Spread Spectrum

Chapter 18

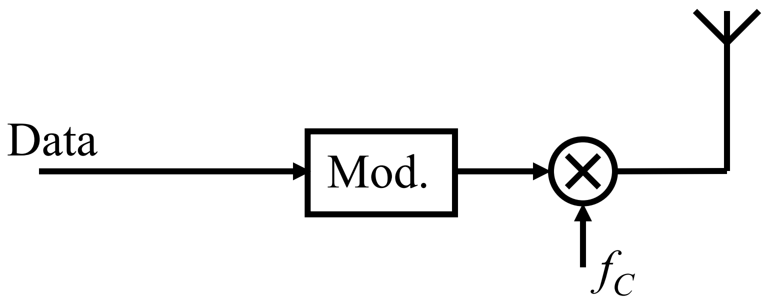
FHSS – Frequency Hopping Spread Spectrum

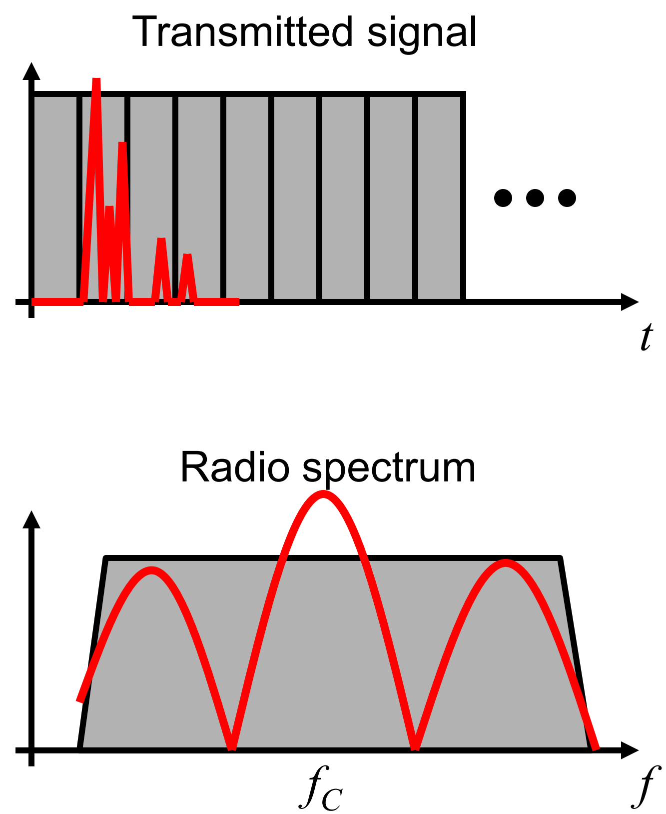
DSSS – Direct Sequence Spread Spectrum

DSSS using CDMA – Code Division Multiple Access (DS-CDMA)

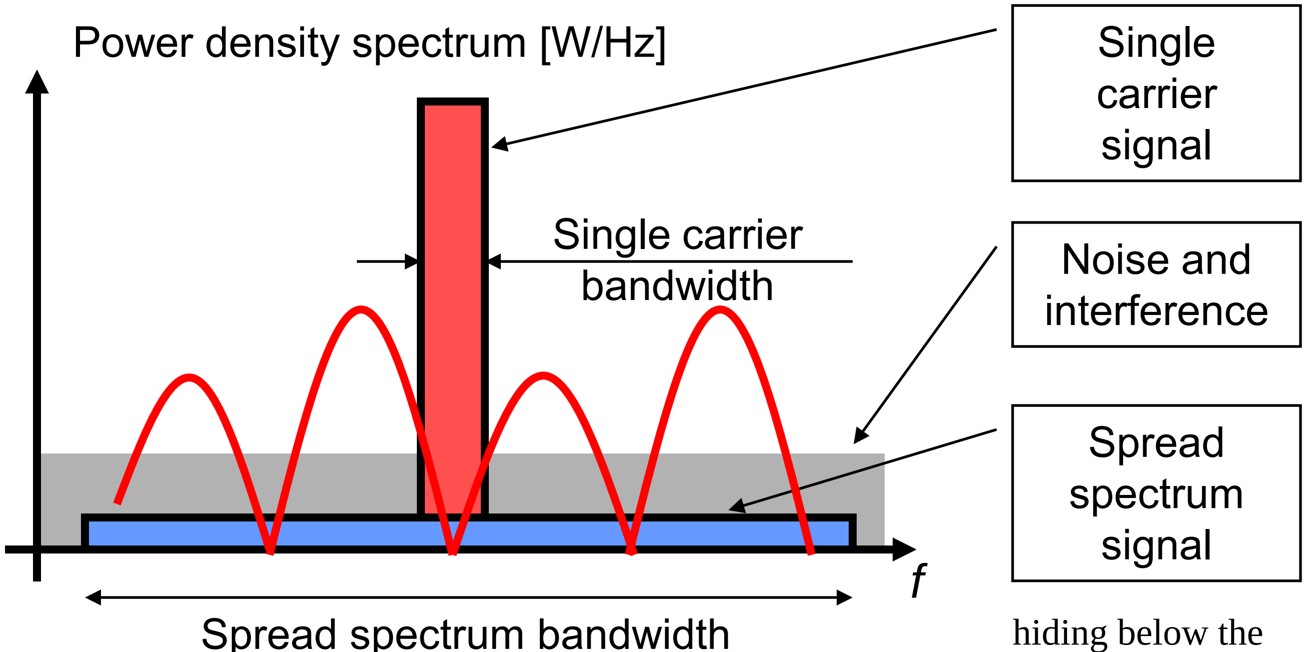
Single Carrier

The traditional way



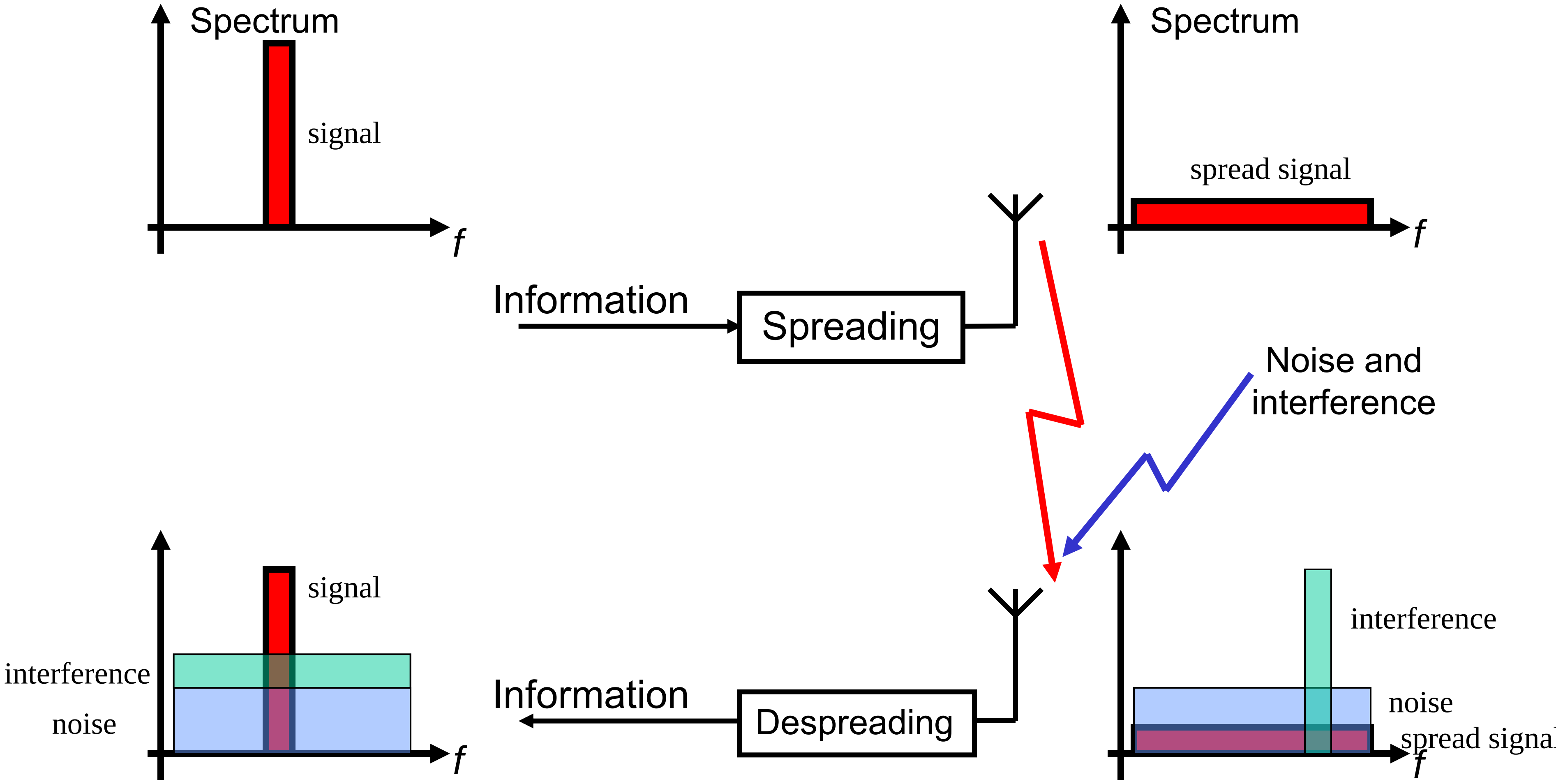


Spread Spectrum Techniques



hiding below the noise-interference power spectral denisty

Spread Spectrum Techniques



Spread Spectrum

- Input is fed into a channel encoder
  - Produces analog signal with narrow bandwidth
- Signal is further modulated using sequence of digits
  - Spreading code or spreading sequence
  - Generated by pseudonoise, or pseudo-random number generator (seed + algorithm)
- Effect of modulation is to increase bandwidth of signal to be transmitted

