CpE 5430 / EE 5430 / SysEngg 5323: Wireless Networking

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Exam 2 Review

News

- Exam 2
  - Exam on Nov 4 (W)
- Lab 4
  - Nov 9 – updates Nov 10 final report
- Lab 5 – Ns3 – Extra Credit
- Semester project
  - Update presentations starting Nov 11th
  - Suggested content:
    - Introduction + motivation and application context
    - Accomplishments until now
      - Survey: present selected papers
      - Implementation/programming: what have you got done
    - Planned work for the rest of semester

Today's Outline

- Orthogonal Frequency Division
- Spread Spectrum
- Error Detection, Correction and Handling

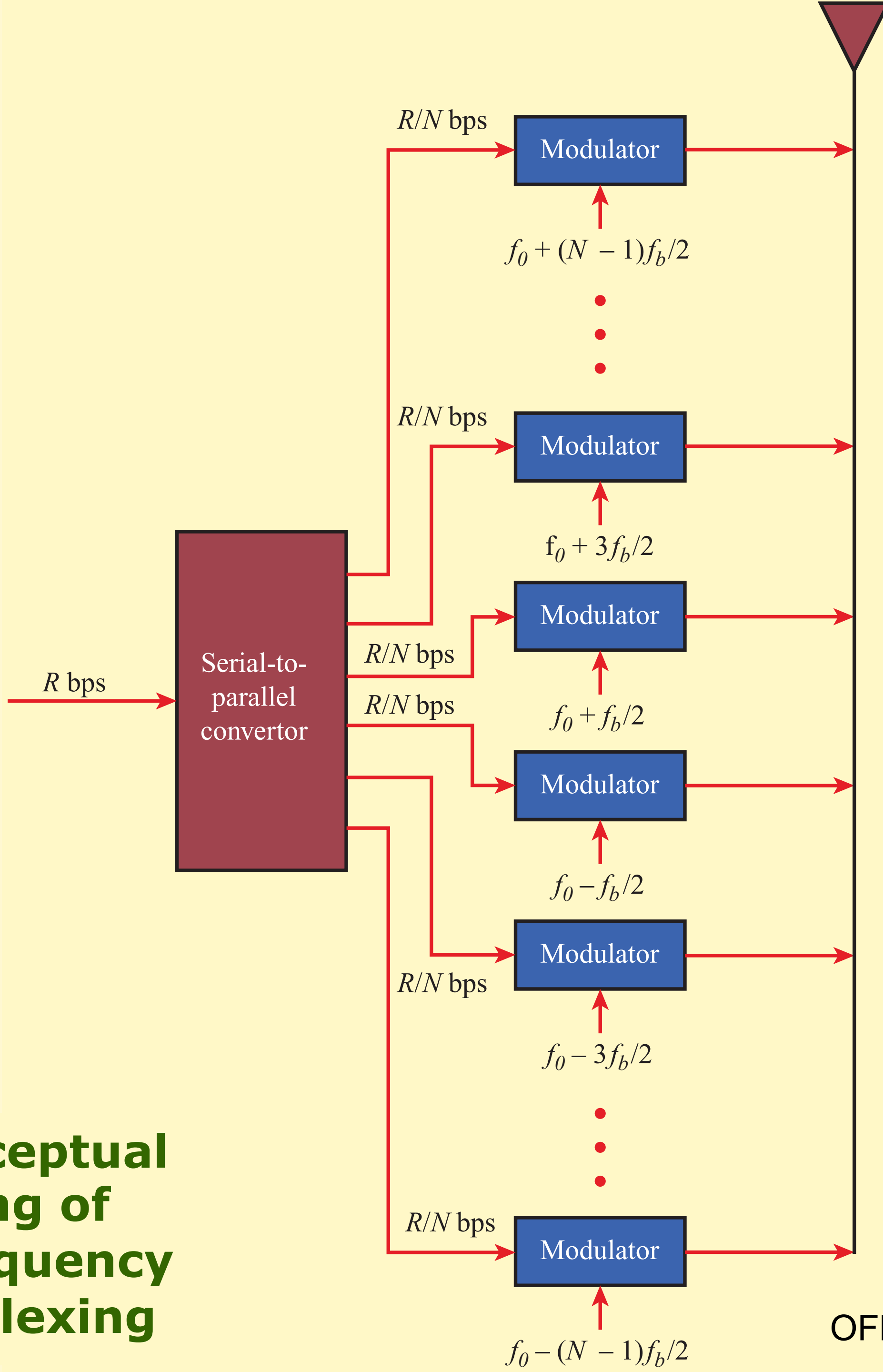


Figure 8.1 Conceptual Understanding of Orthogonal Frequency Division Multiplexing

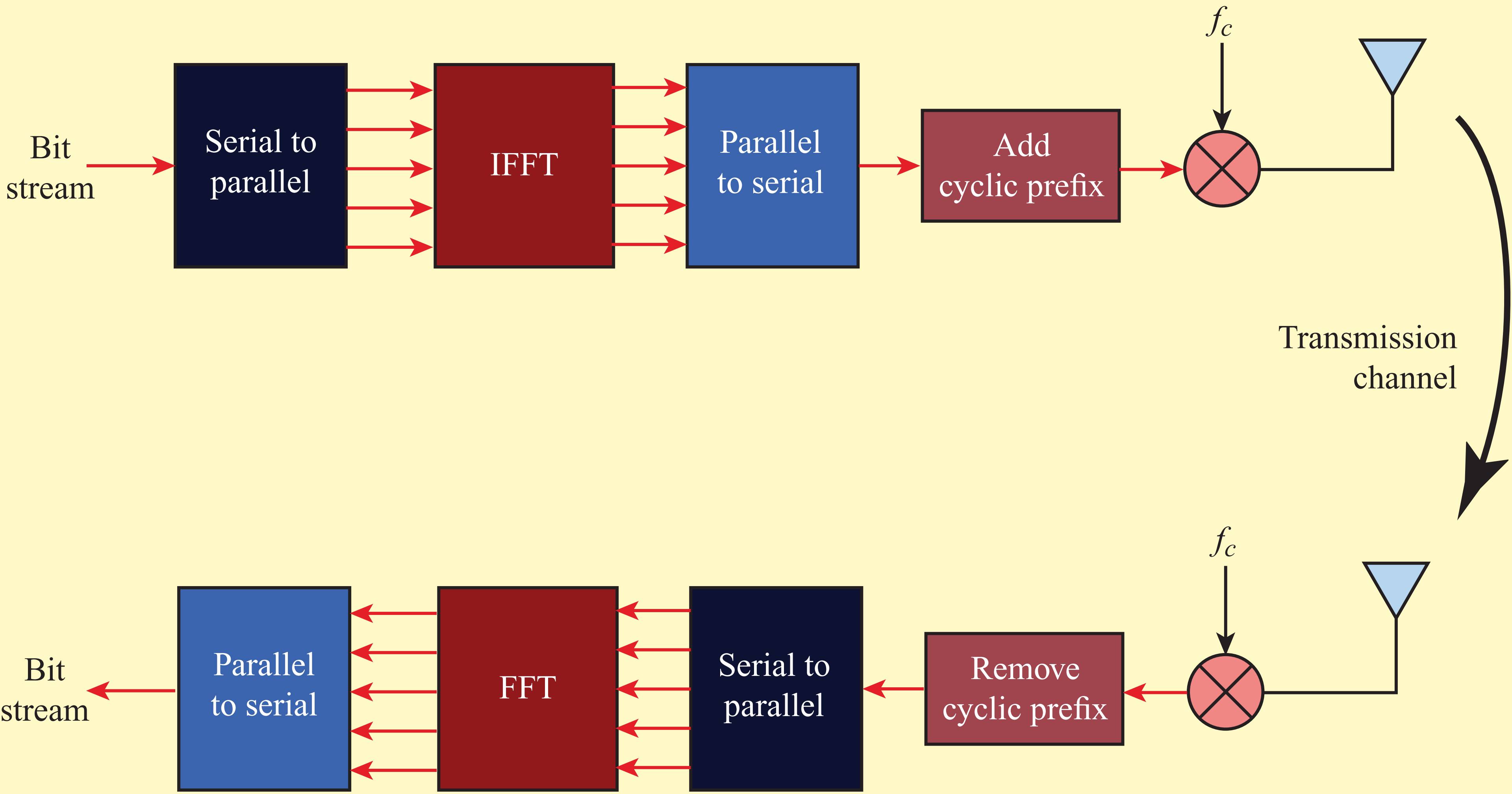
Orthogonality

- Given an OFDM subcarrier bit time of *T*
  - f_b must be a multiple of $1/T$
- Example: IEEE 802.11n wireless LAN
  - 20 MHz total bandwidth
    - Only 15 MHz can be used
  - 48 subcarriers
  - $f_b = 0.3125$ MHz
  - Signal is translated to 2.4 GHz or 5 GHz bands

Benefits of OFDM

- Frequency selective fading only affects some subcarriers
  - Can easily be handled with a forward error-correcting code
- More importantly, OFDM overcomes inter-symbol interference (ISI)
  - ISI is a caused by multipath signals arriving in later bits
  - OFDM bit times are much, much longer (by a factor of *N*)
    - ISI is dramatically reduced
  - *N* is chosen so the root-mean-square delay spread is significantly smaller than the OFDM bit time
  - It may not be necessary to deploy equalizers to overcome ISI
    - Eliminates the use of these complex and expensive devices.

