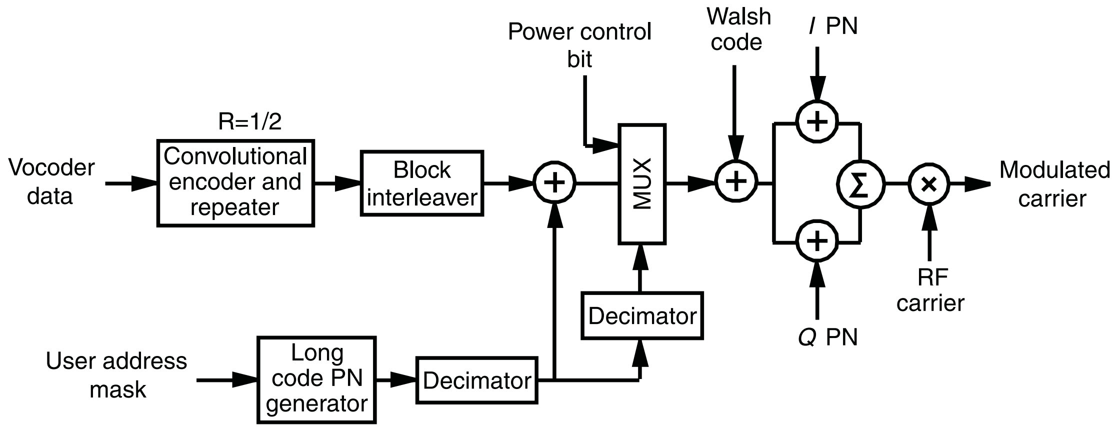

Figure 2.5 Forward-link modulator for CDMA IS95 base station.

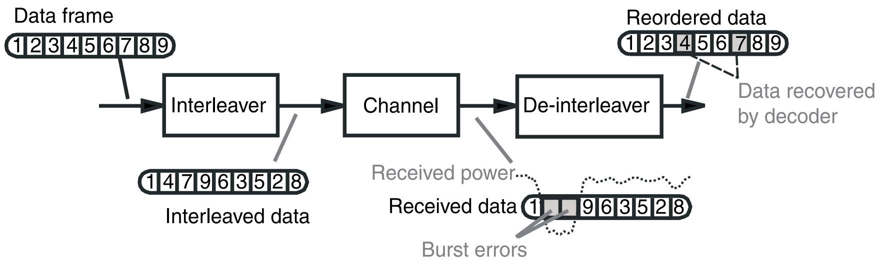

Figure 2.6 Interleaving process provides protection against time-varying channels.

Gaussian and noiselike. Neither of those PN codes spreads the message signal to the wide spread-spectrum bandwidth. It is the Walsh code that provides the orthogonal spreading. It multiplies each message signal by a 64-bit Walsh code unique to each user and spreads the signal bandwidth. As a result, a 64x processing gain is obtained.

The forward link contains several logical channels: the pilot channel, the synchronization (sync) channel, up to seven paging channels, and, at most, 55 traffic channels. The pilot, sync, and paging channels are common control channels, shared by all the users in the cell coverage area, which support communications between the mobile radios and the base station. The traffic channels are dedicated channels that support user communications. The channels are assigned to unique Walsh codes, as shown in Figure 2.7, and are able to share the air interface with very little interaction.

The pilot channel serves three purposes: channel estimation for coherent demodulation, multipath detection by the receiver, and cell acquisition during handoff (a procedure that maintains the radio link as a mobile radio moves from one cell coverage area to another). The pilot channel is a common channel that is broadcast to multiple users. As such, the overhead of the channel is divided by the number of users in the cell coverage area. That means it can be allocated more energy to improve performance without significant impact.

The pilot channel uses Walsh channel 0 (the all-zero entry in the Hadamard matrix) and an all-zero data sequence. Therefore, the pilot channel is just a replica of the short PN sequences. Because the pilot channel is a PN

Figure 2.7 Forward-link channels in CDMA IS95 systems.

sequence, it displays good autocorrelation properties and provides a means for timing synchronization, an important aspect of the CDMA IS95 network.

The short PN sequence is a sequence of 2^{15} chips that is conveniently written about a circle, as shown in Figure 2.8. The figure illustrates the periodicity and pseudorandom characteristics of the PN sequence. The short PN sequence is divided into consecutive segments that are 64 chips long, and each segment is labeled with an offset value[5] relative to the top of the circle. The base stations in the network are assigned to different offsets and are therefore synchronous to each other.

