UNIT V APPLICATION OF SS SYSTEMS

CDMA - multipath channels - FCC part 15 rules - Direct Sequence CDMA –example - IS95 CDMA Digital Spread Spectrum - Satellite communication – Anti jam military communication - Applications in cellular and mobile communications.

5.1 Code-Division Multiple Access

Spread-spectrum multiple access techniques allow multiple signals occupying the same RF bandwidth to be transmitted simultaneously without interfering with one another. Here we consider CDMA using direct sequence (DS/CDMA). In these schemes, each of N user groups is given its own code, g,(t), where i = 1, 2, . . . , N. The user codes are approximately orthogonal, so that the cross-correlation of two different codes is near zero. The main advantage of a CDMA system is that all the participants can share the full spectrum of the resource asynchronously; that is, the transition times of the different users' symbols do not have to coincide.

A typical DS/CDMA block diagram is shown in Figure 5.1. The first block illustrates the data modulation of a carrier, $A\cos\omega_o t$. The output of the data modulator belonging to a user from group 1 is

$$s_1(t) = A_1(t) \cos [\omega_o t + \Phi_1(t)] \qquad (5.1)$$

The waveform is very general in form; no restriction has been placed on the type of modulation that can be used.

Next, the data-modulated signal is multiplied by the spreading signal g_i (t) belonging to user group 1, and the resulting signal $g_i(t)s_i(t)$ is transmitted over the channel.

Simultaneously, users from group 2 through N multiply their signals by their own code functions. Frequently, each code function is kept secret, and its use is restricted to the community of authorized users. The signal present at the receiver is the linear combination of the emanations from each of the users. Neglecting signal delays, we show this linear combination as

$$g_i(t)s \quad + g_2(t)s_2(t) + \bullet \bullet + g_N(t)s_N(t) \tag{5.2}$$

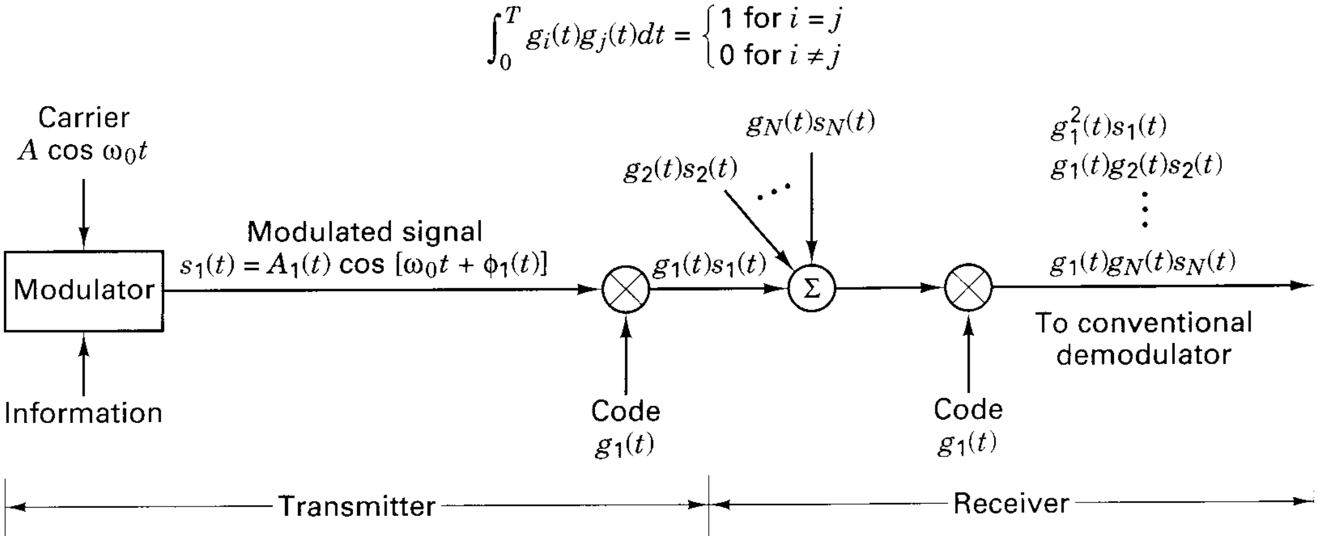

Figure 5.1: Code Division Multiple Access

As mentioned earlier, multiplication of $s_1(t)$ by $g_1(t)$ produces a signal whose spectrum is the convolution of the spectrum of $s_1(t)$ with the spectrum of $g_1(t)$. Thus, assuming that the signal $s_1(t)$ is relatively narrowband compared with the code or spreading signal $g_1(t)$, the product signal $g_i(t)s_1(t)$ will have approximately the bandwidth of $g_1(t)$. Assume that the receiver is configured to receive messages from user group 1. Assume, too, that the $g_1(t)$ code, generated at the receiver, is perfectly synchronized with the received signal from a group 1 user. The first stage of the receiver multiplies the incoming signal of Equation (5.2) by $g_1(t)$. The output of the multiplier will yield the desired signal,

$$g_1^2(t)s_1(t)$$

plus a composite of undesired signals,

$$g_1(t)g_2(t)s_2(t) + g_1(t)g_3(t)s_3(t) + \bullet\bullet\bullet + g_1(t)g_N(t)s_N(t) \tag{5.3}$$

If the code functions $\{g,(t)\}$ are chosen with orthogonal properties, the desired signal can be extracted perfectly in the absence of noise since $f_o^T\ g^2{}_i(t) = 1$, and the undesired signals are easily rejected, since $\int_{0 \text{ to } t} g_i(t)g_j(t)\,dt = 0$ for $i \neq j$. In practice, the codes are not perfectly orthogonal; hence, the cross-correlation between user codes introduces performance degradation, which limits the maximum number of simultaneous users.