Figure 8.3 IFFT Implementation of OFDM



FFT = fast Fourier transform
IFFT = inverse fast Fourier transform

Example 8.1

- OFDM in LTE – 15kHz subcarriers, 1024 subcariers per symbol
  - 600 subcarriers for data (rest for pilots+nulls)
  - 10MHz bandwidth and 16QAM
  - What data rate is possible?
- Nominal CP with 7% (0.07*1024=72)
  - R=10MHz (600/1024+72)*4 = 21.9Mbps
- Extended CP with 25% (0.25*1024=256)
  - R=10MHz (600/1024+256)*4 = 18.8Mbps

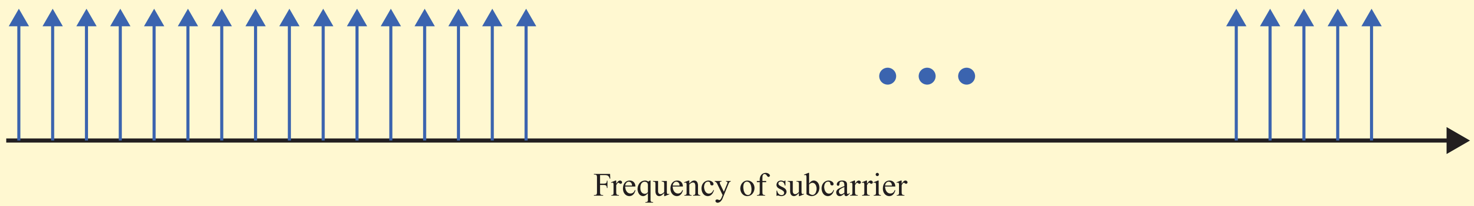
Difficulties of OFDM

- Peak-to-average power ratio (PAPR)
  - For OFDM signals, this ratio is much higher than for single-carrier signals
  - OFDM signal is a sum of many subcarrier signals
    - Total can be very high or very low
- Power amplifiers need to amplify all amplitudes equally

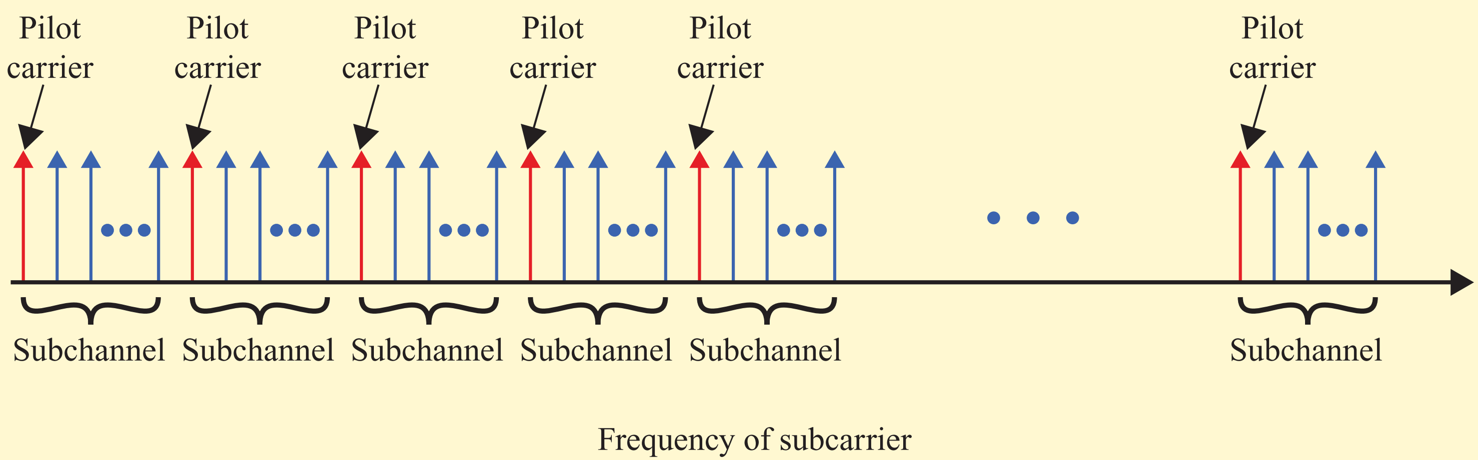
$$V_{out} = KV_{in}$$

  - Should have a linear characteristic with slope K on a V_{out} vs. V_{in} curve
  - Yet practical amplifiers have limited linear ranges
    - Causing distortion if outside the linear range

Figure 8.7 OFDM and OFDMA

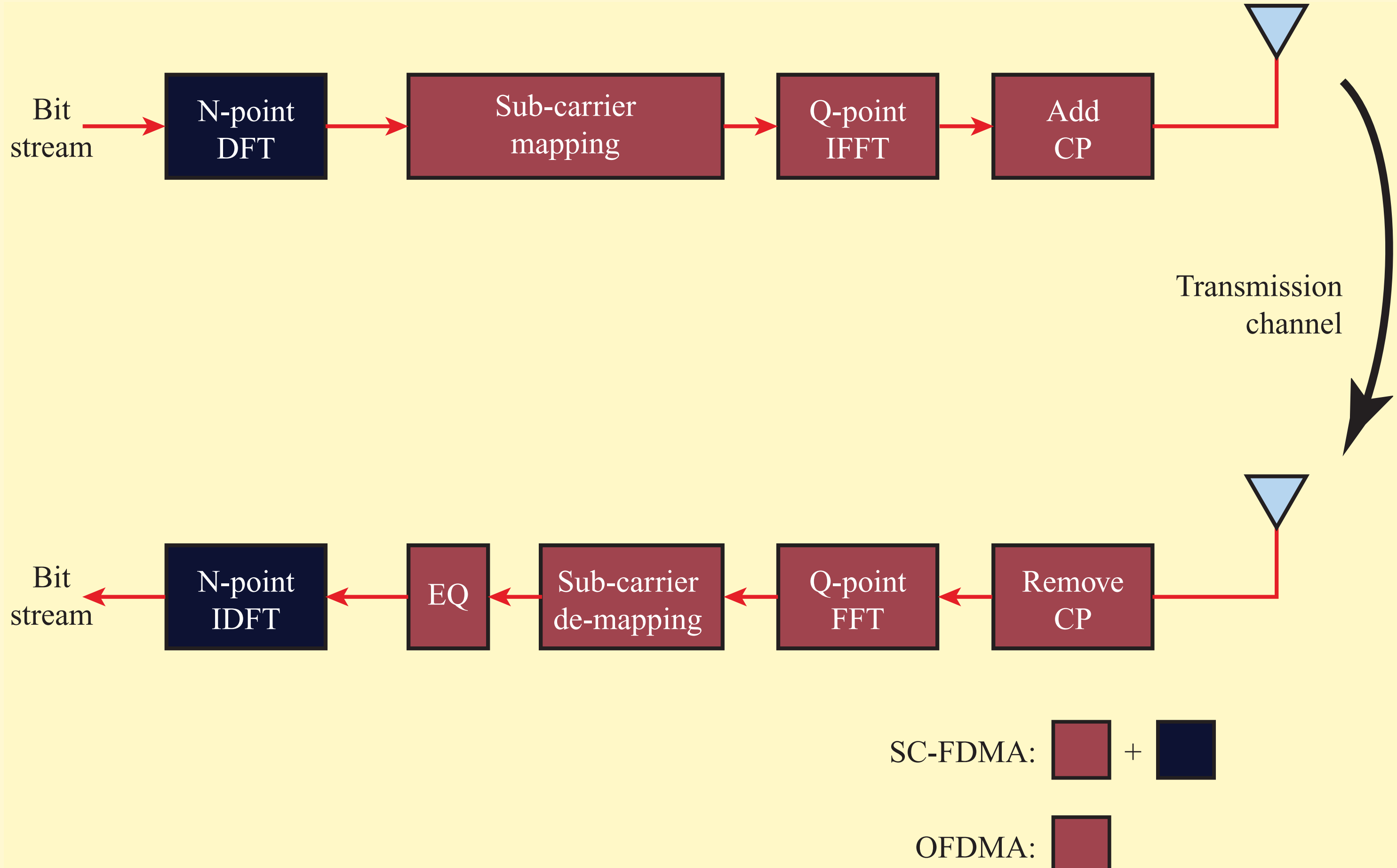


(a) OFDM



(b) OFDMA (adjacent subcarriers)