Spread Spectrum

- On receiving end, the same digit sequence is used to demodulate the spread spectrum signal
- Signal is fed into a channel decoder to recover data

Spread Spectrum

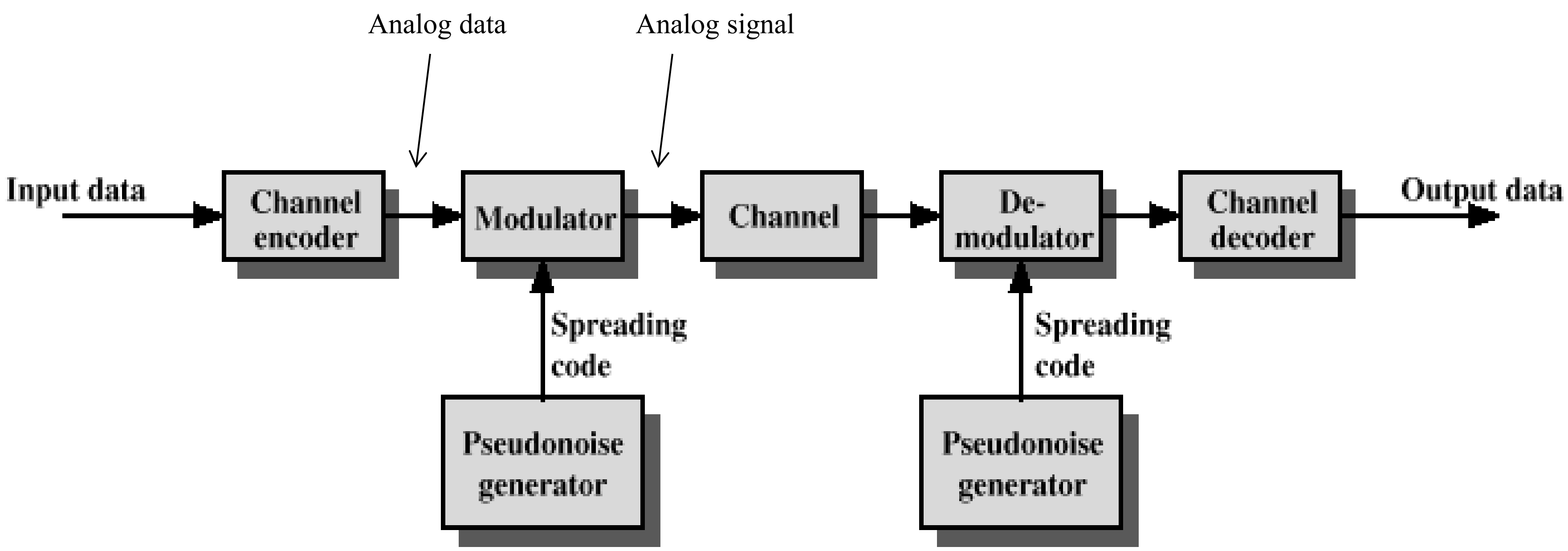


Figure 7.1 General Model of Spread Spectrum Digital Communication System

Spread Spectrum

- What can be gained from apparent waste of spectrum?
  - Immunity from various kinds of noise and multipath distortion
  - Can be used for hiding and encrypting signals
  - Several users can independently use the same bandwidth with very little interference

Frequency Hoping Spread Spectrum (FHSS)

- Signal is broadcast over seemingly random series of radio frequencies
  - A number of channels allocated for the FH signal
  - Width of each channel corresponds to bandwidth of input signal
- Signal hops from frequency to frequency at fixed intervals
  - Transmitter operates in one channel at a time
  - Bits are transmitted using some encoding scheme
  - At each successive interval, a new carrier frequency is selected (IEEE 802.11 standard uses 300 mS intervals)

Frequency Hoping Spread Spectrum

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter using the same spreading code, picks up the message using the same encoding scheme as the transmitter
  - Spreading code = c(t) also known as chipping code

Advantages

- Hackers only hear unintelligible blips (as signal skips around)
- Attempts to jam signal on one frequency succeed only at knocking out a few bits

Frequency Hoping Spread Spectrum

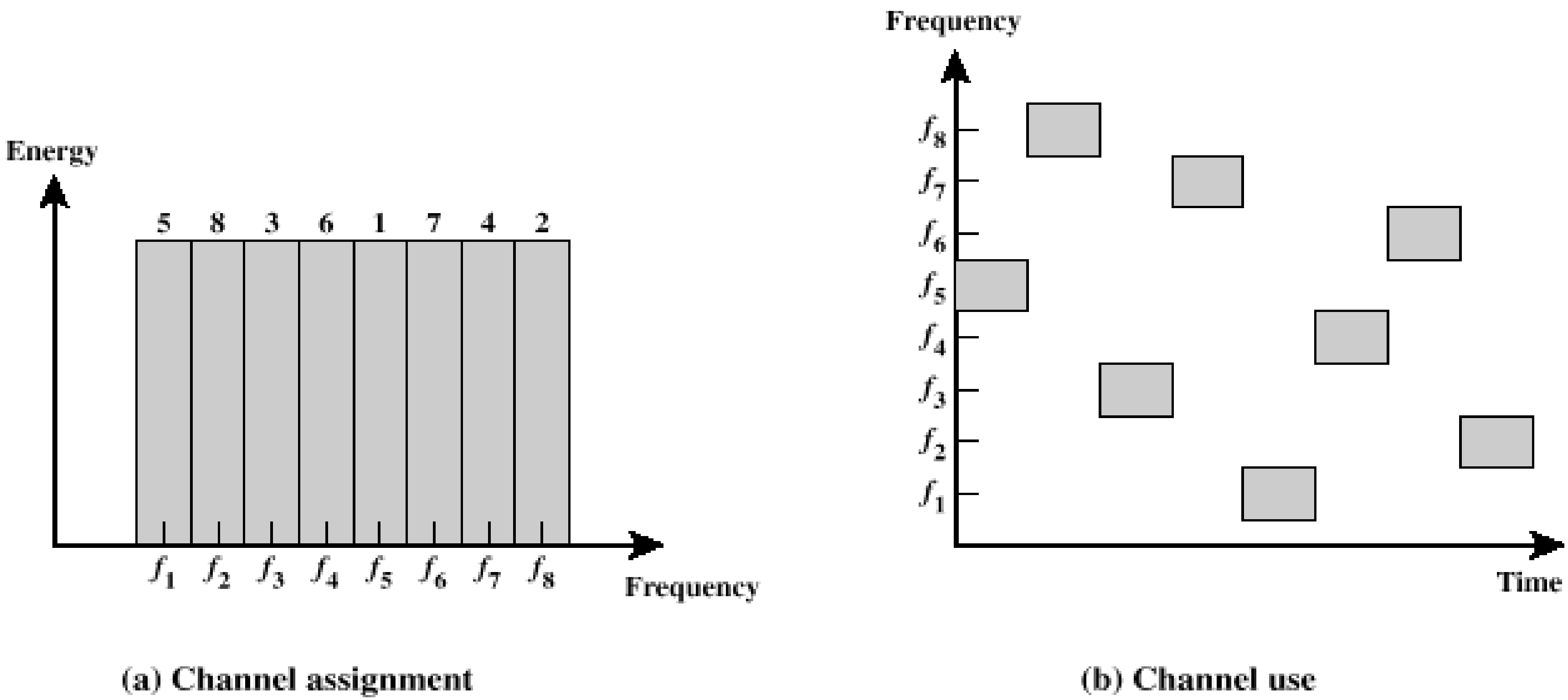
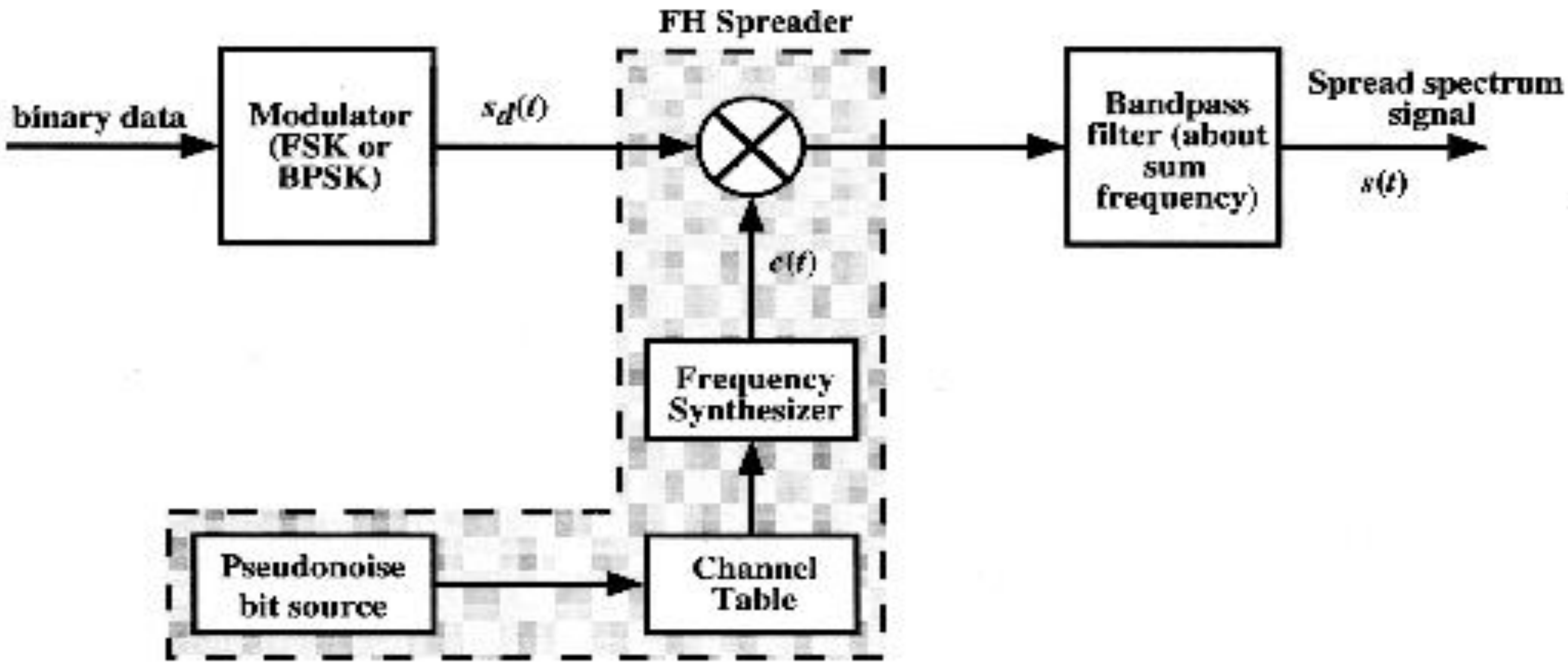


