MUTHAYAMMAL ENGINEERING COLLEGE

Rasipuram - 637 408

COURSE CODE & TITLE – 19ECE14 / WIRELESS COMMUNICATION

Presentation by

Mrs.V.Hema

AP-ECE

History of wireless communication

- Guglielmo Marconi invented the wireless telegraph in 1896
  - Communication by encoding alphanumeric characters in analog signal
  - Sent telegraphic signals across the Atlantic Ocean
- 1914 – first voice communication over radio waves
- Communications satellites launched in 1960s
- Advances in wireless technology
  - Radio, television, mobile telephone, communication satellites
- More recently
  - Satellite communications, wireless networking, cellular technology
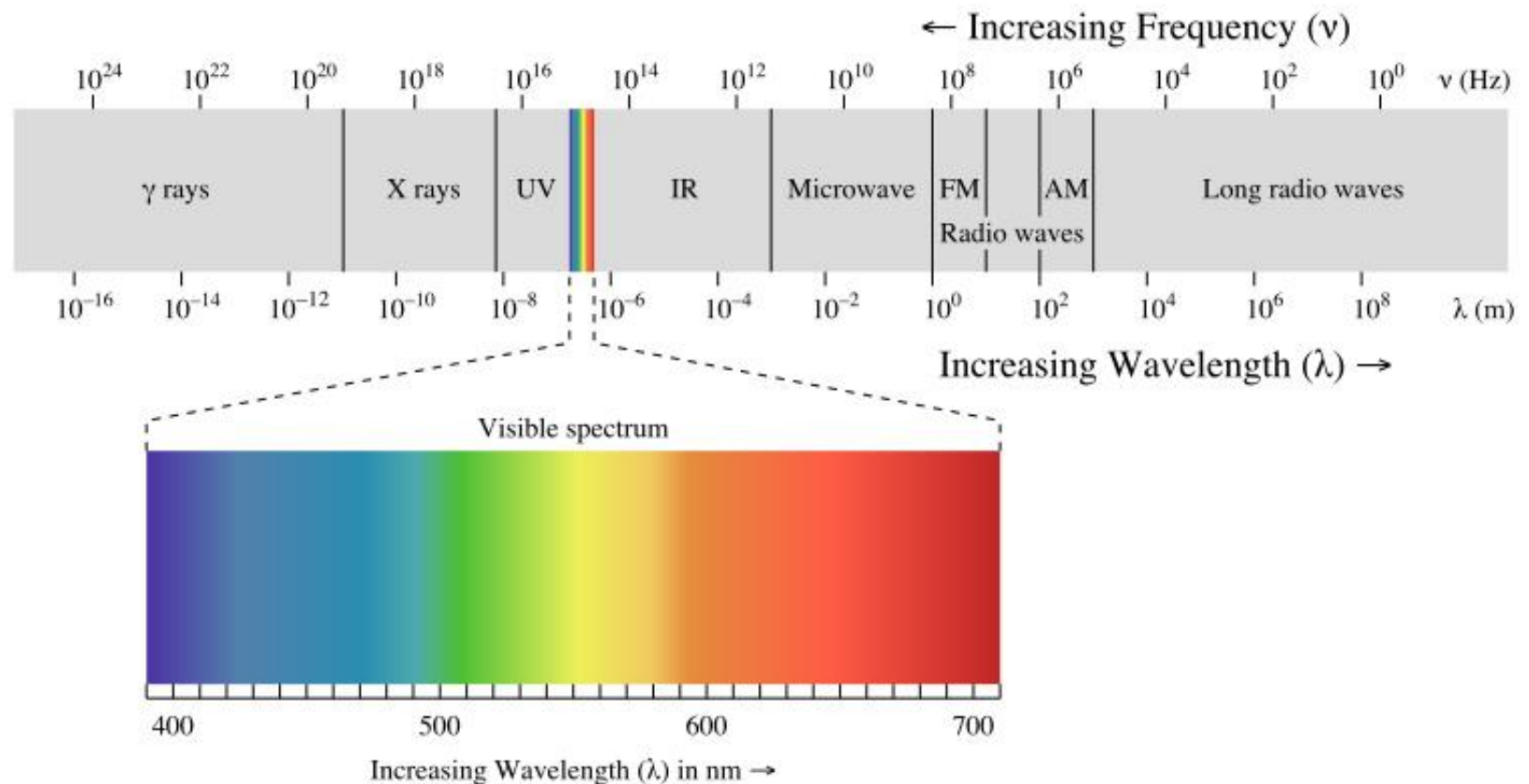
Types of wireless communication
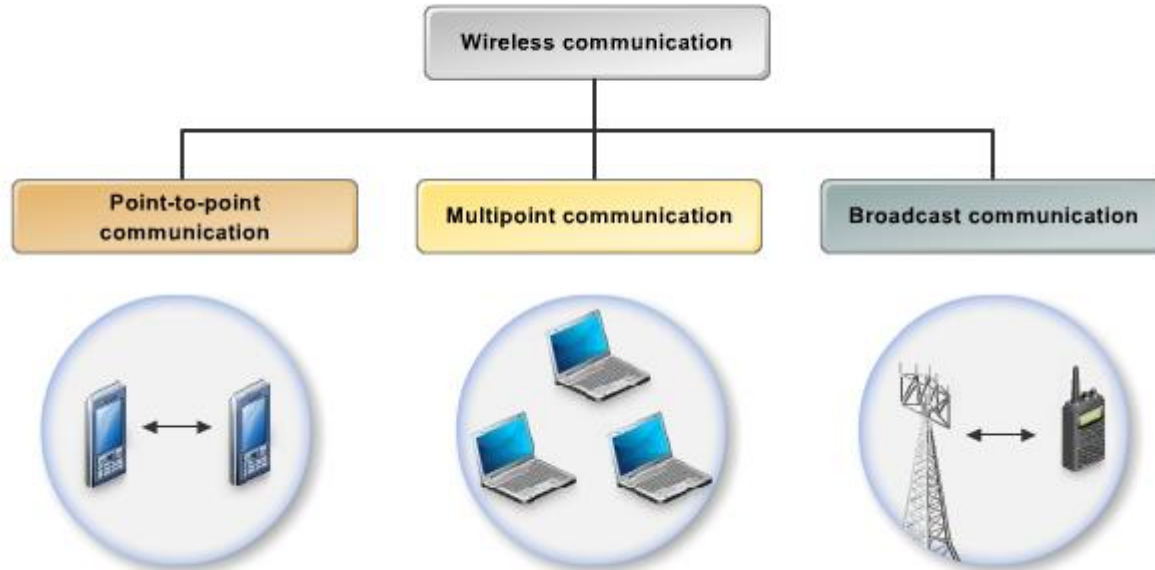
celullar   **wireless computer network**   **radio service**