Figure 8.8 Simplified Block Diagram of OFDMA and SC-FDMA

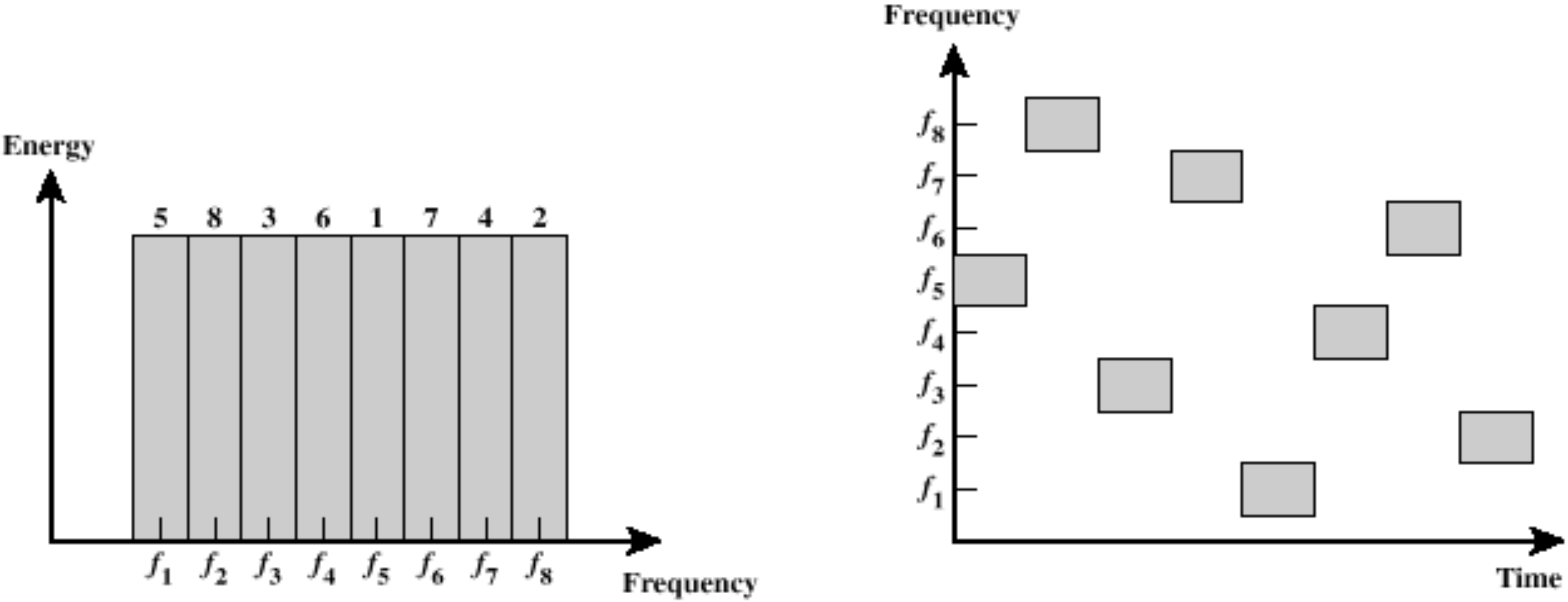


DFT = discrete Fourier transform
IDFT = inverse discrete Fourier transform
FFT = fast Fourier transform
IFFT = inverse fast Fourier transform
EQ = subcarrier equalization
CP = cyclic prefix

Today’s Outline

- Orthogonal Frequency Division
- Spread Spectrum
- Error Detection, Correction and Handling

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 efficiency in any one frequency band
- Reduces the average interference (noise to others) caused by the signal at any one frequency band

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Input data	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	0	1	0
Frequencies	f1		f3		f27		f26		f8		f10		f1		f3		f2		f2	
PN Sequence	001				110				011				001				001			

- The period of the PN sequence
  - 15 bit-times of the PN sequence bit. Or 20 time units
- 4 frequencies in Multiple FSK (MFSK)
- 2 input bits per MFSK symbol
- The length of a PN sequence per hop is equal to 3 bits (PN sequence)
  - Note: the frequency changes twice for a single hop, but the change of frequency within 3-bit word of PN sequence is due to MFSK, not the frequency hopping.
- Assuming that the table represents complete PN sequence (and it will repeat afterwards), there are 5 hops.
  - However, when you assume that the whole range of 3-bit word of PN sequence can be used, the overall number of possible hops is equal to 8 .

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Direct Sequence Spread Spectrum (DSSS)

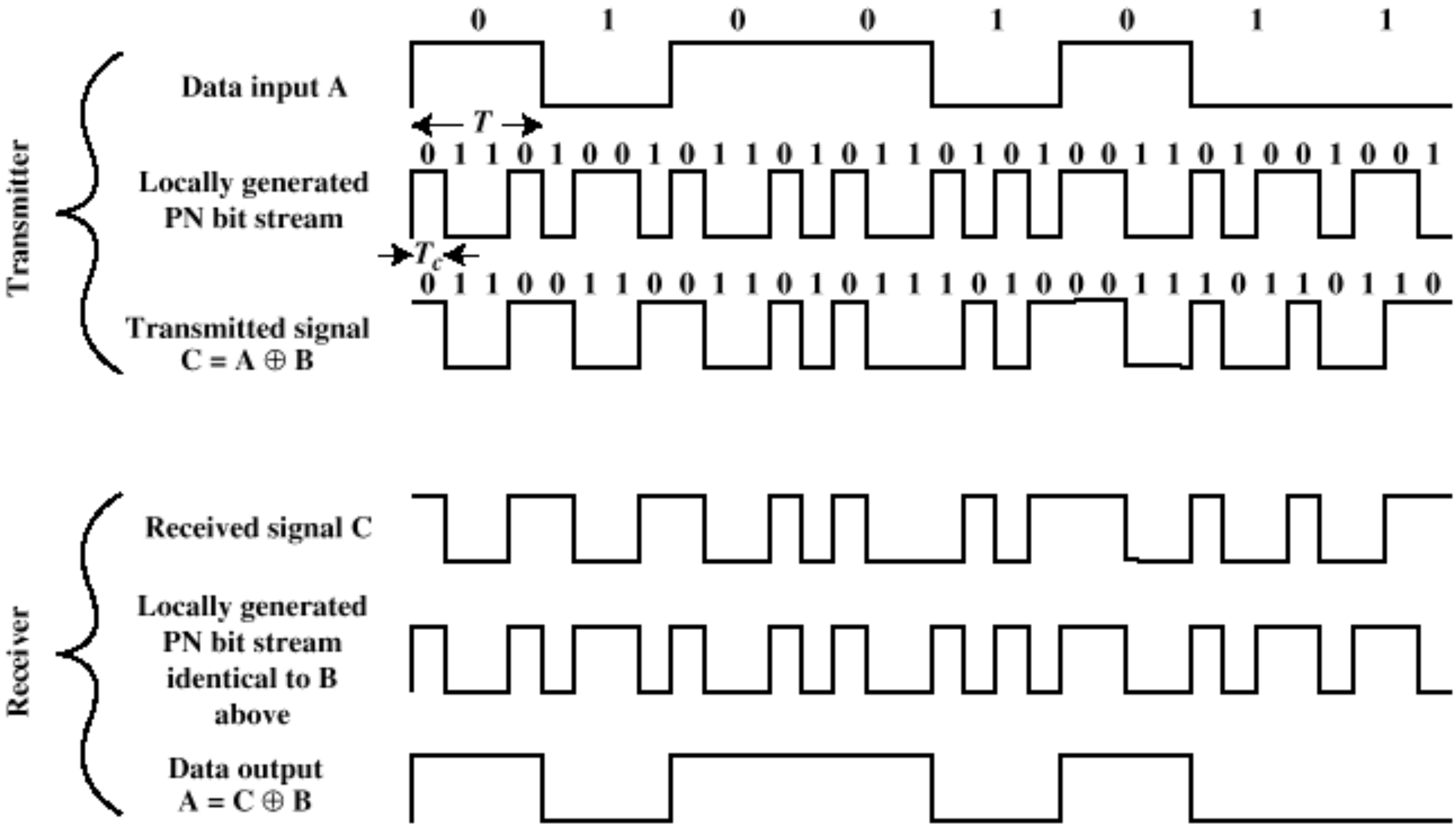


Figure 7.6 Example of Direct Sequence Spread Spectrum

SNR Gain and Immunity to Jamming

- Gain due to DSSS is expressed as

$$G_p = T/T_c = R_c/R \approx W_s/W_d$$

where

  - **T** and $\mathbf{T_c}$ are periods of user data and spreading sequence,
  - **R** and $\mathbf{R_c}$ are data rates for user data and spreading sequence respectively
  - $\mathbf{W_s}$ and $\mathbf{W_d}$ are the signal bandwidth and spread spectrum signal bandwidth
- Power of a jamming signal is reduced by 1/Gp factor
  - Due to bandpass filtering behind DS de-spreader

CDMA Principles

- What if we will select two spreading sequences $c_1(t)$ and $c_2(t)$ such that:
  - $c_1(t) \times c_2(t) = 0$,
  - $c_i(t) \times c_i(t) = 1$?

Orthogonal codes!

- In other words:
  - $[\, s_1(t)\, c_1(t) + s_2(t)\, c_2(t)\,]\;\; c_1(t) = ????$

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

Successful coding and decoding of a transmitted bits

(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

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

Decoding of a transmitted bits using a wrong user code

(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

(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

Table 7.1 CDMA Example

What if signal has been corrupted?

