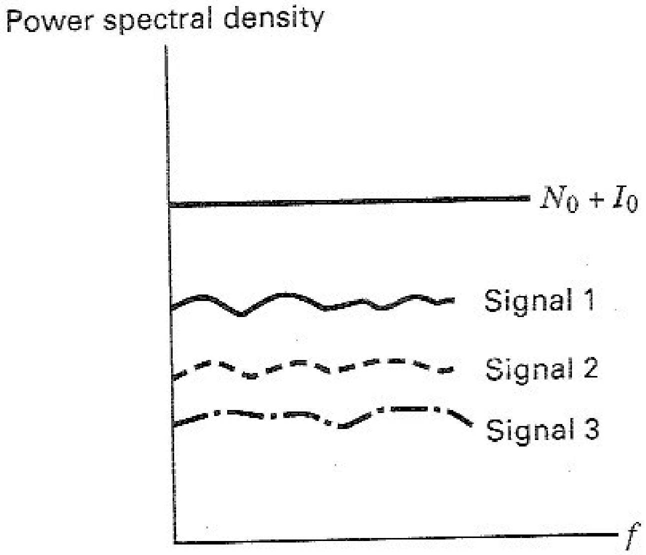

Figure 12.37 Three DS/SS signals occupying the same spectral region.

such a way that no two users are collocated in time and frequency. It is easy to visualize the user transmissions hopping in frequency and time without any contention. However, in the case of direct-sequence spread-spectrum (DS/SS), visualization of the necessary orthogonality conditions (with multiple user's simultaneously occupying the same spectrum) is not as easy. Figure 12.37 shows three different DS/SS signals that are spread over a broad range of frequencies below the level of noise-and-interference power spectral density, $N_0 + I_0$ (assumed to be wideband and Gaussian). An often asked question regarding Figure 12.37 is "How can one of these signals be detected when it is spectrally "buried" below the noise and interference, and it is collocated with other similar signals?" The answer is that the DS/SS receiver correlates the received signal to a particular user's PN code. If the PN codes are orthogonal to each other, then the other users' signals will average to zero during a long observation time. If the codes are not purely orthogonal, they will contribute some interference to the detection process.

In a mobile telephone system using CDMA, each of the users *do* interfere with one another for the following reasons: (1) Two different spreading codes from a family of perfectly orthogonal *long codes* may not yield zero correlation over a short interval of time, such as a symbol time. (2) Serving a large population of users, typically dictates the use of long codes. Such codes can be designed to have low cross-correlation properties but are not orthogonal. (3) Multipath propagation and imperfect synchronization cause interchip interference among the users.

Consider a reverse channel (mobile to base station) in a heavily loaded cell, where the interference caused by the many simultaneous CDMA signals typically outweighs the degradation caused by thermal noise. The assumption is generally made that the thermal noise can be neglected compared with the interference from other users. Thus, for $N_0 << I_0$, the following relationship for the received E_b/I_0, designated as $(E_b/I_0)_r$, can be obtained:

$$\left(\frac{E_b}{N_0 + I_0}\right)_r \approx \left(\frac{E_b}{I_0}\right)_r = \frac{S/R}{I/W_{ss}} = \frac{W_{ss}/R}{I/S} = \frac{G_p S}{I} \tag{12.62}$$

where $G_p = W_{ss}/R$ is the processing gain, W_{ss} is the spread-spectrum bandwidth, S is one user's received power, and I is the interference power from all other users. Equation (12.62) shows that even when the received interference greatly exceeds a user's received power, it is the processing gain (via the mechanism of correlating to a code) that can yield an acceptable value of E_b/I_0. When the base station exercises power control so that each user's received power is balanced, then $I = S \times (M - 1)$, where M is the total number of users contributing to interference at the receiver. It is now possible to express $(E_b/I_0)_r$ in terms of the processing gain and the number of active users in the cell, as follows:

$$\left(\frac{E_b}{I_0}\right)_r \approx \frac{G_p S}{I} = \frac{G_p S}{S \times (M-1)} = \frac{G_p}{M-1} \tag{12.63}$$

Note that the received E_b/I_0 in Equation (12.63) is analogous to the E_b/J_0 for a jammed receiver in Equation (12.41), with J_0 and J replaced by I_0 and I, respectively. CDMA systems are affected by such interference (assumed wideband and Gaussian) in the same way, whether caused by jammers, accidental interferers, or authorized participants. In Equation (12.63), knowing G_p and the *required* E_b/I_0, designated $(E_b/I_0)_{\text{reqd}}$, for a given error performance, the *maximum* number of allowable users (interferers) per cell is

$$M_{\max} \approx \frac{G_p}{(E_b/I_0)_{\text{reqd}}} \tag{12.64}$$

Note that Equation (12.63) indicates that for a heavily loaded cell, a CDMA system is interference limited. For example, if the number of active users occupying a cell were to suddenly double, then the *received* E_b/I_0 would essentially be halved. Also, by examining Equation (12.64), it can be seen that any reduction in $(E_b/I_0)_{\text{reqd}}$ has the effect of increasing the maximum allowable number of users in the cell. The following is a list of other factors that influence the final calculation for the maximum number of allowable users per cell:

- **Sectorizing or Antenna Gain (G_A).** Dividing the cell into three 120° sectors by using a separate directional antenna for each sector, provides a gain G_A of about 2.5 (or 4 dB) in the number of users that can be accommodated.
- **Voice Activity Factor (G_V).** The average speaker pauses about 60% of the time between words and sentences and for listening. Thus, for a CDMA voice circuit, transmission need take place only 40% of the time, whenever there is speech activity. For voice channels, this contributes an improvement factor G_V of about 2.5 (or 4 dB) in the number of users that can be accommodated.
- **Outer-Cell Interference Factor (H_0).** As described in Section 12.8.2, 100% frequency reuse can be employed for CDMA; all neighboring cells can use the same spectrum. Therefore, for a given level of interference I_x originating within a cell, there is additional interference originating outside of the cell. For signal-propagation loss that follows an n = 4th power exponent law (see Section 15.2.1), this additional interference is estimated at about 55% of the within-cell interference [30, 31]. The total interference is therefore approxi-

mately 1.55 I_x, resulting in a user capacity degradation factor H_0 of about 1.55 (or 1.9 dB).