Consider the frequency-domain view of the DS/CDMA receiver. Figure 5.2a illustrates the wideband input to the receiver; it consists of wanted and unwanted signals, each spread by its own code with code rate R_{ch}, and each having a power spectral density of the form $\text{sinc}^2(f/R_{ch})$. Receiver thermal noise is also shown as having a flat spectrum across the band. The combined waveform of Equation 5.3 (desired plus undesired signals) is applied to the input of the receiver correlator driven by a synchronous replica of g_1 (t). Figure 5.2b illustrates the spectrum after correlation with the code $g_i(t)$ (despreading). The desired signal, occupying the information bandwidth centered at an Intermediate Frequency (IF), is then applied to a conventional demodulator, with bandwidth just wide enough to accommodate the despread signal. The undesired signals of Equation 5.3 remain effectively spread by $g_i(t)g_i(t)$. Only that portion of the spectrum of the unwanted signals falling in the information bandwidth of the receiver will cause interference with the desired signal.

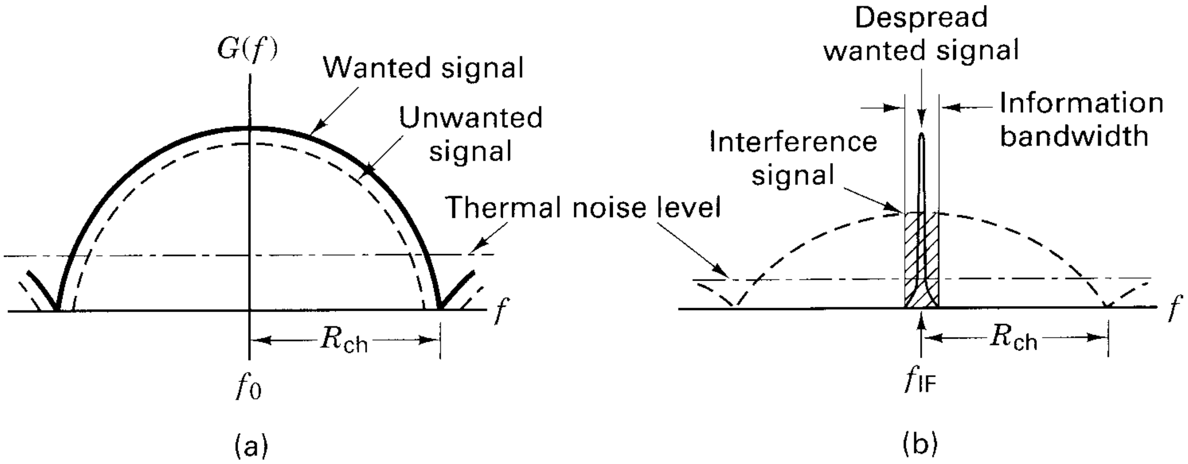

Figure 5.2 Spread-spectrum signal detection. (a) Spectrum at the input to receiver. (b) Spectrum after correlation with the correct and synchronized PN code.

5.2 Multipath Channels

Consider a DS binary PSK communication system operating over a multipath channel that has more than one path from the transmitter to the receiver. Such multiple paths may be due to atmospheric reflection or refraction, or reflections from buildings or other objects, and may result in fluctuations in the received signal level. The different paths may consist of several discrete paths each with a different attenuation and time delay, or they might consist of a continuum of paths. Figure 5.3 illustrates a communication link with two discrete paths. The multipath wave is delayed by sometime τ, compared with the direct wave. In television receivers, signals such as these cause "ghosts," or under extreme conditions, complete loss of picture synchronization

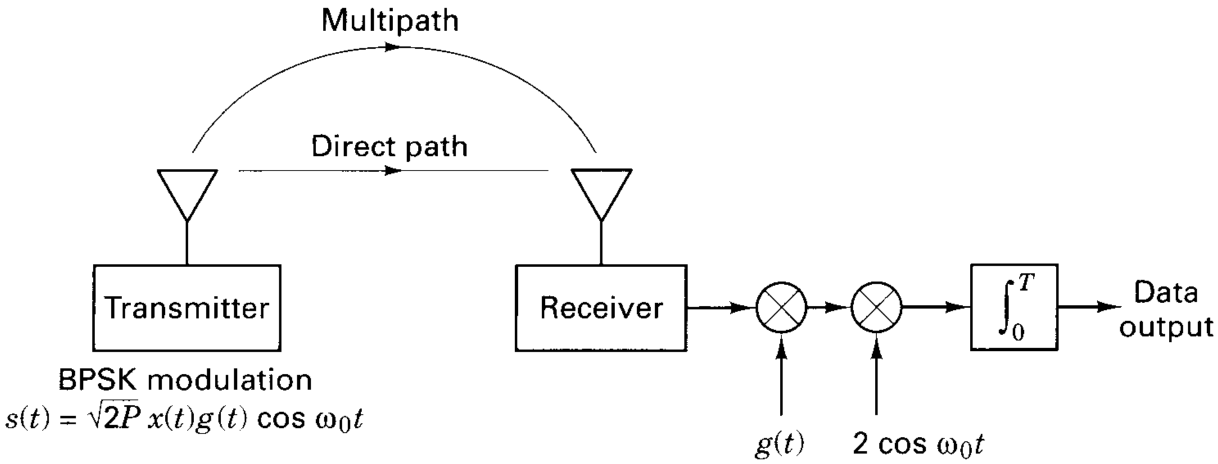

Figure 5.3: Direct-sequence BPSK system operating over a multipath channel.