Figure in textbook is correct

Figure 7.2 Frequency Hopping Example

FHSS Details - Transmitter



Note signal frequency determination source

FHSS Using MFSK

$fc - 3fd$
$fc - fd$
$fc + fd$
$fc + 3fd$
for $M = 4$

- MFSK signal is translated to a new frequency every T_c seconds by modulating the MFSK signal with the FHSS carrier signal
- For data rate of R:
  - duration of a bit: $T = 1/R$ seconds (T is the bit period)
  - duration of signal element: $T_s = LT$ seconds
    where L bits are encoded per signal element ($M = 2^L$)
- $T_c \geq T_s$ - slow-frequency-hop spread spectrum
  frequency hop time larger than signal element time/duration
- $T_c < T_s$ - fast-frequency-hop spread spectrum
  frequency hops within signal element duration

MFSK Signal Before & After FHSS

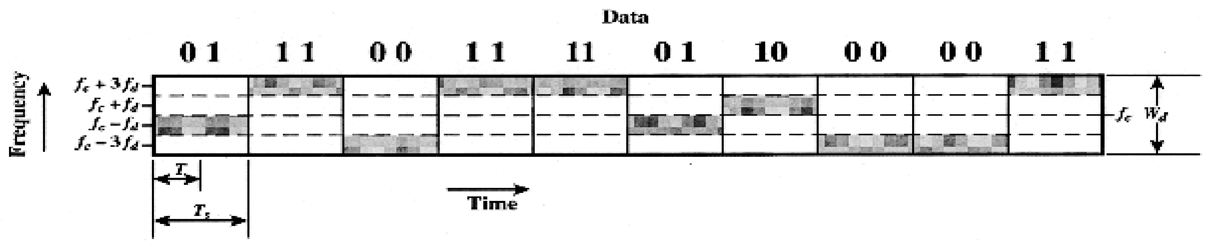


Figure 6.4 MFSK Frequency Use ($M = 4$)

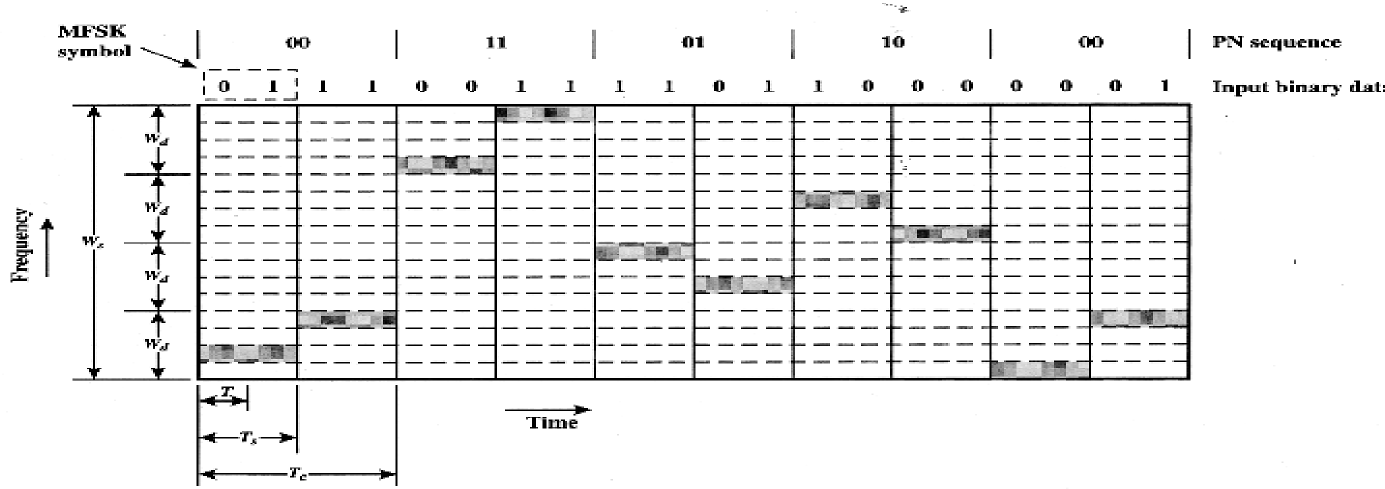


Figure 7.4 Slow Frequency Hop Spread Spectrum Using MFSK ($M = 4$, $k = 2$)

Fast FHSS ($T_s > T_c$)

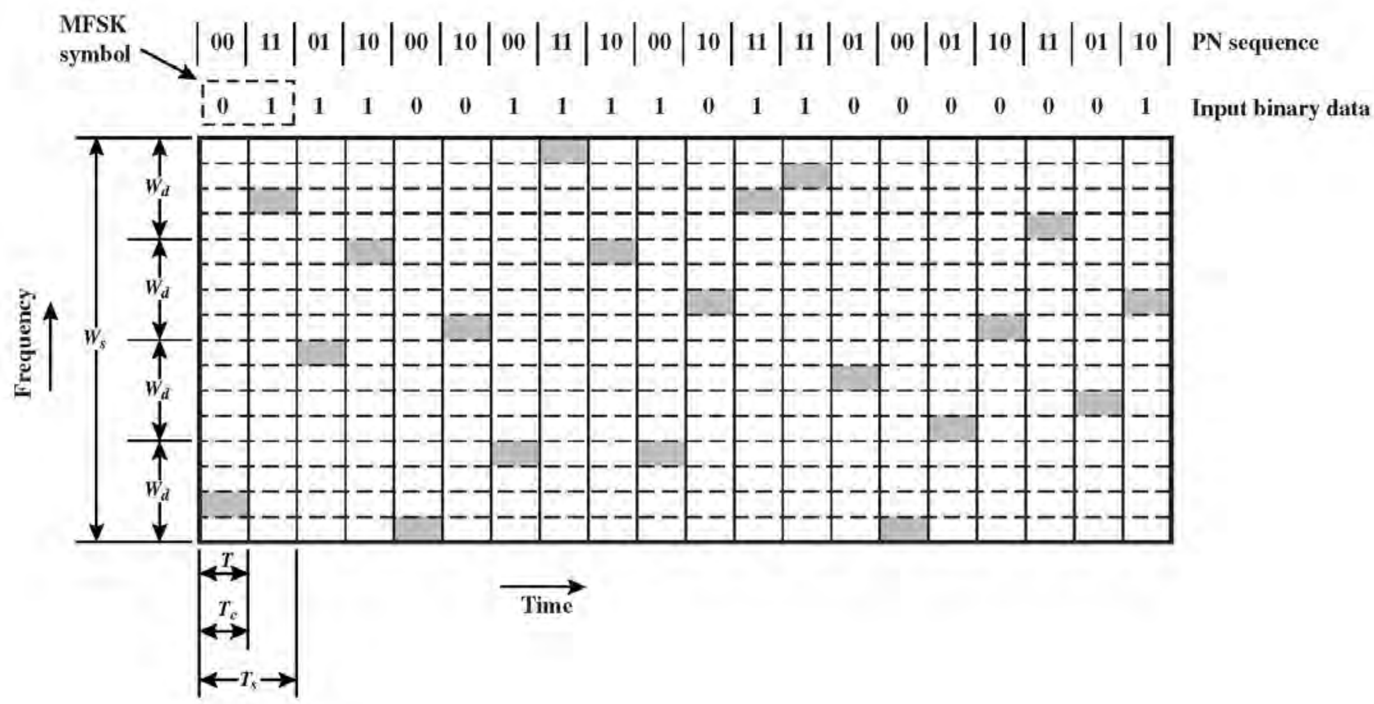
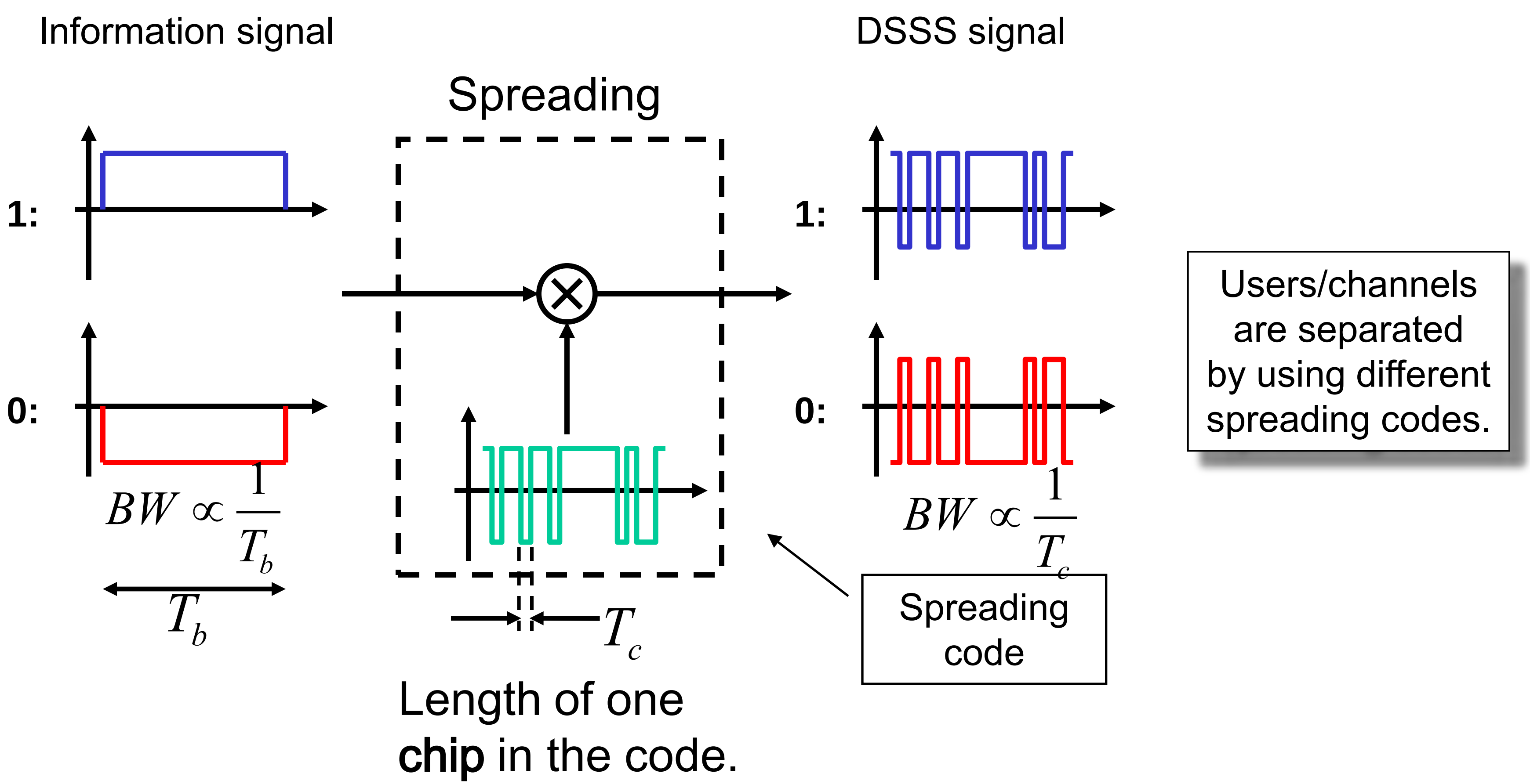