- **Nonsynchronous Interference Factor (γ).** For estimating interference from other (within-cell and outer-cell) users, we assume an identical set of channels (e.g., all voice users requiring the same performance). We further assume that their despread interference can be approximated as a Gaussian random variable, that the users are spatially distributed in a uniform manner, and that power control within each cell is perfect. The worst-case interference comes about if all the interferers are chip and phase synchronized with the desired signal. For a nonsynchronous link, interference will not always be worst case. This lesser interference can be described by a factor γ that modifies Equation (12.64), thereby yielding more users per cell than that of the worst case. Assuming ideal rectangular-shaped chips, γ is equal to 1.5 [31–34]; this value will change for different chip shapes [31].

Using the factors G_A, G_V, H_0, and γ (and their typical values shown above) to determine the maximum possible number of simultaneous users per cell, M', yields

$$M' = \frac{\gamma\, G_A\, G_V}{H_0} \times M_{\max} = \frac{\gamma\, G_p\, G_A G_V}{(E_b/I_0)_{\text{reqd}}\, H_0} \approx 6 \times M_{\max} \tag{12.65}$$

An accurate computation of capacity for a CDMA system is much more involved than Equation (12.65) suggests. The treatment leading to Equation (12.65) assumed perfect power control and a uniform distribution of users' location within cells. Thermal noise was neglected and no provision was made for traffic loading within cells. Terrain variations, which impact the accuracy of assuming an $n = 4$th power exponent law, were not considered. For lower values of n, there is potentially greater interference. The subject of CDMA capacity has been investigated in many publications, particularly in the context of systems designed to meet IS-95. The issue of capacity of CDMA systems is further addressed in [30–32, 35–38]. A very simplified analysis of three multiple access techniques that allow us to illustrate the capacity advantage of CDMA follows.

12.8.2 Analog FM versus TDMA versus CDMA

In 1976, prior to the implementation of cellular communication systems, New York City (with a population exceeding 10 million) could only support 543 simultaneous mobile users—3700 customers were on a waiting list. The cellular concept is illustrated in Figure 12.38 with a 7-cell configuration (one of several used). The idea of dividing a geographical region into cells and allowing the frequency allocation of one cell to be reused at other spatially separated cells represents one of the most important bandwidth-efficiency improvements in radio telephone systems.

In the United States, the frequency allocation for AMPS and other cellular systems is in the range of 869–894 MHz for base station transmit (mobile receive) channels, called *forward* or *downlink* channels, and 824–849 MHz for mobile transmit (base station receive) channels, called *reverse* or *uplink* channels. A single

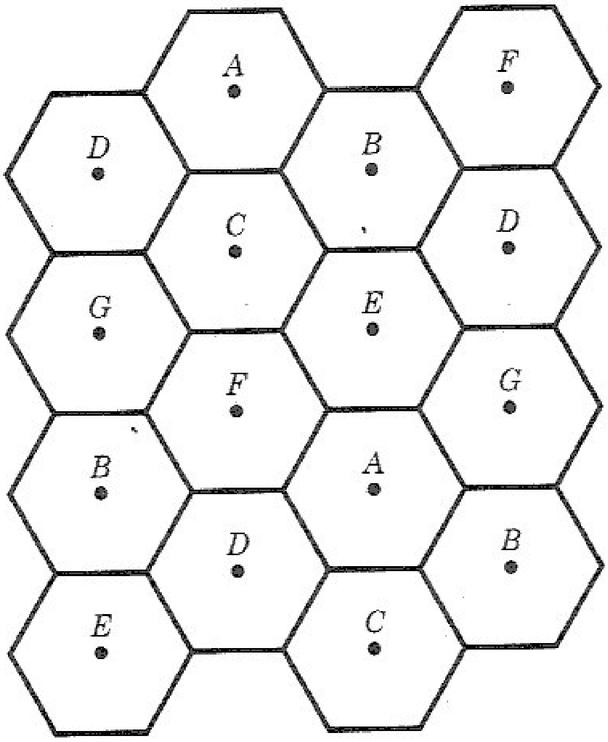

Figure 12.38 Seven-cell structure.

channel occupies a bandwidth of 30 kHz, sometimes called a *subband;* thus, a duplex pair (forward and reverse) occupy 60 kHz. The forward and reverse channels in each duplex pair are separated by 45 MHz. For mobile cellular service, the FCC has allocated each large metropolitan area (there about 750 such areas in the U.S.) 25 MHz for transmit and 25 MHz for receive. To foster competition, there are generally two service-provider companies allocated to each metropolitan area. Thus, each company has a total of 12.5 MHz for transmit and 12.5 MHz for receive.

When considering a wide geographical region made up of many cells, as seen in Figure 12.38, let's compare the capacity in units of channels per cell for three cellular systems: analog FM, TDMA, and CDMA. Computing capacity for the analog FM channels used in the AMPS system is quite straightforward. Consider the 12.5 MHz allocated to a service provider. In order to avoid interference between users operating in the same 12.5-MHz frequency band at comparable power levels, adjacent cells must operate at different frequencies. In the 7-cell configuration of Figure 12.38, communications within cell F may not operate in the same frequency band as communications in cells labeled A, B, C, D, E, and G. Although the service provider has been allocated 12.5 MHz, the frequency reuse pattern involved here dictates that only one-seventh of the allocation can be utilized within each cell. Thus, one-seventh of 12.5 MHz or equivalently 1.78 MHz can be used for transmit (and a similar amount for receive) within each cell. We say that such a 7-cell configuration has a *frequency-reuse factor* of $\frac{1}{7}$. Therefore, the number of 30-kHz subbands for analog FM channels is 1.78 MHz/30 kHz or approximately 57 channels per cell (not counting the control channels).

The U.S. standard describing the multiple access strategy for cellular TDMA is designated IS-54, which has been upgraded to IS-136. Systems designed to these standards must fit into the same frequency plan that was outlined for AMPS.

Therefore, each TDMA channel occupies 30 kHz. Fortunately, capacity improvements have come about only because the discipline of source coding has improved so dramatically since the 1950s. For *terrestrial* digital telephony, each voice signal is digitized to a bit rate of 64 kbits/s. Would a similar standard be used for *cellular* systems? Of course not, because cellular systems are so bandwidth limited. Source coding of speech can now produce telephone-quality fidelity at data rates of 8 kilobit/s, and it can even produce acceptable quality at lower data rates. For purposes of computation, if the often-chosen benchmark value of 10 kbit/s is used, then the capacity computation is again straightforward. Each of the 30 kHz channels can service 30 kHz/10 kbits/s = 3 users per 30 kHz subband. Thus, in TDMA, the number of simultaneous users per cell can be increased by a factor of 3 over the analog FM system. In other words, the number of TDMA channels is 57 × 3 = 171 channels per cell.

