Chapter 8
Spread Spectrum and CDMA

Chapter 8 Spread Spectrum and CDMA

8.1 Introduction

- Spread spectrum system encompass modulation techniques in which the signal of interest, with an information bandwidth R_b , is spread to occupy

  a much larger transmission bandwidth R_c .

- Code-division multiple access (CDMA) refers to a multiple access technique in which the individual terminals use spread spectrum techniques and occupy all of the spectrum whenever they transmit.
- It is the interference attenuation property of spread spectrum that allows multiple users to occupy the same spectrum at the same time.
- Spread spectrum techniques were originally developed for military applications just before and during the World War II.

- There are two basic spread spectrum techniques :

  Direct sequence spread spectrum (DS-SS) and frequency-hopping spread spectrum (FH-SS)

- With direct-sequence spreading, the original signal is multiplied by a known pseudorandom signal of much larger bandwidth.

  With frequency-hopped spreading, the center frequency of the transmitted signal is varied in a pseudorandom pattern.

- Spread spectrum techniques have a number of advantages :

1. increased tolerance to interference
2. low probability of detection or interception
3. increased tolerance to multipath effect
4. increased ranging capability

8.2 Direct-Sequence Modulation

- Direct-sequence modulators process a narrowband signal to spread it over a much wider bandwidth.

  With this approach, each user terminal is assigned a unique spreading signature that makes each user's communications approximately orthogonal to those of other users.

- The modulated (spectrum spread) signal looks like noise to any receiver that does not know the signal structure. This makes the signal difficult to detect. This property has a distinct advantage for military applications.

8.2.1 The Spreading Equation

- In complex envelope form , one symbol of a BPSK signal may be represented as

$$s(t) = b \cdot (\sqrt{E_b}) \cdot g(t) \qquad (8.1)$$

where b is the data symbol , g(t) is the symbol-shaping function , and T is the symbol duration. For BPSK signal , *b* is either +1 or – 1 .

If the symbol-shaping function is assumed to be rectangular , then

$$g(t) = \begin{cases} \sqrt{(1/T)} & 0 \leqq t \leqq T \\ 0 & \text{otherwise} \end{cases} \qquad (8.2)$$

The transmit energy spectral density is given by

$$S_g(f) = T \, sinc^2 (fT) \qquad (8.3)$$

- For a direct-sequence signal, the symbol-shaping function is selected to be a sequence of Q rectangular pulses

$$g(t) = \Sigma \; c(q)\, g_c(t - qT_c) \qquad (8.4)$$

where $\{c(q)\}$ is the spreading sequence. The individual chips $c(q)$ in the spreading sequence are either +1 or -1 .

T_c is the chip duration. The constant Q, the upper limit of the summation , is the spreading factor and, usually,

$$Q\,T_c = T$$

- The chip shape , $g_c(t)$,is also often assumed to be rectangular ; that is,

$$g_c(t) = \begin{cases} \sqrt{(1/T)} & 0 \leqq t \leqq T_c \\ 0 & \text{otherwise} \end{cases} \qquad (8.5)$$

where the scaling is chosen to provide unit energy in the pulse $g_c(t)$.

- The chips are a pseudorandom sequence (PN sequence) of +1's and -1's known at the receiver and often having a repetition period equal to the symbol period.

- In general, the spread spectrum scheme increases the bandwidth of the message signal by a factor of Q, called the processing gain .

  If the message signal bandwidth is B Hz and the corresponding spread spectrum signal bandwidth is B_{ss} Hz , then

  Processing gain $N_{PG} = Q = B_{ss} / B = T / T_b$

- Fig.8.1 the spread sequence of length 4 and the corresponding power spectrum.

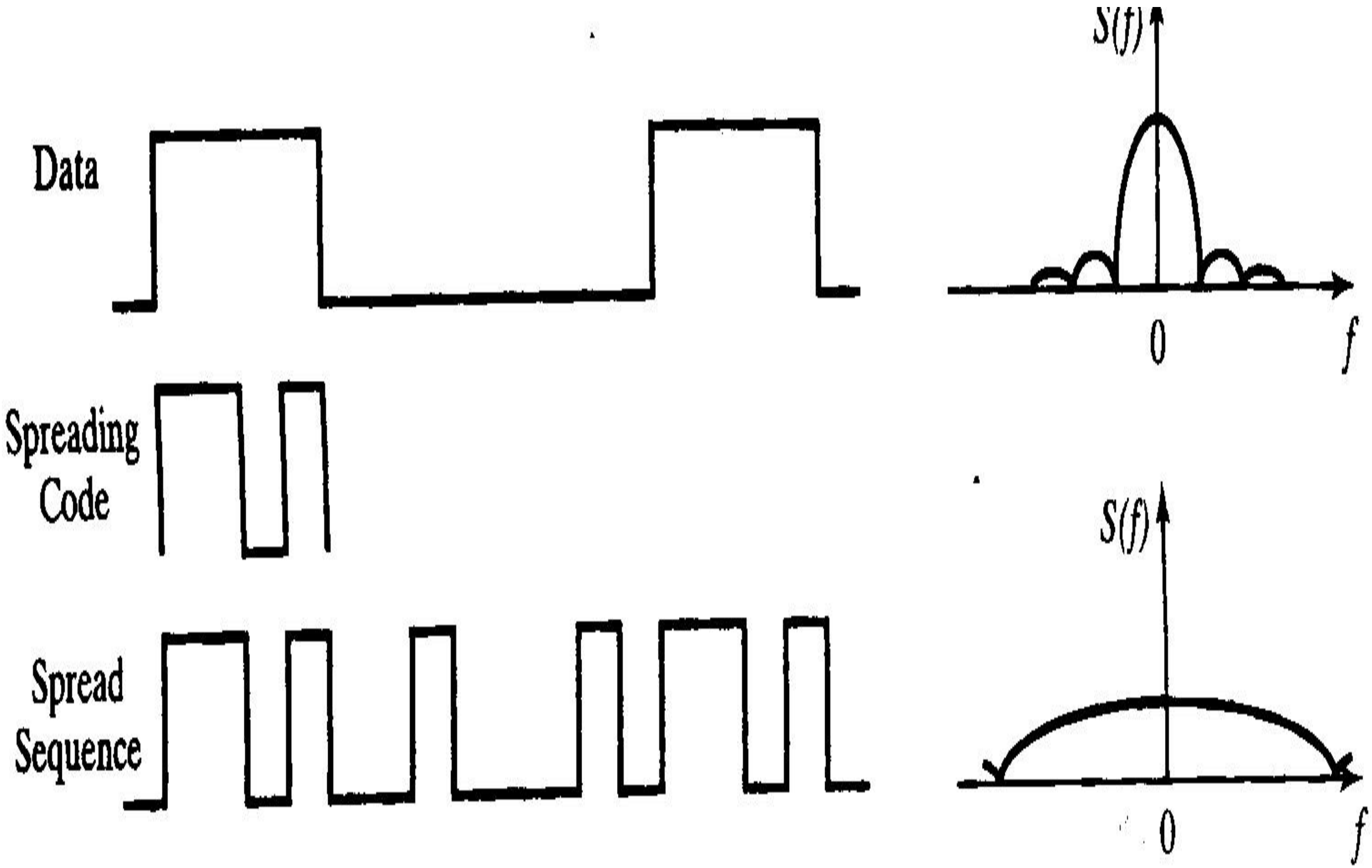
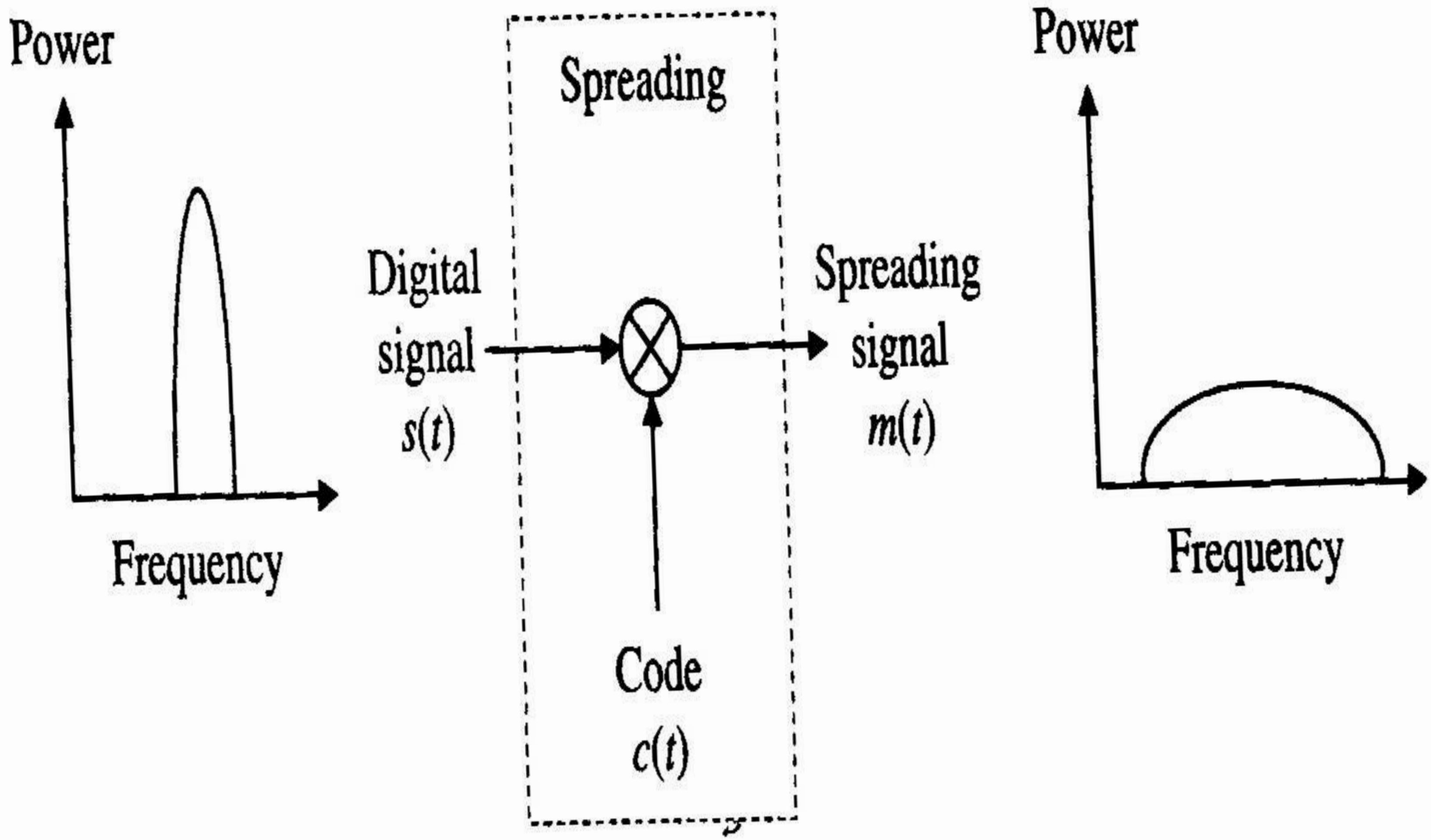
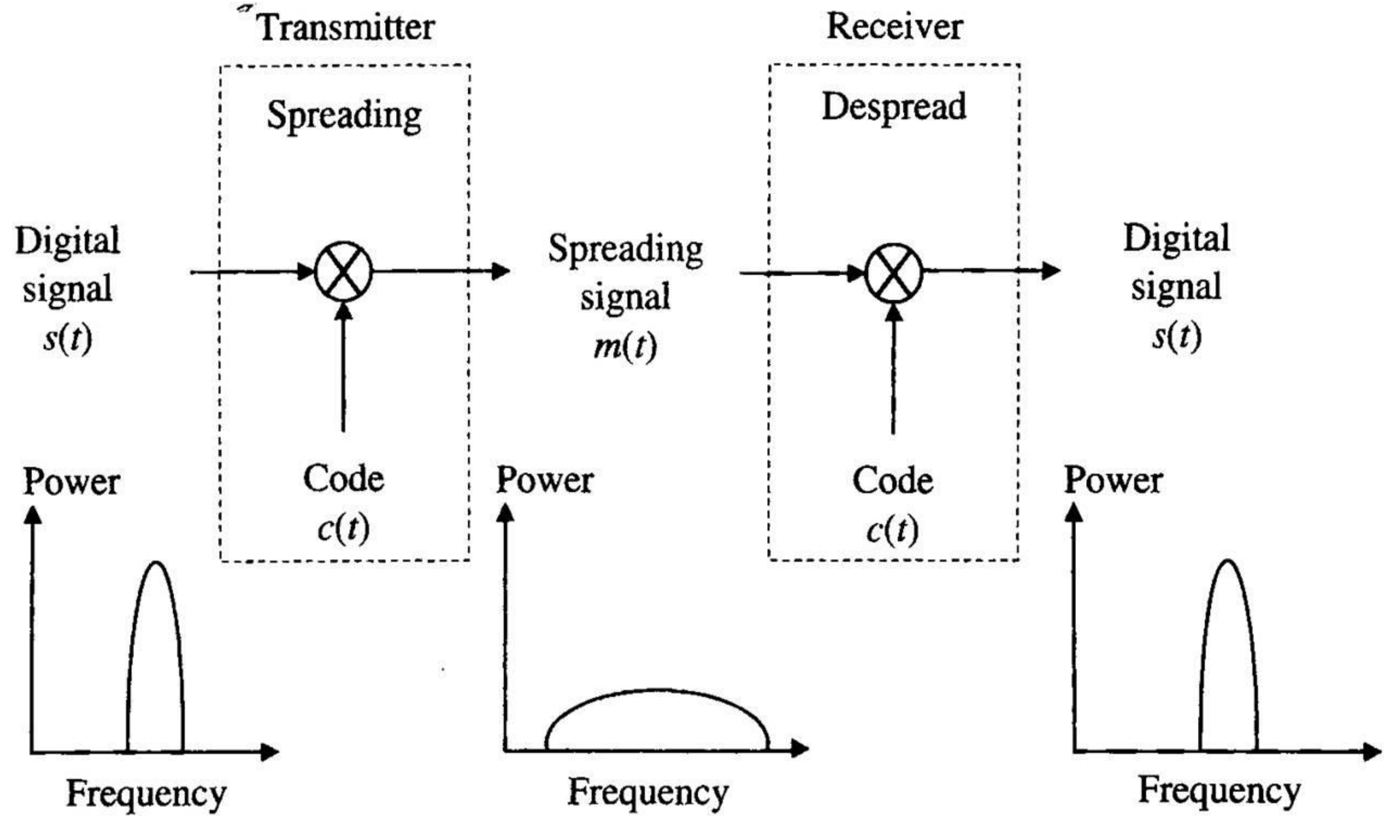


FIGURE 5.1 Spreading by a factor of four in the time and frequency domains.