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 -2	
Receiver codeword	1	1	–1	–1	1	1	
Multiplication	2	2	2	0	2	0	= 8

-2 → 6

Still it gives a correct indication (>0)

Definitions

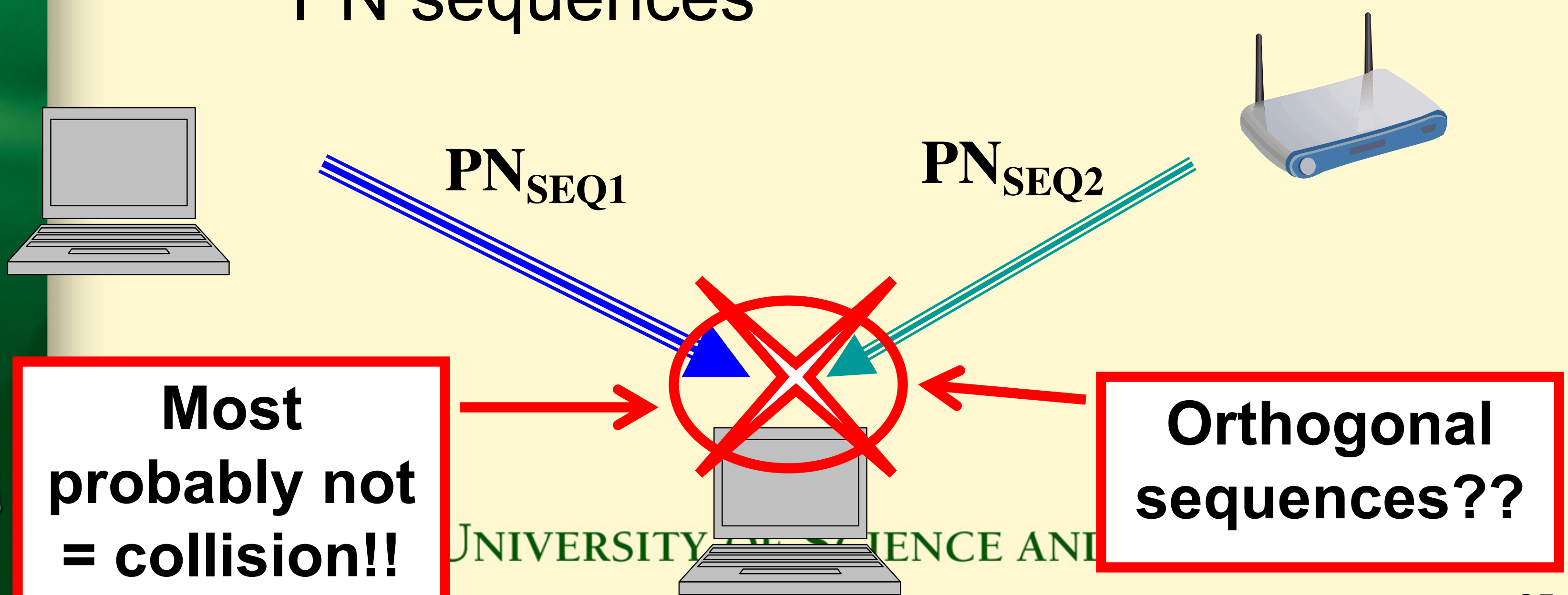
- Correlation
  - The concept of determining how much similarity one set of data has with another
  - Range between -1 and 1
    - 1 The second sequence matches the first sequence
    - 0 There is no relation at all between the two sequences
    - -1 The two sequences are mirror images
- Cross correlation
  - The comparison between two sequences from different sources rather than a shifted copy of a sequence with itself

Advantages of Cross Correlation

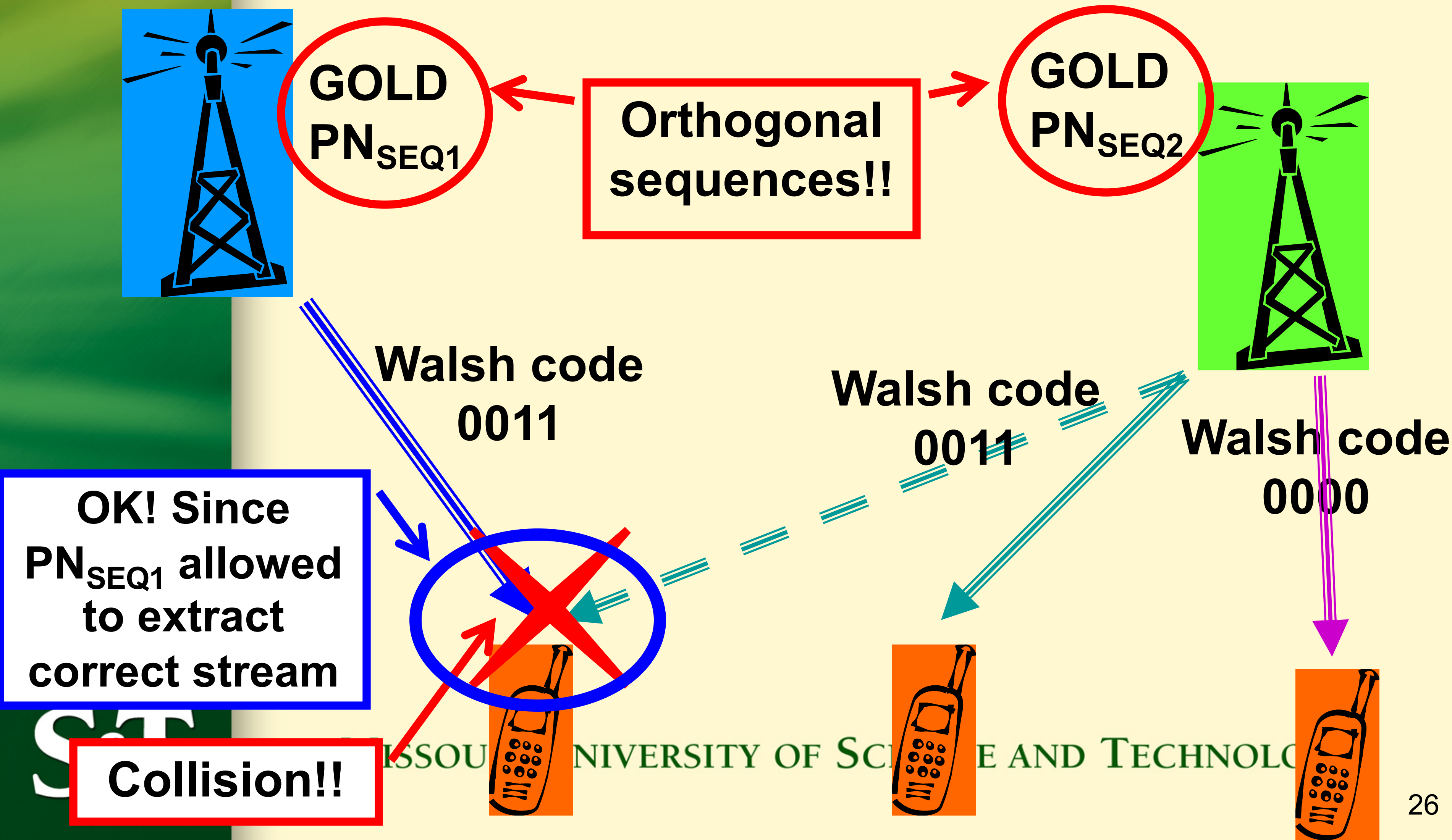
- The cross correlation between an m-sequence and noise is low
  – This property is useful to the receiver in filtering out noise
- The cross correlation between two different m-sequences is low
  – This property is useful for CDMA applications
  – Enables a receiver to discriminate among spread spectrum signals generated by different m-sequences

PN Sequences and Orthogonal Codes – Example

- FHSS and DSSS
  - **PN sequence** ("ordinary") used for spreading
  - No well-defined orthogonality between PN sequences