Neighboring base stations are typically separated by 12 PN offsets, equal to 625 μs. By comparison, typical values for multipath delay spread lie between a few hundred nanoseconds and a few microseconds. As a result, pilot signals from neighboring base stations are clearly distinguishable from any multipath rays.

The sync channel is assigned to Walsh code 32 and used for system timing. The base station transmits several messages on that channel at a data rate of 1.2 Kbps. One of the messages is the pilot PN offset, which is a reference point for the short PN sequence. Another message is the value of the long-code generator advanced by 320 ms. That is used to offset or rotate the mobile's PN generator and align it to the base station. In CDMA IS95, the base stations rely on the global positioning system (GPS) for system timing and to establish a synchronous network. The following messages also are transmitted by way of the sync channel: the communication air interface (CAI) reference level,

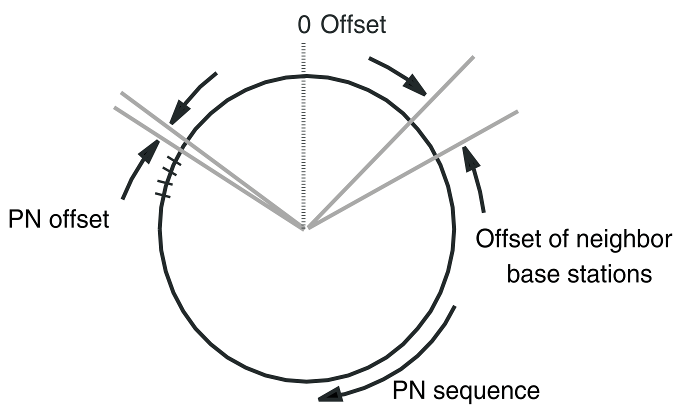

Figure 2.8 Short PN sequence written in circular form to show pattern and rotation of PN offsets.

5. The offsets indicate a rotation in time of a common PN sequence.

the system identification (SID) number, and the paging channel data rate (9.6, 4.8, or 2.4 Kbps).

The paging channel is used to control the base station to mobile link and is assigned to one of seven Walsh channels (codes 1–7). The base station uses this channel to wake up the mobile, respond to access messages, relay overhead information, and support handoff functions. It communicates several overhead messages, including the neighbor list. The neighbor list contains the PN offsets of nearby base stations, which accelerates pilot acquisition during handoff in a synchronous network. The paging channel also assigns the subscriber to one of the available traffic channels.

Traffic channels are assigned to the remaining 55 Walsh codes. These channels carry information at one of two primary rates: 8 Kbps (rate set 1) and 13 Kbps (rate set 2).[6] It is possible to lower the voice data rate during low speech activity periods, such as pauses that occur during listening, by using a variable rate vocoder (Chapter 4 covers speech coding) [8]. These algorithms support full, half, quarter, and one-eighth data rates that reduce system interference.

Table 2.1 summarizes the data rates and the channel coding characteristics of forward-link channels.

The message data are divided into blocks known as frames. Each frame consists of 192 symbols and spans 20 ms. This is a convenient period because speech signals appear pseudostationary over short periods of time, typically 5 to 20 ms, while longer periods of time produce noticeable distortion to the listener. Each 20-ms block of speech is analyzed to determine its content and to set the vocoder rate.

Each speech frame is appended with CRC and tail bits, as shown in Figure 2.9. The CRC is a parity check that is available at most data rates[7] and

Table 2.1
Forward-Link Channel Parameters for CDMA IS95 System

Channel	Data Rate (Kbps)	Channel Coding	Access Method	Processing Gain
Pilot	—	None	Walsh 0	—
Sync	1.2	Rate 1/2	Walsh 32	1024
Paging	4.8, 9.6	Rate 1/2	Walsh 1-7	128, 256
Traffic				
Rate set 1	1.2*N*	Rate 1/2	Walsh 8-31, 33-63	1024/*N*
Rate set 2	1.8*N*	Rate 1/2		682.6/*N*

6. The rates in Table 2.1 are higher because these include parity bits.
7. The CRC is available at full and half rates for rate set 1 and all rates for rate set 2.