The main advantage of a CDMA cellular system over either analog FM or TDMA is that a frequency reuse factor of unity (100%) can be used. This means that the total FCC allocation of 12.5 MHz can be used for transmit (similarly for receive). In order to compare CDMA with the multiple access strategies in AMPS involving analog FM (which we can call FDMA) and IS-54-based TDMA, we start with Equation (12.65), but for a fair comparison, we eliminate the antenna gain factor G_A achieved through sectorizing the cell. The reason for this elimination is that G_A was not used in calculating the capacity for FDMA or TDMA, although both systems would also benefit from sectorization. Hence, the capacity of CDMA without sectorization becomes

$$M'' = \frac{\gamma\, G_p\, G_V}{(E_b/I_0)_{\text{reqd}}\, H_0} \tag{12.66}$$

Equation (12.28) then gives the processing gain

$$G_p = \frac{R_{\text{ch}}}{R} = \frac{12.5 \text{ Mchips/s}}{10 \text{ kbits/s}} = 1250 \tag{12.67}$$

Note that the chip rate of 12.5 Mchips/s is *not consistent* with IS-95 standards. It is used here to equitably compare CDMA across the entire allocation of the 12.5 MHz bandwidth, the same bandwidth used for analog FM and TDMA.

Selecting a nominal value of $(E_b/I_0)_{\text{reqd}}$ to be 7 dB (or the factor 5) [30], and for the factors G_V, γ, and H_0, using the values 2.5, 1.5 and 1.55, respectively, as described in Section 12.8.1, we then use Equation (12.66) to obtain

$$M'' = \frac{1.5 \times 1250 \times 2.5}{5 \times 1.55} \approx 605 \tag{12.68}$$

In summary, FDMA, using analog FM, TDMA, and CDMA, support 57, 171, and 605 channels per cell, respectively. Hence, it can be said that, in a given bandwidth, CDMA can exhibit about 10 times more user capacity than AMPS, and about 3.5 times the capacity of TDMA. It should be noted that the simple analysis leading to Equation (12.68) does not take into account other considerations, such as flat fading (see Chapter 15), which is sometimes encountered and may degrade the results of Equation (12.68). It should also be emphasized that the analysis was based on a CDMA reverse link, where unsynchronized users with long codes were assumed. In the forward direction (base station to mobile) orthogonal channelization can be used, which would improve the results of Equation (12.68).

It is difficult to compare CDMA with TDMA/FDMA in a fair way. On a single-cell basis, TDMA/FDMA capacity is dimension limited, while CDMA capacity is interference limited (discussed in the following section). From a multi-cell system view, all the systems are eventually interference limited. They attempt to optimize capacity with the following trade-offs. TDMA/FDMA systems trade-off larger reuse factors at the expense of greater interference. CDMA systems trade-off increased loading at the expense of greater interference.

12.8.3 Interference-Limited versus Dimension-Limited Systems

The interference in a properly designed and operating CDMA system is not severe; hence, all users can occupy the same spectrum. Nevertheless, from Equations (12.63) and (12.64), a CDMA system must be classified as interference-limited. Any reduction in $(E_b/I_0)_{\text{reqd}}$ can be translated almost directly into a larger number of simultaneous users. One can therefore see how important the incorporation of error-correction coding is to CDMA systems. An increase in coding gain by only 1 dB, which of course would reduce the $(E_b/I_0)_{\text{reqd}}$ by 1 dB, would yield a 25% increase in the number of allowable active users per cell.

In the context of single-cell operation, an FDMA and a TDMA system can be termed *frequency-dimension* and *time-dimension* limited, respectively. Consider a TDMA system. As time slots are assigned to an increasing number of users, there is no interference at the base station receiver caused by other mobile radios to the reception of a given user (assuming perfect synchronization). The user population can be increased until the number of time slots are exhausted. It is not possible to increase the number of users beyond the time-slot limit without intolerable interference. In a similar way, FDMA is frequency-dimension limited. It is not possible to increase the number of users beyond the frequency band limit without intolerable interference.

CDMA is interference limited because the introduction of each additional user raises the overall level of interference at the base station receivers. Each mobile radio introduces interference as a function of power level, synchronization, and code cross-correlation with other CDMA signals. The number of CDMA channels allowed depends on the level of total interference that can be tolerated. Figure 12.39 illustrates the basic difference between interference-limited systems, such as CDMA, and dimension-limited systems, such as TDMA. Assume that a fixed-size bandwidth is available for both. With TDMA in the context of a single cell, as time slots are filled by an increasing number of TDMA users, there is no interference at the base station receiver (caused by other mobile radios) to the reception of a given user. The number of TDMA users can increase until the number of available time slots is exhausted. It is then not possible to assign another time slot without causing an intolerable amount of interference. With CDMA, the introduction of each addi-