Figure 7.5 Fast Frequency Hop Spread Spectrum Using MFSK ($M = 4, k = 2$)

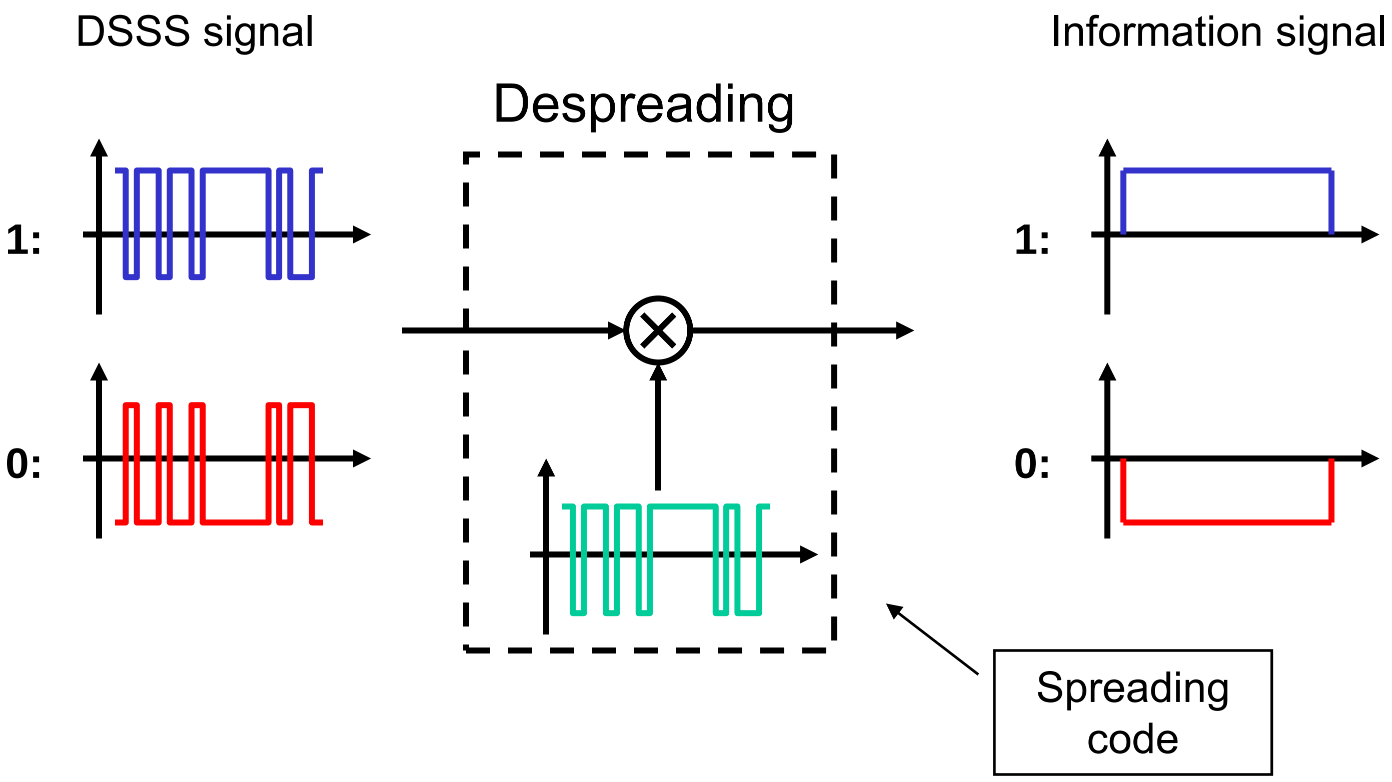
FHSS Performance Considerations

- Large number of frequencies used
- Results in a system that is quite resistant to jamming
  - Jammer must jam all (hopping) frequencies
  - With fixed power, this reduces the jamming power in any one frequency band
  - The gain in jamming is the processor gain
    $G_p = W_s / W_d$ (FHSS bandwidth / MFSK bandwidth)
  - Fast FHSS is more jamming robust than slow FHSS since multiple frequencies (chips) are used for each signal element (majority voting could be used)

Direct-Sequence Spread Spectrum DSSS (1)



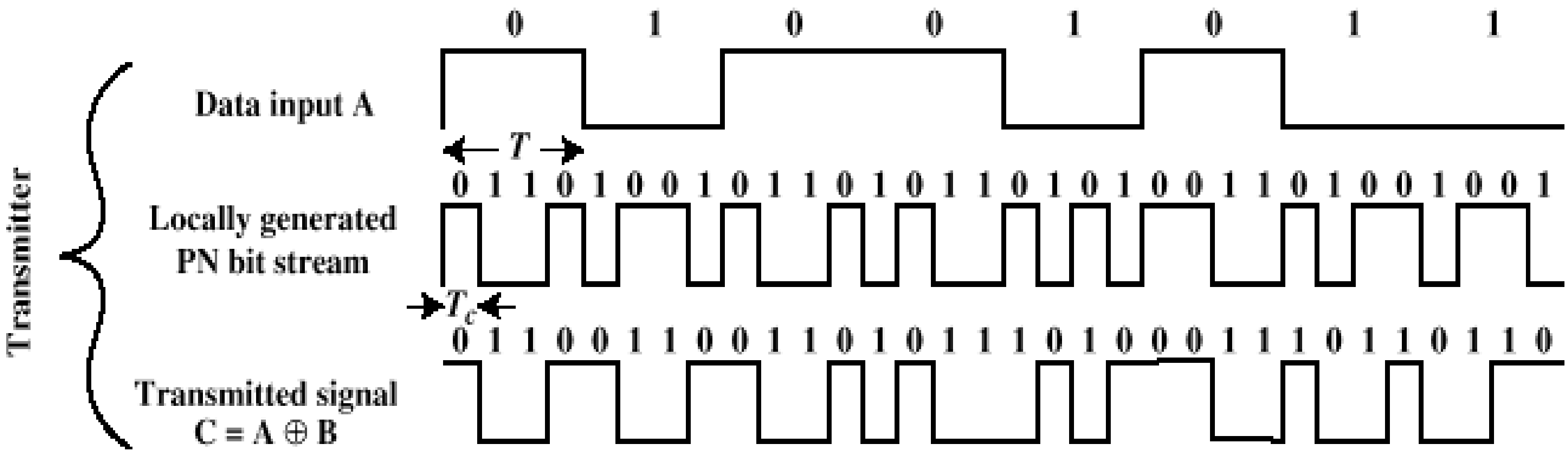
Direct-Sequence Spread Spectrum DSSS (2)



Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by **multiple** bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - The amount of sperading is in direct proportion to number of pseudonoise (PN) bits used
- One technique combines digital information stream with the spreading code bit stream (PN bit stream) using exclusive-OR

  d(t) * c(t) & then BPSK modulation



See errata sheet for 1st edition

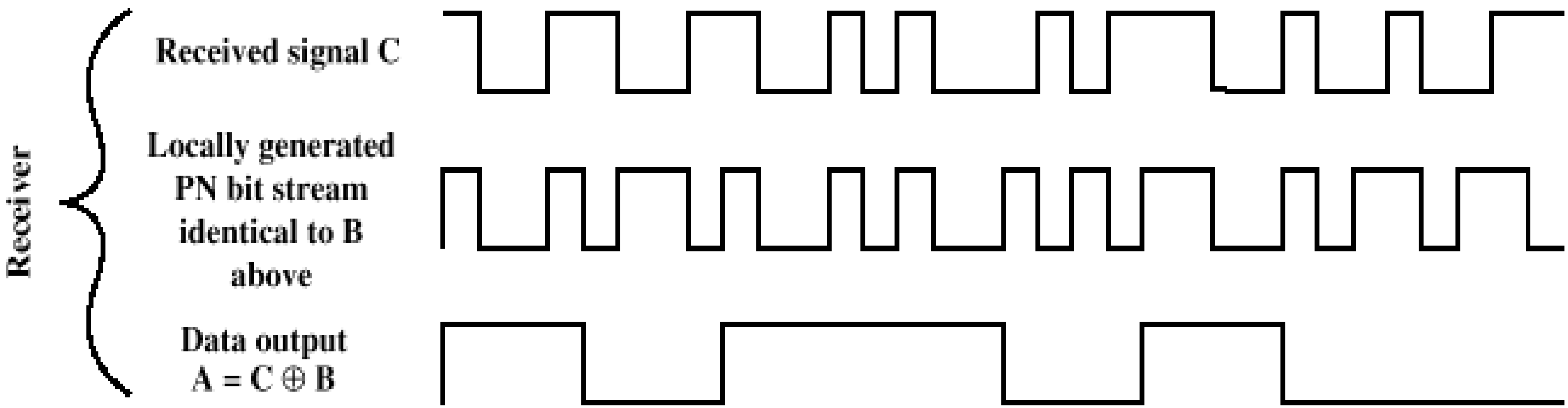


Figure 7.6 Example of Direct Sequence Spread Spectrum

DSSS Using BPSK

- Multiply BPSK signal,

$$s_d(t) = A\, d(t) \cos(2\pi f_c t)$$

  by $c(t)$ [takes values +1, -1] to get

$$s(t) = A\, d(t)\, c(t) \cos(2\pi f_c t)$$

  - A = amplitude of signal f_c = carrier frequency
  - $d(\mathrm{t})$ = discrete function [+1, -1 used to represent binary 1 & 0]
- At receiver, incoming signal multiplied by $c(t)$
  - Since $c(t)$ x $c(t)$ = 1, incoming signal is recovered
- Can perform BPSK modulation either before or after the chipping signal c(t) is used in direct sequence spreader
- DSSS Performance similar to FHSS in terms of the SNR or 'performance' gain Gp ≈ Ws/Wd
  Gp = signal bandwidth/spread spectrum bandwidth
  the 'spread'of the jamming power over the signal bandwidth

DSSS Using BPSK

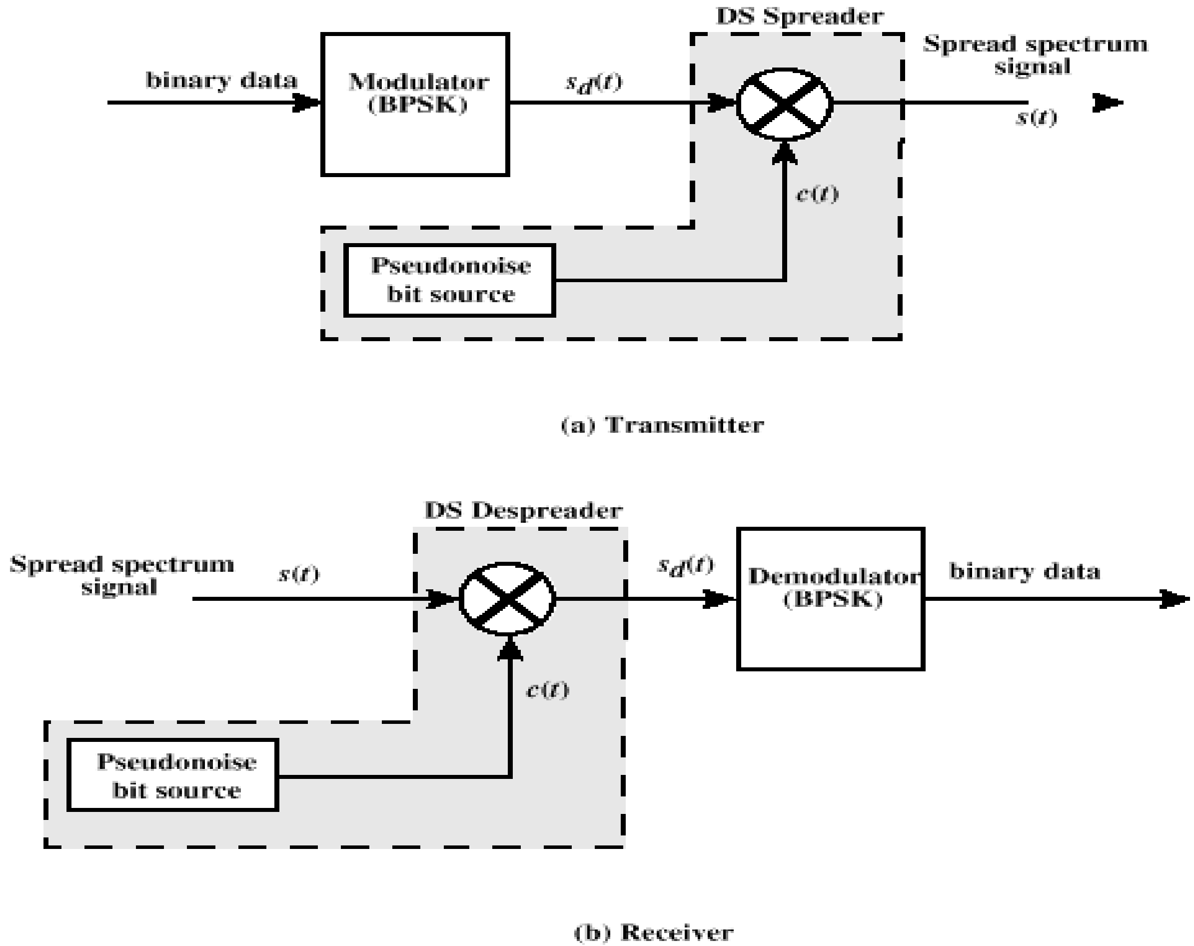


Figure 7.7 Direct Sequence Spread Spectrum System

Chipping signal applied after BPSK modulation. Note data rate sources vs FHSS frequency determination sources