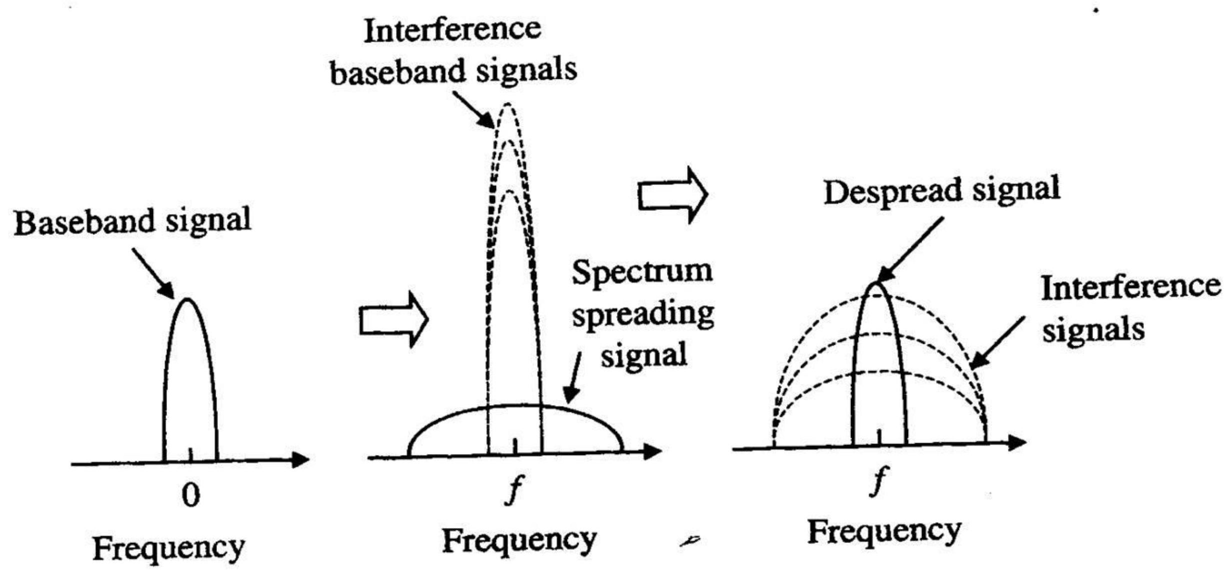

Power
Frequency
Spreading
Digital
signal
s(t)
Spreading
signal
m(t)
Code
c(t)
Power
Frequency



Concept of direct sequence spread spectrum.

8.2.2 Interference Suppression Benefits

- **One advantage of DS modulation is the reduced receiver sensitivity to (narrowband) interference . The narrowband interference can be an intentional jammer , i.e. an enemy interferer.**



Interference in spread spectrum system.

8.3 Spreading Codes and CDMA

- **The objective of every multiple-access strategy is to allow multiple users to access the radio resource in a manner that maximizes the use of the resource and minimizes the interference among users. These users must be , in some sense , approximately orthogonal.**
- **With TDMA , the users are time orthogonal ; with FDMA , the users are approximately frequency orthogonal. With CDMA , the users are approximately code orthogonal .**
- **To achieve the code-orthogonality , a different symbol-shaping function**

$$g_k(t) = \Sigma \; c_k(q)\, g_c(t - qT_c) \qquad 0 \leqq t \leqq T \qquad (8.6)$$

is assigned to each user *k*

- **Note : Orthogonal Sequences**

Two sequences ,

{a }= $(a_1 , a_2 ,\ldots, a_N)$ **and**

{ b } = $(b_1, b_2,\ldots,b_N)$ **, are orthogonal if**

$$\{a\}.\{b\} = a_1 b_1 + a_2 b_2 + \ldots + a_N b_N = 0$$

For example , { a} = [-1, -1, -1, +1, +1, -1, +1, +1]

{ b} = [-1, -1, +1, -1, +1, +1, +1, -1]

then, { a} .{ b} = 0

- The sequence $\{ c_k (q)\}$ is referred to as the spreading code or signature sequence for user *k* .
- The approximate orthogonality of $g_j (t)$ and $g_k (t)$ for different time offsets T can be represented as the requirement

$$R_{jk}(\tau) = \int g_j(t+\tau)\, g_k(t)\, dt \quad 0 \qquad \text{for } j \neq k \tag{8.7}$$

This relationship assumes that the receiver is using a matched filter(or correlator).

- An additional self-orthogonality requirement that minimizes a number of practical channel and receiver effects is

$$R_{kk}(\tau)\ 0 \qquad \text{for } \tau > 0 \tag{8.8}$$

- The orthogonality conditions of Eqs. (8.7) and (8.8) mean that different user messages can be separated at the receiver , even though they occupy the same channel and the same period. Example 5.1 (pp. 266-267, Haykin)

- **Pseudorandom (PN) Sequence**
  - A binary sequence with an autocorrelation resembles the autocorrelation of white noise
  - Nearly equal number of 0s and 1s in the sequence
  - Low correlation between time-shifted versions of the same sequence
  - Very low crosscorrelation between any two sequences

There are many methods exist for generating PN sequences, such as

Walsh-Hadamard sequence

m-sequence

Gold sequence

…..

8.3.1 Walsh-Hadamard Sequences

- **To construct a Walsh-Hadamard sequence , we begin with sequence of length 2.**

$$H_1 = \left[\quad \right]$$

- **A length of 4 Walsh-Hadamard sequence can be constructed from the sequence of length 2**

$$H_2 = \left[\quad \right]$$

$$=$$

- In general , we may construct 2^n orthogonal sequences of length 2^n from sequences of length 2^{n-1} by the operation

$$H_n = \left[\qquad\qquad\qquad \right]$$

- Each row of the matrix is a PN sequence.
- The PN sequences of length $N = T/T_c$ generated by using Walsh-Hadamard sequence are perfectly orthogonal with each other over a symbol time if they are synchronized in time.

Thus, synchronous users modulated with Walsh-Hadamard codes can be separated out at the receiver with no interference between them , as long as the the channel does not corrupt the orthogonality of the codes.

The orthogonality properties of the Walsh-Hadamard codes can be very poor when they do not align in time

8.3.2 Orthogonal Variable Spreading Factors (OVSF)

- In some applications, we may want to combine messages having different data rates in an orthogonal manner.

In particular , a message of rate r_1 is to be spread by a factor n_1 to produce an overall chip rate of ρ , while a second message of rate r_2 is to be spread by a factor n_2 to produce the same overall chip rate ρ.

If the spreading factors n_1 and n_2 are powers of 2 , then this can be done with the Walsh- Hadamard sequences.

The result so obtained is referred to as *orthogonal variable spreading factors* (OVSF) and is illustrated in Fig. 8.x x .

At each node of the tree , a code $w_k(n)$ of length generates two new codes by the rule

$$w_k(n) \rightarrow \begin{cases} w_{2k-1}(n) = [\, w_k(n) , w_k(n) \,] \\ w_{2k}(n) = [\, w_k(n) , -w_k(n) \,] \end{cases}$$

In CDMA system, by selecting different spreading factors, physical channels with different data rates can be provided .

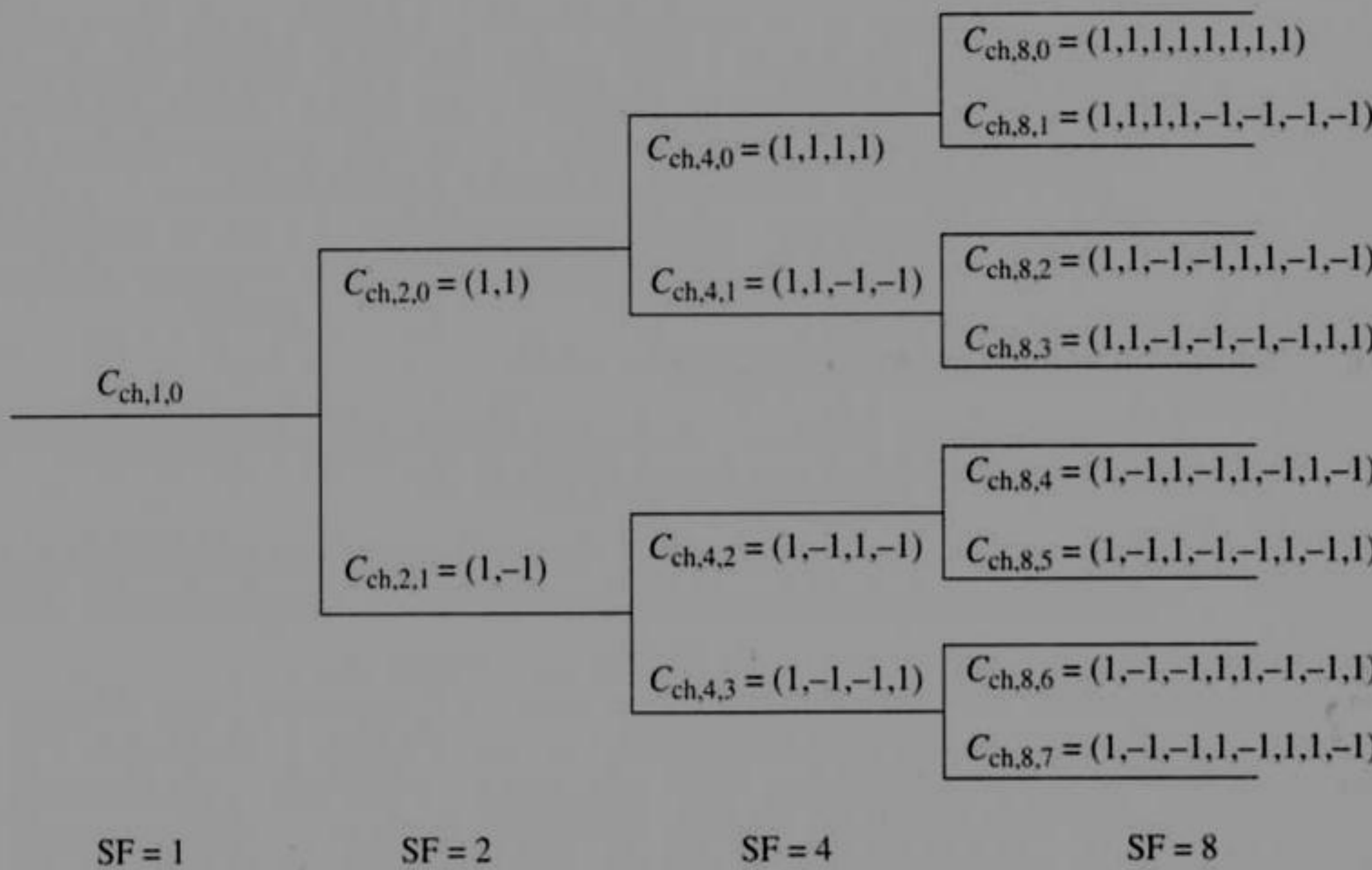


FIGURE 7.42 OVSF code tree.

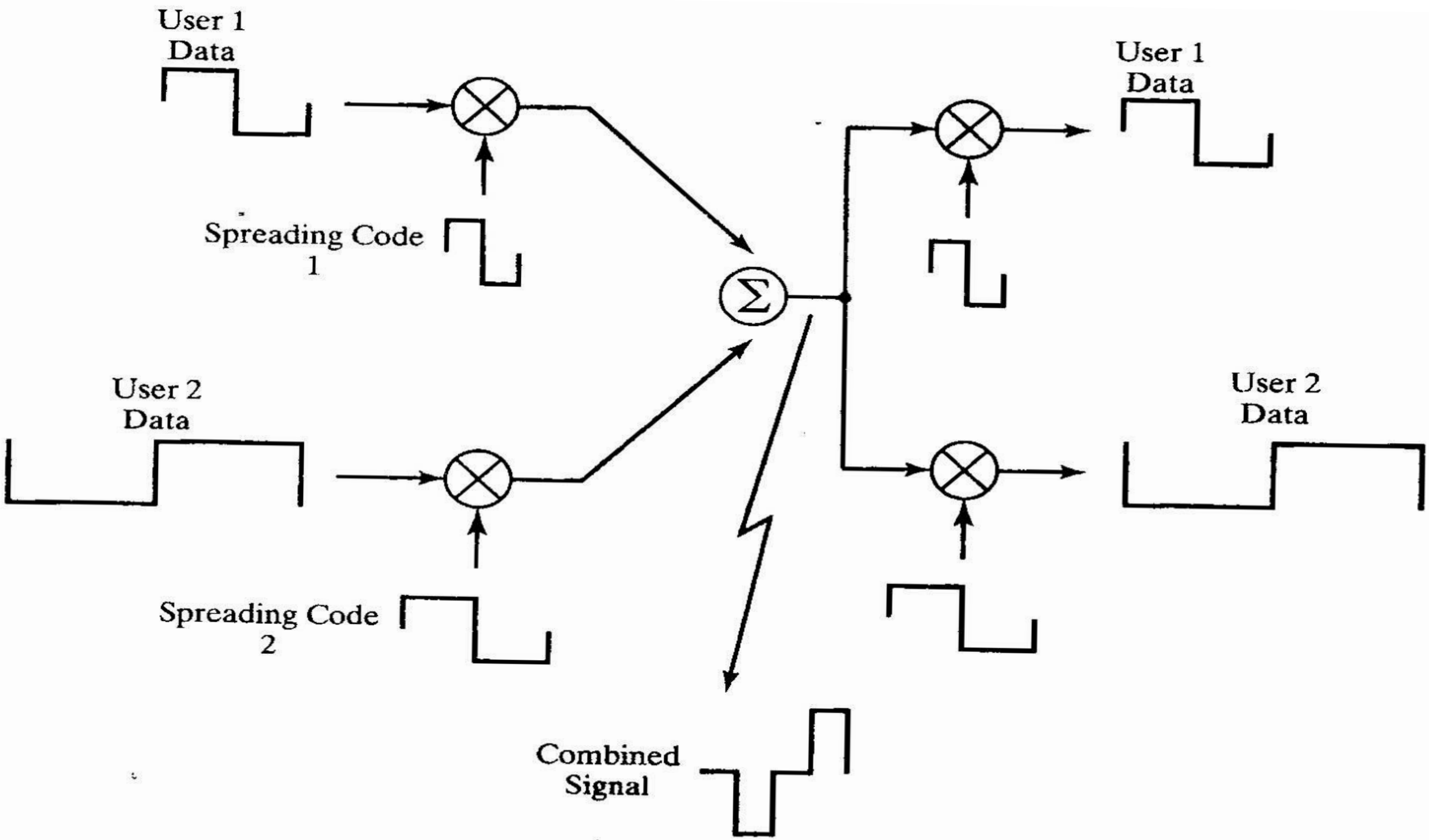


FIGURE 5.6 Illustration of orthogonal variable spreading factors.

8.3.3 Maximal-Length Sequence (m-sequence)

- **A pseudo-noise sequence is a periodic binary sequence with a noise-like waveform that is usually generated by means of a feedback shift register .**

  - A feedback shift register is said to be linear when the feedback logic consists entirely of modulo-2 adders . In such case , the zero state (i.e., all flip-flops are in state 0) is not permitted. Thus, the period of a PN sequence produced by a linear feedback shift register with m flip-flops cannot exceed $2^m - 1$.

  When the period is exactly $2^m - 1$, the PN sequence is called a maximal-length sequence , or simply m- sequence.

- The feedback connections in Fig. 5.8 are determined by the polynomial

$$g(D) = 1 + c_1 D + c_2 D^2 + \ldots + c_m D^m$$

It can be shown that if $g(D)$ is a primitive polynomial , the sequence generated by the shift registers is maximal length sequence.

