Spread Spectrum

Chapter 7

Spread Spectrum - Introduction

- **Modulation** techniques aim to make efficient use of bandwidth.
- **Spread spectrum** techniques, on the other hand, use a much higher bandwidth than necessary.
  - There is unnecessary waste of bandwidth for a single user, but in multiple usage users can use the same bandwidth without interference.
  - Therefore, spread spectrum is an effective method in terms of bandwidth in multiple uses.

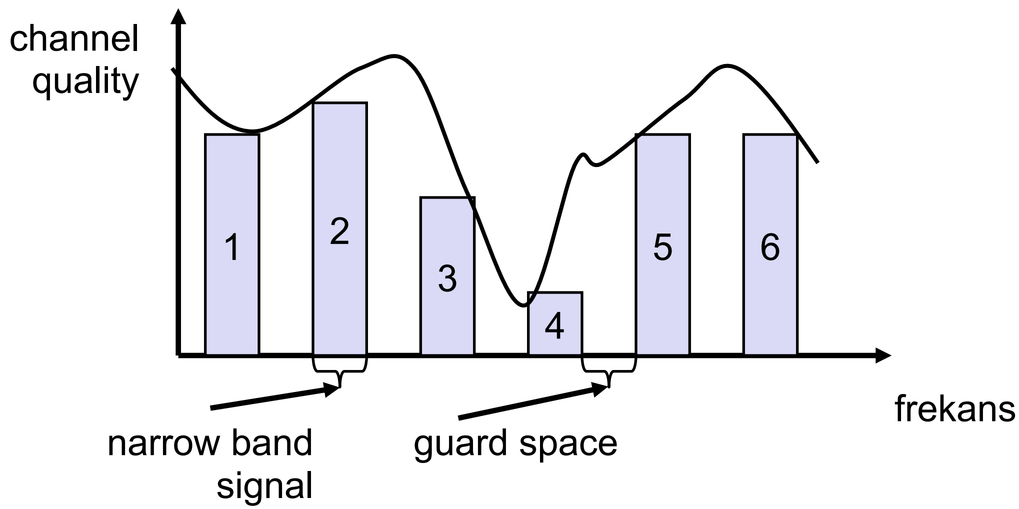
Spread Spectrum - Introduction

- Spread spectrum contains the spread of the bandwidth required for the data to be transmitted
- For example , it is a multiple access model based on the **CDMA** spread spectrum technique. In CDMA, each user using a common channel is given a signal (code) covering the same frequency band.
  - Many users can be found simultaneously on the same band
  - The data rate allocated to users can be adjusted according to variable load conditions.
- Spreading data across the wide bandwidth makes jamming and interception difficult.

Spread spectrum - introduction

- Narrowband interference
  - 6 channels for FDM multiplexing
  - Requires frequency planning
  - Channel quality depends on frequency. In other words, channel quality is a measure of the interference at that frequency.

Spread Spectrum - Motivation



narrowband channels

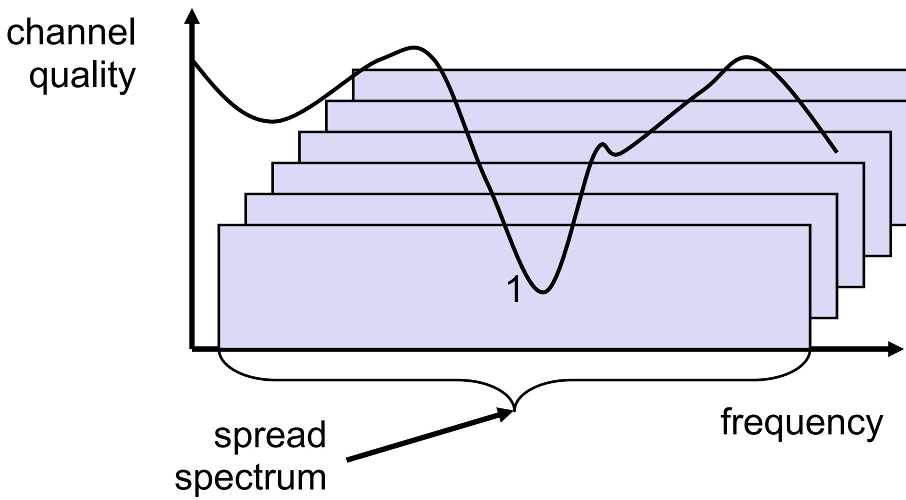
- Signal on channels 3 and 4 due to Narrowband interference
- it cannot be taken right by the buyer as its quality is very low
  - Solution?