Data Before & After DSSS

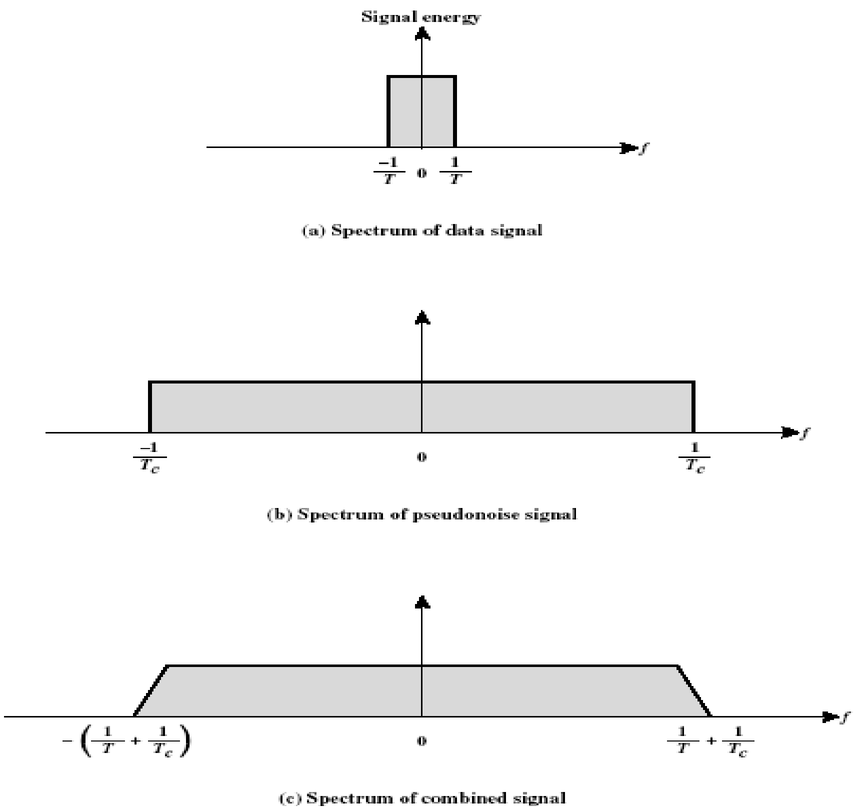
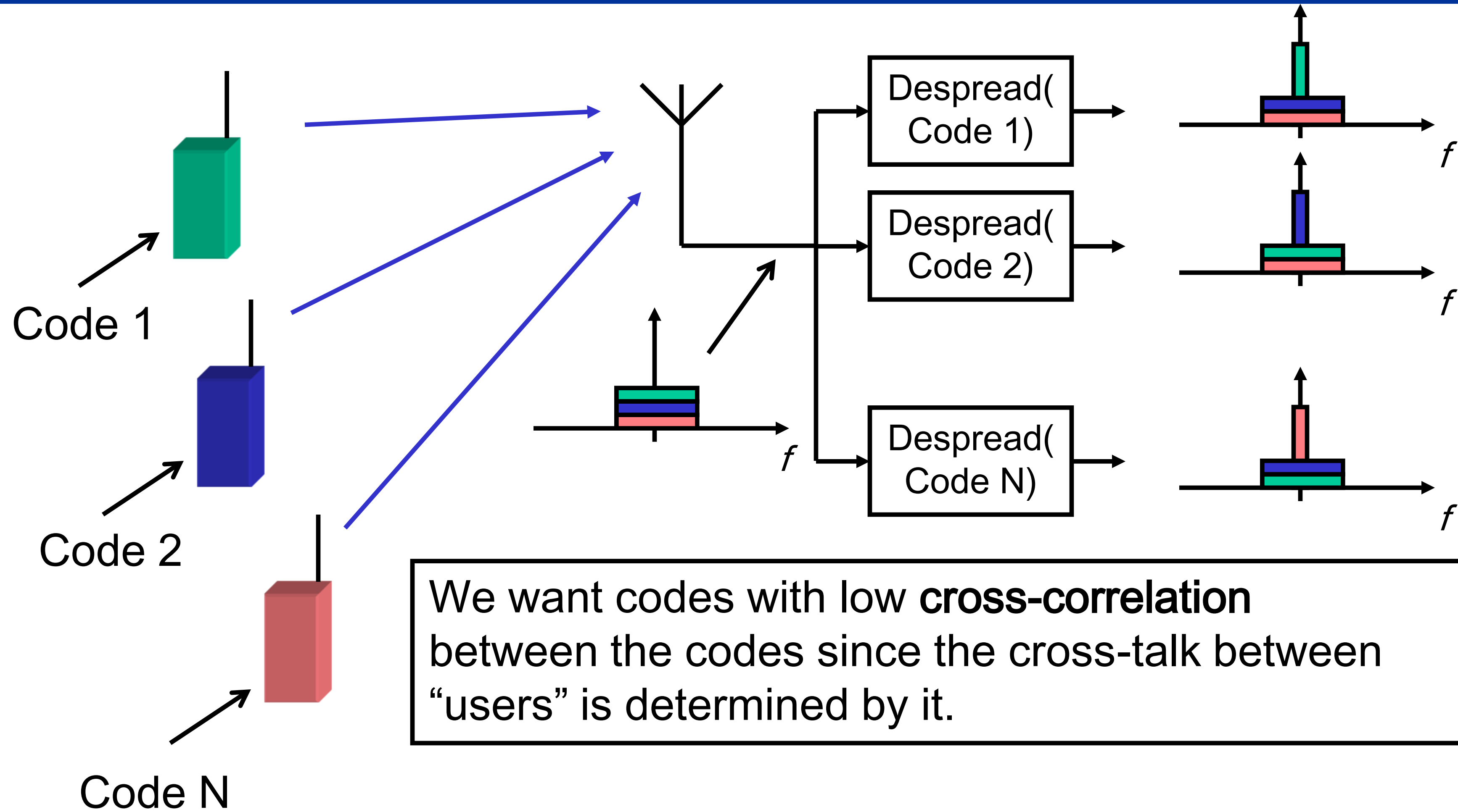


Figure 7.9 Approximate Spectrum of Direct-Sequence Spread Spectrum Signal

Code-division multiple access (CDMA)



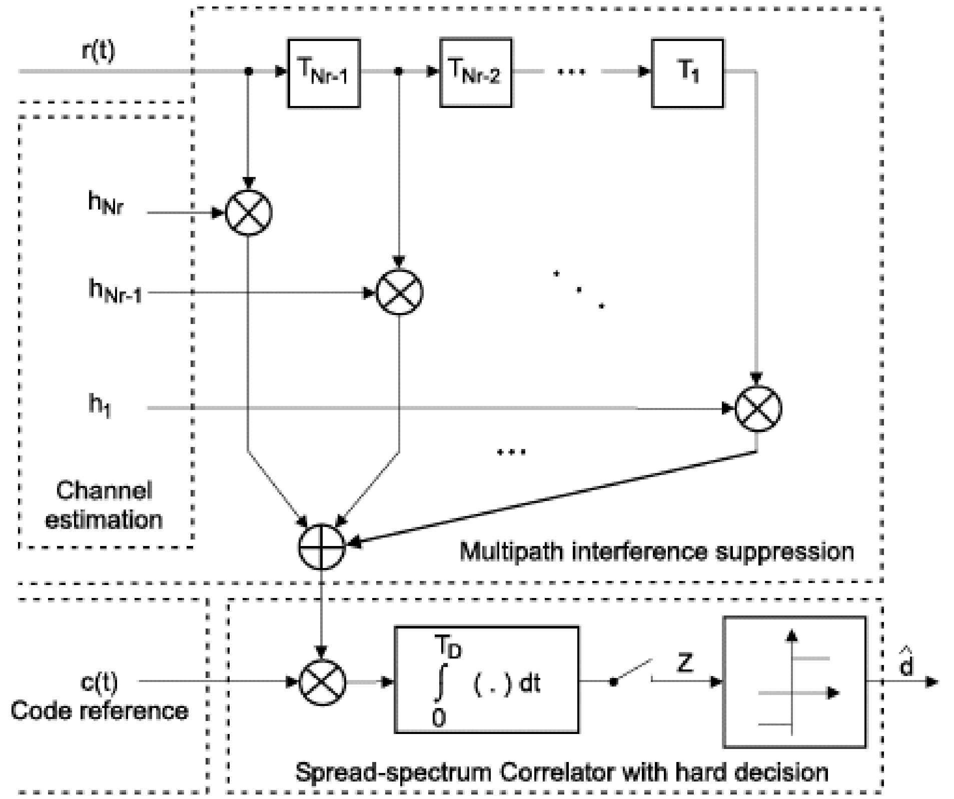
We want codes with low **cross-correlation** between the codes since the cross-talk between “users” is determined by it.

Impact of delay dispersion

- CDMA spreads signals over larger bandwidth -> delay dispersion has bigger impact.
- Two effects:
  - Intersymbol interference: independent of spreading; needs to be combatted by equalizer
  - Output of despreader is not impulse, but rather an approximation to the impulse response
- Needs Rake receiver to collect all energy

Rake receivers

Despreading becomes a bit more complicated ...



... but we gain frequency diversity.

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA (a multiplexing scheme used with spread spectrum)
  - D = rate of data signal
  - Break each bit into *k chips*
    - Chips are a user-specific fixed pattern
    - This pattern is called the User's Code
    - The codes are orthogonal (limited set)
  - Chip data rate of new channel = kD chips/sec

CDMA Example

- If $k = 6$ and code is a sequence of 1's and -1's
  - For each '1' bit, A sends user code as a chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For each '0' bit (-1), A sends complement of user code
    - <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender's code and performs decode function (assume synchronized so that the receiver knows when to apply the user code)

$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

- < d1, d2, d3, d4, d5, d6 > = received chip pattern
- < c1, c2, c3, c4, c5, c6 > = sender's code

CDMA Example

- User A code = <1, –1, –1, 1, –1, 1>
  - To send a 1 bit = <1, –1, –1, 1, –1, 1>
  - To send a 0 bit = <–1, 1, 1, –1, 1, –1>
- User B code = <1, 1, –1, – 1, 1, 1>
  - To send a 1 bit = <1, 1, –1, –1, 1, 1>
- Receiver receiving with A's code
  - (A's code) x (received chip pattern)
    - User A '1' bit decoded results: + 6 which translates into 1
    - User A '0' bit: - 6 → binary 0
    - User B '1' or '0' bit decoded result: 0 → signal ignored, S_A signal decode results in a value of 0 which is different from a decode value of +/- 6 for transmitted bits '1' or '0' from User A

CDMA Example Continued

User A	1	−1	−1	1	−1	1
User B	1	1	−1	−1	1	1
User C	1	1	−1	1	1	−1

B Sends (data bit = 1)	1	1	-1	-1	1	1	
Receiver codeword **A** (decode)	1	-1	-1	1	-1	1	
Multiplication	1	-1	1	-1	-1	1	= 0

$S_A(1,1,-1,-1,1,1) = 1 \times 1 + 1 \times (-1) + (-1) \times (-1) + (-1) \times 1 + 1 \times (-1) + 1 \times 1 = 0$

B Sends (data bit = 0)	-1	-1	1	1	-1	-1	
Receiver codeword **A**	1	-1	-1	1	-1	1	
Multiplication	-1	1	-1	1	1	-1	= 0

$S_A(-1,-1,1,1,-1,-1) = (-1) \times 1 + (-1) \times (-1) + 1 \times (-1) + 1 \times 1 + (-1) \times (-1) + (-1) \times 1 = 0$

Transmission from B and C, receiver attempts to recover B's transmission

B (data bit = 1)	1	1	–1	–1	1	1	
C (data bit = 1)	1	1	–1	1	1	–1	
Combined signal	2	2	–2	0	2	0	
Receiver codeword	1	1	–1	–1	1	1	
Multiplication	2	2	2	0	2	0	= 8

B (data bit = 0)	-1	-1	1	1	-1	-1	
C (data bit = 1)	1	1	-1	1	1	-1	
Combined signal	0	0	0	2	0	-2	
Receiver codeword **B**	1	1	-1	-1	1	1	
Multiplication	0	0	0	-2	0	-2	= -4