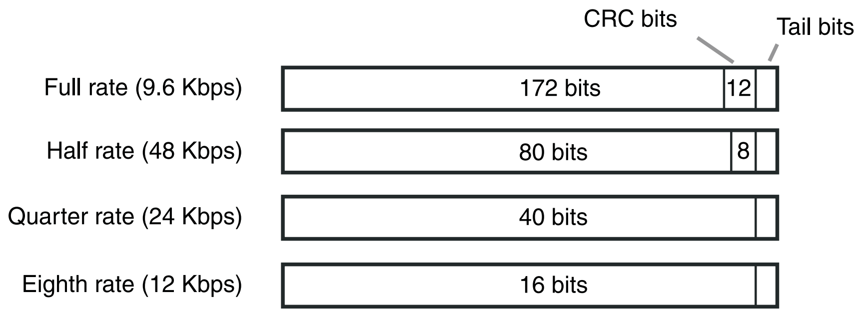

Figure 2.9 Forward-link frame structure in CDMA IS95 systems.

is used to assist rate determination. The tail bits are used to flush out the convolutional encoder after each frame is processed.

The variable rate vocoder increases the capacity of the CDMA IS95 communication system. That is because at half-rate, each symbol is transmitted twice at one-half the nominal power; at quarter-rate, each symbol is transmitted four times at one-fourth the nominal power; and at eighth rate, each symbol is transmitted eight times at one-eighth the nominal power. That achieves the same energy per bit at the receiver but progressively lowers the transmit power.

Another way to increase capacity in a communication system is to limit the transmit energy outside the channel bandwidth. The base station transmitter includes a bandwidth-shaping filter for that purpose. It is a Chebyshev equiripple finite impulse response (FIR) filter with an extremely narrow transition band. The transmitter also includes an all-pass filter to compensate for group delay distortion expected at the mobile radio receiver. Group delay and phase distortion are critical parameters for phase-modulated communication systems.

Table 2.2 lists the minimum performance requirements for a cellular-band mobile radio receiver.[8] For these tests, the connecting base station transmits a full suite of channels at defined power levels. The CDMA IS95 standard does not provide any additional information regarding the mobile radio receiver. Its design is proprietary to each manufacturer and is extremely challenging.

2.2.2 Reverse Link

The mobile radio transmits signals to the base station and thereby forms the reverse link, or uplink. It employs the reverse-link modulator to protect the message signal against radio propagation impairments and to align to system

8. The minimum performance requirements specify the power levels assigned to the pilot, sync, paging, and interfering users as well as the desired user.

Table 2.2
Minimum Performance Requirements for CDMA IS95 Mobile Radio Receiver

Parameter	Conditions	Requirement
Sensitivity	FER < 0.005	–104 dBm
Maximum input	FER < 0.005	–25 dBm
Single tone desensitization	Adjacent channel @ –30 dBm FER < 0.01	–101 dBm
Low-level intermodulation distortion (IMD)	Adjacent channel @ –40 dBm FER < 0.01	–101 dBm
High-level IMD	Adjacent channel @ –21 dBm Alternate channel @ –21 dBm FER < 0.01	–79 dBm

timing. The reverse-link modulator is shown in Figure 2.10 and its operation is outlined next.

Unlike the forward link, it is nearly impossible to establish truly orthogonal traffic channels on the reverse link. That is because the mobile radios are located randomly in the cell area, at different distances to the base station, and with different propagation delays. As such, synchronization breaks down and spreading codes become less effective. Mobile radios are further constrained by portable operation and other consumer form-factor requirements. Consequently, the reverse-link modulator is comparatively simple, and the performance burden of the reverse link is shouldered by the base station.

The input to the reverse-link modulator is digital data from the vocoder or an application. The signal is encoded and repeated to fill the frame buffer. The data is then interleaved and Walsh-modulated. Each frame is then divided into 16 equal sets of data called power control groups. When the vocoder is running at less than full-rate, the repeater and the interleaver work together to produce duplicate sets of data within the frame. The details are fed forward to control the data burst randomizer, which pseudorandomly blanks redundant data. The transmitter is punctured off (turned off) during blank periods, thereby lowering its time-averaged output power. The resulting data stream is then multiplied by the masked long code and randomized by the I and Q channels short PN codes. Both the short and long codes are synchronized to the base station using information received on the sync channel.