Spread Spectrum - Motivation

- The narrow band signal is propagated as a broadband signal using **a special code**
  - Pseudo-noise (PN) sequence, pseudo-noise code
  - Seemingly random binary sequence (but can be reproduced by the receiver)
- **spread spectrum improves resistance to narrowband interference**

Spread Spectrum - Motivation

- It does not require frequency planning
- all narrowband signals propagate as broadband signals in the same (wide) frequency range

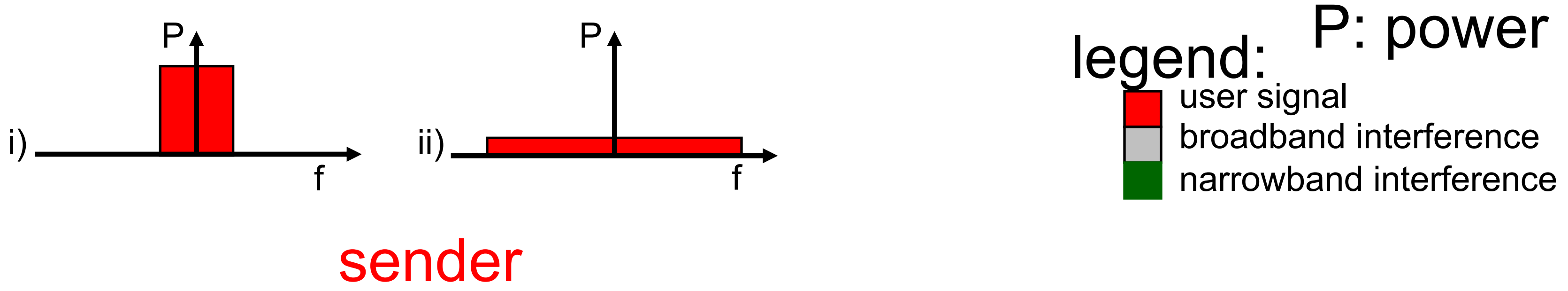


spread spectrum channels

Spread Spectrum - Gain

- 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 higher bandwidth with very little interference

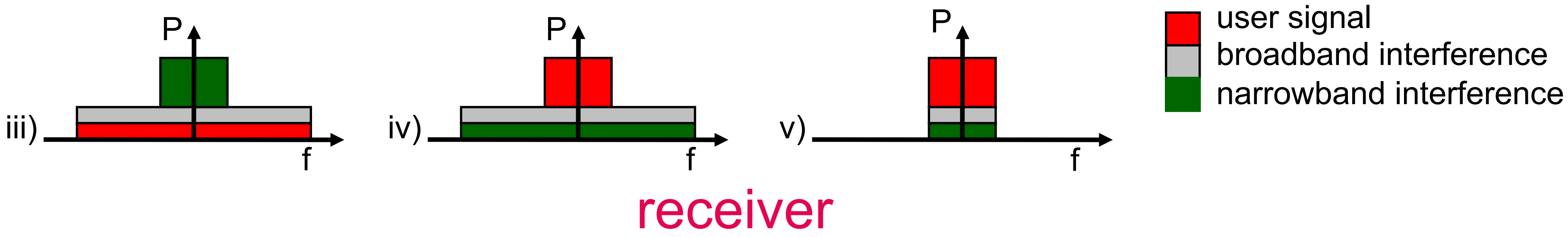
Spreading and interference



i) narrowband signal

ii) the sender spreads the signal, converting the narrowband signal into a broadband signal (the same energy is spread over a larger frequency range)

Spreading and interference



iii) During transmission, narrowband and broadband interference join the signal

iv) Receiver collects the signal and emits narrowband interference

v) Receiver uses a bandpass filter to obtain the original signal.