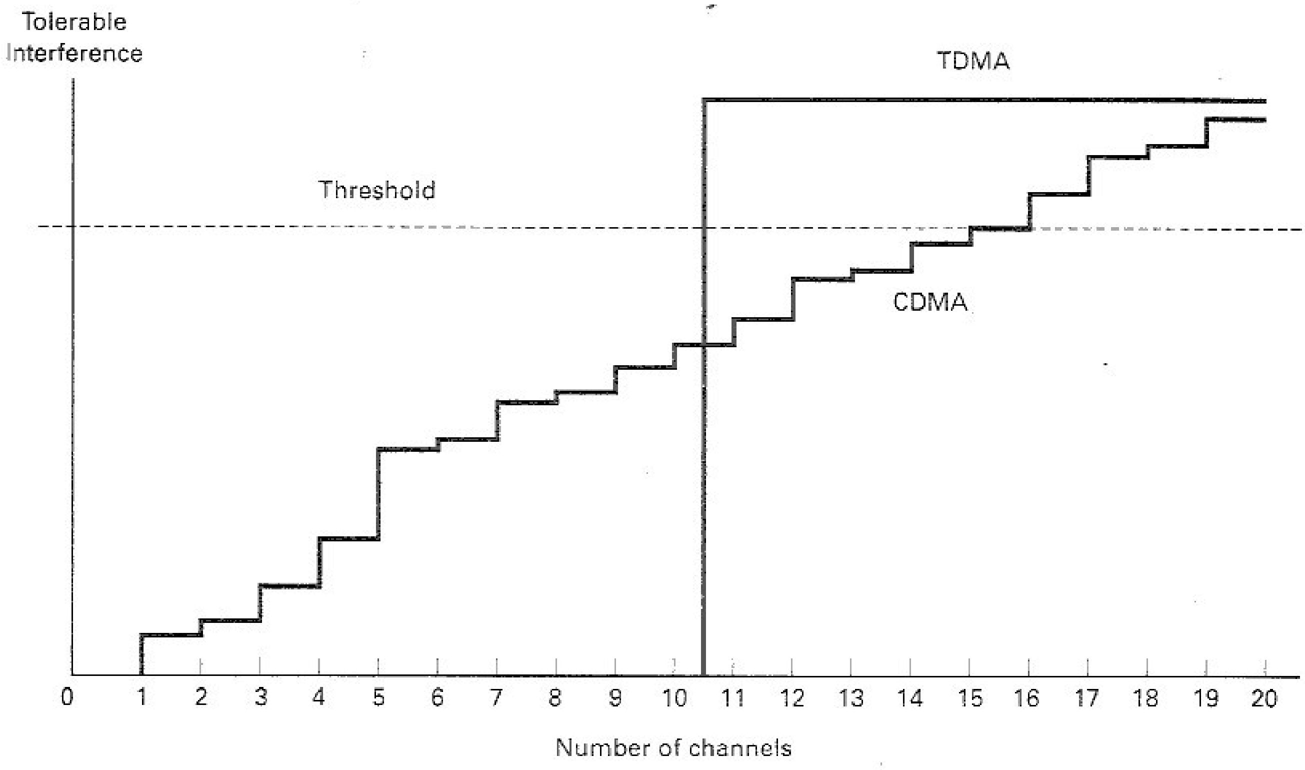

Figure 12.39 TDMA is time-dimension limited. CDMA is interference limited.

tional user raises the overall level of interference to the base station receivers. Each mobile radio might introduce a unique level of interference, owing to differences in power level, timing-synchronization, and cross-correlation with other code signals. Within a cell, channels are assigned to users until some predetermined interference threshold is reached [29]. Figure 12.39 shows that an interference-limited system is inherently more adaptive than a dimension-limited system. For example, on certain days of the year when it is well known that telephone traffic increases (such as Christmas Day and Mother's Day), a CDMA Operations Center can choose to tolerate a bit more interference in order to allow a larger number of users. With dimension-limited systems, no such dynamic trade-off can be made.

It is worth repeating that dimension-limited systems, such as FDMA and TDMA, are strictly dimension limited in the context of a single-cell operation. However, from a multi-cell perspective, one can trade-off frequency reuse factors versus the signal-to-interference (*S/I*) ratio to arrive at an interference-limited situation.

12.8.4 IS-95 CDMA Digital Cellular System

Interim Standard 95 (IS-95) specifies a wireless telephony system that uses direct-sequence spread-spectrum (DS/SS) as a multiple access technique. It was introduced by Qualcomm Corporation, and it was designed to operate in the same frequency band as the U.S. analog cellular system (AMPS), in which full duplex operation is achieved by using frequency division duplexing (FDD). The frequency allocation for AMPS provides 25 MHz in the range of 869–894 MHz for base station to mobile transmission (forward channels), and 25 MHz in the range of 824–849 MHz for mobile-to-base-station transmission (reverse channels). The IS-95 implementation strategy has been to introduce this code-division multiple-access (CDMA) system 1.25 MHz at a time, using dual-mode (AMPS and CDMA) mobile units. Being interference limited, systems designed to meet IS-95 specifications utilize various signal processing techniques to help reduce the $(E_b/N_0)_{\text{reqd}}$. The basic waveform, coding, and interference suppression features of such systems are outlined as follows:

- Each channel is spread across a bandwidth of about 1.25 MHz and filtered for spectral containment.
- The chip rate R_{ch} of the PN code is 1.2288 Mchips/s. The nominal data rate, known as Rate Set 1 (RS1), is 9.6 kbits/s, making the processing gain $G_p = R_{\text{ch}}/R = 128$. An extension to the original IS-95 introduced Rate Set 2 (RS2) at 14.4 kbits/s.
- The data modulation is binary phase-shift keying (BPSK), with quadrature phase-shift keying (QPSK) spreading. (Each quadrature component of the carrier wave is a BPSK signal modulated with the same data.)
- Convolutional coding with Viterbi decoding is used.
- Interleavers with a 20-ms time span are used for time diversity.
- Path diversity is exploited with a Rake receiver, and spatial diversity is implemented with two receive antennas per cell sector.
- Orthogonal code multiplexing is used for channelization.
- Power control is used to minimize transmitted power and thereby reduce interference.

The forward link comprises four types of channels: pilot, synchronization (SYNC), paging, and traffic. The reverse link comprises two types of channels: access and traffic. The history of IS-95 involves several standard committees and versions, with numbers such as IS-95A, JSTD-008, IS-95B, and IS-2000. IS-95B is a merging of IS-95-based methods for the cellular frequency band and the personal communication services (PCS) frequency band, for both voice and data. It provides data rates up to 115.2 kbits/s by aggregating up to eight RS2 channels. IS-2000 is a specification used to denote third-generation CDMA wireless systems, known as multicarrier systems and having an assortment of new features. The treatment of CDMA in this section focuses on the original IS-95; the original structure remains valid for all IS-95-based variations, because they all share the basic architecture of the original system.