Walsh modulation is a 64-ary modulation method that translates 6-bit symbols to one of 64 modulation states. Each modulation state is a 64-bit entry from the 64-by-64 Hadamard matrix used by the forward-link modulator. The difference is that here the Hadamard matrix is used to define the distinct

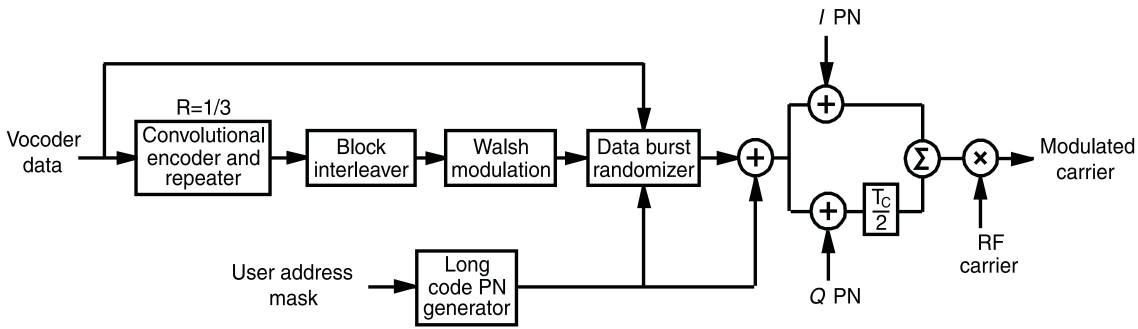

Figure 2.10 Reverse-link modulator for CDMA IS95 mobile radio.

points (or modulation states) of the constellation and is not used for spreading or multiple access.

The reverse link contains two types of channels, as shown in Figure 2.11. The access channel is the complement to the forward link's paging channel. It is used to originate calls, respond to pages, register the mobile phone, and communicate other overhead messages. It transmits data at 4.8 Kbps. The other type of channel is the traffic channel, which carries the message signal and uses the Walsh code assigned by the base station.

The long code, which is masked by the electronic serial number (ESN) of the mobile, is used to distinguish between CDMA users on the reverse link. (The masking operation is described in Section 5.1.2.) It provides pseudo-orthogonal PN spreading of the users on the reverse link based on its autocorrelation properties. There are up to 32 access channels (for each dedicated paging channel) and as many as 62 traffic channels on the reverse link. In practice, fewer traffic channels are allowed because of minimum performance requirements.

Table 2.3 summarizes the data rate and channel coding characteristics of reverse-link channels. Table 2.4 lists the minimum performance requirements for the mobile radio transmitter. The requirements ensure the quality of the reverse link and help maximize network capacity.

The waveform quality factor (ρ) measures the modulation accuracy using the cross-correlation of the transmitted signal to the ideal baseband signal [9], that is,

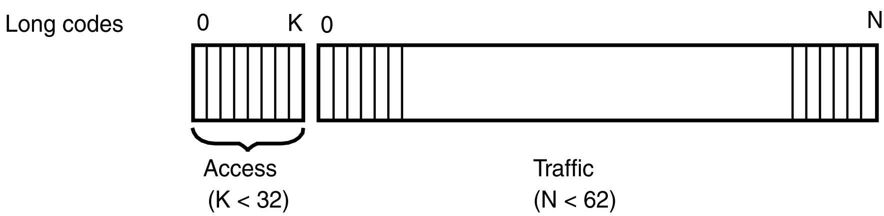

Figure 2.11 Allocation of reverse-link channels in CDMA IS95 systems.

Table 2.3
Reverse-Link Channel Parameters for CDMA IS95 Systems

Channel	Data Rate (Kbps)	Channel Coding	Access Method	Processing Gain
Access	4.8	Rate 1/3	Long-code mask	4
Traffic				
Rate set 1	1.2*N*	Rate 1/3	Long-code mask	4
Rate set 2	1.8*N*	Rate 1/2	Long-code mask	4

Table 2.4
Minimum Performance Requirements for IS95 CDMA Mobile Radio Transmitter

Parameter	Conditions	Capability
Maximum RF level		+23 dBm
Minimum controlled RF level	–50 dBm	
Adjacent channel power	900 kHz offset	–42 dBc/30 kHz
	2.385 MHz offset	–55 dBm/1 MHz
Alternate channel power	1.98 MHz offset	–54 dBc/30 kHz
	2.465 MHz offset	–55 dBm/1 MHz
Waveform quality		$\rho > 0.944$

$$\rho = \frac{\sum_{k=1}^{M} D_k S_k}{\sum_{k=1}^{M} D_k \sum_{k=1}^{M} S_k} \tag{2.17}$$

where S_k is the kth sample of the transmitted signal, D_k is the kth sample of the ideal baseband signal, and M is the measurement period in half-chip intervals. In practice, the waveform quality factor usually measures about or above 0.98 [10].