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
- Effect of modulation is to increase bandwidth of signal to be transmitted

Spread Spectrum

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

Spread Spectrum

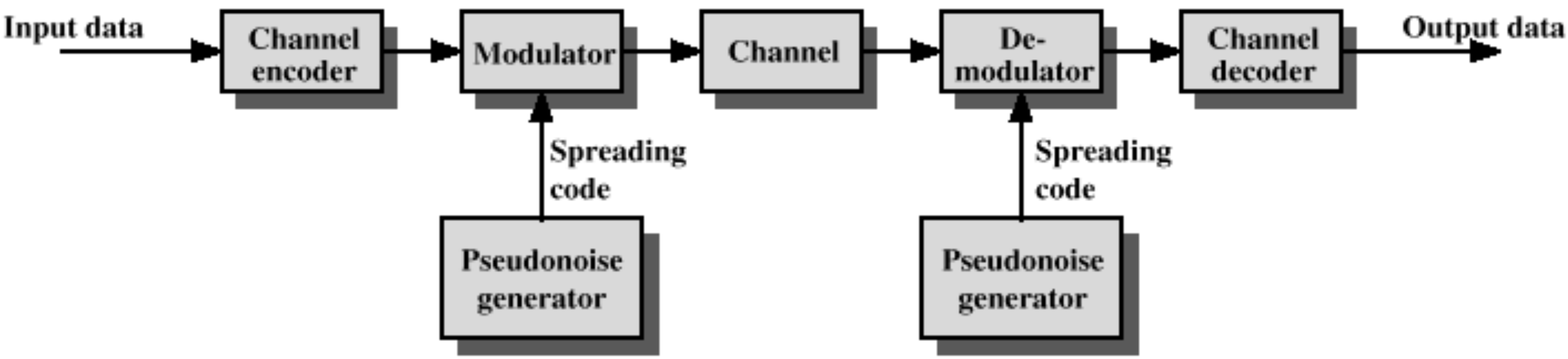


Figure 7.1 General Model of Spread Spectrum Digital Communication System

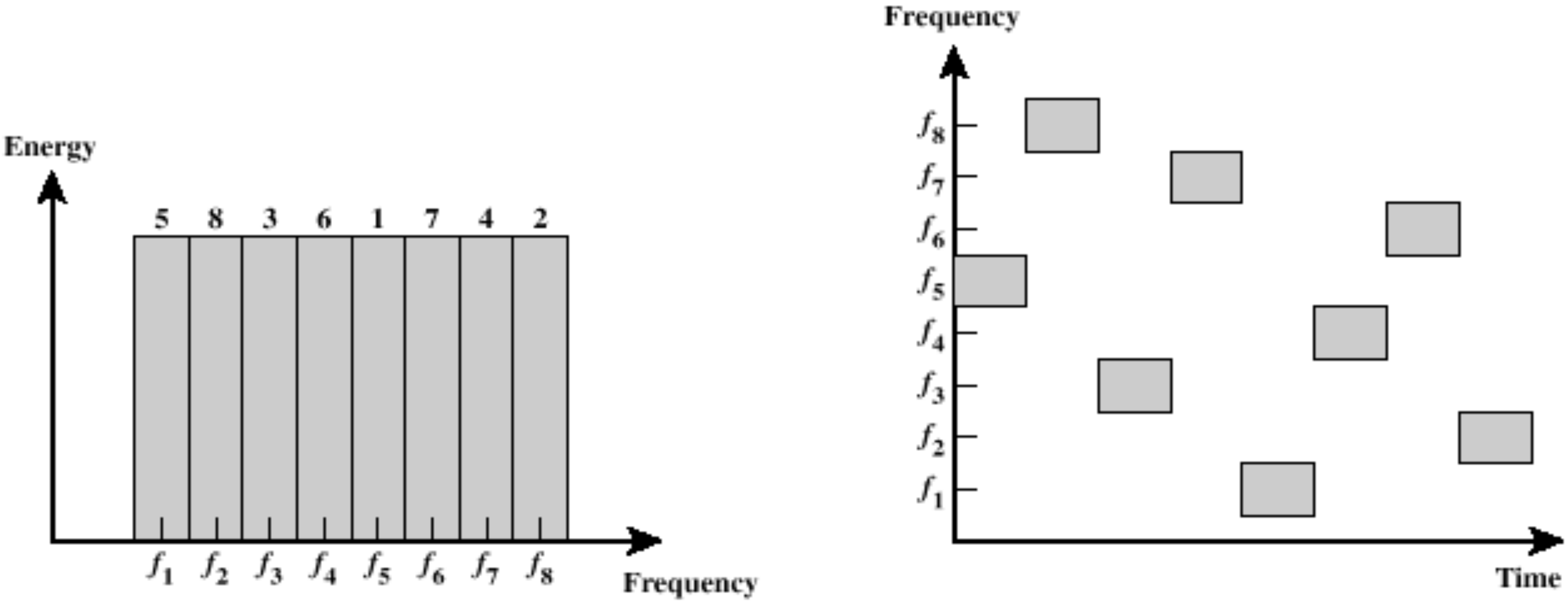
Frequency Hoping Spread Spectrum (FHSS)