12.8.4.1 Forward Channel

The base station transmits a multiplex of 64 channels containing one pilot channel, one SYNC channel and at least one paging channel. The remaining 61 (or fewer) channels transmit user traffic. The IS-95 standard supports simultaneous transmission of voice, data, and signaling; variable rates for speech signals of 9600,

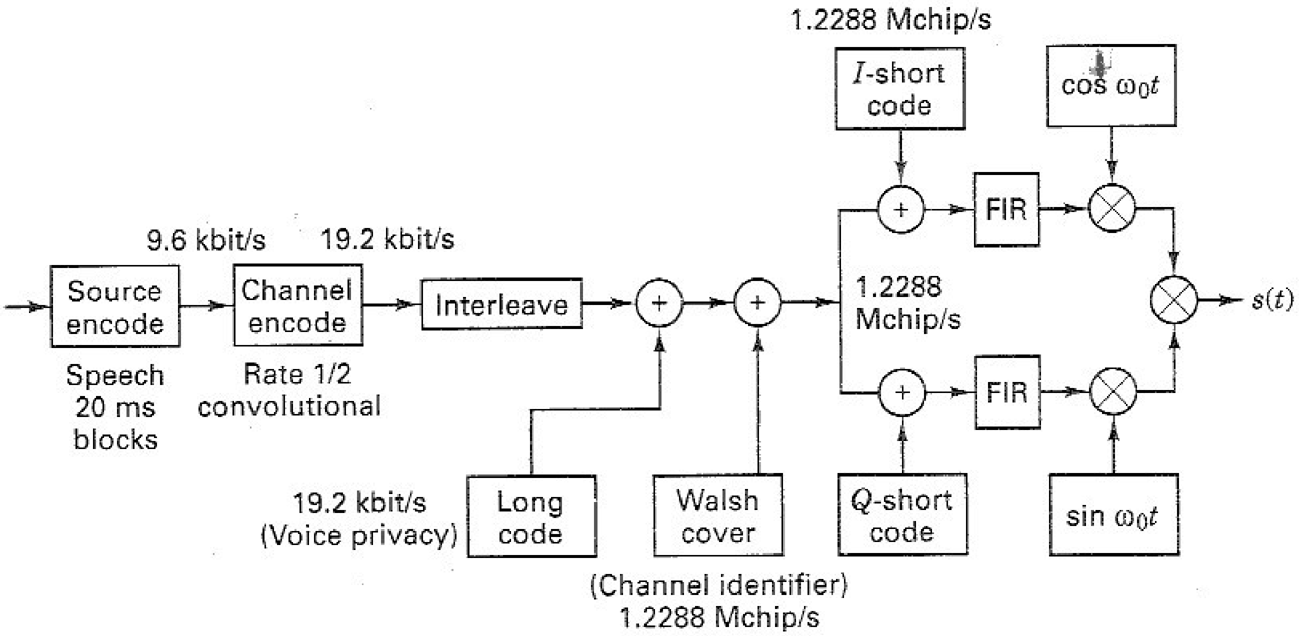

Figure 12.40 CDMA forward-traffic channel with full-rate speech.

4800, 2400, and 1200 bit/s are permitted. These rates are known as Rate Set 1. (Rate Set 2 supports up to 14.4 kbit/s.) Figure 12.40 is a simplified block diagram of the base station transmitter, implementing a typical 9.6 kilobits/s traffic channel. Using a linear predictive coding (LPC) algorithm (see Section 13.4.2), voice is first digitized to yield approximately 8 kilobits/s of raw digital speech. Error-detection bits are added, bringing the digital rate to 9.6 kilobits/s. The bit sequence is then processed in frame lengths of 20 ms. Hence, each 9.6 kilobits/s frame contains 192 bits. The next step shown in Figure 12.40 is convolutional coding (rate $\frac{1}{2}$, $K = 9$), where all information bits are equally protected. This brings the channel bit rate to 19.2 kilobits/s, which remains unchanged after interleaving by a block interleaver, with a span equal to one frame length of 20 ms. The next three steps involve the modulo-2 addition of binary digits representing different PN codes and orthogonal sequences for privacy, channelization, and base station identification. Each time a code is introduced, it can be thought of as a *barrier* or *door* that separates a specific message from others for a particular reason. Consider the privacy code. It is a *long* PN code implemented with a maximal-length, 42-stage shift register. at the system chip rate of 1.2288 Mchips/s, the code repeats approximately every 41 days. Systems designed to IS-95 specifications employ the same long-code hardware for all base stations and mobile units. To provide each mobile unit with its own unique code for privacy, each mobile is assigned a phase (time) offset of a privacy code. The parties carrying on a conversation do not need knowledge of each other's unique long-code offsets, since the base station demodulates and remodulates all traffic signals it processes. At the point that the privacy code is introduced in Figure 12.40, the channel-bit rate of 19.2 kilobits/s is not yet at the final chip rate. Hence, in the forward direction, the user's private code is applied in decimated fashion; that is, only every 64th bit of the sequence is used (which doesn't take away from the code's uniqueness).