In a direct-sequence spread-spectrum system, if we assume that the receiver is synchronized to the time delay and RF phase of the direct path, the received signal can be expressed as

$$r(t) = Ax(t)\, g(t) \cos\omega_0^{t} + \alpha Ax(t — \tau)g\,(t — \tau) \cos(\omega_0^{t} + {}^{\theta}) + n(t) \qquad (5.4)$$

where x(t) is the data signal, g(t) is the code signal, n(t) is a zero-mean Gaussian noise process, and T is the differential time delay between the two paths, assumed to be in the interval $0 < \tau < T$ The angle $^{\theta}$ is a random phase, assumed to be uniformly distributed in the range (0, 2п), and α is the attenuation of the multipath signal relative to the direct path signal. For the receiver, synchronized to the direct path signal, the output of the correlator can be written as

$$z(t = T) = \int_0^t [Ax(t)g^2(t)\cos\omega_0 t + \alpha Ax(t-\tau)g(t)g(t-\tau)\cos(\omega_0 t + \theta) + n(t)g(t)]2\cos\omega_0 t \, dt \quad (5.5)$$

where $g^2(t) = 1$. Also, for $\tau > T_c$, $g(t)g(t-\tau) = 0$ (for codes with long periods),

where T_c is the chip duration. Therefore, if T_c, is less than the differential time delay between the multipath and direct path signals, we can write

$$z(t = T) = \int^T 2Ax(t)\cos^2\omega_0 t + 2n(t)g(t)\cos\omega_0 t \, dt = Ax(T) + n_0(T) \quad (5.6)$$

where $n_0(T)$ is a zero-mean Gaussian random variable. We see that the spread-spectrum system, similar to the case of CDMA, effectively eliminates the multipath interference by virtue of its code-correlation receiver.

If frequency hopping (FH) is used against the multipath problem, improvement in system performance is also possible but through a different mechanism. FH receivers avoid multipath losses by rapid changes in the transmitter frequency band, thus avoiding the interference by changing the receiver band position before the arrival of the multipath signal.

5.3 The FCC Part 15 Rules for Spread-Spectrum Systems

In the United States, the Federal Communications Commission (FCC) allows the general unlicensed operation of very lower power (less than 1 mW) radio equipment freely, except in certain restricted frequency bands. In 1985, Dr. Michael Marcus of the FCC was responsible for allowing higher power (up to 1 W) spread-spectrum radios in some of the bands, referred to as Industrial, Scientific, and Medical (ISM). The rules of allowable electromagnetic radiation for unlicensed devices appear in the Code of Federal Regulations (CFR).

The ISM frequency bands are used for instruments (e.g.. medical diathermy equipment) as well as for critical government systems (e.g.. radio location equipment) that radiate strong electromagnetic fields which can cause interference to other users. The ISM bands are particularly noisy bands. An unlicensed radio can be thought of as an "unwelcome guest" in a licensee's band. An unlicensed radio must be able to suffer interference but is not permitted to cause any interference to a licensed user.

For frequency-hopping systems, the Part-15 rules require that the average time of occupancy on any frequency shall not be greater than 0.4 second (or a minimum hopping rate of 2.5 hops/s). For direct sequence systems, the minimum required processing gain is 10 dB. For hybrid systems employing both direct sequence and frequency hopping, the minimum required processing gain is 17 dB. Three ISM spectral regions were designated for the operation of unlicensed spread-spectrum radios. Some of the details regarding the operation in these bands are shown in Table 5.1.

As a result of allowing higher power limits and no FCC licensing as described previously, commercial companies have introduced a wide range of innovative spread-spectrum radios capable of communications over greater distances than earlier low-power narrowband unlicensed radios. Some of these products include radios that link office equipment (e.g., shared printer. wireless local area networks), cordless telephones, wireless point-of-sales equipment (e.g.. cash registers, bar-code readers).

TABLE 5.1 Spread-Spectrum Operation Under Part-15 Rules

ISM Band	Total Bandwidth	Max. Bandwidth per Channel for FH*	Min. Number of Hopping Frequencies per Channel	Min. Bandwidth per Channel for DS*
902-928 MHz	26 MHz	500 kHz	25-50**	500 kHz
2.4000-2.4835 Ghz	83.5 MHz	1 MHz	75	500 kHz
5.7250-5.8500 GHz	125 MHz	1 MHz	75	500 kHz

*Maximum bandwidth per channel for frequency hopping is defined as the 20 dB bandwidth; minimum bandwidth per channel for direct sequence is defined as the 6 dB bandwidth.

**FH channels with bandwidth less than 250 kHz require at least 50 hopping frequencies per channel; FH channels with bandwidth greater than 250 kHz require at least 25 hopping frequencies per channel.

5.4 Direct Sequence versus Frequency Hopping

Without interference from other radios and in free space, both direct-sequence (DS) and frequency-hopping (FH) spread-spectrum radios can, in theory, give the same performance. For mobile applications with large multipath delays. DS represents a reliable mitigation method, because such signaling renders all multipath signal copies that are delayed by more than one chip time from the direct signal as "invisible" to the receiver. FH systems can provide the same mitigation, only if the hopping rate is faster than the symbol rate, and if the hopping bandwidth is large.

Implementing a fast frequency-hopping (FFH) radio can be costly due to the need for high-speed frequency synthesizers. Consequently, hopping rates of commercial FH radios are generally slow compared with the data rate, and hence such systems behave like narrowband radios. Slow frequency hopping (SFH) and DS signaling each experience somewhat different interference. SFH radios typically suffer occasional strong bursty errors, while DS radios encounter more randomly distributed errors that are continuous and lower level. For high data rates, the impact of multipath tends to degrade such SFH radios more than DS radios. To mitigate the effects of bursty errors in FH radios, interleaving would have to be performed over long time durations. SFH is used for providing diversity in fixed wireless access applications or slowly moving systems, or merely to meet the Part-15 Rules. For commercial applications, implementation of DS radios with large processing gain can also be costly due to the need for high-speed circuits; thus, the processing gain for such radios is usually limited to less than 20 dB to avoid having to use high-speed circuits.

5.5 CELLULAR SYSTEMS

Wireless personal communication systems, particularly cellular systems are relatively young applications of the communications technology. The following list includes some of the events that illustrate the evolution of this ever-growing business:

- 1921Radio dispatch service initiated for police cars in Detroit, Michigan.
- 1934 Amplitude modulation (AM) mobile communication systems used by hundreds of state and municipal police forces in the U.S.
- 1946 Radiotelephone connections made to the public-switched telephone network (PSTN).
- 1968 Development of the cellular telephony concept at Bell Laboratories.
- 1981 Ericsson Corporation's Nordic Mobile Telephone (NMT) in Scandinavian countries becomes the first cellular system fielded.