- Generator polynomials

Order m	polynomial
2	$1+D+D^2$
3	$1+D+D^3$
4	$1+D+D^4$
5	$1+D^2+D^5$, $1+D^2+D^3+D^4+D^5$
6	$1+D+D^6$, $1+D+D^2+D^5+D^6$
7	$1+D^3+D^7$, $1+D+\mathrm{D}^7$

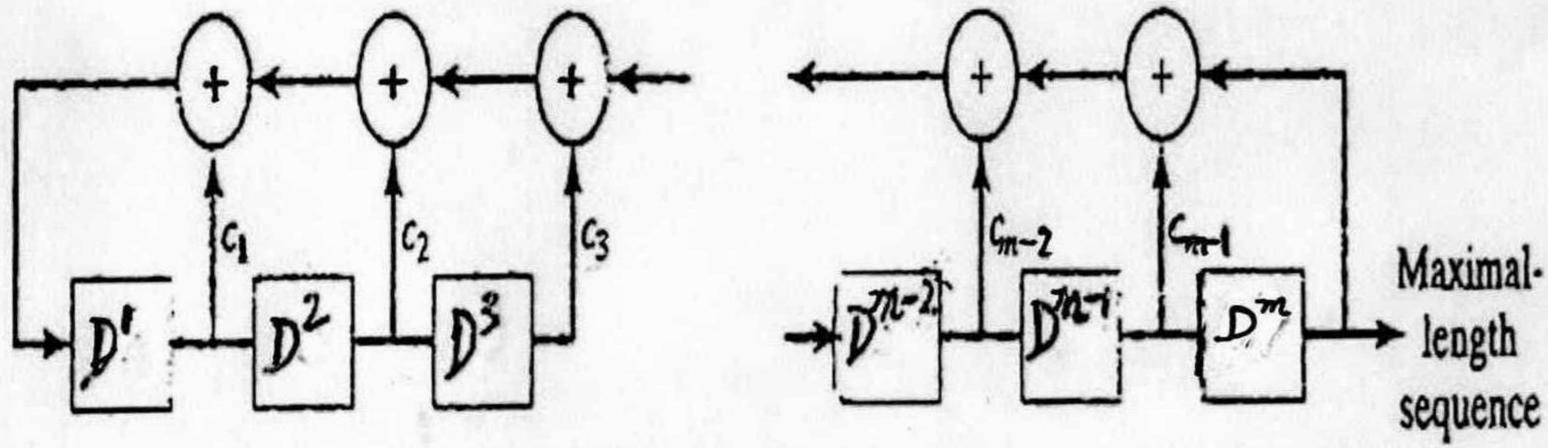
From R.C. Dixon, spread spectrum Systems

TABLE 7.1 *Maximal-length sequences of shift-register lengths 2–8*

Shift-Register Length, m	*Feedback Taps*
2*	[2, 1]
3*	[3, 1]
4	[4, 1]
5*	[5, 2], [5, 4, 3, 2], [5, 4, 2, 1]
6	[6, 1], [6, 5, 2, 1], [6, 5, 3, 2]
7*	[7, 1], [7, 3], [7, 3, 2, 1], [7, 4, 3, 2], [7, 6, 4, 2], [7, 6, 3, 1], [7, 6, 5, 2], [7, 6, 5, 4, 2, 1], [7, 5, 4, 3, 2, 1]
8	[8, 4, 3, 2], [8, 6, 5, 3], [8, 6, 5, 2], [8, 5, 3, 1], [8, 6, 5, 1], [8, 7, 6, 1], [8, 7, 6, 5, 2, 1], [8, 6, 4, 3, 2, 1]

$$g(D) = 1 + c_1 D + c_2 D^2 + \ldots + c_m D^m$$

$$c_m = 1$$



- **A configurations for generating m-sequences**

$$g(D) = 1 + g_1 D + g_2 D^2 + \dots + g_{m-1} D^{r-1} + g_r D^r$$

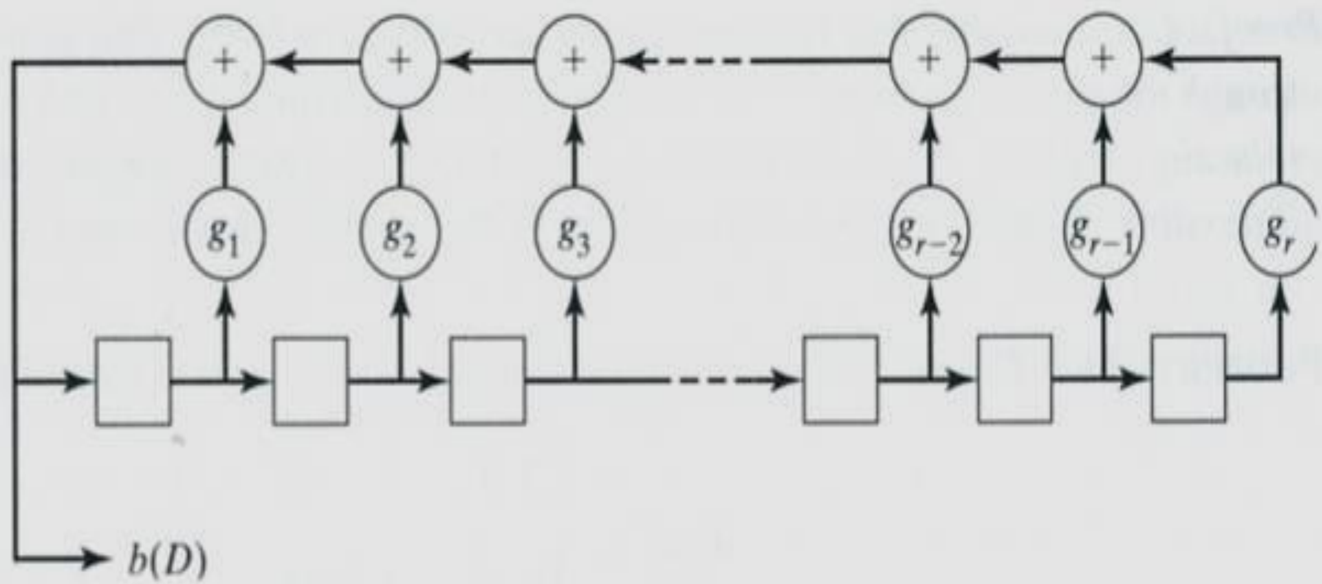
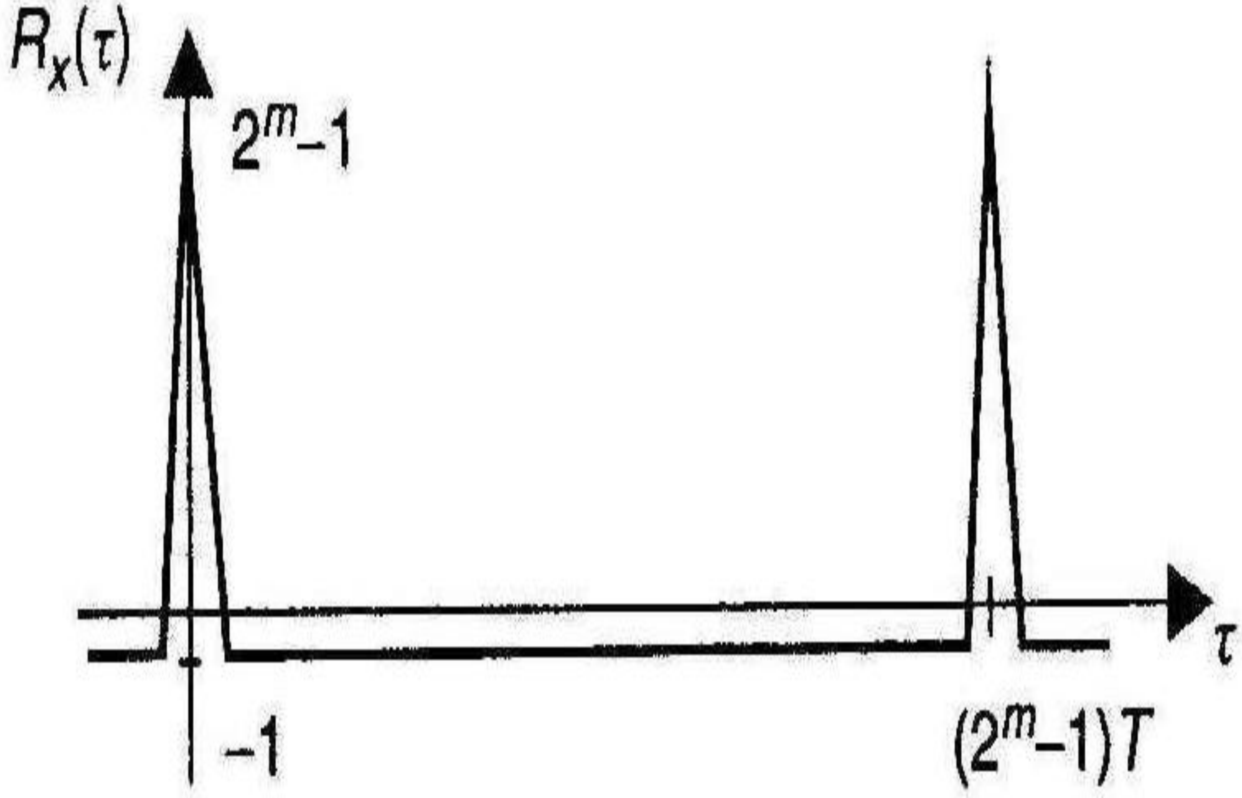


FIGURE 9–21 Linear feedback shift-register whose output satisfies the same re-currence relationship as the generator of Figure 9–20. (Reproduced from Refer



$R_x(\tau)$
2^m-1
τ
-1
$(2^m-1)T$

8.3.4 Scrambler

- A long m-sequence can also be used as data scramblers, for example , m= 42 , $N = 2^{42} - 1 = 4398$ *billions* .
- The purpose of a scrambler is to prevent the transmission of long string of zeros and ones that may appear in raw data.
- Long strings of zeros or ones can cause difficulties for tracking circuits in the receiver and can cause peaks in the transmit spectrum that may result in excess interference to other services.
- To implement a scrambler, the output of the maximal-length shift register is modulo-2-added with the data as shown in Fig. 5.10 .

  At the receiver, the same operation is repeated to undo the scrambling of the transmitter.

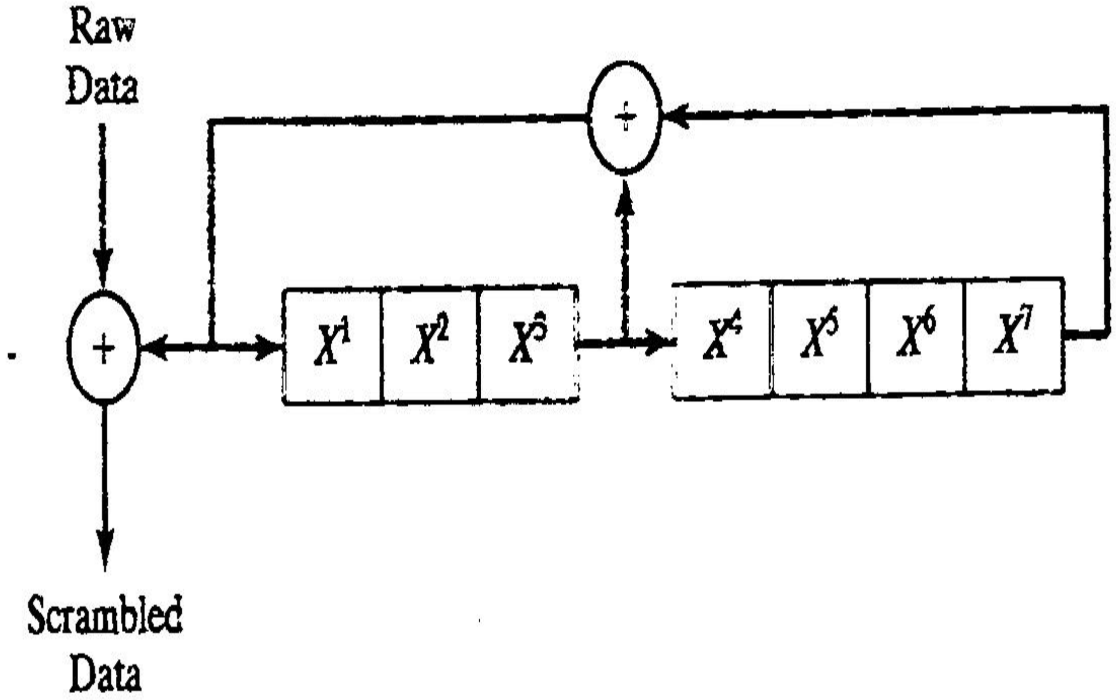


FIGURE 5.10 Scrambler implementation for $f(x) = x^7 + x^3 + 1$.

8.3.5 Gold Codes

- In practical applications, we would like to assign transmitters different codes that have good cross-correlation properties.

  Maximal –length sequences have good correlation properties.

  However, the cross-correlation properties are poor .
- An approach proposed by Gold is to sum two maximal-length sequences of the same length, but using different

  generators , as shown in Fig. 8.xx .
- Gold was able to show that, for particular choices of generator polynomials, these sequences have good cross-correlation properties.