2.2.3 Power Control Algorithm

The user capacity in direct-sequence CDMA is limited by self-interference and adversely affected by the near-far problem at the base station receiver. Thus, accurate power control of all the mobile radio transmitters in the system is essential and an added challenge for the transceiver design. The receiver includes an automatic gain control (AGC) loop to track the received power level, which varies because of large-scale path loss and small-scale fading. To compensate for those effects, CDMA IS95 employs two power control methods.

The open-loop method uses the power level at the mobile radio receiver (P_{Rx}) to estimate the forward-link path loss. It then specifies the transmit power (P_{Tx}) of the mobile radio as

$$P_{Tx} \approx -73dBm - P_{Rx} \tag{2.18}$$

For example, if the received power level is −85 dBm, then the transmit power level is adjusted to +12 dBm. Note that the response of the open-loop method is made intentionally slow, as shown in Figure 2.12, to ignore small-scale fading.

Adding a feedback signal completes the AGC loop and improves the accuracy of the open-loop method. The feedback signal is an error signal sent from the base station to the mobile radio that instructs the mobile radio to increase or decrease power by a set amount, generally 1 dB. It is sent once per power control group and is therefore updated at a rate of 800 Hz. As such, it is sufficient to support vehicle speeds up to 100 km/h [11]. This second power control method is referred to as closed-loop power control.

2.2.4 Performance Summary

Communication systems are designed to provide high quality services to as many subscribers as possible. The tradeoff between the maximum number of subscribers and the quality of service is not straightforward in CDMA communication networks.

In direct-sequence spread-spectrum CDMA systems, capacity is soft limited by self-interference. The interference in this system was given in (2.14) as $I \approx kS$. In CDMA IS95 systems, that interference is reduced by the lower transmit power due to the variable rate vocoder and is increased by adjacent cells using the same frequency channel. As a result,

$$I \approx kS(1 + f)\nu \tag{2.19}$$

where f is a factor that accounts for "other-cell" interference effects (on average 0.55) [12] and ν is the voice activity rate (typically 3/8 for English speech) [13].

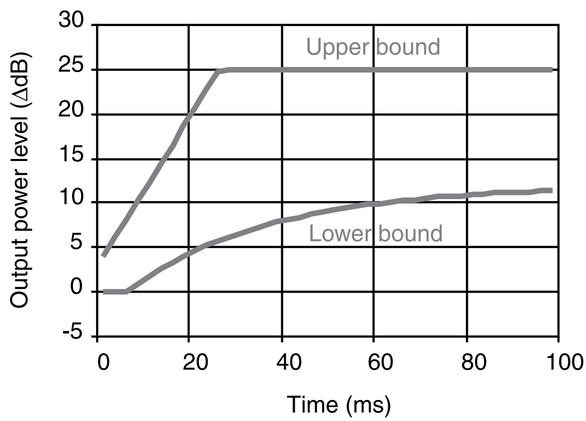

Figure 2.12 Open-loop power response of the mobile radio transmitter.

In practice, where high capacity is needed, each cell is sectored using directional antennas. For a three-sector cell, that provides an antenna gain (G_s) of about 2.5 [14]. Consequently, the capacity of the reverse link of a CDMA IS95 cell is

$$k \approx \frac{G_s}{\nu(1+f)} \frac{W/R}{(E_b/N_o)_{min}} \tag{2.20}$$

where ideal power control is assumed. The minimum value of E_b/N_o depends on the communication channel and the required performance of the receiver. For low mobility, the channel becomes more predictable, power control methods improve, while interleaving breaks down. In that situation, $(E_b/N_o)_{min}$ is about 4 dB and the estimated capacity is 46 users/cell. For high mobility, interleaving performs well but power control falls apart. There, the required E_b/N_o is approximately 6 dB and the estimated capacity is 29 users/cell. Of course, those numbers will be lower with nonideal power control [9].

The forward link is limited differently. Power control within the cell is ideal because all the transmit signals originate from a single base station and experience similar radio propagation effects. (Power control still is needed to minimize cell-to-cell interference.) In CDMA IS95 systems, the forward link is actually limited by available Walsh codes and soft handoff effects. To improve performance through spatial diversity and to assist handoff, a mobile user usually is linked to more than one base station, a situation known as soft handoff. Each connection requires a dedicated traffic channel and Walsh code. In fact, field tests show each user occupies, on average, 1.92 traffic channels. Therefore, the capacity of the forward link is

$$k \approx \frac{m}{1.92} \tag{2.21}$$

where m is the number of Walsh codes. Since $m = 55$, the capacity is 28, which is lower than the reverse link. Surprisingly, the user capacity of CDMA IS95 is limited by the forward link, even though the reverse-link channels are not orthogonal.

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