PN Sequences and Orthogonal Codes – DSSS CDMA Example



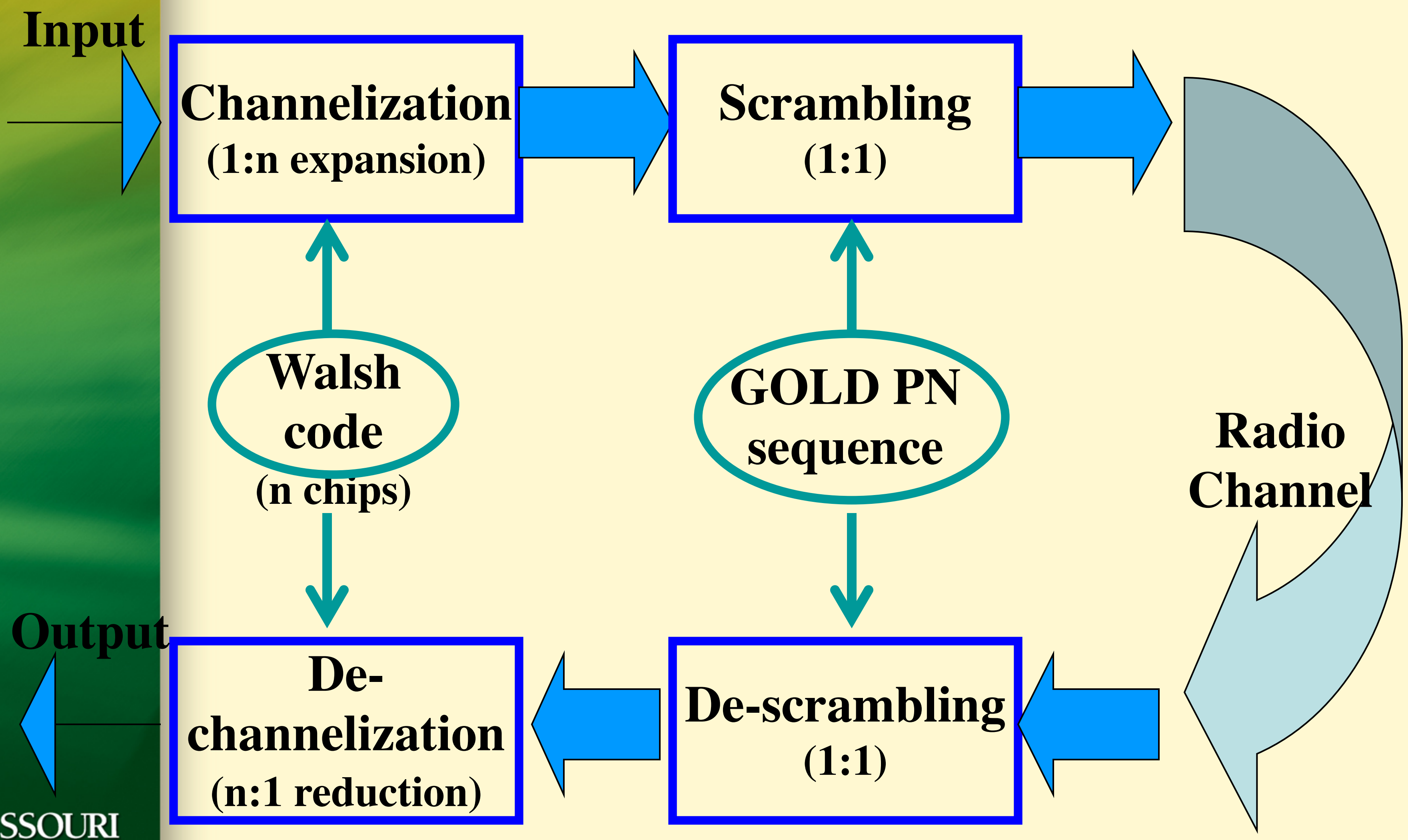
Gold Sequences

- Multi-user case in CDMA requires that
  - Codes have well-defined cross correlation properties
- Gold sequences
  - Constructed by the XOR of two m-sequences with the same clocking
  - Only simple circuitry needed to generate large number of unique codes

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

DSSS CDMA



Input
Channelization
(1:n expansion)
Scrambling
(1:1)
Walsh
code
(n chips)
GOLD PN
sequence
Radio
Channel
Output
De-
channelization
(n:1 reduction)
De-scrambling
(1:1)

Today's Outline

- Spread Spectrum
- Error Detection, Correction and Handling
- Satellite Communication
- Cellular Communication

Coping with Data Transmission Errors

- Error detection codes
  - Detects the presence of an error
- Automatic repeat request (ARQ) protocols
  - Block of data with error is discarded
  - Transmitter retransmits that block of data
- Error correction codes, or forward correction codes (FEC)
  - Designed to detect and correct errors

Error Detection Probabilities

- Definitions
  - P_b : Probability of single bit error (BER – Bit Error Rate)
  - P_1 : Probability that a frame arrives with no bit errors
  - P_2 : Probability that error detection mechanism does not detects error(s)
  - P_3 : Probability that all errors are detected for a frame

$$P_1 = (1 - P_b)^F$$

$$P_2 = 1 - P_3$$

where

F – Number of bits per frame

Pb – probability of a bit error

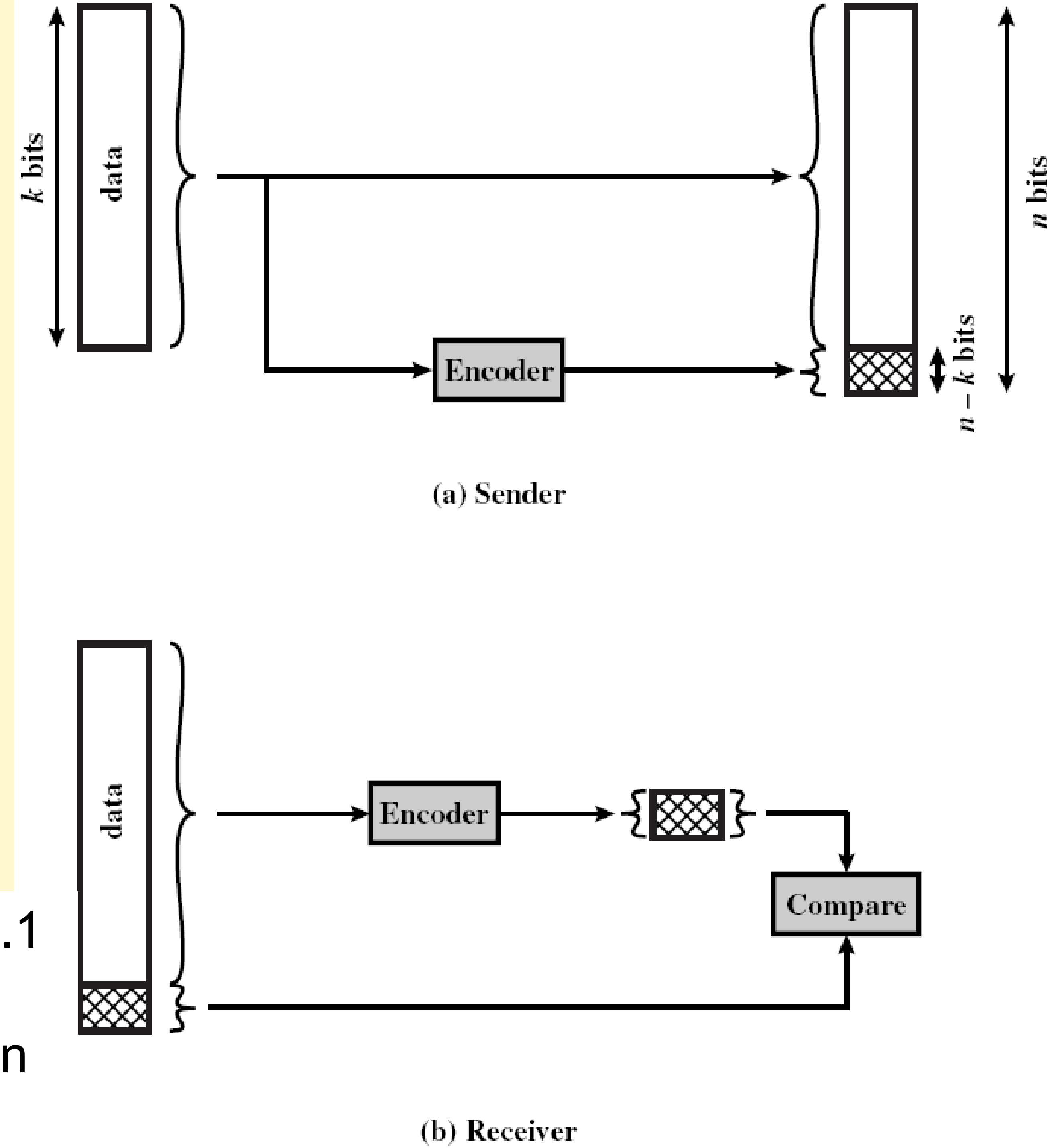


Figure 8.1 Error Detection Process

Error Detection Schemes

- Parity Check
  - Only detects odd number of bit-errors
- Cyclic Redundancy Check (CRC)
  - Modulo 2 – mathematical representation
  - Polynomial – algorithmic representation
  - Digital Logic – structural representation

CRC using Polynomials

- Widely used versions of *P(X)*
  - CRC–12
    - $X^{12} + X^{11} + X^3 + X^2 + X + 1$
  - CRC–16
    - $X^{16} + X^{15} + X^2 + 1$
  - CRC – CCITT
    - $X^{16} + X^{12} + X^5 + 1$
  - CRC – 32
    - $X^{32} + X^{26} + X^{23} + X^{22} + X^{16} + X^{12} + X^{11} + X^{10} + X^8 + X^7 + X^5 + X^4 + X^2 + X + 1$