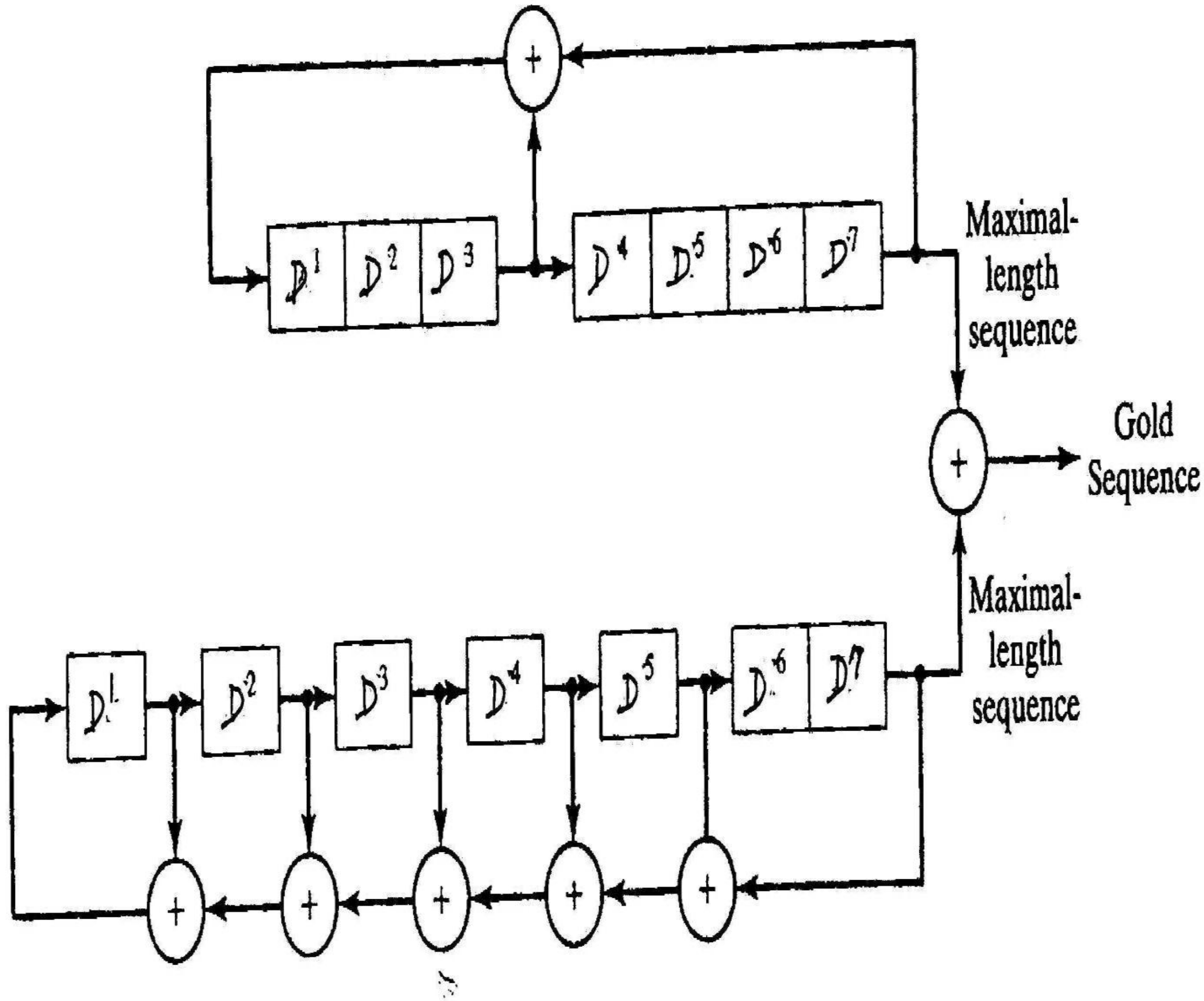


FIGURE 5.11 Generation of a Gold sequence.

8.4 CDMA for Wireless

- **CDMA is a multiple access strategy for wireless communications based on direct sequence spread spectrum (DS-SS) .**

-- The spreading provided by the code simply changes the spectrum of the signal used to transmit the information

--- If the spreading codes are perfectly orthogonal , it is possible to achieve the single user performance in the multiuser case. However, it is very difficult to design perfectly orthogonal codes for all cases.

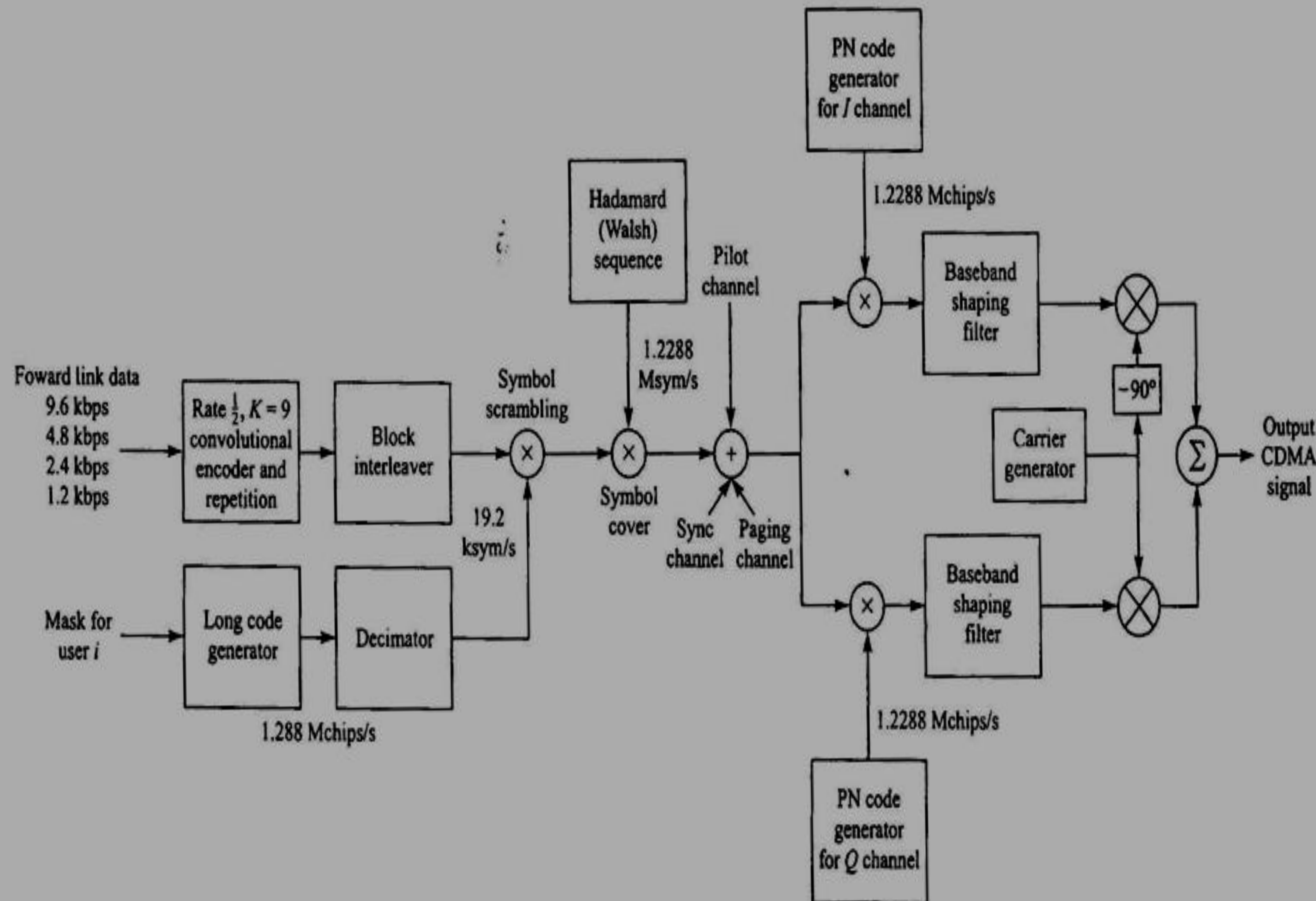


FIGURE 12.2–7
Block diagram of IS-95 forward link.

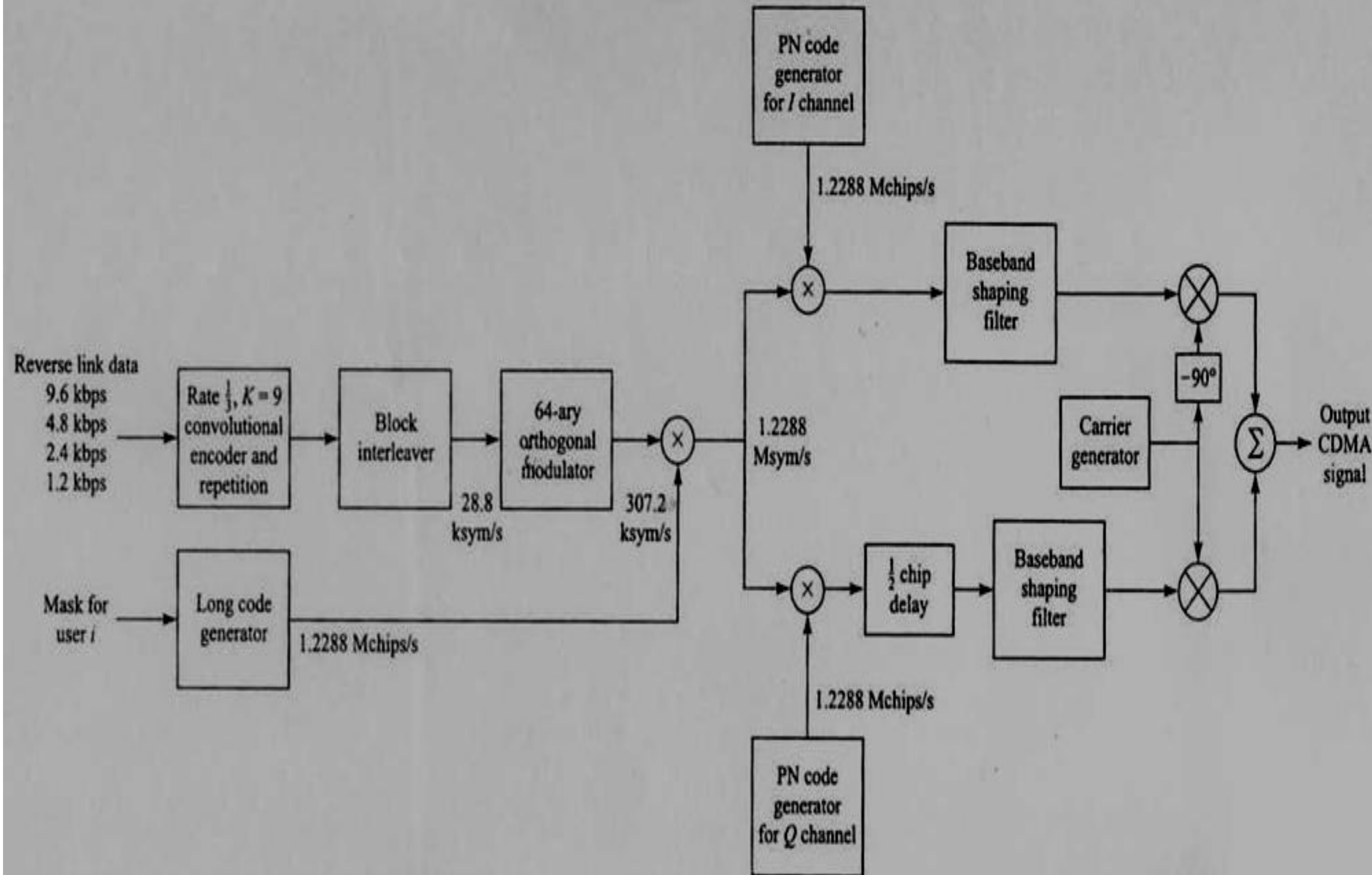


FIGURE 12.2–8
Block diagram of IS-95 reverse link.

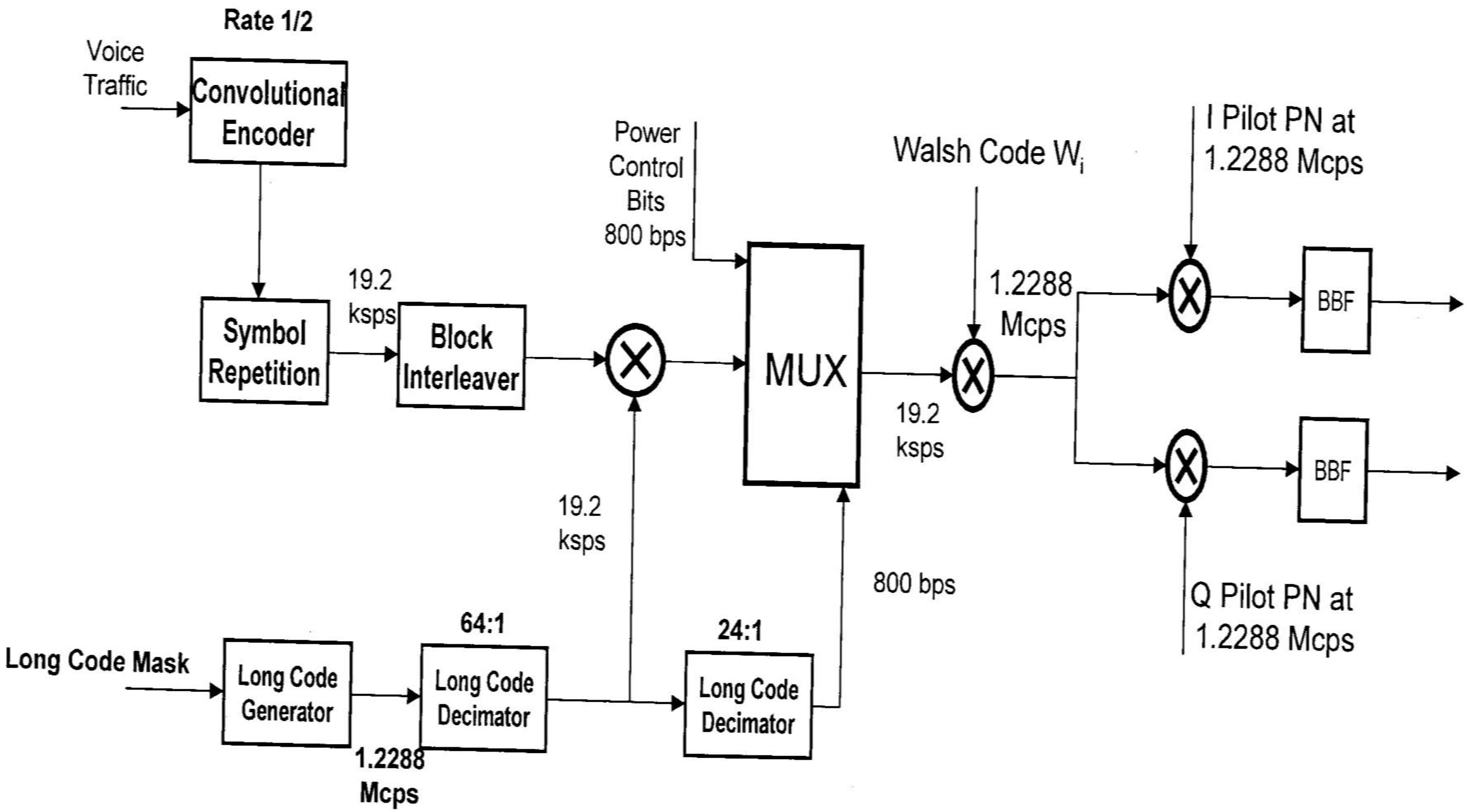


Figure 8.8: Forward Traffic Channel Processing in IS –95 (Rate Set 1)