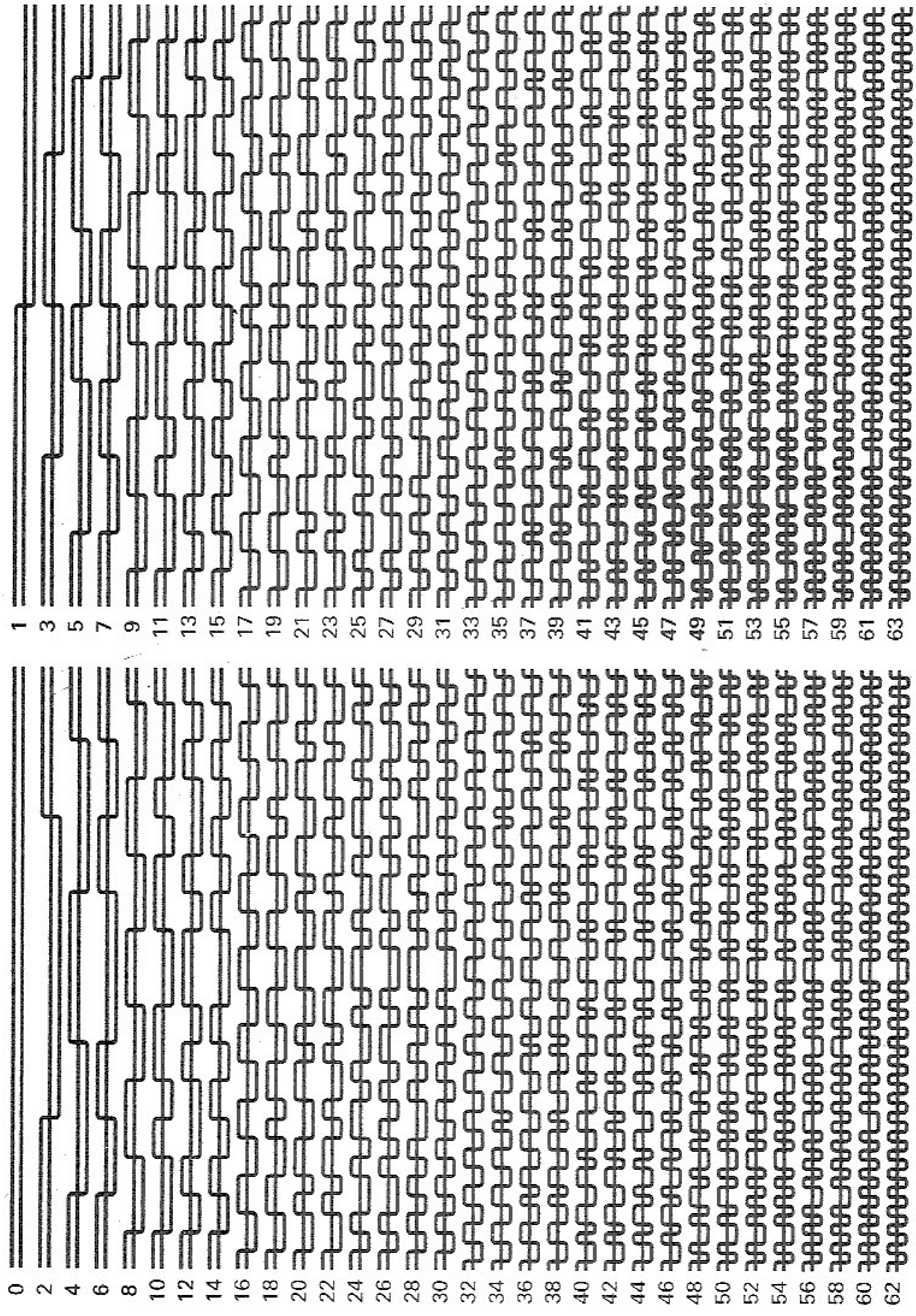

Figure 12.41 The set of 64 Walsh waveforms.

The next code, called a *Walsh cover,* is used for channelization plus spreading. It is an orthogonal code, which is mathematically constructed via the *Hadamard matrix.* (See Section 6.1.3.1 for the construction rules.) Using such a rule, one can form an orthogonal Walsh code of any desired dimension $2^k \times 2^k$, where k is a positive integer. The set of Walsh codes is described by a 64×64 array, where each row generates a different code. One of the 64 Walsh codes is modulo-2 added to the privacy-protected binary sequence, as shown in Figure 12.40. Because each of the 64 members of the Walsh code set are orthogonal to one another, their use in this manner channelizes the forward transmissions into 64 orthogonal signals. Channel number 0 is used as a pilot signal to assist coherent reception at the mobile unit, channel number 32 is used for synchronization, and at least one channel is reserved for paging. That leaves a maximum of 61 channels for traffic use. The Walsh cover is applied at the chip rate of 1.2288 Mchips/s. Thus, in the forward direction, each channel bit (at a rate of 19.2 kilobits/s) is transformed into 64 Walsh chips, producing a final chip rate of 1.2288 Mchips/s. Figure 12.41 illustrates the set of 64 Walsh waveforms. Figure 12.42 shows a simple channelization example using an orthogonal code such as a Walsh code. Unless the receiver applies the correct waveform for accessing a user's channel, the output is zero. Applying the correct waveform yields some nonzero value, A, that "unlocks the door" to that channel.

The next code in the forward direction (see Figure 12.40) is called the *short code* because it is configured with a 15-stage shift register, it repeats every $2^{15} - 1$ chips, and one period lasts 26.67 ms. This final "cloak" or "barrier," applied in quadrature at the chip rate of 1.2288 Mchips/s, provides scrambling of the signal. All base stations reuse the same Walsh channelization; without such scrambling,

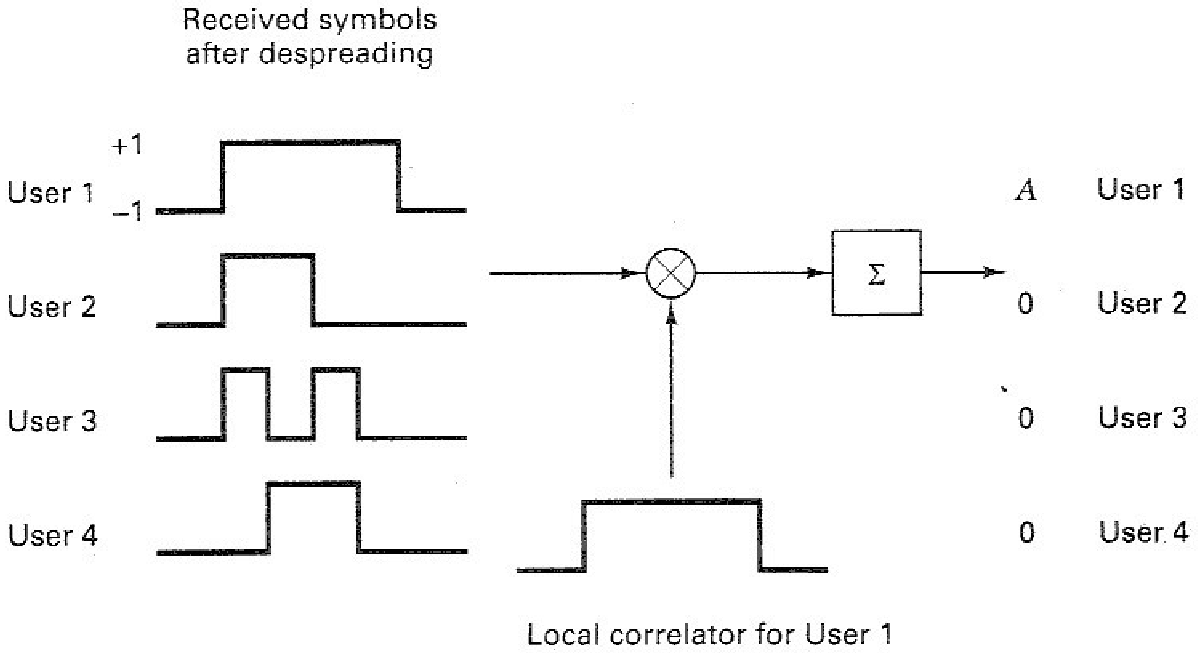

Figure 12.42 Example of channelizing transmissions with orthogonal functions.

the signals from different base stations would be somewhat correlated (which is certainly not desired). The short code can also be thought of as the address of the base station. Its implementation requires two different 15-stage shift registers: one for the inphase (*I*) channel, and one for the quadrature (*Q*) channel. Each base station uses a different 64-chip offset of the *I* and *Q* codes to identify its location; thus allowing for 512 unique addresses. This is deemed to be a sufficiently large number because addresses can be reused at base stations that are sufficiently separated from one another.