- 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

Frequency Hoping Spread Spectrum

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message
- Advantages
  - Eavesdroppers hear only unintelligible blips
  - Attempts to jam signal on one frequency succeed only at knocking out a few bits

Frequency Hoping Spread Spectrum



(a) Channel assignment

(b) Channel use

Figure 7.2 Frequency Hopping Example

FHSS Using MFSK

- 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
  - duration of signal element: $T_s = LT$ seconds
- $T_c \geq T_s$ - slow-frequency-hop spread spectrum
- $T_c < T_s$ - fast-frequency-hop spread spectrum

FHSS Performance Considerations

- Large number of frequencies used
- Results in a system that is quite resistant to jamming
  - Jammer must jam all frequencies
  - With fixed power, this reduces the jamming power in any one frequency band

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
  - Spread is in direct proportion to number of bits used
- One technique combines digital information stream with the spreading code bit stream using exclusive-OR (Figure 7.6)

Direct Sequence Spread Spectrum (DSSS)

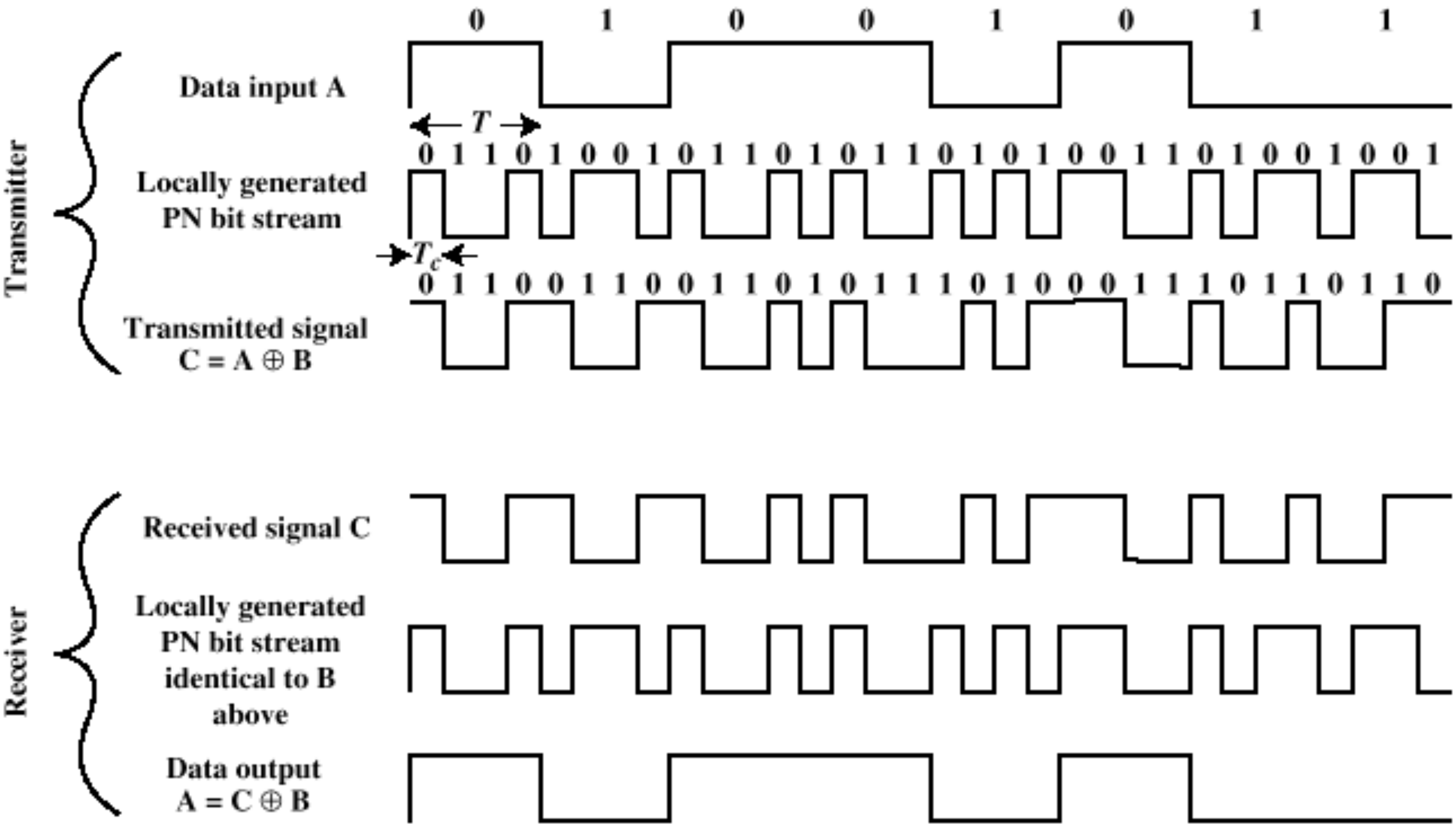


Figure 7.6 Example of Direct Sequence Spread Spectrum

DSSS Using BPSK

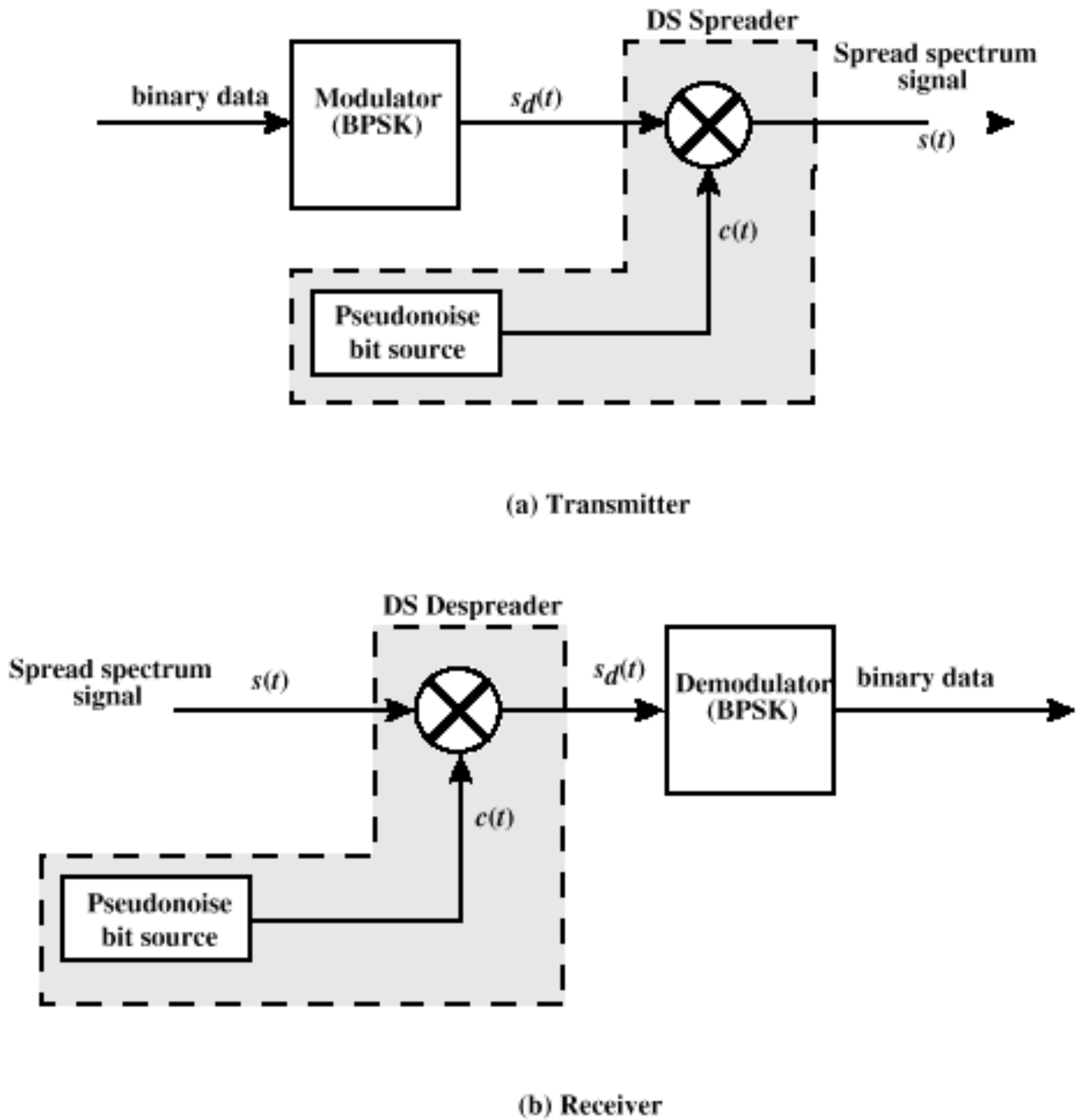
- Multiply BPSK signal,

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