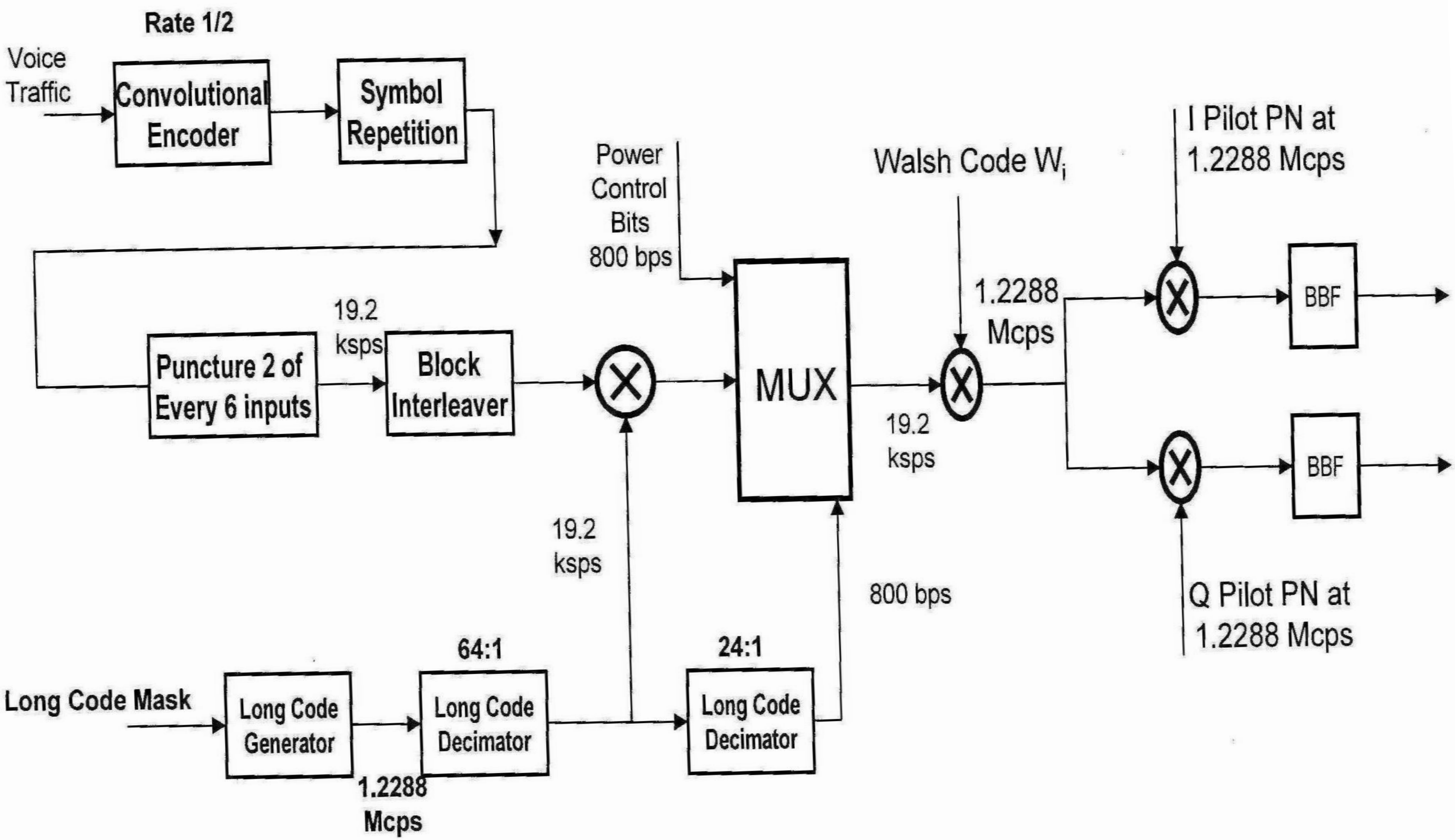


Figure 8.9: Forward Traffic Channel Processing in IS –95 (Rate Set 2)

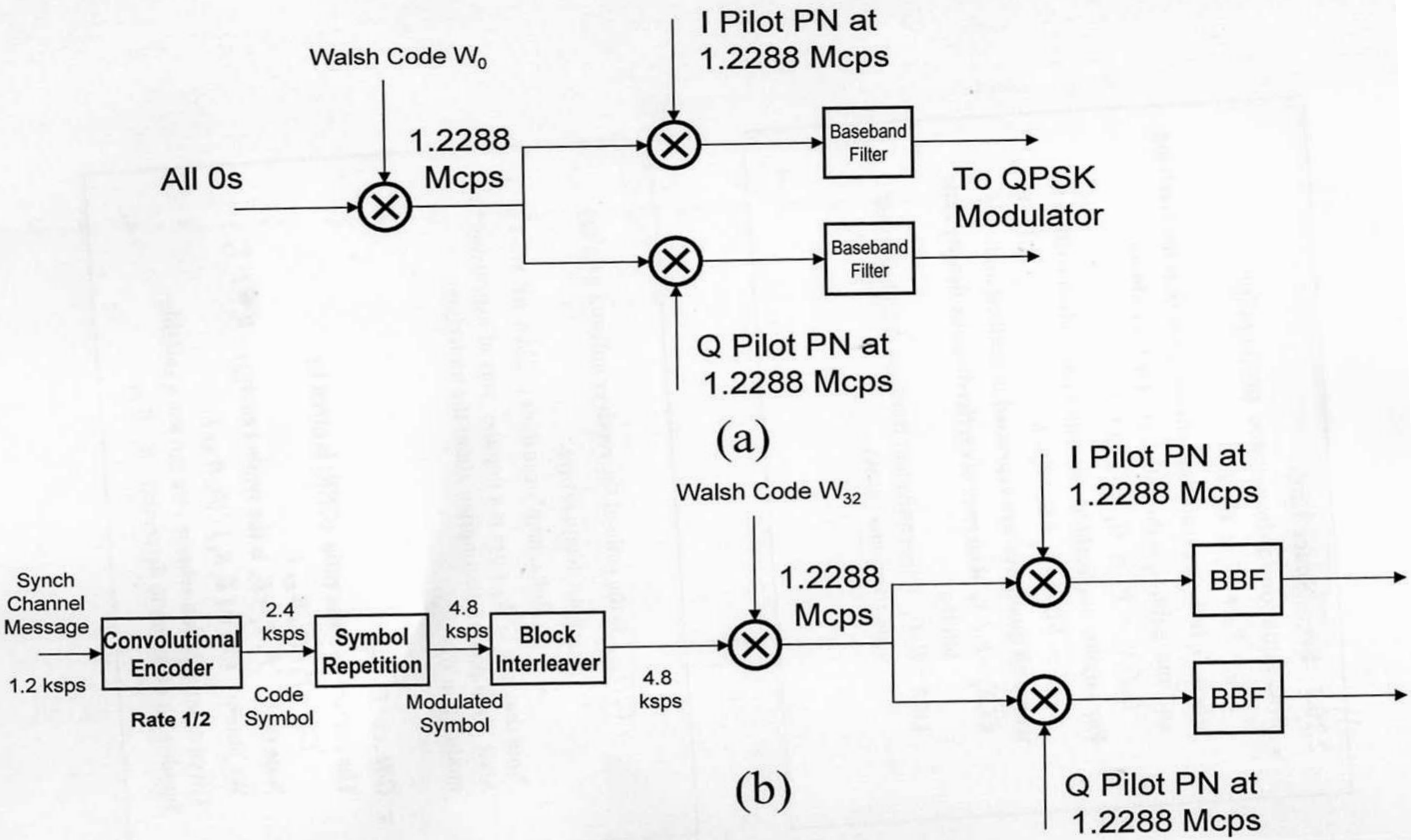


Figure 8.6: (a) Pilot and (b) Sync Channel Processing in IS -95

8.4.1 Multiple-Access Interference (MAI)

- In practical CDMA systems, users are not perfectly synchronized so that codes are time-shifted.
- When the codes are no longer perfectly orthogonal, there exist interferences among users. That is, multiple access interferences (MAI) occur among users.
- At the receiver, the received (sequence) signal is given by

$$\{r\} = \sum S_m \cdot \{C_m\} + \{n\}$$

To detect the signal of the kth user

$$\{r\} \bullet \{C_k\} = S_k(\{C_k\} \cdot \{C_k\}) + \sum S_m(\{C_m\} \cdot \{C_k\}) + \{n\} \cdot \{C_k\}$$

$$= S_k + \sum I_m + Z_k$$

Usually , $\{C_m\} \cdot \{C_k\} << \{C_k\} \cdot \{C_k\} = 1$

therefore , $E[\,|\,\Sigma I_m\,|^2\,] << E[\,|\,\Sigma S_k\,|^2\,]$

- **The power of MAI depends on two factors :**

  1. the cross-correlation between different PN codes

  2. the signal power of interfering users.

8.4.2 Near-Far Problem and Power Control

- **When the interfering users are close (“near”) to base station (BS) , the received interference power is high. And, if the desired user is “ far “ away from the BS , the received desired signal power is low. Then the power of the interfering users is much higher than the desired signal . This results in low signal-to-MAI ratio and leads to the poor performance of the desired user.**
- **In general, near-far problem will seriously affect the performance of the CDMA system.**
- **To reduce the impairments of near-far problem , the power at the receiver should be the same for all users.**

- The near-far problem is mitigated by **fast closed- loop power control**. Fast closed –loop power control is implemented by having the base station estimate the power received from the mobile station , comparing this power estimate with a threshold , and telling the mobile to power up or down by 1 dB to place the base station received power closer to the threshold.
- The power up/down message to the mobile is implemented via the insertion of a **Power Control Bit (PCB)** periodically on the forward-link (also known as down-link) transmission.

8.4.3 Multipath Channels

- **In a spread spectrum system, the signal bandwidth is very large , i.e., signal bandwidth >> channel bandwith.**

  Thus the channel is modeled as a frequency-selective fading channel.

- **For a channel consisting of L multipath rays of amplitude $\{\alpha_l\}$ and relative delays $\{\tau_l\}$, the complex envelope of the channel impulse response is given by**

$$h(t) = \sum \alpha_l \, \delta(t - \tau_l)$$

- **Fig.5.16 shows a three-ray multipath model. Each of the three paths has an independent delay and independent complex gain.**

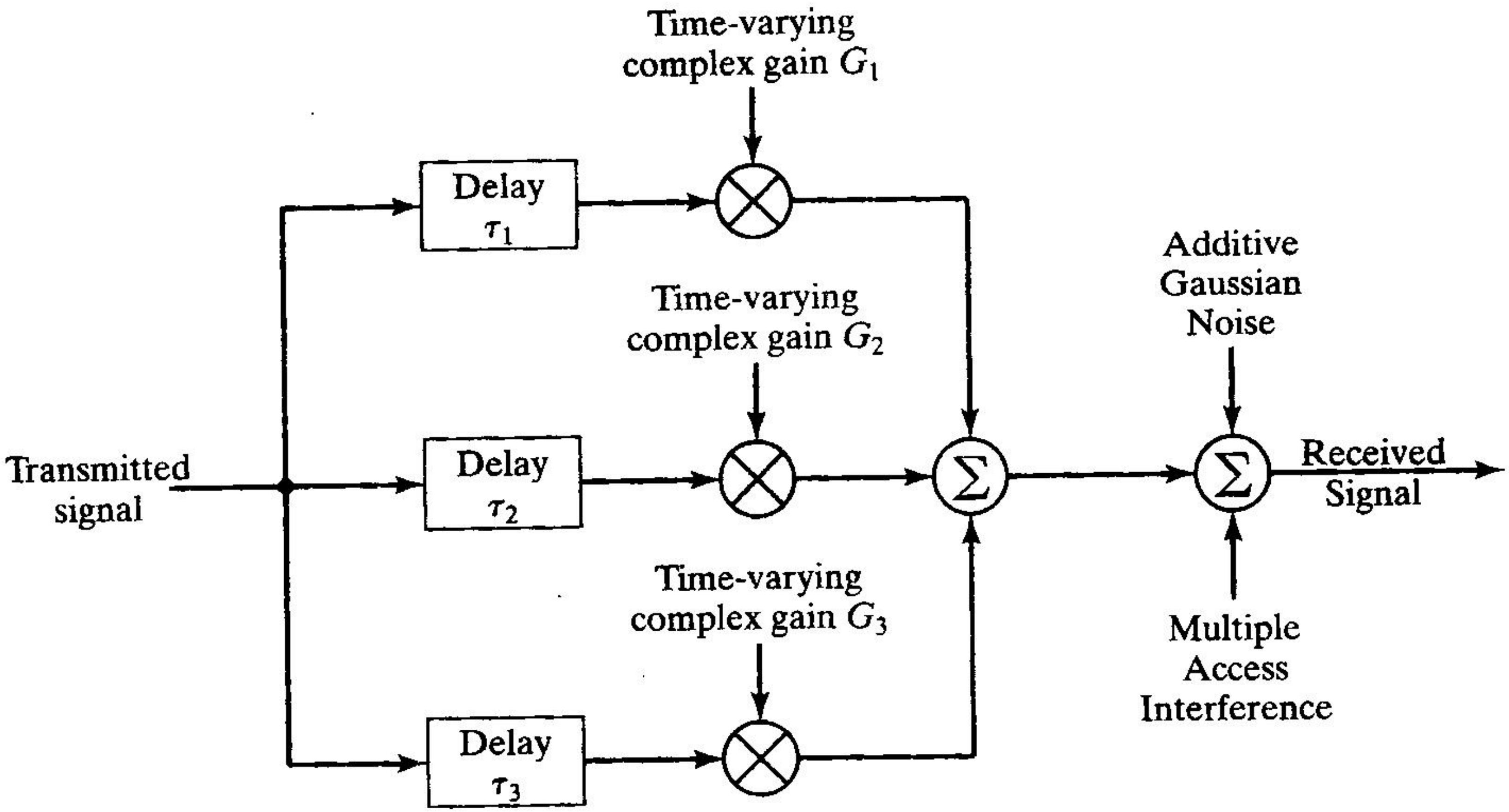


FIGURE 5.16 Multipath channel model.

8.4.4 Rake Receiver

- A receiver structure that is often used for CDMA systems operating in multipath environment is the RAKE receiver , depicted in Fig.8.xx .

  This receiver has *L+1* fingers and gets the name "RAKE" from its resemblance to the common garden rake.

  Each finger of the receiver attempts to demodulate one path of the composite multipath signal.
- With a RAKE receiver , the signal is sampled at the chip rate and then passed through a delay line with T_c – spaced

  elements.
- Due to the low correlation between time- shifted version of the same PN code , each finger can be treated as flat fading.

- The output of each delay element is processed by a single-user correlator (or matched filter).

$$y_i = \int x(t + iT_c)\, g^*(t)\, dt$$

- The combined estimate of the data is obtained by taking a weighted combination of the outputs of each finger of the RAKE receiver.

$$y = \Sigma\, h_i^* y_i$$

The processing described by the above equation is known as maximal-ratio combining (MRC).