To summarize the functions of the three codes: the Walsh code provides orthogonality (for channelization) among all users located in the same cell; the short PN code maintains mutual randomness among users of different cells (for base station addressing); and the long PN code provides mutual randomness among different users of the system (for privacy). For the Walsh code to provide perfect orthogonality among channels, all the users must be synchronized in time with an accuracy corresponding to a small fraction of one chip. This is theoretically possible for the forward link because transmissions to all mobiles have a common origin at the base station. However, due to multipath effects, it is more accurate to say that the Walsh codes provide partial orthogonality. To obtain similar benefits on the reverse link would require closed-loop timing control, which is not implemented in IS-95. The reduced complexity is realized at the cost of greater within-cell interference. For third-generation wideband CDMA (WCDMA) systems, this option is present [39].

The last blocks of Figure 12.40 show wideband filtering (1.25 MHz) with finite impulse response (FIR) filters and the heterodyning of a carrier wave with BPSK modulation and QPSK spreading. The same coded bits are simultaneously present on the *I* and *Q* channels, but due to the short-code scrambling, the *I* and *Q* signals are different.

12.8.4.2 Reverse Channel

Each base station can transmit a multiplex of 64 channels, where 61 or fewer channels are used for traffic. But in the reverse direction (mobile to base station), there is just a single channel (signal) being transmitted (access request or traffic). Figure 12.43 depicts a simplified block diagram of a reverse-traffic channel transmission. The general structure is similar to the forward-traffic channel shown in Figure 12.40; however, there are several important differences. In IS-95, the reverse link does not support a pilot channel, since one would be required for each mobile unit. Thus, the reverse-channel signal is demodulated noncoherently at the base station. (In IS-2000, a pilot signal is provided for each reverse channel.) Since the reverse channel is less robust than the forward channel, a more powerful rate $\frac{1}{3}$ convolutional code is used to improve performance. Also, following the interleaver, notice that the channel bits modulate a 64-ary Walsh waveform. This is the same type of waveform that was used for channelization in the forward direction. However, in the reverse direction, Walsh waveforms are used for a totally different purpose: They become the modulating waveforms. Assuming a data rate of $R = 9.6$ kilobits/s, two information bits (which after coding are transformed into six channel bits, sometimes called code

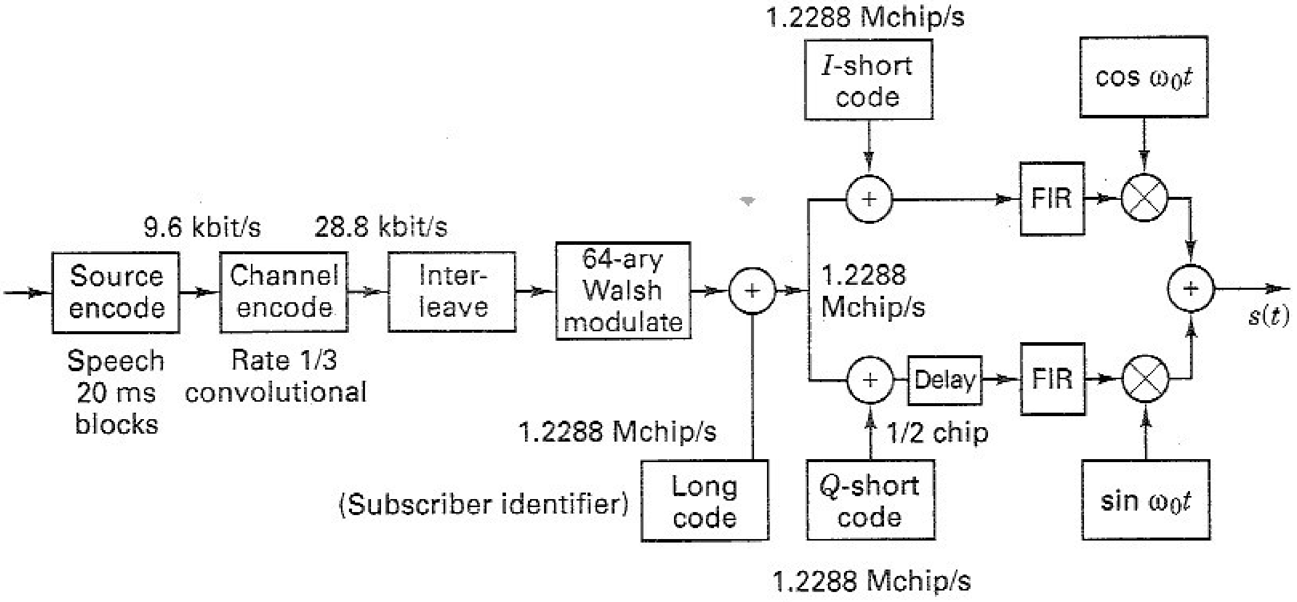

Figure 12.43 CDMA reverse-traffic channel with full-rate speech.

symbols), are mapped after interleaving into one of 64 orthogonal Walsh waveforms to be transmitted. Therefore, the Walsh waveform rate is

$$R_w = \frac{R_c}{\log_2 M} = \frac{R(n/k)}{\log_2 M} = \frac{9600 \times 3}{6} = 4{,}800 \text{ Walsh-symbols/s} \qquad (12.69)$$

where the channel-bit rate R_c is equal to the data rate times the inverse of the code rate, namely, R (n/k). Each of the 64-ary Walsh waveforms is made up of 64 elements, termed *Walsh chips.* Then, from Equation (12.69), we see that the Walsh chip rate is $64 \times 4800 = 307{,}200$ Walsh chips/s. Thus, the modulation has resulted in some spreading (not to the full bandwidth). The Walsh chips are then repeated 4 times to arrive at the final spread-spectrum rate of 1.2288 Mchips/s.