- 1983 Cellular service in the United States—called the Advanced Mobile Phone System (AMPS) and using frequency modulation (FM)—placed in service in Chicago by Ameritech Corporation.
- 1990s Second generation digital cellular deployed throughout the world. The Global system for Mobile (GSM) Communications becomes the pan-European standard. (Prior to GSM, many different cellular systems operating in Europe became operationally impractical.)
- 1990s Second generation digital systems known as IS-54 and its successor 1S-136 (TDMA), and IS-95 (CDMA) become operational in the United States.
- 2000s Third-generation digital systems standardized at the network level to allow world-wide roaming start becoming operational. They offer enhanced services, such as connection to various PSTN systems with a single phone, and connecting to high data rate packet systems such as Internet Protocol (IP) networks.

5.5.1 Direct Sequence CDMA

In the case of FDMA, different frequency bands are orthogonal to one another (assuming ideal filtering), and in the case of TDMA, different time slots are orthogonal to one another (assuming perfect timing). One can visualize a similar orthogonality among different channels in the case of frequency-hopping CDMA (as shown in Figure 5.4) if the codes that control the frequency hopping operate in

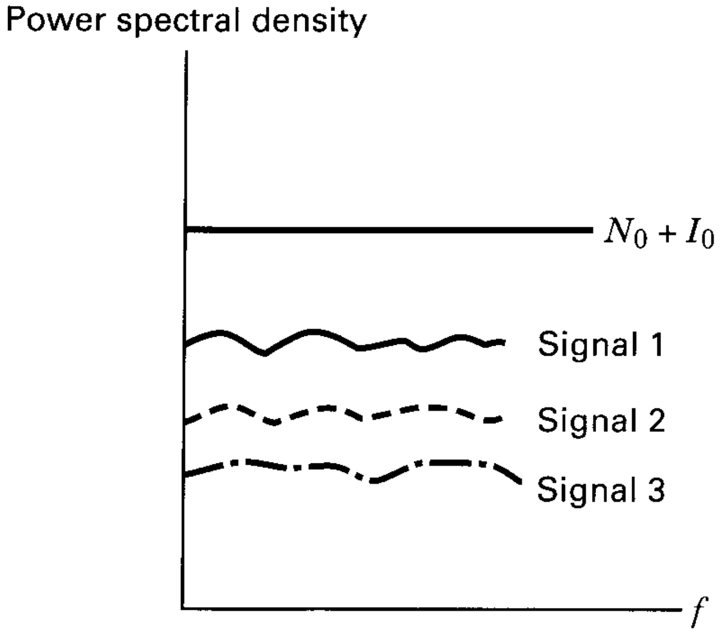

Figure 5.4 Three DS/SS signal occupying the same spectral region.

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 users simultaneously occupying the same spectrum) is not as easy. Figure 5.4 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_o + $/_0$ (assumed to be wideband and Gaussian). An often asked question regarding Figure 5.4 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 $N_o << 1_0$, the following relationship for the received E_b/I_0, designated as (E_b/I_0), can be obtained:

$$\left(\frac{E_b}{N_0 + I_0}\right)_r \approx \left(\frac{E_b}{I_0}\right)_r = \frac{S/R}{I/W_{ss}} = \frac{W_{ss}/R}{I/S} = \frac{G_p S}{I} \qquad (5.7)$$

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 (5.7) 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 x (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:

$$\left(\frac{E_b}{I_0}\right)_r \approx \frac{G_p S}{I} = \frac{G_p S}{S \times (M-1)} = \frac{G_p}{M-1} \tag{5.8}$$

Note that the received E_b/I_o in Equation (5.8) is analogous to the E_b/I_o for a jammed receiver with J_o and J replaced by I_o 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 (5.8), knowing Gp and the required E_b/I_o, designated (E_b/I_o)reqd, for a given error performance, the maximum number of allowable users (interferers) per cell is

$$M_{\max} \approx \frac{G_p}{(E_b/I_0)_{\text{reqd}}} \tag{5.9}$$

Note that Equation (5.8) 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_o would essentially be halved. Also. by examining Equation (5.9), it can be seen that any reduction in (E_b/I_o)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).** 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, this additional interference is estimated at about 55% of the within-cell interference. The total interference is therefore approximately $1.55I_{x,}$ resulting in a user capacity degradation factor H_0 of about 1.55 (or 1.9 dB).
- **Nonsynchronous Interference Factor (y).** 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 vari¬able, 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 sig¬nal. For a nonsynchronous link, interference will not always be worst case. This lesser interference can be described by a factor -y that modifies Equation (5.9), thereby yielding more users per cell than that of the worst case. As¬suming ideal rectangular-shaped chips, -y is equal to 1.5 this value will change for different chip shapes.

Using the factors GA, G_v, H_0, and -y (and their typical values shown above) to determine the maximum possible number of simultaneous users per cell, M', yields

$$M' = \frac{\gamma\, G_A\, G_V}{H_0} \times M_{\max} = \frac{\gamma\, G_p\, G_A G_V}{(E_b/I_0)_{\text{reqd}}\, H_0} \approx 6 \times M_{\max} \tag{5.10}$$

An accurate computation of capacity for a CDMA system is much more involved than Equation (5.10) suggests. The treatment leading to Equation (5.10) 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 = 4th 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. A very simplified analysis of three multiple access techniques that allow us to illustrate the capacity advantage of CDMA follows.