- **In the Rake receiver, to perform MRC , knowledge of the channel coefficients { h_l } is required , regardless of the modulation strategy. Consequently, a significat number of parameters must be estimated. It is critical to receiver performance to have an accurate channel estimation and tracking strategy to track these variations in the slowly-varying mobile channel.**

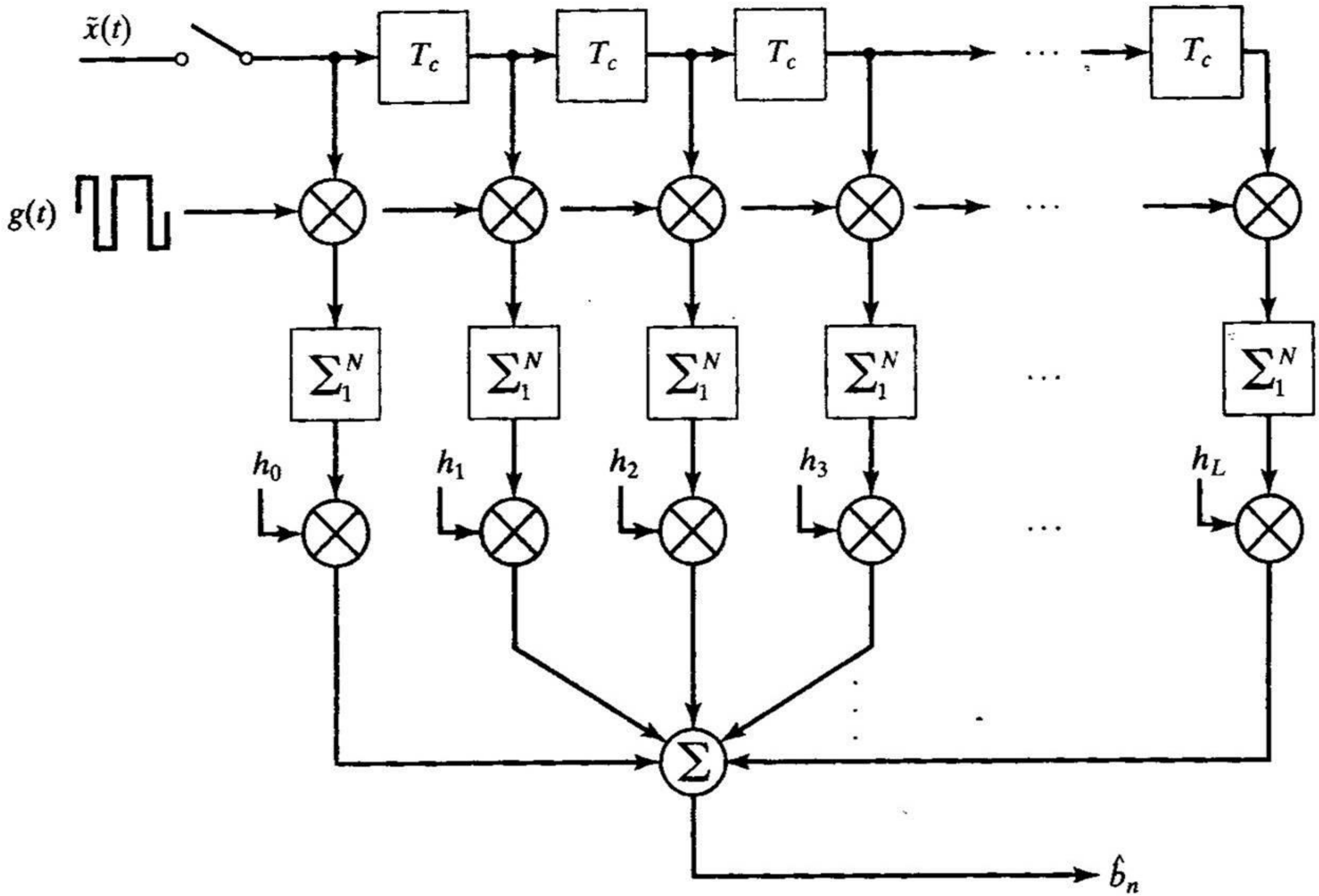


FIGURE 5.17 RAKE receiver for CDMA over multipath channels.

8.4.5 Summary of the Benefits of DS-SS

- **DS-SS has a number of features that are important in a multiple access system :**

  1. **The spectral density of the transmitted signal is reduced by a factor equal to the processing gain.**
  2. **The effect of narrowband interference can be reduced by a factor of processing gain , that is the ratio of the spread bandwidth to the original bandwidth.**
  3. **In multipath channels , if multipath is treated as interference , then its effect can be reduced by the processing gain.**
  4. **Through proper receiver design (e.g. using Rake receiver), we can use multipath to advantage to improve receiver performance by capturing the energy in paths having different transmission delays.**

5. The choice of spreading codes is critical to reducing multiple access interference (related to spreading –code cross-correlations) and multipath self- interference (related to spreading –code autocorrelation).

8.4.6 Technical Challenges of DS- CDMA System

1. Power control
2. Code synchronization
3. Channel estimation
4. Multiuser detection
5. Intercell interference

- **Multiuser Detection**

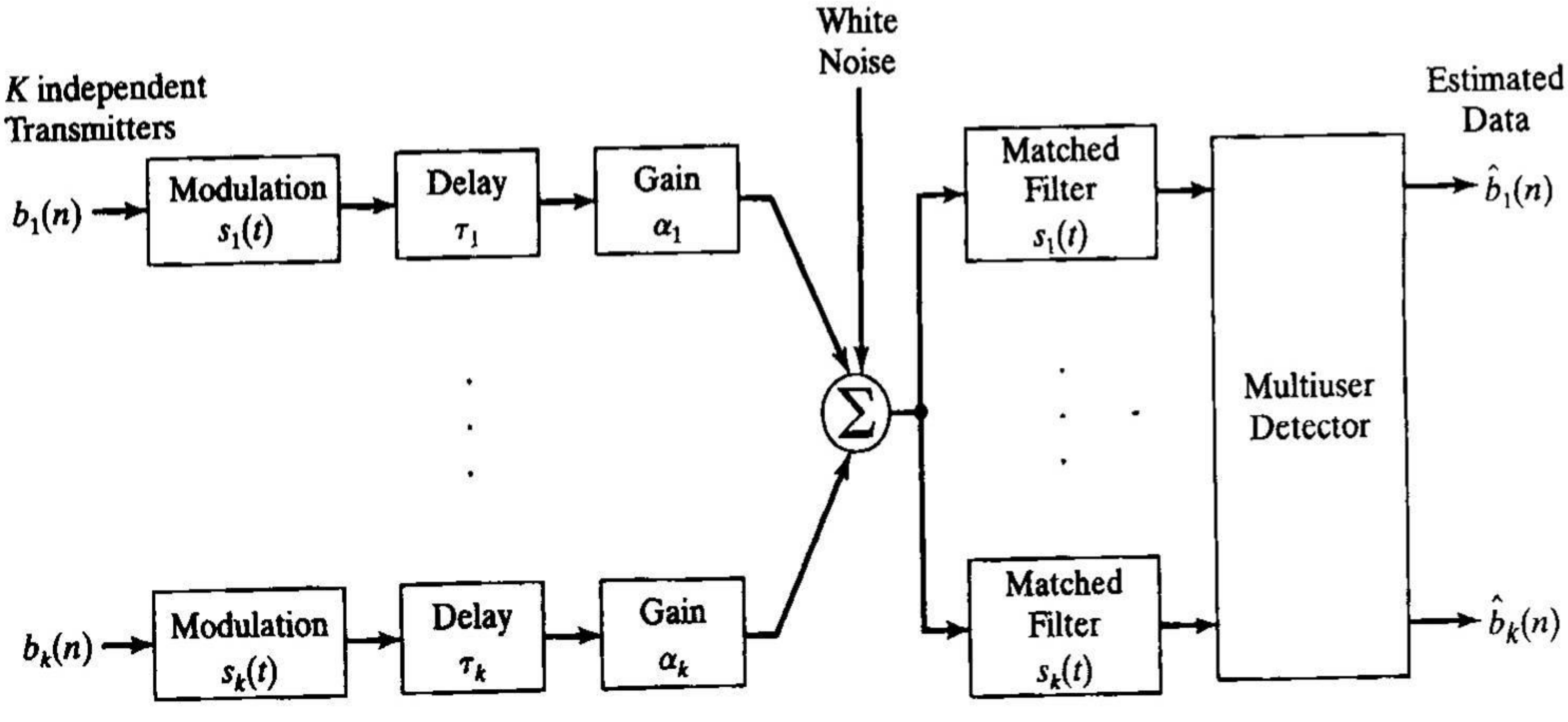
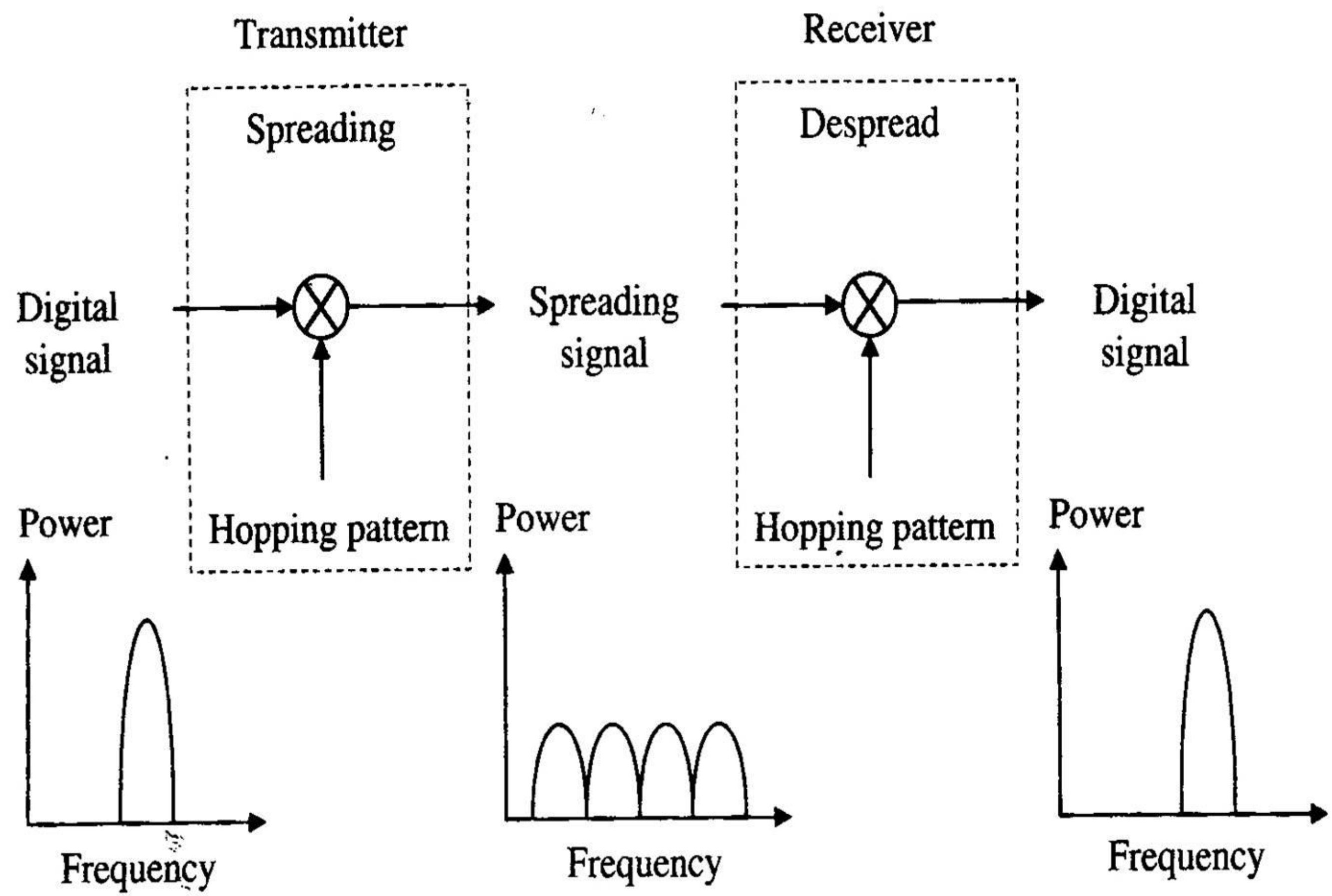


FIGURE 5.24 Multiuser system model.

8.5 Frequency Hopping Spread spectrum (FH-SS)

- **The modulation mostly common used with freq1uency hopping is M-ary frequency shift keying (MFSK), where**

  $k = log_2 M$ **information bits are used to determine which one of** M **frequencies is to be transmitted.**
- **The frequency-hopping pattern in the FH-SS system is determined by a pseudorandom spreading code .**
- **The position of the M-ary signal set is shifted pseudorandomly by the frequency synthesizer over a hopping bandwidth** W_{ss} **.**
- **The FH system can be thought of as a two-step modulation process : data modulation and frequency hopping modulation.**



Concept of frequency hopping spread spectrum system.