Digital Logic CRC

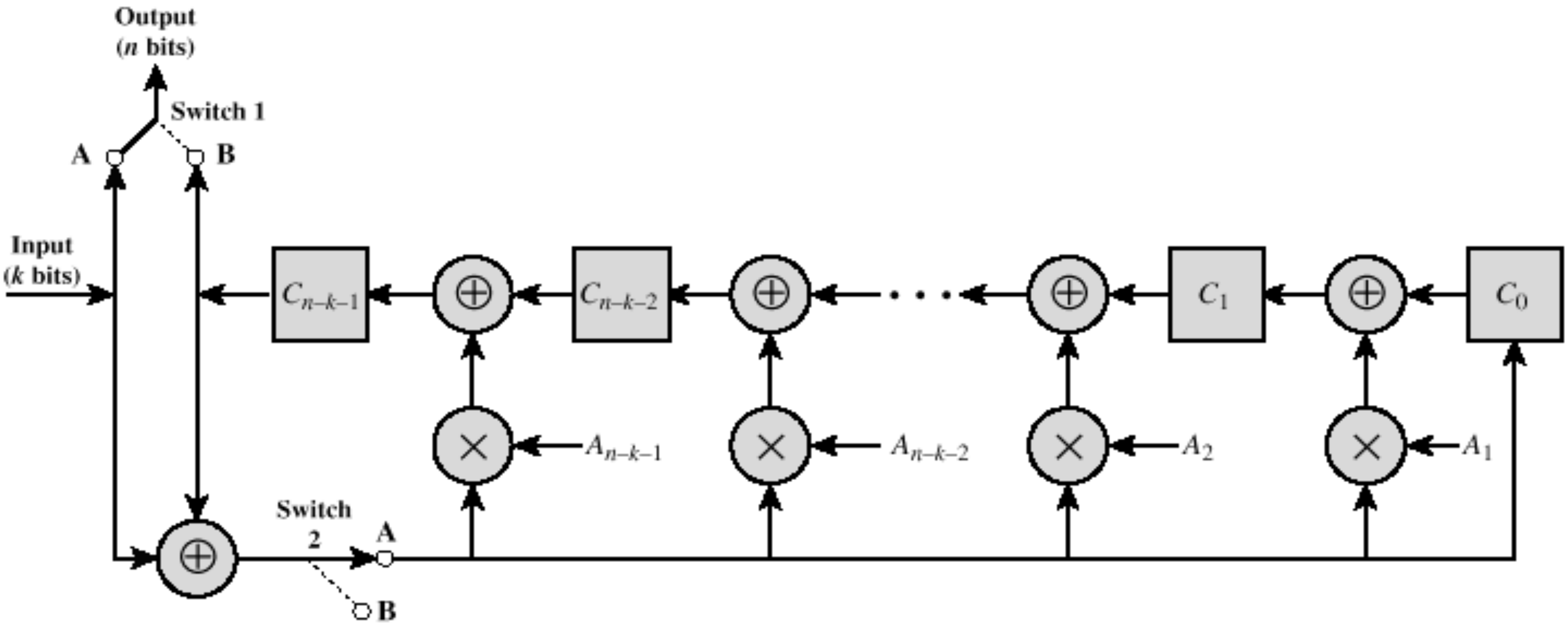


Figure 8.4 General CRC Architecture to Implement Divisor
$$1 + A_1X + A_2X^2 + \ldots + A_{n-1}X^{n-k-1} + X^{n-k}$$

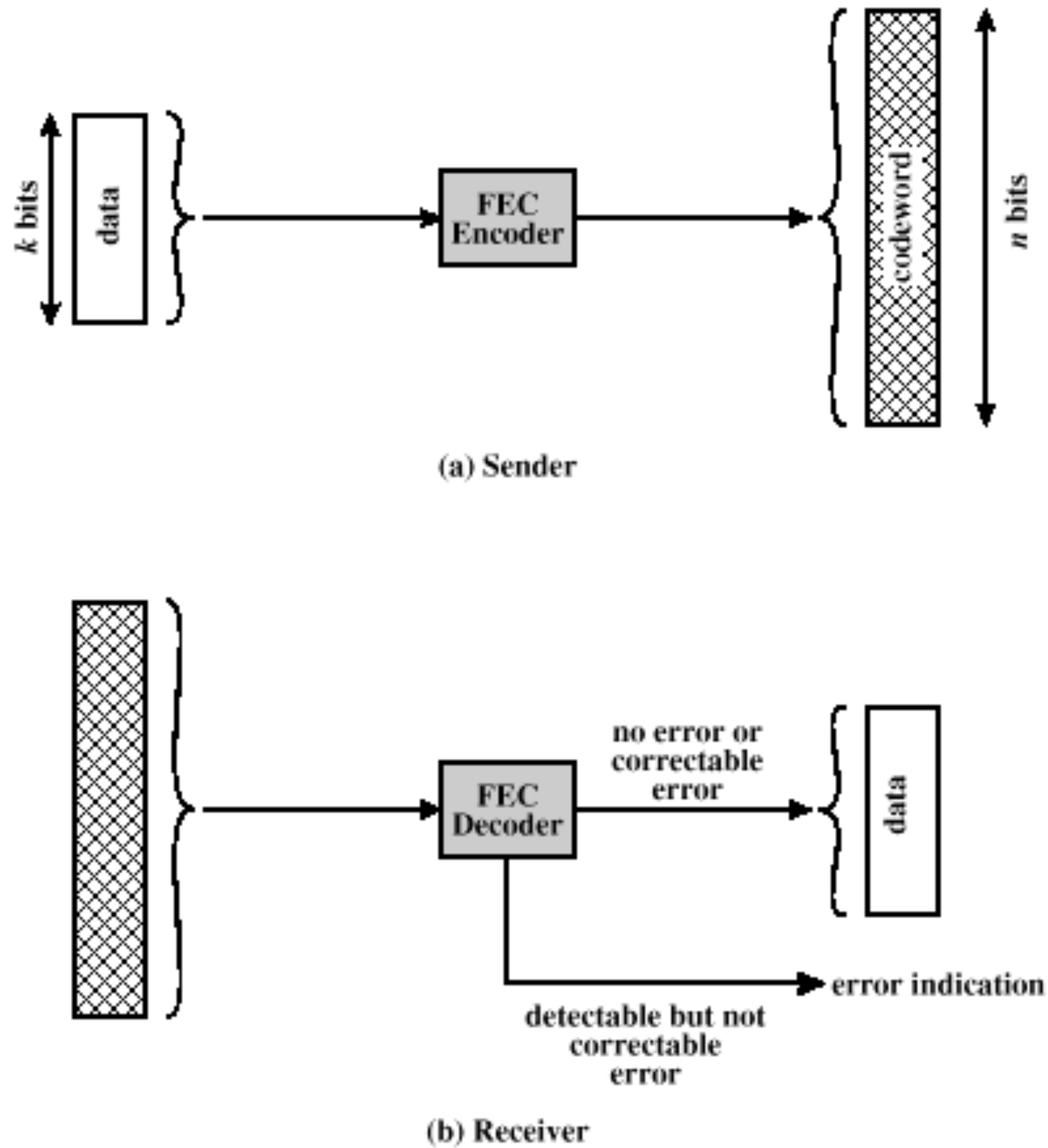


Figure 8.5 Forward Error Correction Process

Block Code Principles

- Hamming distance
  - number of different bits between two blocks
- Redundancy – ratio of redundant bits to data bits
  - (n-k)/k
- Code rate – ratio of data bits to total bits
  - n/k
- Coding gain – the reduction, in decibels, in the required E_b/N_0 to achieve a specified BER of an error-correcting coded system

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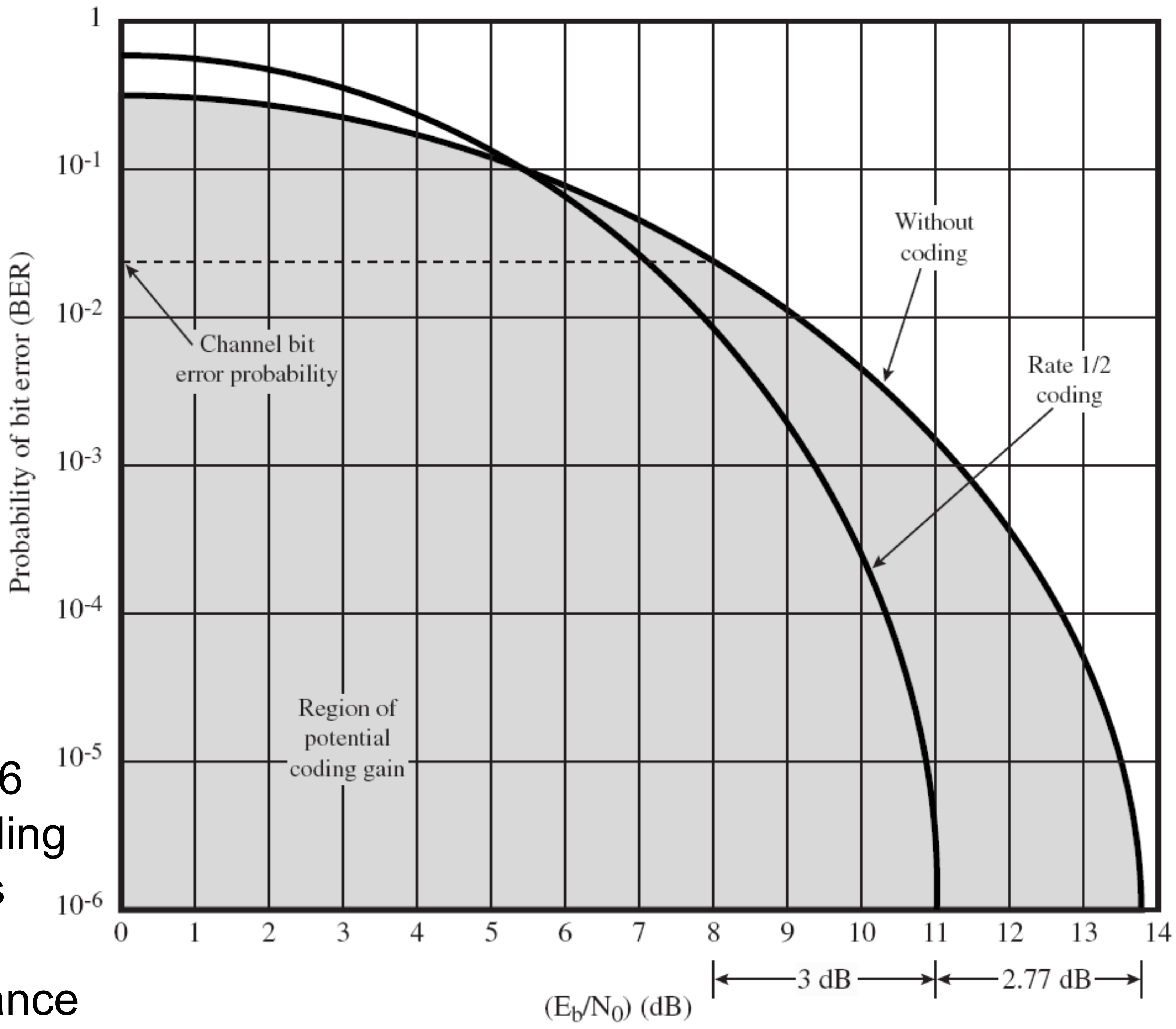