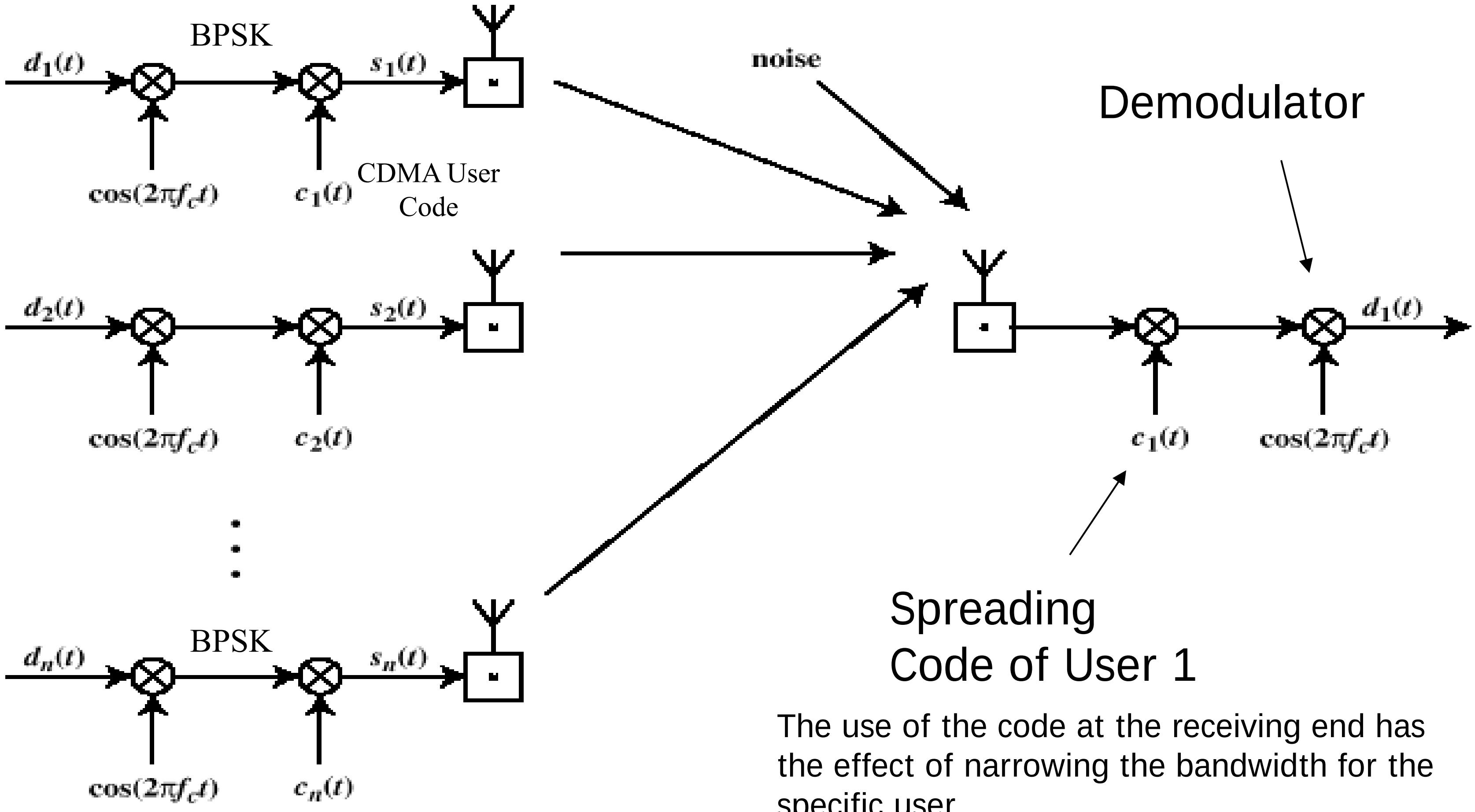
Top Case B sends a 1 → S_B = 8 Bottom Case B sends a 0 → S_B = - 4

Transmissions from B and C, receiver attempts recovery using A's codeword (an error situation)

B (data bit = 0)	-1	-1	1	1	-1	-1	
C (data bit = 1)	1	1	-1	1	1	-1	
Combined signal	0	0	0	2	0	-2	
Receiver codeword **A**	1	-1	-1	1	-1	1	
Multiplication (S_A)	0	0	0	2	0	-2	= 0

Decode result: S_A = 0 for this case where B and C have sent data and we attempt to recover a transmission from A . Different receiver codeword can result in S_x that is non-zero but much less than the correct orthogonal result.

CDMA for Direct Sequence Spread Spectrum



The use of the code at the receiving end has the effect of narrowing the bandwidth for the specific user.

Figure 7.11 CDMA in a DSSS Environment Includes noise

Categories of Spreading Sequences

- Spreading Sequence Categories
  - PN sequences (pseudonoise)
  - Orthogonal codes
- For FHSS systems
  - PN sequences most common
- For DSSS systems not employing CDMA
  - PN sequences most common
- For DSSS CDMA systems
  - PN sequences
  - Orthogonal codes

    Codes with perfect orthogonality are possible, but only for perfectly synchronized users
- Spreading codes result in a higher transmitted data rate → increased bandwidth; increased system redundancy (jamming resilient); the spreading codes are noise like in their appearance

PN Sequences

- PN generator produces periodic sequence that appears to be random
- PN Sequences
  - Generated by an algorithm using initial seed
  - The algorithm is deterministic
  - Sequence isn’t statistically random but will pass many test of randomness
  - Sequences referred to as pseudorandom numbers or pseudonoise sequences
  - Unless algorithm and seed are known, the sequence is impractical to predict

Important PN Properties

- Randomness
  - Uniform distribution (frequency of occurrence)
    - Balance property (equal # of 1 and 0 in a long sequence)
    - Run property (length of a sequence of all 1 or 0 diminishes)
  - Independence (no value in sequence inferred from the others)
  - Correlation property (comparisons of shifts of itself)

    # of terms that are the same differs from those that are different by at most 1
- Unpredictability

Linear Feedback Shift Register Implementation (LSFR)

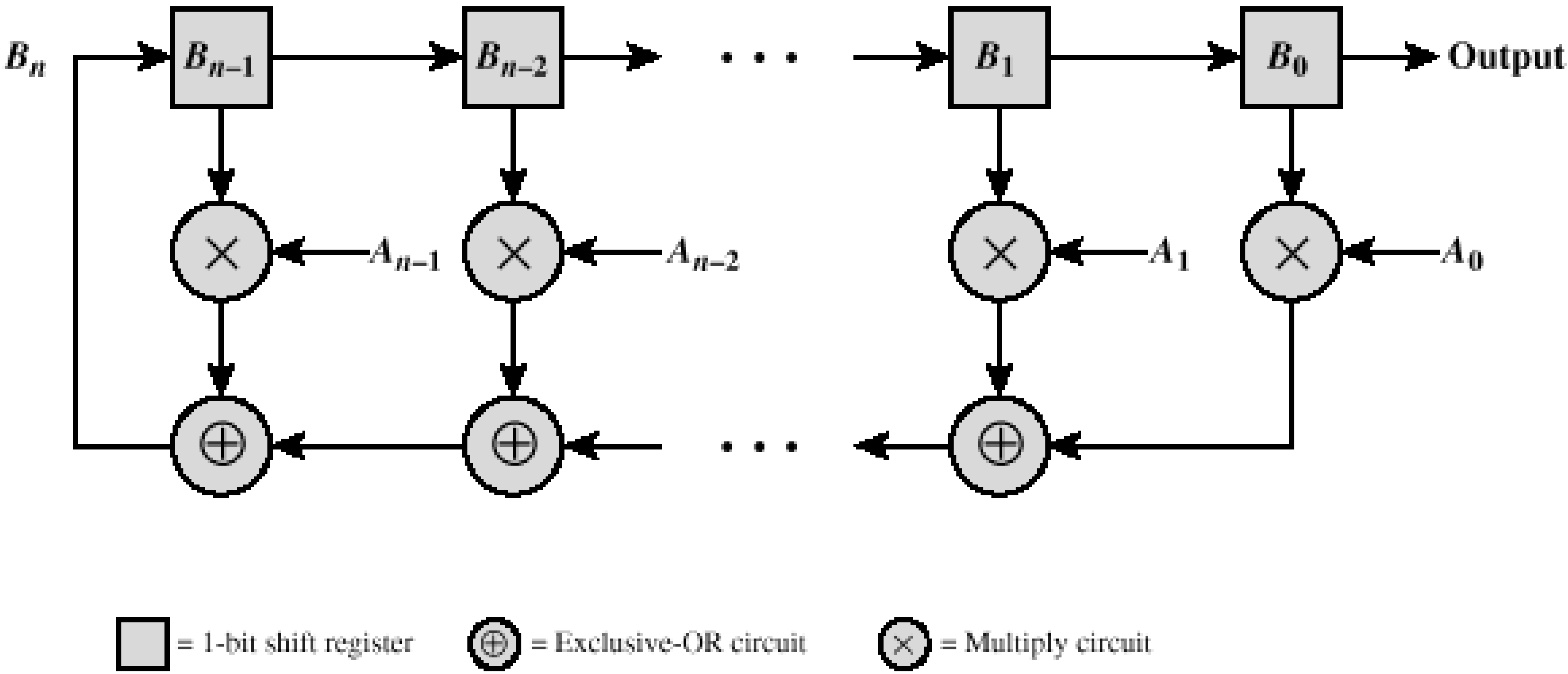


Figure 7.12 Binary Linear Feedback Shift Register Sequence Generator

Linear Feedback Shift Register (LSFR)