  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]
- At receiver, incoming signal multiplied by $c(t)$
  - Since, $c(t)$ x $c(t)$ = 1, incoming signal is recovered



(a) Transmitter

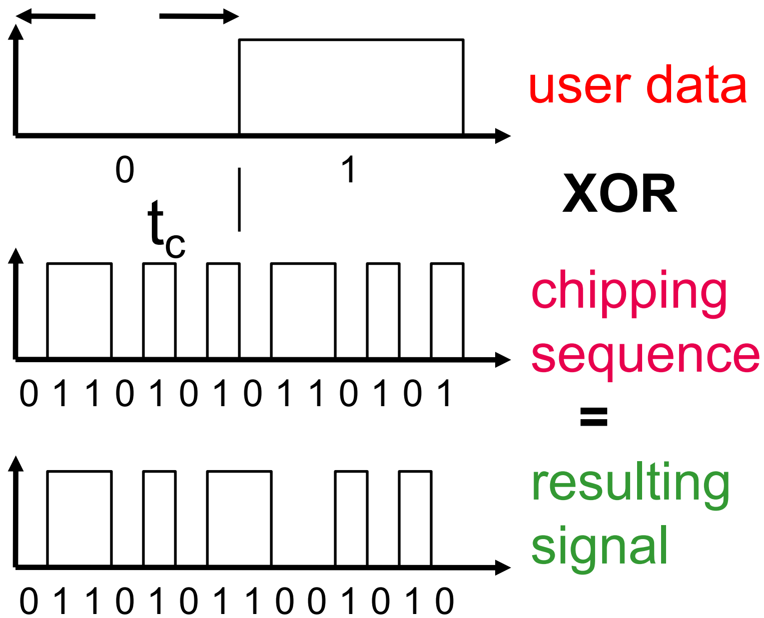
(b) Receiver

Figure 7.7 Direct Sequence Spread Spectrum System

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA
  - D = rate of data signal
  - Break each bit into k *chips*
    - Chips are a user-specific fixed pattern
  - Chip data rate of new channel = kD

CDMA



spreading factor: 7
chipping sequence: 0110101

t_b: bit period
t_c: chip period

- XOR (or modulo-2 addition) of the signal with chipping sequence
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal

CDMA Example

- If k=6 and code is a sequence of 1s and -1s
  - For a '1' bit, A sends code as chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For a '0' bit, A sends complement of code
    - <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender's code and performs electronic decode function

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

- <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: 6 -> 1
    - User A '0' bit: -6 -> 0
    - User B '1' bit: 0 -> unwanted signal ignored

CDMA

- Codes whose product adds to 0 are called orthogonal (vertical) codes.

$$A \bullet B = \sum_{i=1}^{k} A_i B_i = 0$$ then A and B orthogonal codes

- Two codes are said to be **orthogonal** when their **inner product** is zero.
  - The inner product, in the case of codes with elements +1 and –1, is the sum of all the terms we get by multiplying two codes element by element.
- Each bit of data is split into **k** small chunks called **chips**

Table 7.1 CDMA Example

(a) User's codes

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) Transmission from A

Transmit (data bit = 1)	1	−1	−1	1	−1	1	
Receiver codeword	1	−1	−1	1	−1	1	
Multiplication	1	1	1	1	1	1	= 6

Transmit (data bit = 0)	−1	1	1	−1	1	−1	
Receiver codeword	1	−1	−1	1	−1	1	
Multiplication	−1	−1	−1	−1	−1	−1	= −6

(c) Transmission from B, receiver attempts to recover A's transmission

Transmit (data bit = 1)	1	1	−1	−1	1	1	
Receiver codeword	1	−1	−1	1	−1	1	
Multiplication	1	−1	1	−1	−1	1	= 0

(d) Transmission from C, receiver attempts to recover B's transmission

Transmit (data bit = 1)	1	1	−1	1	1	−1	
Receiver codeword	1	1	−1	−1	1	1	
Multiplication	1	1	1	−1	1	−1	= 2

(e) 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

Categories of Spreading Sequences

- Spreading Sequence Categories
  - PN sequences
  - 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

PN Sequences

- PN generator produces periodic sequence that appears to be random
- PN Sequences
  - Generated by an algorithm using initial seed
  - 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
    - Balance property
    - Run property
  - Independence
  - Correlation property
- Unpredictability