Figure 8.6 How Coding Improves System Performance

Block Code Principles - Capabilities

- Minimal Humming distance for a given scheme
  - d_{min}=min[d(v_i, v_j)], for all $i \neq j$
- Correction of ***t*** error bits
  - $d_{min} \geq 2t+1$
- Correction of ***t-1*** error bits and detection of ***t*** error bits
  - $d_{min} \geq 2t$

Block Code Principles - Example

- For k = 2 and n = 5, we can make the following assignment:

Data block	Codeword
00	00000
01	00111
10	11001
11	11110

min Humming distance = 3

Invalid Codeword	Minimum distance	Valid codeword
00001	1	00000
00010	1	00000
00011	1	00111
00100	1	00000
00101	1	00111
00110	1	00111
01000	1	00000
01001	1	11001
01010	2	00000 or 11110
01011	2	00111 or 11001
01100	2	00000 or 11110

Hamming Code

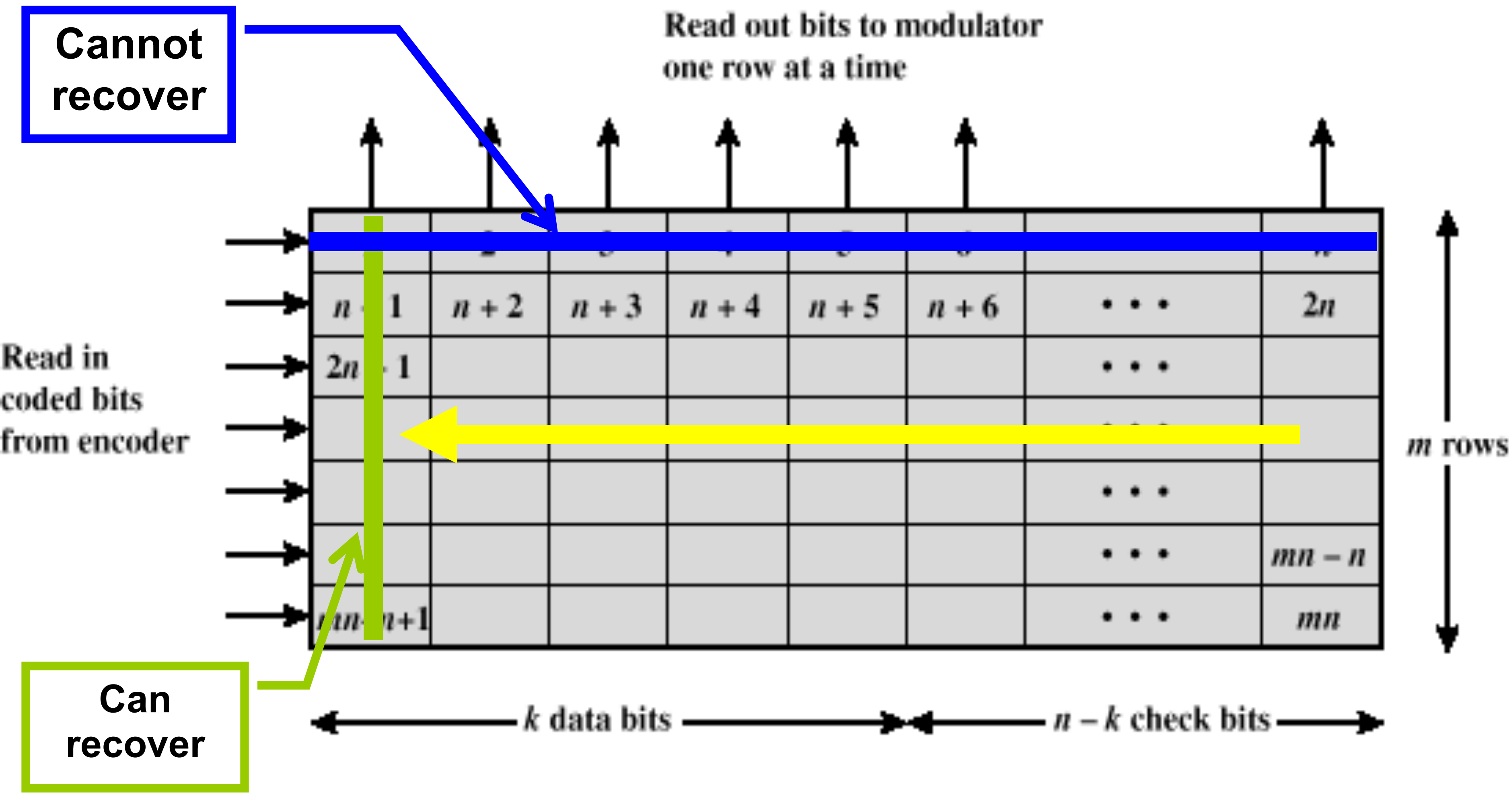
- Designed to correct single bit errors
- Family of (n, k) block error-correcting codes with parameters:
  - Block length: $n = 2^m - 1$
  - Number of data bits: $k = 2^m - m - 1$
  - Number of check bits: $n - k = m$
  - Minimum distance: $d_{\min} = 3$
- Single-error-correcting (SEC) code
  - SEC double-error-detecting (SEC-DED) code with $d_{\min} = 4$

Table 8.1. Hamming Code Requirements (page 220)

	Single-Error Correction		Single-Error Correction/Double-Error Detection	
Data Bits	Check Bits	% Increase	Check Bits	% Increase
8	4	50.00	5	62.5
16	5	31.25	6	37.5
32	6	18.75	7	21.875
64	7	10.94	8	12.5
128	8	6.25	9	7.03
256	9	3.52	10	3.91

Cyclic Codes for Error Correction

- Cyclic Codes
  - Based on CRC principles
  - Syndrome indicates if there is an error
  - But syndrome also provides info where the error happened
- Categories of CRC for Error Correction
  - BCH Codes (powerful ones)
  - Reed-Salomon Codes
- In contrast, CRC error-detecting code accepts arbitrary length input for fixed-length check code



Note: The numbers in the matrix indicate the order in which bits are read in.
Interleaver output sequence: 1, $n + 1$, $2n + 1$, …

Figure 8.8 Block Interleaving

Convolutional Codes

- Generates redundant bits continuously
- Error checking and correcting carried out continuously
  - (n, k, K) code
    - Input processes k bits at a time
    - Output produces n bits for every k input bits
    - K = constraint factor
    - k and n generally very small
  - n-bit output of (n, k, K) code depends on:
    - Current block of k input bits
    - Previous K-1 blocks of k input bits

Trellis Diagram Example

- Trellis diagram – expanded encoder diagram
- Viterbi code – error correction algorithm