One might ask, "Why were 64-ary Walsh functions chosen as the modulation waveforms?" Consider the trade-offs described in Section 9.7.3 for power-limited channels. A natural choice for conserving power at the expense of bandwidth is M-ary orthogonal signaling such as MFSK. The larger the value of M, the greater will be the bandwidth expansion—yet, the greater will be the reduction in required E_b/N_0 for a specified level of performance. Choosing such a signaling scheme in a narrowband system is a true trade-off—for the price of expanded bandwidth, a reduction in required power is obtained. However, in spread-spectrum systems such as those that meet IS-95 specifications, the selection of 64-ary Walsh waveforms for modulation can be seen as "getting something for nothing," because the spread-spectrum system already occupies an expanded bandwith of 1.25 MHz. The choice of 64-ary orthogonal waveforms does not expand the bandwidth any further. When you look at the Walsh waveforms in Figure 12.41, imagine the pulse shapes to be somewhat rounded. Doesn't this waveform set remind you of MFSK? Well, they are in fact similar, and at the base station, a 64-ary Walsh waveform is (generally) detected noncoherently, much like the noncoherent detection of a 64-ary FSK tone. (Some base station receivers use coherent processing techniques, thereby providing 1-2 dB gain over noncoherent processing.)

One might ask, "Isn't channelization needed in the reverse direction?" Yes. It is always necessary to keep users separated; however, in the reverse direction, one user is distinguished from another via the long (privacy) code. In the forward direction, this code was used in a decimated fashion for privacy. In the reverse direction, as shown in Figure 12.43, the code is applied at the 1.2288 Mchips/s rate for channelization (addressing), and also for privacy, scrambling, and spreading. After spreading by this long code, the waveform is further spread by a pair of short PN codes to assure that the I and Q symbols are uncorrelated. The last blocks in Figure 12.43 show FIR filtering (1.25 MHz) and heterodyning a carrier with BPSK modulation in an offset QPSK (OQPSK) fashion. OQPSK is used in order to eliminate the possibility of the carrier wave changing phase by 180°. (See Section 9.8.1.) This feature reduces the peak-to-average power specification of the transmitter power amplifier, making its design easier. Notice that OQPSK is not used on the forward link since the transmitter sends a multiplex of 64 signals. Each forward transmission consists of a phasor representing the entire muliplex, whose resultant value can be one of a myriad of phase/amplitude possibilities. Hence, there would be no benefit from offsetting the I and Q channels, since carrier transitions through the origin could not be avoided. The final waveform is filtered to generate a spectrum with a 3-dB double-sided bandwidth of 1.25 MHz.

12.8.4.3 Receiver Structures

Mobile Receiver. The mobile receiver demodulates each of the forward-channel quadrature-BPSK waveforms coherently, using the pilot signal as a reference. The receiver structure implements a 3-finger Rake receiver to recover the three strongest multipath components (the minimum as defined in IS-95). The multipath components of the spread-spectrum signal are resolved and separated by the Rake receiver, provided that the differential path delays exceed one chip duration. FDMA waveforms cannot be so separated because they are inherently narrowband. Multipath components of TDMA waveforms can be better separated since each user transmits data in bursts. However, in a typical TDMA system, the bursts produce waveforms that are still too narrowband for multipath resolution at nominal delays. But for CDMA, if the spread-spectrum bandwidth exceeds 1 MHz, any multipath components that are separated by 1 μs delays or greater are separable. The Rake receiver tracks such paths rapidly and combines them constructively (even coherently at the mobile receiver). The operation of the Rake receiver is presented in Section 15.7.2. The soft-decision outputs of the demodulator are processed by a Viterbi decoder. The final step in recovering the information consists of determining which of the four possible data rates (9600, 4600, 2400, or 1200 bits/s) was actually utilized at the transmitter. This is accomplished without any overhead penalty by decoding the demodulated output four times, once for each of the four hypotheses. Several metrics are obtained from the decoding process and also from the pass/fail metrics of the error-detection bits. These are analyzed in order to select one final decoded sequence.

Base Station Receiver. The base station dedicates a separate channel in order to receive the transmissions of each active user in the cell. Each user's reverse-channel 64-ary Walsh-modulated signals are received noncoherently (much like the reception of noncoherent orthogonal MFSK). The receiver structure typically implements a 4-finger Rake receiver to demodulate the four strongest multipath components at the output of two antennas (see Section 15.7.2), which are spatially separated by several wavelengths for diversity reception. The soft-decision outputs of the demodulator are processed by a Viterbi decoder. The final step in recovering the information consists of decoding the demodulated data four times, using a procedure similar to that used in the forward direction, where metrics are compared in order to select one final decoded sequence.

12.8.4.4 Power Control

Power control is a necessity for a system in which many users simultaneously transmit to a base station using the same frequency. Without power control, users transmitting from locations near the base station would be received at power levels much higher than those of users transmitting from locations near the cell's edge. The main goal of power control is to adjust the users' transmitted power so as to provide at the base station an equal (and near constant) received power level from each mobile unit. In order to accomplish this, a key feature of the power-control algorithm is to command users to transmit at power levels that are inversely proportional to the received power level (from the base station). There are three power-control methods specified in IS-95: reverse-link open-loop control, forward/reverse-link closed-loop control, and forward link control.

Reverse-Link Open-Loop Control. The assumption is made that there are similar path losses on a forward and reverse channel, even though this is not completely true since they operate at frequencies that are separated by 45 MHz. The bast station continually transmits a calibration constant (determined by its EIRP) on the SYNC channel. This information allows the mobile unit to use an estimated transmit power in order for the received power at the base station to be the same as that of other mobile units. Consider the following example of an open-loop control algorithm. The mobile transmission power is selected so that its transmission power plus the power received from the base station (reflecting path loss) should equal some value (for example, –73 dBm). This value is a function of the base station EIRP and appears on the SYNC channel. Before a mobile begins its transmission, it determines the power received on the forward link from the automatic gain control (AGC) circuit in its receiver. If the received power is, for example, –83 dBm, then the open-loop power-control algorithm dictates a transmit power of (–73 dBm) – (–83 dBm), or 10 dBm.

Forward/Reverse Link Closed-Loop Control. Power-control bits are sent on the forward link by "stealing" from the channel bits transmitting encoded traffic (resulting in a punctured code). Once every 6 Walsh waveforms, 2 channel bits are replaced with a power-control bit. Since the Walsh waveforms are transmitted at a