Linear Feedback Shift Register Implementation

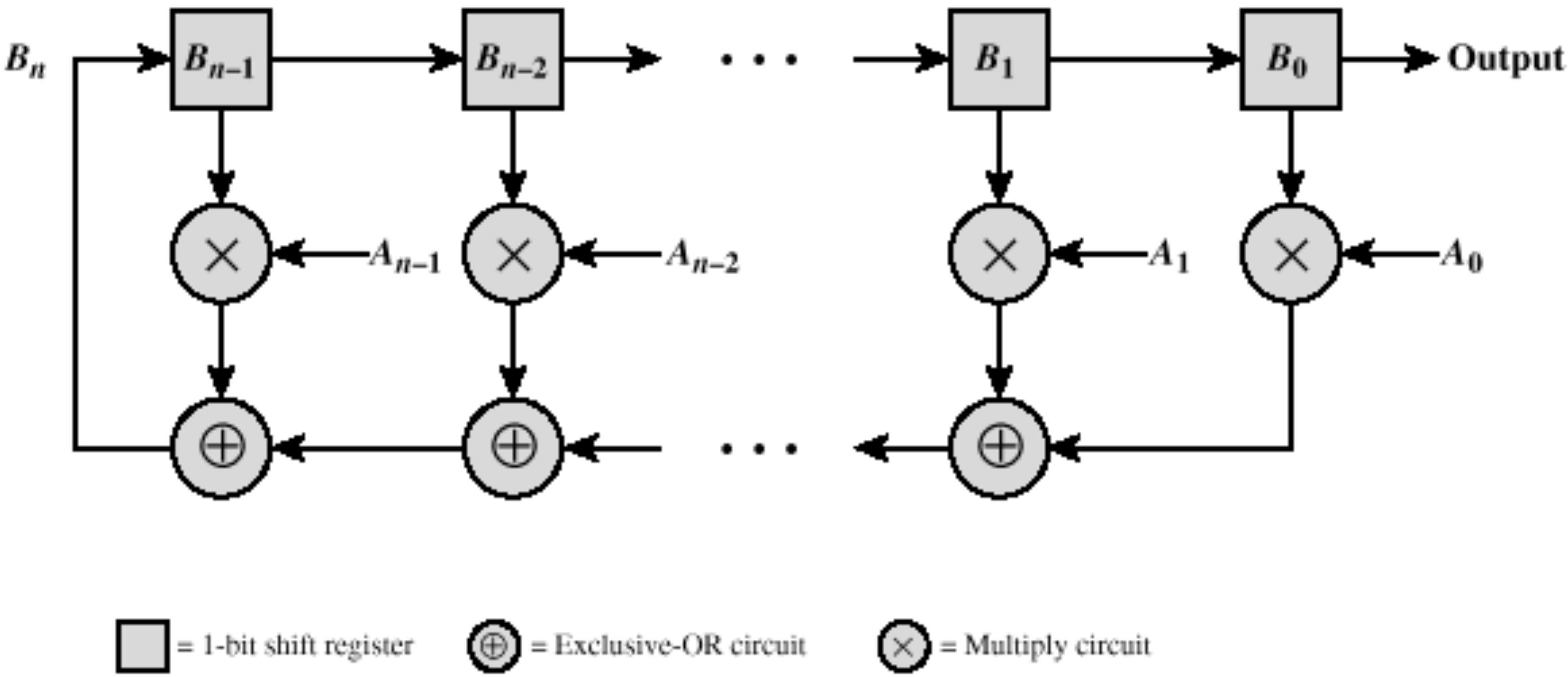
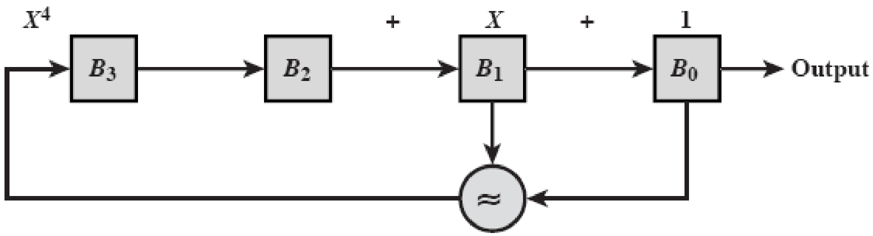


Figure 7.12 Binary Linear Feedback Shift Register Sequence Generator

Linear Feedback Shift Register Implementation



(a) Shift-register implementation

State	B_3	B_2	B_1	B_0	$B_0 \approx B_1$	output
Initial = 0	1	0	0	0	0	0
1	0	1	0	0	0	0
2	0	0	1	0	1	0
3	1	0	0	1	1	1
4	1	1	0	0	0	0
5	0	1	1	0	1	0
6	1	0	1	1	0	1
7	0	1	0	1	1	1
8	1	0	1	0	1	0
9	1	1	0	1	1	1
10	1	1	1	0	1	0
11	1	1	1	1	0	1
12	0	1	1	1	0	1
13	0	0	1	1	0	1
14	0	0	0	1	1	1
15 = 0	1	0	0	0	0	0

(b) Example with initial state of 1000

Figure 7.13 Circuit with Shift Registers for Generating PN Sequence

- LFSR consists of *n* bits
- The number of XOR gates is between 1 and (*n* -1)
- Generates a random sequence of length n = 2n -1
  - Maximal -length or M-sequence
- Advantages
  - Generates near random sequences
  - Easy to apply

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

- Set of Walsh codes of length n consists of the n rows of an n ´ n Walsh matrix:
  - $W_1 = (0)$ $$W_{2n} = \begin{pmatrix} W_n & W_n \\ W_n & \overline{W_n} \end{pmatrix}$$
    - n = dimension of the matrix
  - 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

$$W_1 = (0)$$

(a) 1×1

$$W_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

(b) 2×2

$$W_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

(c) 4×4

$$W_8 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

(d) 8×8

Figure 7.17 Walsh Matrices

Typical Multiple Spreading Approach

- 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