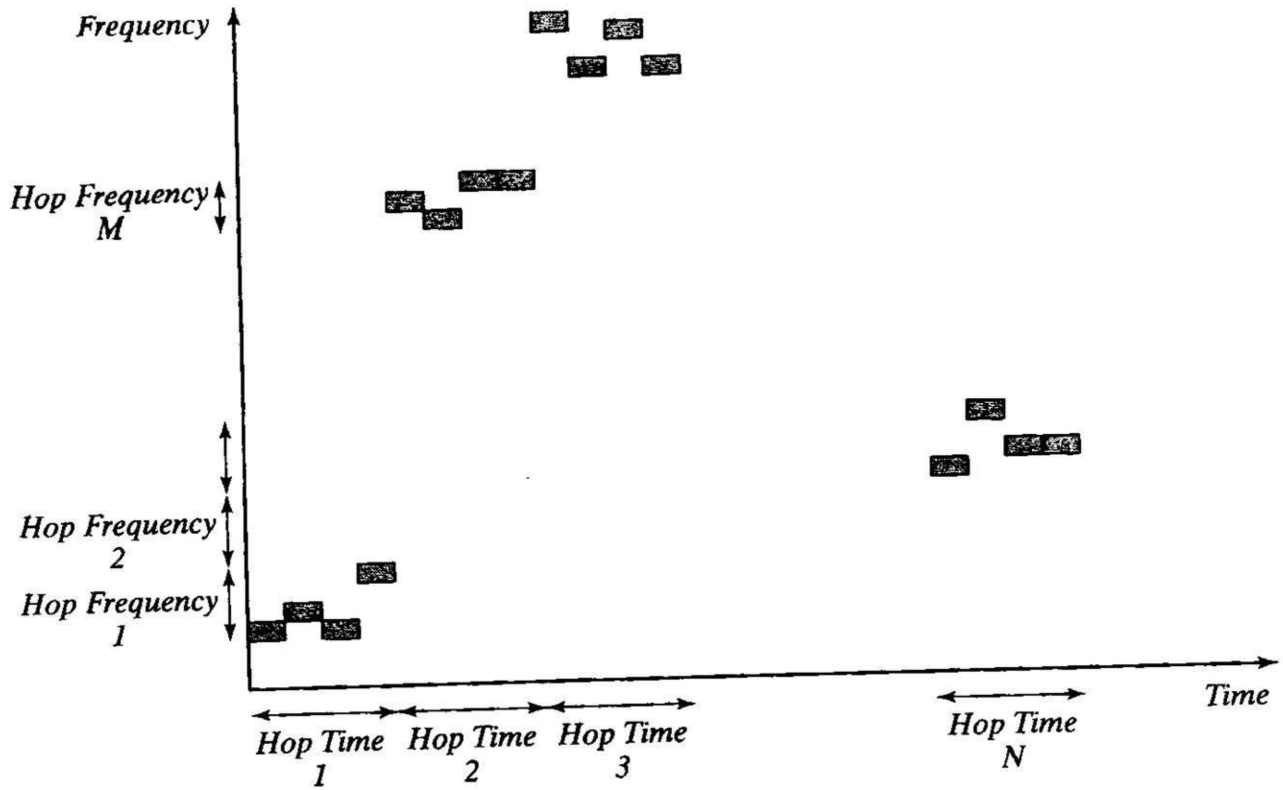
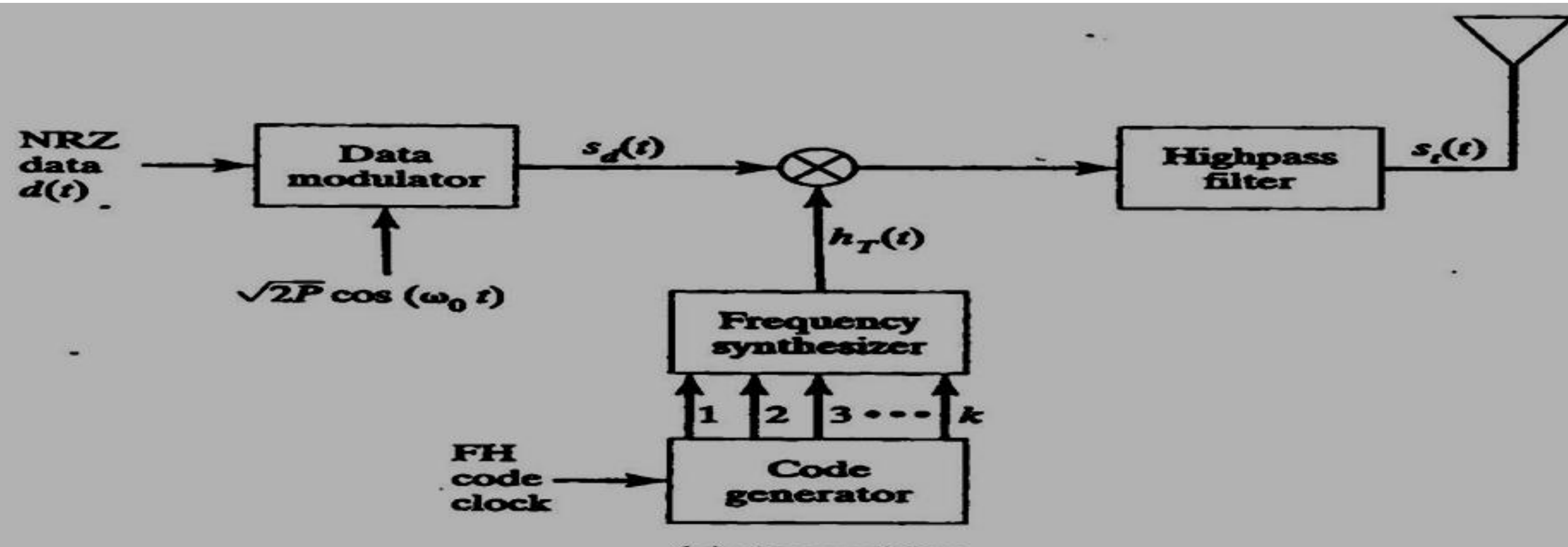
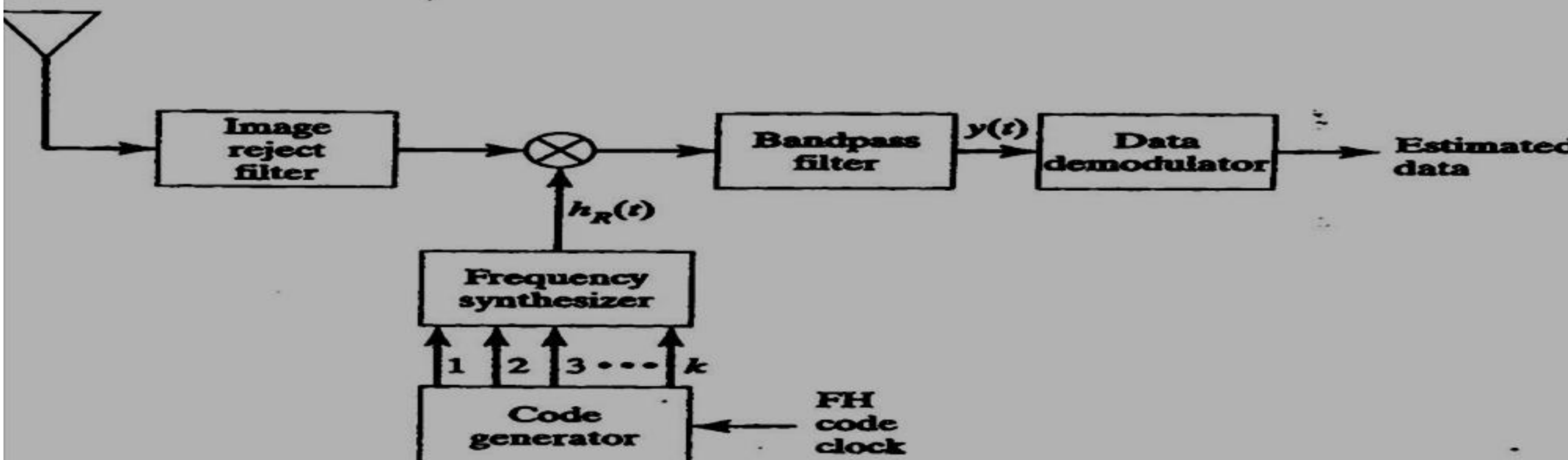


FIGURE 5.28 Frequency–time plot of output of FH/MFSK system.



(a) Transmitter



(b) Receiver

Frequency-hop spread-spectrum modem.

TABLE 5.4 Comparison of second- and third-generati...

	IS-95	WCDMA
Channel bandwidth	1.25 MHz	5 MHz
Chip rate	1.2288 MHz	3.84 MHz
Data rates	up to 9.6 kbps	up to 2 Mbps
Frame size	20ms	10 ms
Pulse shaping	48-tap FIR	22% root-raised cosine
Spreading factor	64	up to 512
Number of channels /per terminal	1	variable
Downlink/uplink sharing	FDD	FDD/TDD
Downlink modulation	QPSK/Pilot	QPSK/Pilot
Uplink modulation	OQPSK/Orthogonal	QPSK/Pilot
Downlink FEC	$r = 1/2, K = 9$ convol. code	$r = 1/2, 1/3$ convol. or turbo
Uplink FEC	$r = 1/3, K = 9$ convol. code	$r = 1/2, 1/3$ convol. or turbo

8.6.1 Introduction

- For spread spectrums, both DS and FH , a receiver must employed a synchronized replica of the spreading code signal to demodulate the received signal successfully. The synchronization process usually consists two steps :
- (a) Acquisition. It consists of bringing the two spreading signals into coarse alignment with one another.

  (b) Tracking . Once the received signal has been acquired, the tracking process takes over and continously maintains the best possible waveform fine by means of a feedback loop alignment .

8.6.2. Acquisition

- The acquisition problem is one of searching throughout a region of time and frequency uncertainty in order to synchronize the received spread-spectrum signal with the locally generated spreading code signal.
- Acquisition schemes can be classified as coherent or noncoherent.
- Since the despreading process typically takes place before carrier synchronization , and therefore the carrier phase is unknown at this point , most acquisition schemes utilize noncoherent detection.
- In acquisition process, the two PN codes are aligned to within a fraction of the chip interval in as short a time as possible.

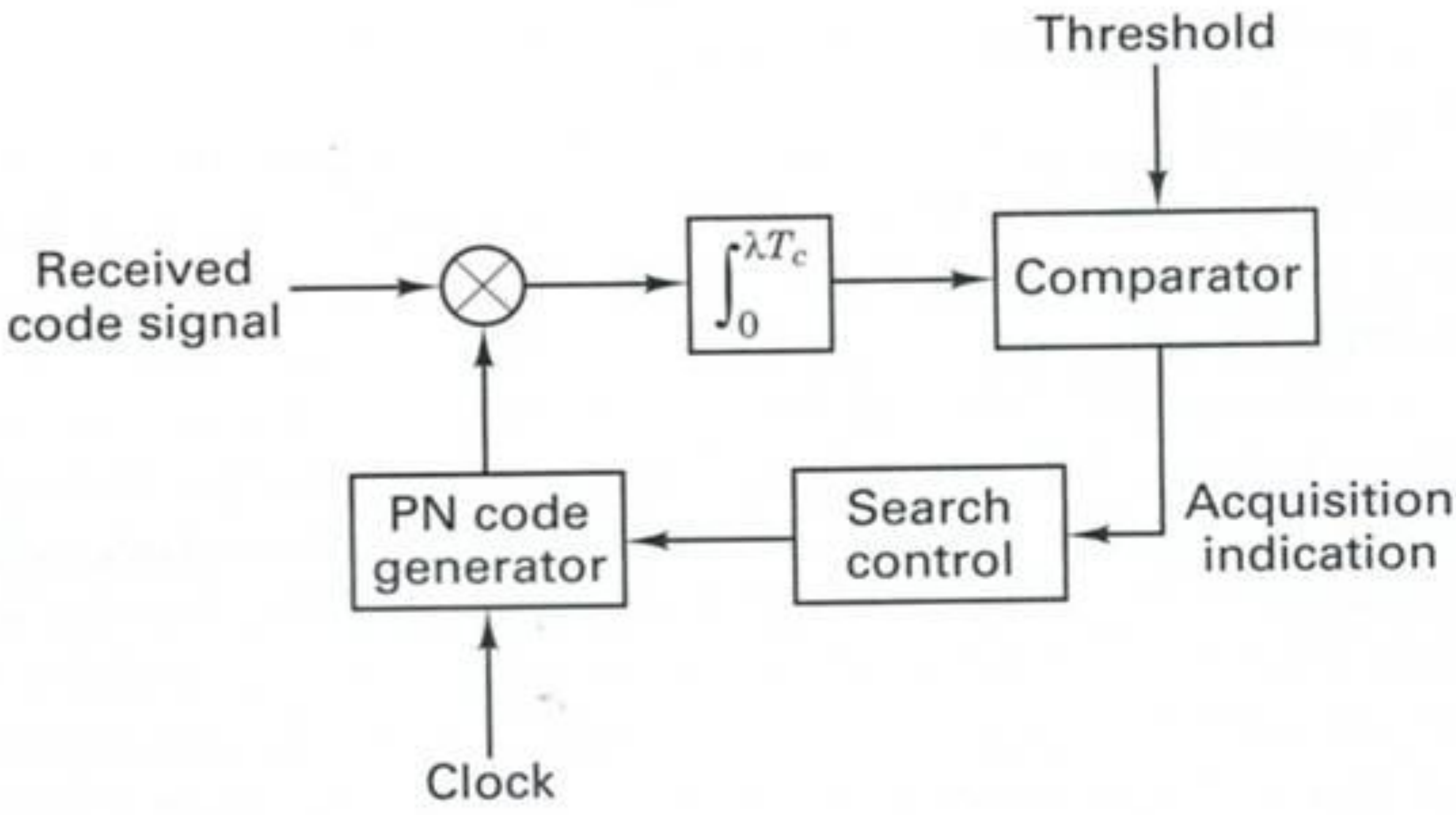
- Typically, PN acquisition proceeds in two steps . First, the received signal is multiplied by a locally generated PN code to produce a measure of correlation between the two PN codes.
- Next , an appropriate decision-rule and search strategy is used to process the measure of correlation so obtained to determine whether the two codes are in synchronization and have to do if they are not.
- A popular strategy for the acquisition spread spectrum signal is to use a single correlator to serially search for the correct phase of the DS code signal.
- A considerable reduction in complexity, size, and cost can be achieved by a serial implementation that repeats the correlation procedure for each possible sequence shift.

8.6.2.1 Serial Search Acquisition Using Sliding Correlator

- **Fig 1.x illustrates a basic configuration of sliding correlator for direct sequence signal acquisition.**
- **The correlator cycles through the time uncertainty , usually in time intervals of ½ T_c, and correlates the received signal with the known synchronization sequence . The crosscorrelation is performed over time interval (dwell time) λT_c , $\lambda \gg 1$.**

  The correlatior output is compared with a preset threshold to determine if the known signal sequence is present. If the threshold is not exceeded , the known reference is advanced in time by ½ T_c seconds and the correlation process is repeated.
- **When the threshold is exceeded , the PN code is assumed to have been acquired , and the phase-incrementing process of the local code is inhibited , and the code tracking procedure will be initiated.**

Fig.xx Direct-sequence serial search acquisition



- **The maximum time required for a fully serial DS search, assuming that the search proceeds in half-chip increments , is**

$$(T_{acq.})_{\max} = 2 N_c \lambda T_c$$

where N_c is the uncertainty region to be searched .

- **Note : Usually , extremely accurate and stable time clocks are used in spread spectrum systems. Consequently , accurate time clocking results in a reduction of the time uncertainty between the transmitter and the receiver. However , there is always an initial timing uncertainty due to range uncertainty between the transmitter and receiver. This uncertainty region is N_c chips long .**

8.6.3. Tracking

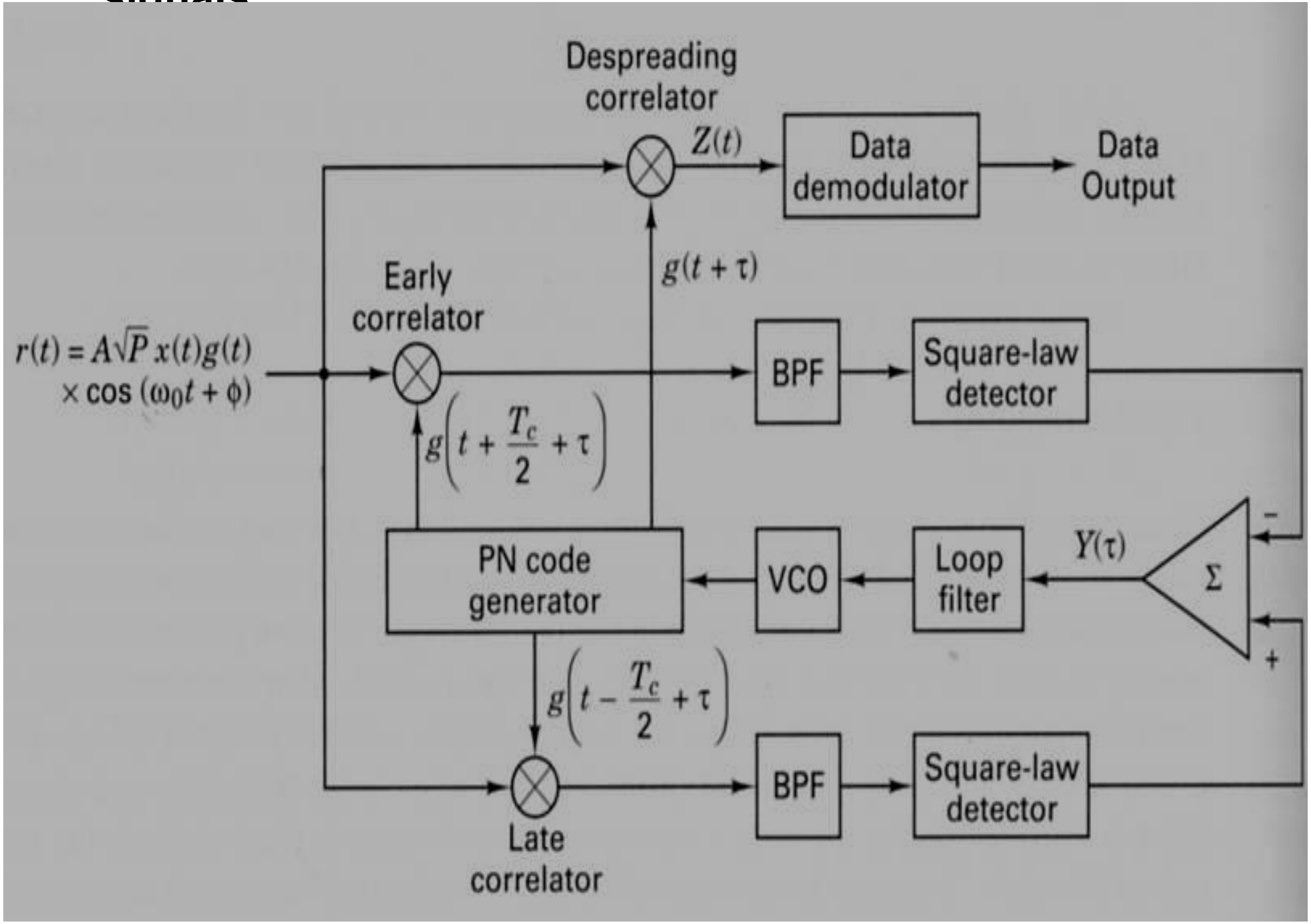
- Once acquisition or coarse synchronization is completed, tracking or fine synchronization takes place.
  Since the carrier frequency and phase are not known in most mobile fading channel , a noncoherent code loop is used to track the received PN code. The tracking loops are classified as a full-time early-late tracking loop ,such as delay-locked loop (DLL) , or a

.time-shared early-late tracking , such as tau-dither
loop (TDL) .