5.5.2 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 5.5 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

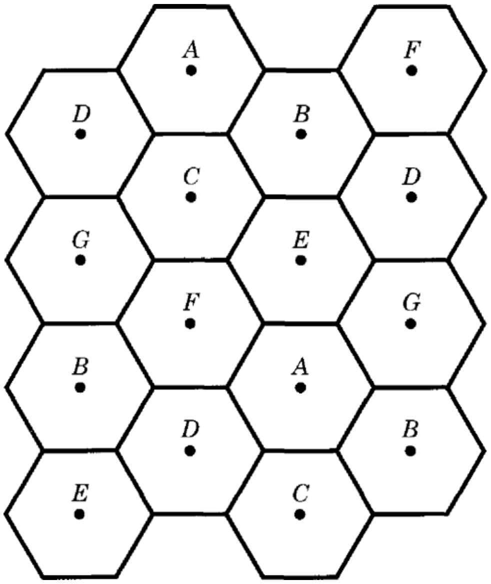

Figure 5.5 Seven cell structure

A single 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 5.5, 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 5.5, 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 Therefore, the number of 30-kHz sub-bands 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 x 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 (5.10), but for a fair comparison, we eliminate the antenna gain factor GA 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

$$M'' = \frac{\gamma\, G_p\, G_V}{(E_b/I_0)_{\text{reqd}}\, H_0} \tag{5.11}$$

$$G_p = \frac{R_{\text{ch}}}{R} = \frac{12.5\ \text{Mchips/s}}{10\ \text{kbits/s}} = 1250 \tag{5.12}$$

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 (Eb/I_0)reqd to be 7 dB (or the factor 5), and for the factors G_v,-y, and H_o, using the values 2.5, 1.5 and 1.55, respectively, we then use Equation (5.11) to obtain

$$M'' = \frac{1.5 \times 1250 \times 2.5}{5 \times 1.55} \approx 605 \tag{5.13}$$

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 (5.13) does not take into account other considerations, such as flat fading, which is sometimes encountered and may degrade the results of Equation (5.13). 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 (5.13).

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 tradeoff increased loading at the expense of greater interference.

5.5.3 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 (5.8) and (5.9), a CDMA system must be classified as interference-limited. Any reduction in $(E_b/I_o)_{reqd}$ 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 $(E_b/I_o,)_{reqd}$ 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 5.6 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 additional 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. Figure 5.6 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.

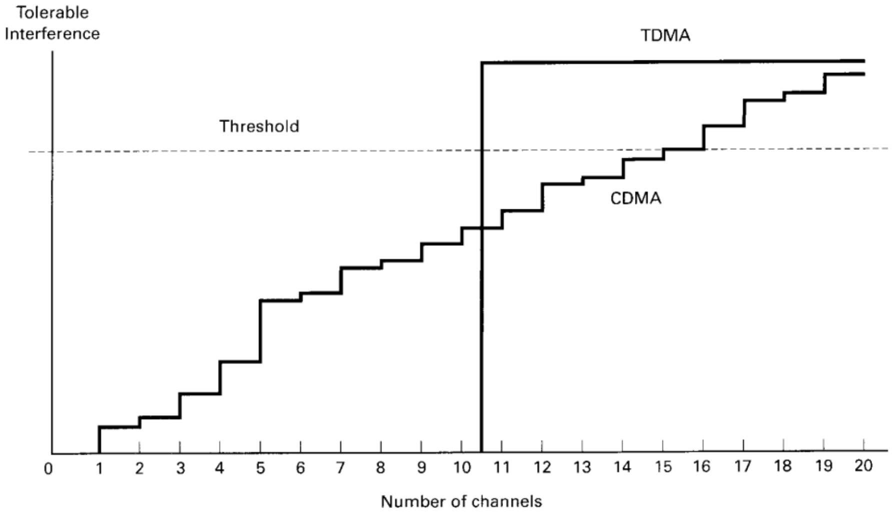

Figure 5.6 TDMA is time-dimension limited. CDMA is interference limited.

5.5.4 15-95 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 $(E_b/N_o)_{reqd}$. 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 $G_p = R_{ch}/R = 128$. 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.
- 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 multi-carrier 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.

5.5.4.1 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.

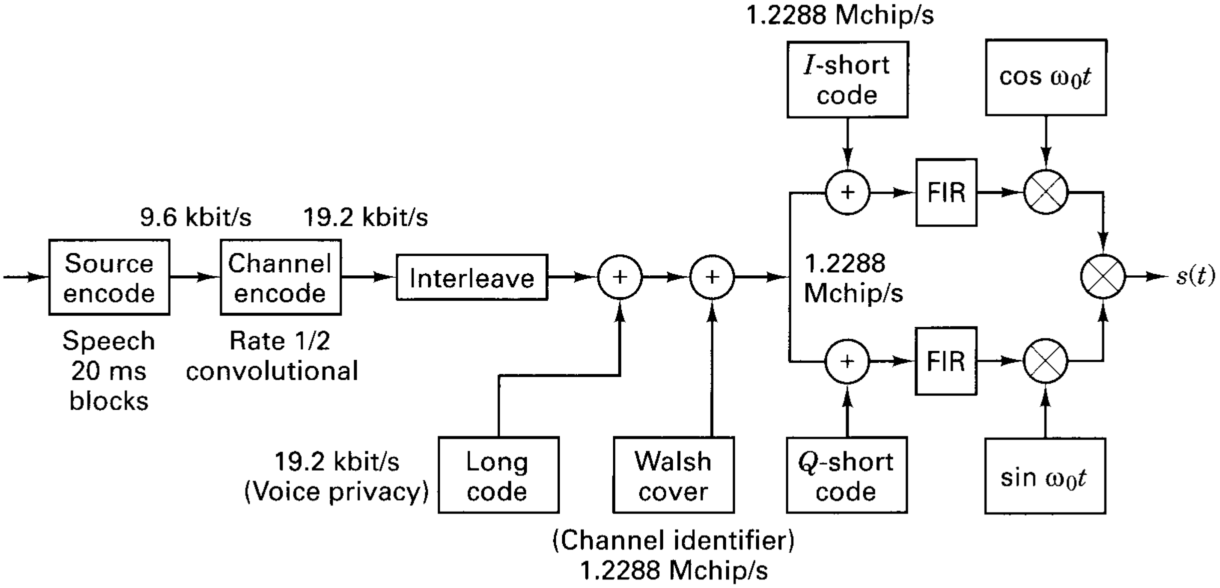

Figure 5.7 CDMA forward-traffic channel with full-rate speech.