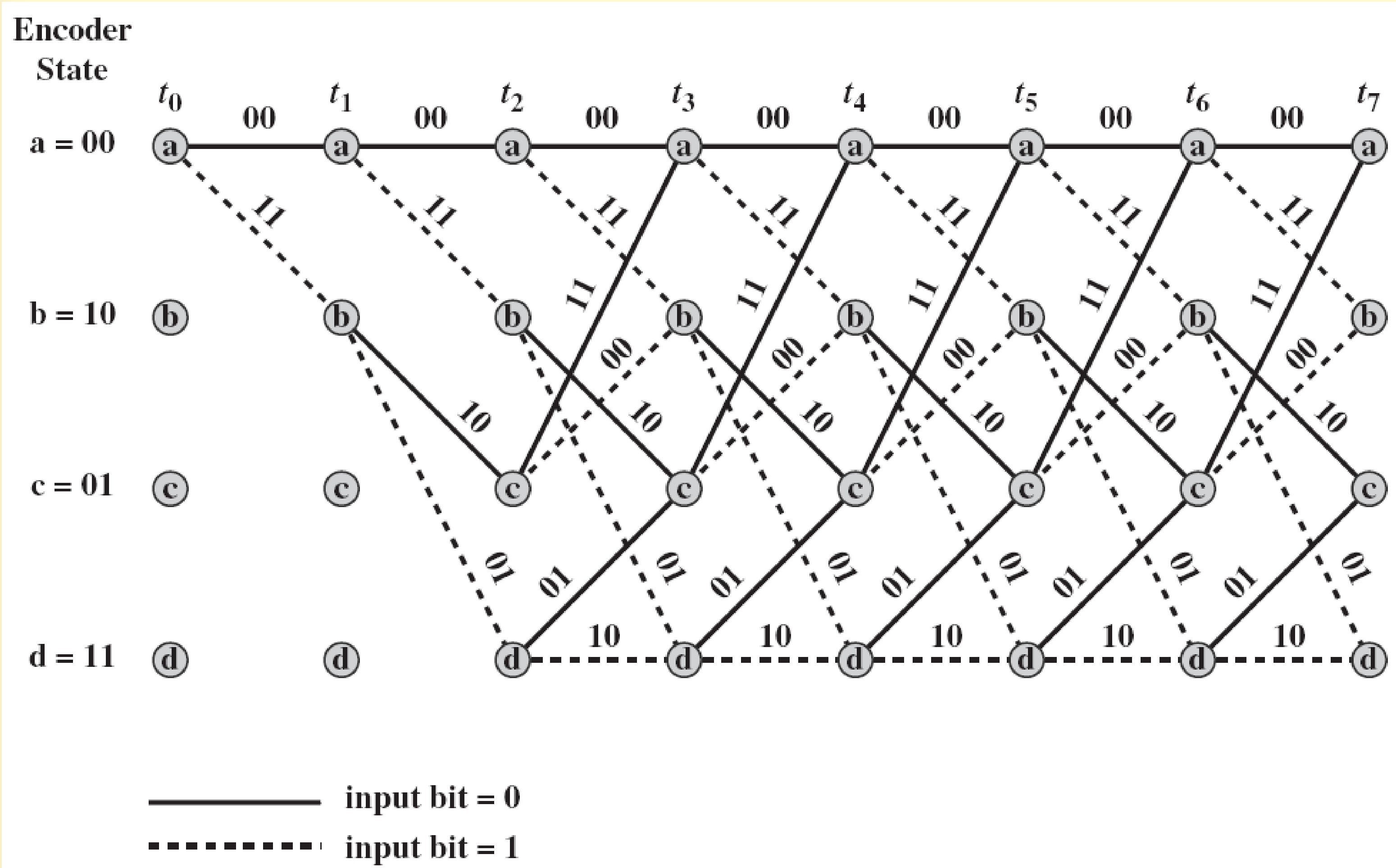
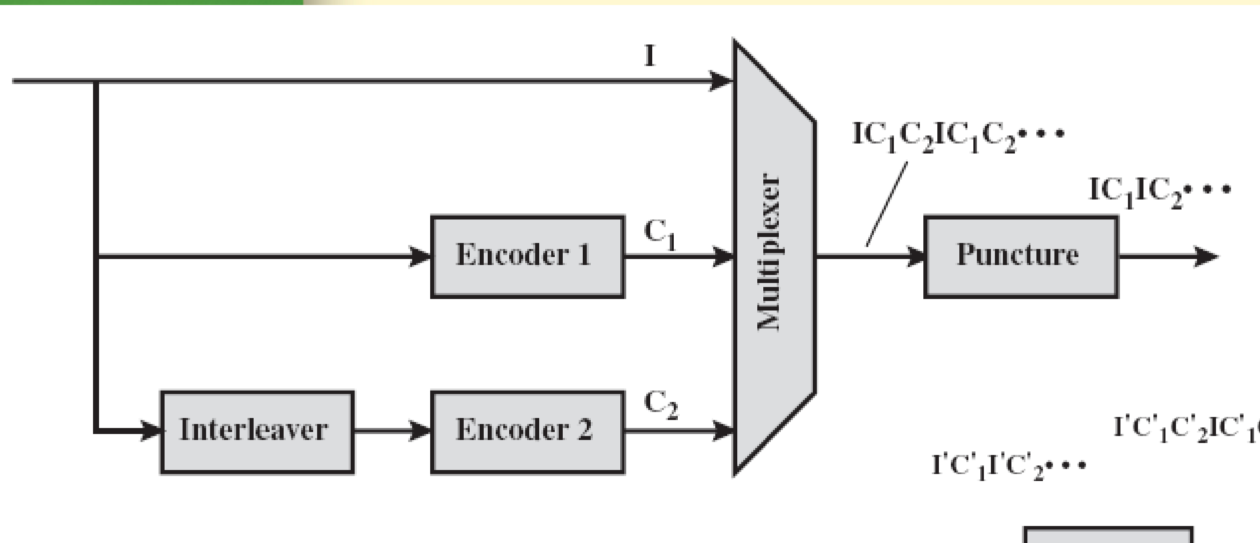


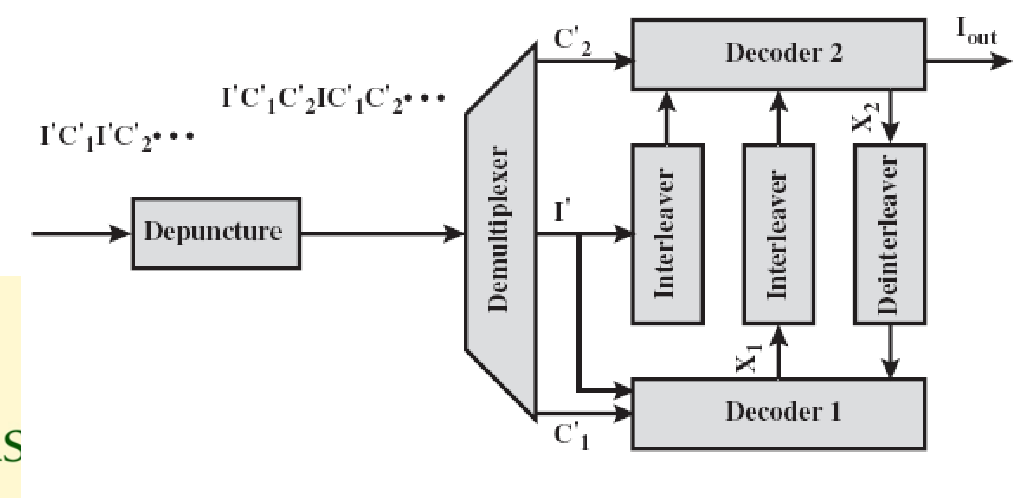
Figure 8.10 Trellis Diagram for Encoder of Figure 8.9

Turbo Coding

- Bit-error probability close to Shannon limit
- Suitable for high speed communication



(a) Encoder



(b) Decoder

Flow Control Methods

- Stop-and-wait
  - Send one message and wait for acknowledgement
  - Slower than sliding window methods
- Sliding Window
  - Go-back-N
  - Selective-reject

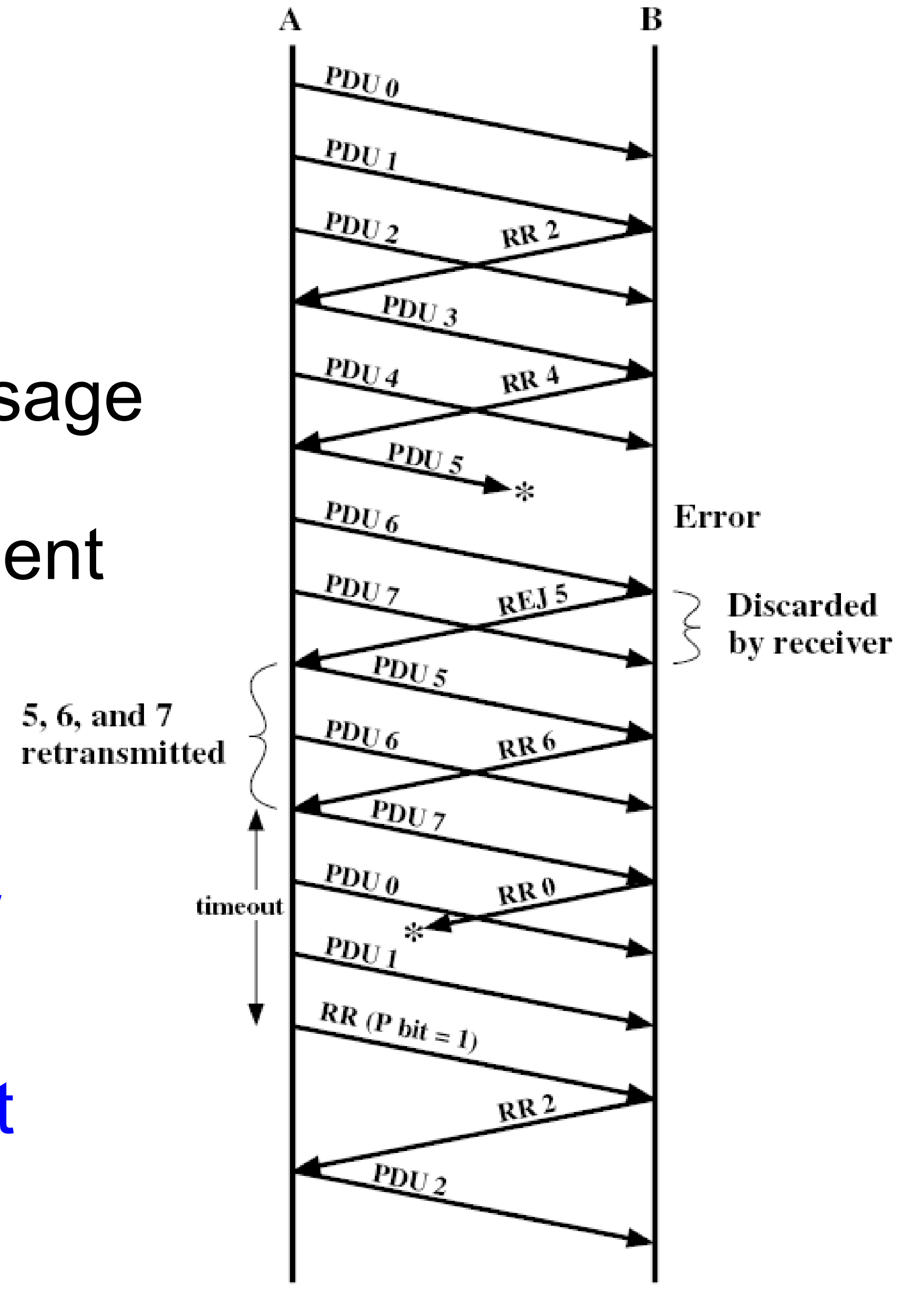


Figure 8.19 Go-back-N ARQ

Program Completed

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