8.6.3.1 Delay-Locked Loop

- A basic noncoherent delay-locked loop (DLL) for a direct-sequence spread-spectrum system using BPSK is shown in Fig. XX .

Fig.xx Delay-locked loop to track ditect-sequence spread –spectrum signals



- The data signal $x(t)$ and the code $g(t)$ each modulate the carrier wave using BPSK. In the absence of noise and interference , the received signal can be expressed as

$$r(t) = A \sqrt{(2P)}\ x(t)\ g(t)\ \cos(\omega_0 t + \varphi)$$

where A is a system gain parameter and φ is a random phase in the range $(0, 2\pi)$.

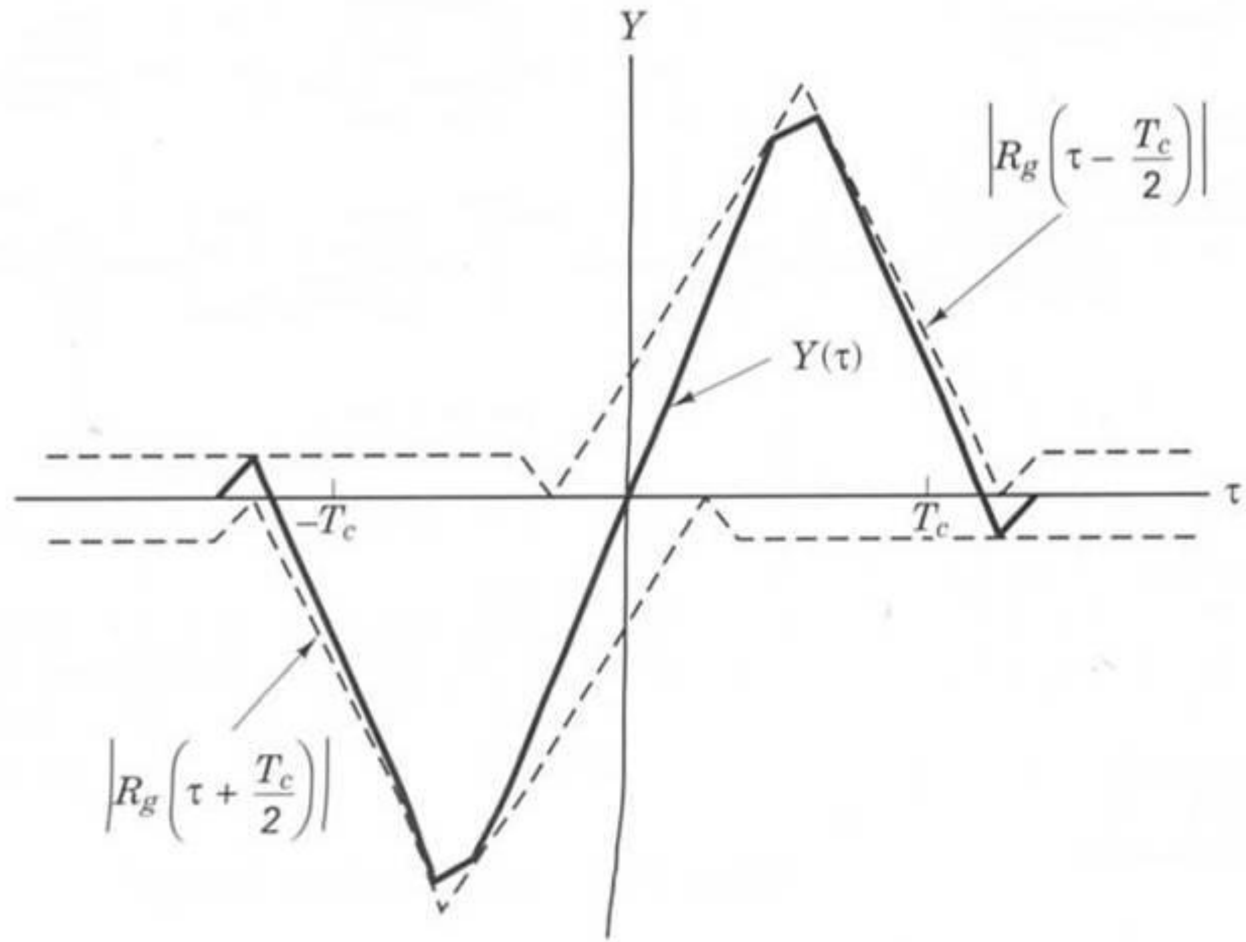
- The locally generated code of the tracking loop is offset in phase from the incoming $g(t)$ by a time τ , where $\tau < T_c / 2$.
- The loop provides fine synchronization by first generating two PN sequences, $g(t + T_c / 2 + \tau)$ and $g(t - T_c / 2 + \tau)$, delayed from each other by one chip.

- **The output of each envelope detector is given approximately by**

$$E_D \fallingdotseq \{\ |\ g(t)\, g(t \quad T_c/2 + \tau)\ |\ \} = R_g(\tau \ \ T_c/2\ )$$

where $R_g(x)$ **is the autocorrelation function of the PN waveform . The feedback signal** $Y(\tau)$ **is shown in Fig.xx .**

- **When τ is positive , the feedback signal $Y(\tau)$ instructs the voltage-controlled oscillator (VCO) to increase its frequency , thereby force τ to decrease . When τ is negative , $Y(\tau)$ instructs the voltage-controlled oscillator (VCO) to decrease its frequency , thereby forcing τ to increase. When τ is a suitable small number , g(t) g(t + τ) ≒ 1 , yielding the despread signal Z(t) , which is then applied to the input of a conventional data demodulator.**
- **A problem with the DLL is that the early and late arms must be precisely gain- balanced.**


Y
$\left|R_g\left(\tau - \frac{T_c}{2}\right)\right|$
$Y(\tau)$
τ
$-T_c$
T_c
$\left|R_g\left(\tau + \frac{T_c}{2}\right)\right|$

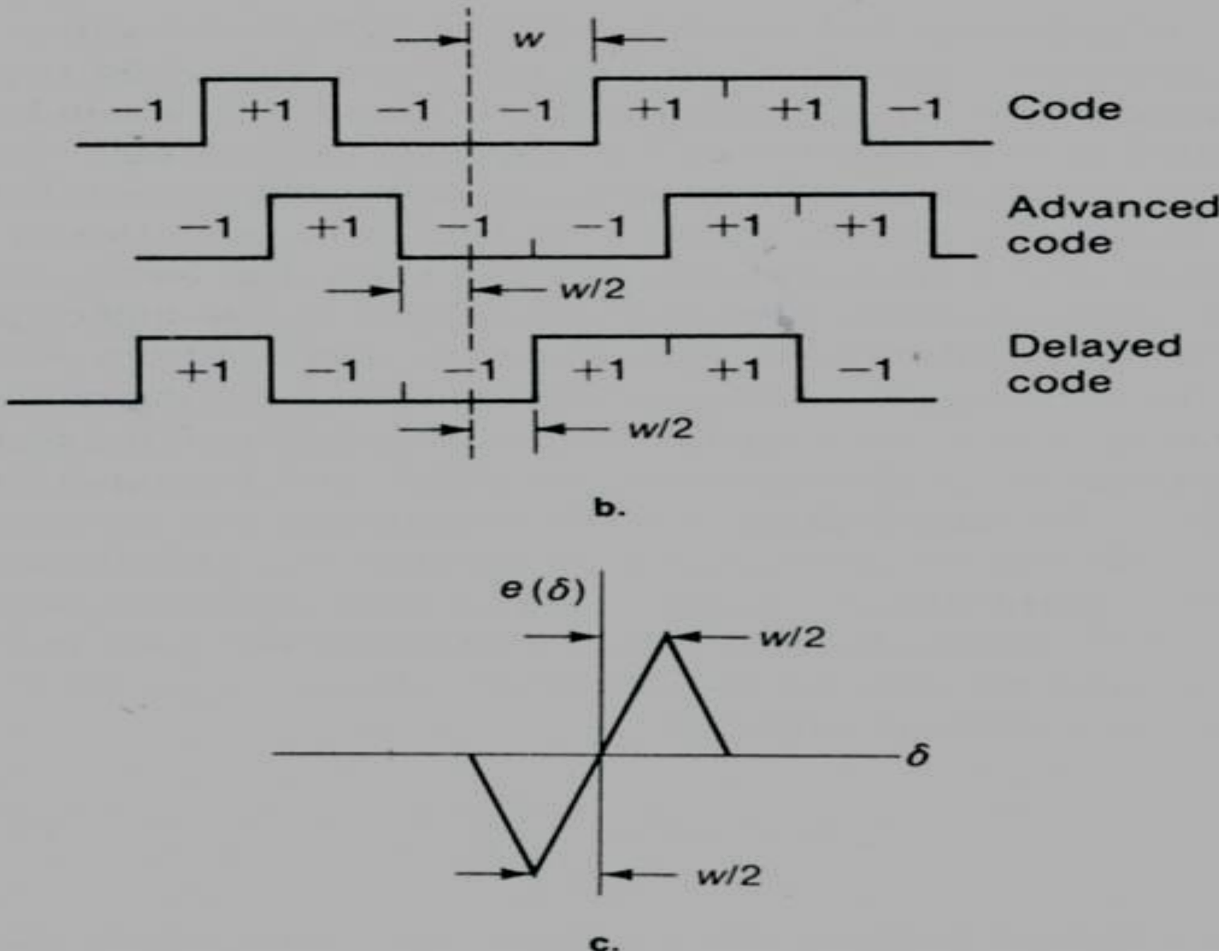


FIGURE 7.13 Delay-locked code-tracking subsystem. (a) Block diagram. (b) Advanced and delayed code alignment. (c) Code-error voltage vs. timing offset.

8.6.3.2 Tau-Dither Loop

- The problem with the DLL can be solved by using a time-shared tracking loop called tau-dither l, illustrated by the block diagram Fig.xx.
- The tau-dither loop (TDL) uses only one correlator in the design of the loop. The PN code generator is driven by a clock signal whose phase is dithered back and forth with a square- wave switching function ; this eliminates the necessity of ensuring identical transfer functions of the early and late path.

  The signal-to noise performance of the TDL is only about 1.1 dB worse than that of the DLL if the arm filters are designed properly.

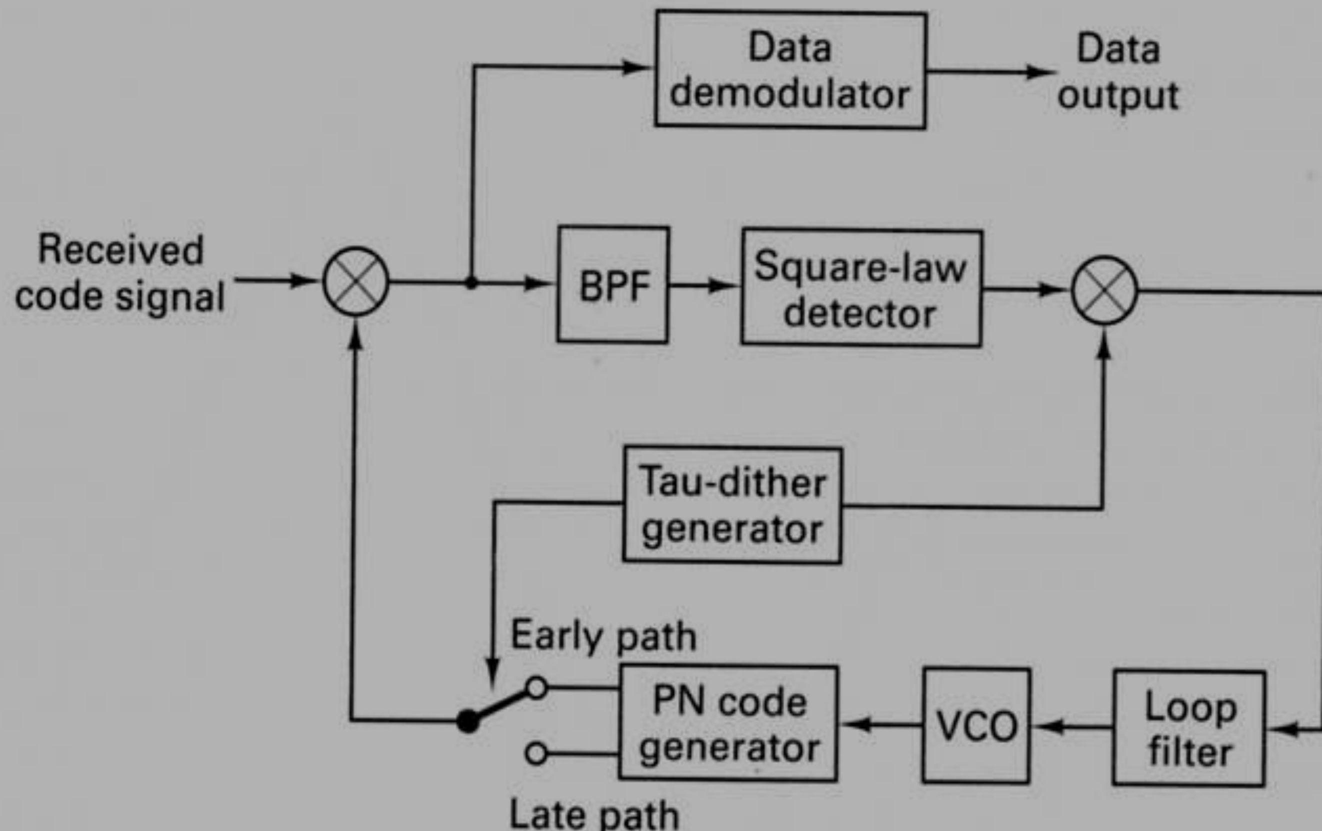


Figure 12.24 Tau-dither tracking loop.