4800, 2400, and 1200 bits are permitted. These rates are known as Rate Set 1. (Rate Set 2 supports up to 14.4 kbit/s.) Figure 5.7 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, 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 5.7 is convolutional coding (rate 1, 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 re-modulates all traffic signals it processes. At the point that the privacy code is introduced in Figure 5.7, 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).

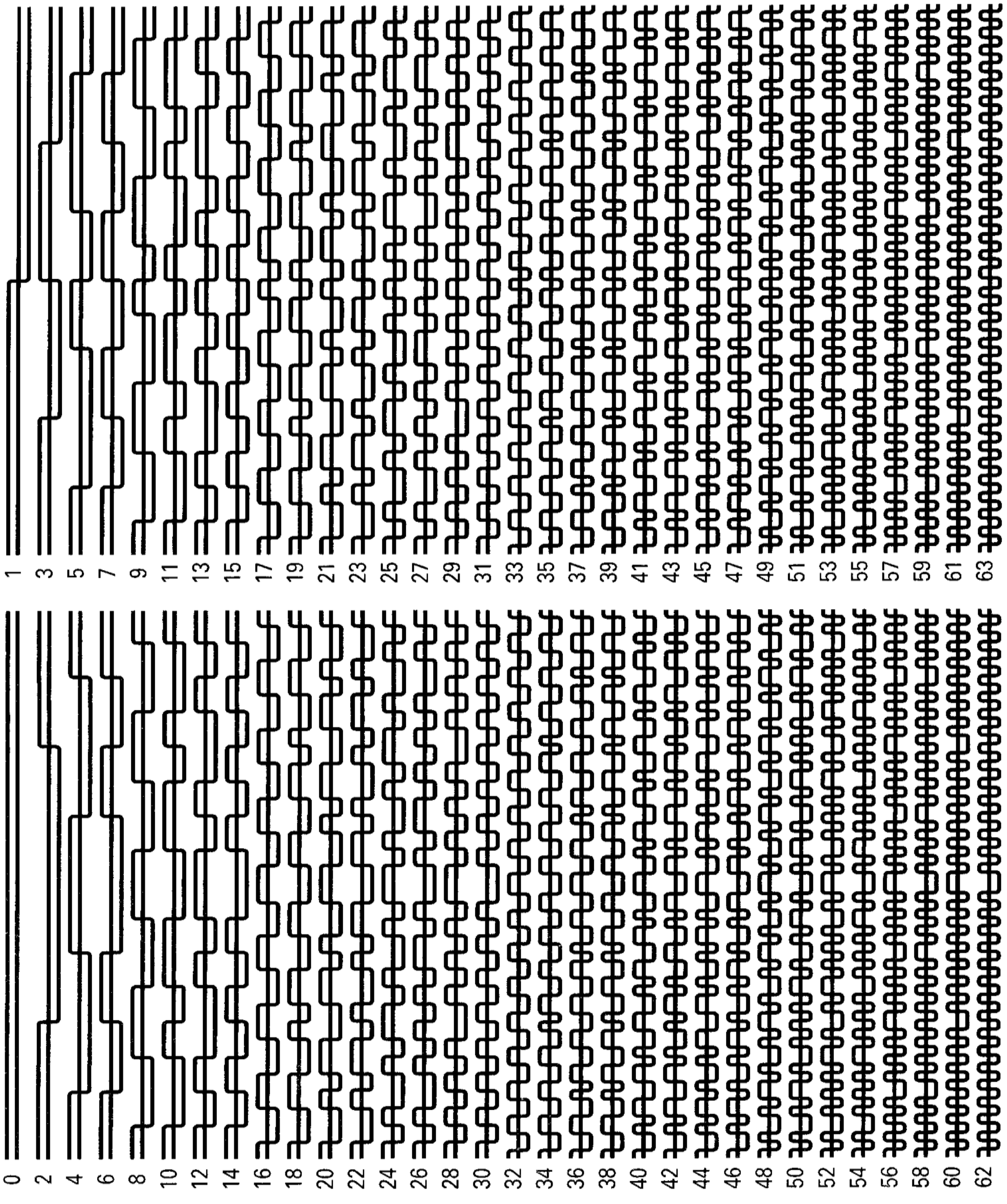

Figure 5.8: The set of 64 WALSH waveforms

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. Using such a rule, one can form an orthogonal Walsh code of any desired dimension 2^k x 2^k, where k is a positive integer. The set of Walsh codes is described by a 64 x 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 5.7. 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 5.8 illustrates the set of 64 Walsh waveforms. Figure 5.9 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 5.7) 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,