- Clocked high-speed sequential circuit, generates a sequence of period N (the output repeats every N bits). Must be fast since spreading rate > data rate
- Generates a sum of XOR terms

  $$B_n = A_0B_0 \oplus A_1B_1 \oplus A_2B_2 \oplus \cdots\cdots \oplus A_{n-1}B_{n-1}$$
- LSFRs produce a generator polynomial (Ex-OR gates represent the terms in the generator polynomial; actual circuit implementation doesn't need multiply circuits as previously shown. Same type of circuit used in CRC generation and checking.)
- Modulo 2 arithmetic (Ex-OR function)
- Resulting sequences are maximal-length sequences or **m-sequences**

Properties of M-Sequences (enables synchronization)

- Property 1 of maximal-length sequences:
  - Has 2^{n-1} ones and $2^{n-1}-1$ zeros
- Property 2:
  - For a window of length n slid along output for N shifts, where $N = 2^n - 1$ each n-tuple appears exactly once, except for the all zeros sequence
- Property 3:
  - Sequence contains one run of ones, length n
  - One run of zeros, length n-1
  - One run of ones and one run of zeros, length n-2
  - Two runs of ones and two runs of zeros, length n-3
  - In general 2^{n-3} runs of ones and 2^{n-3} runs of zeros, length 1

Properties of M-Sequences

- Property 4:
  - The periodic autocorrelation of a ± 1 (changed from 0,1) m-sequence is

$$R(\tau) = \begin{cases} 1 & \tau = 0, \mathrm{N}, 2\mathrm{N}, \ldots \\ -\dfrac{1}{N} & \text{otherwise} \end{cases}$$

This is the definition of *periodic autocorrelation* which is the correlation of a sequence with all phase shifts of ITSELF

Definitions: Autocorrelation and Cross Correlation

- Correlation
  - The concept of determining how much similarity one set of data has with another
  - **Autocorrelation** is the correlation or comparison of a sequence with all phase shifts of itself.

$$R(\tau) = 1/N \sum_{k=1}^{N} B_k B_{k-\tau}$$

  - The periodic autocorrelation of a PN generator implemented with a Linear Feedback Shift Register or mathematically generated called a maximal-length sequence (m-sequence) is

$R(\tau) = 1$ for $\tau = 0, N, 2N, \ldots..$ High degree of correlation

$R(\tau) = -1/N$ otherwise Low degree of correlation

Autocorrelation and Cross Correlation

- Range between -1 and 1
  - 1 The second sequence matches the first sequence
  - 0 There is no relation at all between the two sequences
  - -1 The two sequences are mirror images of each other
- Random data has a correlation of close to 0 whereas the same m-sequences have a sharp peak correlation at the chipping period which aids synchronization by the receiver (since the receiver knows the m-sequence).

- Cross Correlation

$$R_{A,B}(\tau) = 1/N \sum_{k=1}^{N} A_k B_{k-\tau}$$

- The comparison between two sequences from different sources rather than a shifted copy of a sequence with itself
- Same general properties as for Autocorrelation

Advantages of Cross Correlation

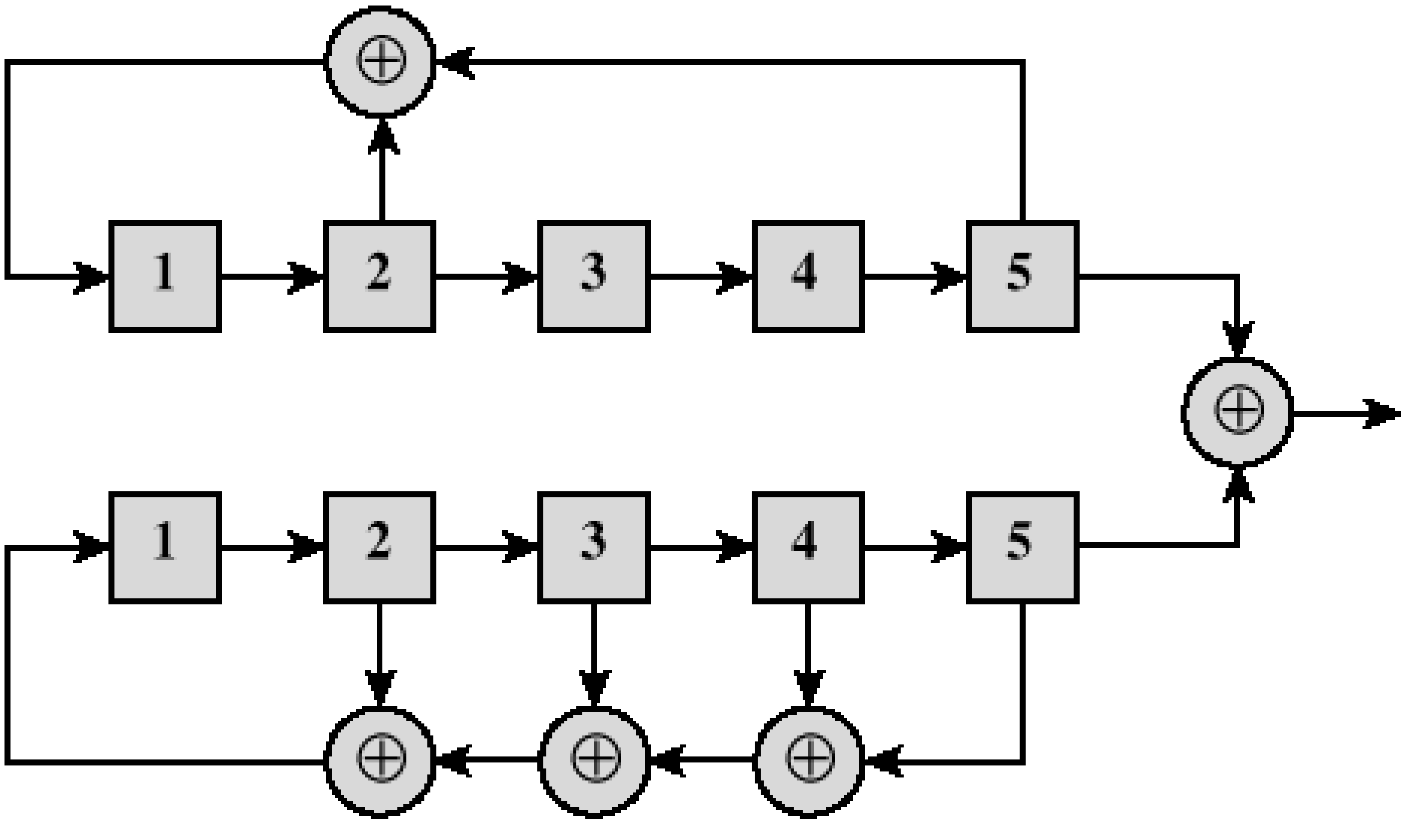
- The cross correlation between a pseudo noise sequence (an m-sequence) and noise is low
  - This property is useful to the receiver in filtering out noise
  - Noise is random (autocorrelation = 0 for all phase shifts of itself)
- The cross correlation between two different m-sequences is low (should be 0 or close to 0 - orthogonal)
  - This property is the basis of CDMA applications
  - Enables a receiver to discriminate among spread spectrum signals generated by different m-sequences
  - High cross correlation for spread spectrum signal with the same PN bit stream applied at receiver
  - Low cross correlation for spread spectrum signal and different PN applied at receiver.

Gold Sequences

- Gold sequences constructed by the XOR of two m-sequences (preferred pairs) with the same clocking (bit shifts)
- Gold Codes have well-defined cross correlation properties (not generally produced by m-sequences and thus m-sequences are not optimal for CDMA DSSS)
- Only simple circuitry needed to generate large number of unique codes using *preferred* pairs of m-sequences.

- In following example, two shift registers generate the two m-sequences and these sequences are then bitwise XORed to produce the Gold sequence.

Gold Sequences



(a) Shift-register implementation

Orthogonal Codes

- Orthogonal codes
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- Types
  - Welsh codes
  - Variable-Length Orthogonal codes

Walsh Codes (most common in CDMA)

- Set of Walsh codes of length *n* consists of the n rows of an *n* x *n* Walsh matrix:
  - $W_1 = (0)$ $$W_{2n} = \begin{pmatrix} W_n & W_{2n} \\ W_n & \overline{W_n} \end{pmatrix}$$
    - n = dimension of the matrix (overscore → logical NOT)
  - Every row is orthogonal to every other row and to the logical not of every other row
  - Requires tight synchronization
    - Cross correlation between different shifts of Walsh sequences is not zero; alternative is to use PN

Multiple Spreading Approaches

- Spread data rate by an orthogonal code (channelization code)
  - Provides mutual orthogonality among all users in the **same** cell
- Further spread result by a PN sequence (scrambling code)
  - Provides mutual randomness (low cross correlation) between users in **different** cells - advantageous for reuse distant cells
- Requires sufficient bandwidth (since each ‘spread’ increases the data rate) but is effective for decoding users in the same cell and reducing interference between users in different cells
- CDMA in combination with FDMA – total bandwidth is divided into multiple subbands in which CDMA is used as the multiple access method

Summary

- The available radio resource is shared among users in a **multiple access** scheme.
- When we apply a **cellular structure**, we can **reuse** the same channel again after a certain distance (based on signal to interferrence levels).
- In cellular systems the limiting factor is **interference**.
- For FDMA and TDMA the tolerance against interference determines the possible **cluster size** and thereby the amount of resources available in each cell.
- For CDMA systems, we use **cluster size one**, and the number of users depends on **code properties** and the capacity to perform **interference cancellation** (**multi-user detection**).