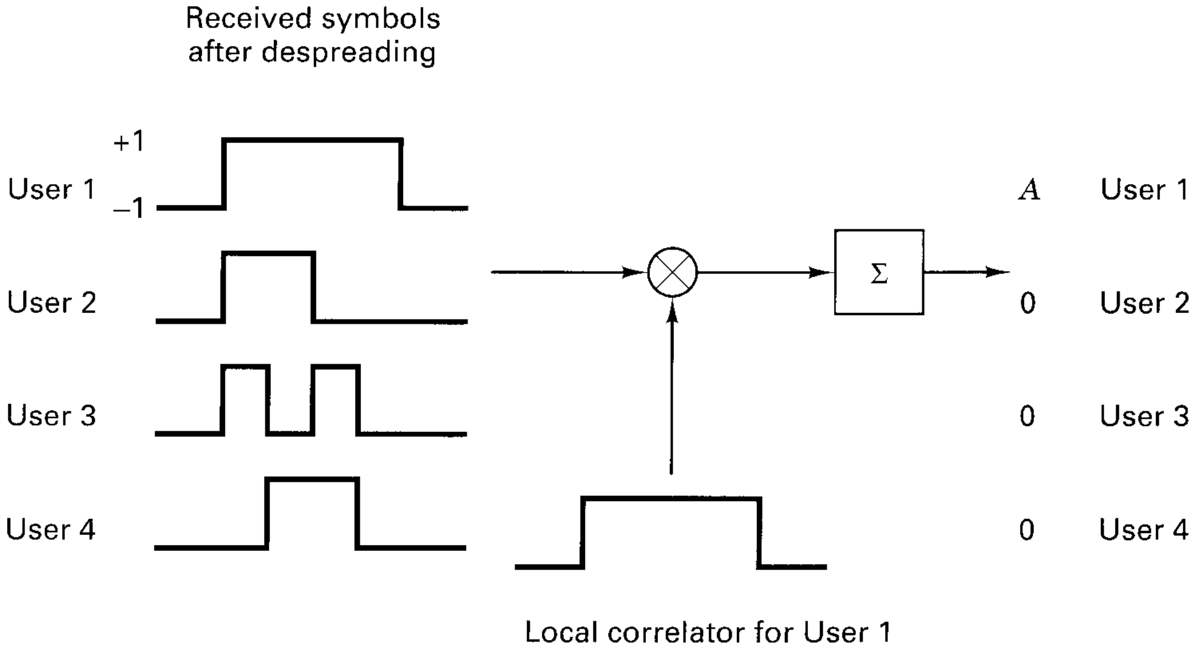

Figure 5.9 Example of channelizing transmissions with orthogonal functions.

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.

The last blocks of Figure 5.7 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.

5.5.4.2 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 5.10 depicts a simplified block diagram of a reverse-traffic channel transmission. The general structure is similar to the forward-traffic channel shown in Figure 5.7; 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 non coherently 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 1/3 convolutional code is used to improve performance. Also, the following interleavers 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 Symbols) are mapped after interleaving into one of 64 orthogonal Walsh waveforms to be transmitted.

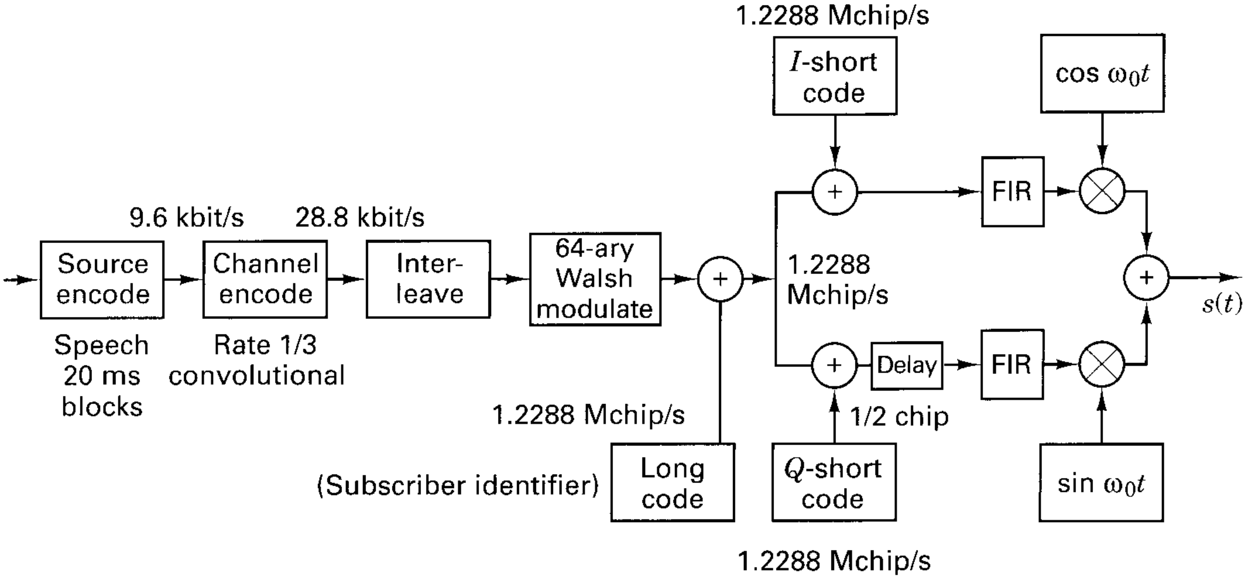

Figure 5.10 CDMA reverse-traffic channel with full-rate speech.

Therefore, the Walsh waveform rate is

$$R_w = \frac{R_c}{\log_2 M} = \frac{R(n/k)}{\log_2 M} = \frac{9600 \times 3}{6} = 4{,}800 \text{ Walsh-symbols/s} \qquad \textbf{(5.14)}$$

where the channel-bit rate R, 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 (5.14), we see that the Walsh chip rate is 64 x 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?" 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_o 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 5.8, 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 5.10, 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 **I** and Q symbols are uncorrelated. The last blocks in Figure 5.10 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°. 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 **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.

5.5.4.3 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. Multi-path 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 **p,S** delays or greater are separable. The Rake receiver tracks such paths rapidly and combines them constructively (even coherently at the mobile receiver). 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 multi-path 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.

5.5.4.4 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 El RP 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

rate of 4800 waveforms/s, the rate at which the power-control bits are transmitted is 800 bits/s. Thus, there are 16 such control bits in each 20 ms frame. The goal of this closed-loop power control is to correct the open-loop power-control estimate every 1.25 ms in steps of 1 dB. Later versions added the option for step sizes of 0.5 dB and 0.25 dB. The most significant benefit of such fast and accurate closed-loop power control is a significant reduction in the average transmitter power on the reverse channel. Analog mobile radios transmit enough power to maintain a link even during fading. Thus, most of the time such analog radios transmit excessive amounts of power. CDMA mobile radios operate at power levels no greater than what is needed to close the reverse link. A mobile unit using CDMA designed to meet IS-95 specifications requires approximately 20 dB to 30 dB less power than a mobile unit operating in an analog AMPS system 130].

Forward Link Control. The base station periodically reduces the power transmitted to the mobile unit. Whenever the mobile senses an increased frame-error rate, it requests additional power from the base station. Adjustments can be made periodically based on reported frame-error rates (FER).

5.5.4.5 Typical Telephone Call Scenario

Turn on and Synchronization. Once power is applied to the mobile unit, the receiver scans continuously in search of available pilot signals. Such signals will be received from different base stations with different time-offsets of the short PN code. The time-offset used by a base station differs by a multiple of 64 chips from all other base stations. Since the short code is maximal length, its 15-stage shift register produces 2^{15} — 1 = 32,767 bits. After ˉbit stuffing" the sequences with one bit, 32,768 bits are produced before the whole process repeats itself. Thus, there are 32,768/64, or 512 available unique addresses. The 512 short PN codes can be generated by a simple time shift of a single PN sequence, because the base stations are time synchronized within a few microseconds of each other. At the chip rate of 1.2288 Mchips s. there are 75 frames of the short code corresponding to a 2-second interval. The zero-offset address of the short code occurs on even second time marks. Consider the case of a base station whose address is represented by offset number 18. Then its transmission cycle begins at (18 x 64 chips x (1/1.2288 x 10^6) s/chip, or 937.5 microsecond after every even-second time mark.

Once the mobile unit completes its scan and is correlated to the strongest pilot signal, it is now synchronized with one of the 512 unique base station addresses. The mobile unit can now despread any of that base station's transmissions; however, it does not yet have system time, which is needed for access, paging, and traffic channels. Next, using the pilot signal as a reference, the mobile unit coherently demodulates the SYNC channel signal (Walsh 32), which the base station transmits continuously. The SYNC channel transmissions provide several system parameters, the key one being the state of a long code 320 ms in the future, giving the mobile unit time to decode, load its registers, and become system-time synchronized. This long code is one of a specific group of long codes used for access and paging. The mobile selects a predefined paging channel based on its serial number, and it monitors this paging channel for incoming calls. The mobile can now register with the base station, which allows for location-based paging rather than system-based paging when there is an incoming telephone call.

Idle-State Handoff. The mobile unit continually scans for alternative pilot signals. If it finds a stronger pilot signal from a different base station, the mobile locks on to the base station with the stronger pilot. Since there is no call in progress, the process simply serves to update the location of the mobile. The mobile has obtained system time from the SYNC channel. If there were only one base station, system time could be defined by whatever reference the base station chooses. With several operating base stations, the handoff process is facilitated if time is coordinated throughout the system. In IS-95, system time is specified to be Universally Coordinated Time (UTC) ± 3 p,s. A practical way to implement this is with the use of a Global Positioning System (GPS) receiver at each base station.

Call Initiation. A call is initiated by the user keying in a telephone number and pushing the send button. This initiates an access probe. The mobile uses open-loop power control, choosing an initial transmission power level estimated from the pilot signal. All access channels use different long-code offsets. At the beginning of an access probe, the mobile pseudorandomly chooses one of the access channels associated with its paging channel. The transmission of an access probe is timed to begin at the start of an access channel slot, which is determined pseudorandomly. A key element of the access procedure involves the identification of the caller's serial number. Identification is needed because the base station cannot discriminate accesses from different users, since the access channel is a common channel.

The mobile-terminal time reference for transmission is determined by the earliest multipath component being used for demodulation. The mobile does not make transmission adjustments to account for propagation delay. Instead, the base station continually searches and tests for the presence of reverse channel signals. The mobile "listens" on the paging channel for a response from the base station. If there is none (collisions can occur during transmission on the access channels), the mobile attempts access again after waiting a pseudorandom time. When the mobile's access probe is successful, the base station response is a traffic channel assignment (Walsh code number).

Traffic channels use different long-code offsets than paging channels. Therefore, the mobile unit changes its long-code offset to one based on its serial number. After receiving the Walsh code assignment, the mobile begins an all-zeros data transmission on the traffic channel, and waits for a positive acknowledgment on the forward traffic channel. If the exchange is successful, the next step is ringing at the telephone that was called. Conversation can then commence.

Soft Handoff During a call, the mobile may find an alternate strong pilot signal. It then transmits a control message to its base station, identifying the new base station with the stronger pilot signal and requesting a soft handoff. The original base station passes the request to a base station controller (BSC) that handles the radio resource control of the link; the BSC may or may not be collocated with a Mobile Switching Center (MSC) that handles the non-radio aspects of the link (e.g., switching). The BSC contacts the new base station and obtains a Walsh number assignment. This assignment is sent to the mobile via its original base station connection. During the transition, the mobile is supported by (connected to) both base stations, and a land link connection is maintained from the BSC to both base stations. The mobile combines the signals received from both base stations by using the two respective pilot signals as coherent phase references. Signal reception from two base stations simultaneously is facilitated by the Rake receiver, since the transmissions from both base stations appear as multipath components to the mobile receiver. At the BSC, where the signals are received noncoherently, the two received signals from the mobile are examined, and the better one is chosen in each 20-ms frame. The original base station drops the call when connection is firmly established in the new cell. Such dual connection, sometimes called "make before break," reduces the probability of a dropped call and of poor reception at a cell's edge.

5.6 CONCLUSION

Spread-spectrum (SS) technology has only emerged since the 1950s. Yet, this novel approach to applications, such as multiple access, ranging, and interference rejection, has rendered SS techniques extremely important to most current NASA and military communication systems. In this chapter we presented an overview enumerating the benefits and types of spread-spectrum techniques, as well as some historical background.

Since SS techniques were initially developed with military applications in mind, we started the treatment with discussions of anti-jam (AJ) systems. Pseudorandom sequences are at the heart of all present-day SS systems; we therefore treated PN generation and properties. Emphasis was placed on the two major spread-spectrum techniques; direct sequence and frequency hopping. Consideration was given to synchronization, a crucial aspect of spread-spectrum operation. Also, attention was devoted to the commercial use of spread-spectrum techniques for code-division multiple access (CDMA) systems, particularly direct-sequence CDMA, as it is specified in interim standard 95 (IS-95).