Electromagnetic radiation spectrum

Wavelength of Some Technologies

- **GSM Phones**:
  - frequency ~= 900 Mhz
  - wavelength ~= 33cm
- **PCS Phones**
  - frequency ~= 1.8 Ghz
  - wavelength ~= 17.5 cm
- **Bluetooth:**
  - frequency ~= 2.4Gz
  - wavelength ~= 12.5cm

Wireless applications (services)

Communication Radio

Wireless Networks

Cellular Phones

Short Range Communication

Advantages and disadvantages of wireless communication

- advantages:

    - mobility

    - a wireless communication network is a solution in areas where cables are impossible to install (e.g. hazardous areas, long distances etc.)

    - easier to maintain

- disadvantages:

    - has security vulnerabilities

    - high costs for setting the infrastructure

    - unlike wired comm., wireless comm. is influenced by physical obstructions, climatic conditions, interference from other wireless devices

Cellular telephone

- Started as a replacement to the wired telephone
- Early generations offered voice and limited data
- Current third and fourth generation systems
    - Voice
    - Texting
    - Social networking
    - Mobile apps
    - Mobile Web
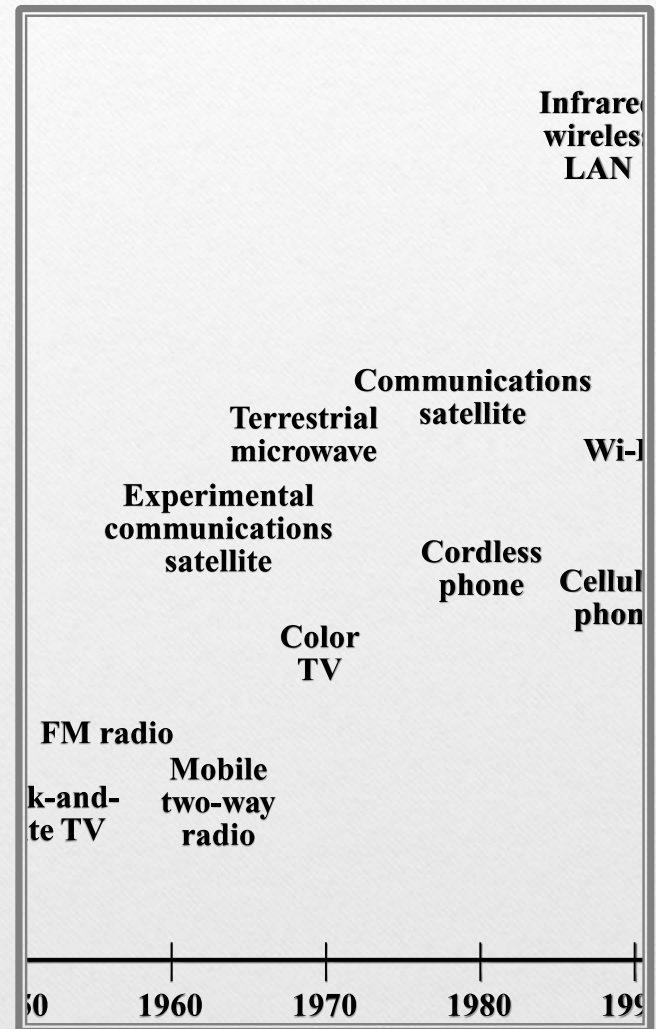   - Mobile commerce
    - Video streaming

Wireless Impact

- Profound
- Shrinks the world
- Always on
- Always connected
- Changes the way people communicate
  - Social networking
- Converged global wireless network

Figure 1.1 Some Milestones in Wireless Communications

Infrared wireless LAN

Communications satellite

Terrestrial microwave

Wi-Fi

Experimental communications satellite

Cordless phone

Cellular phone

Color TV

FM radio

Mobile two-way radio

k-and-te TV

50   1960   1970   1980   199

Global cellular network

- Growth
  - 11 million users in 1990
  - Over 7 billion today
- Mobile devices
  - Convenient
  - Location aware
  - Only economical form of communications in some places

Global cellular network

- Generations
  - 1G – Analog
  - 2G – Digital voice
    - Voice services with some moderate rate data services
  - 3G – Packet networks
    - Universal Mobile Phone Service (UMTS)
    - CDMA2000
  - 4G – New wireless approach (OFDM)
    - Higher spectral efficiency
    - 100 Mbps for high mobility users
    - 1 Gbps for low mobility access
    - Long Term Evolution (LTE) and LTE-Advanced

Mobile device revolution

- Originally just mobile phones
- Today's devices
  - Multi-megabit Internet access
  - Mobile apps
  - High megapixel digital cameras
  - Access to multiple types of wireless networks
    - Wi-Fi, Bluetooth, 3G, and 4G
  - Several on-board sensors
- Key to how many people interact with the world around them

Mobile device revolution

- Better use of spectrum
- Decreased costs
- Limited displays and input capabilities
- Tablets provide balance between smartphones and PCs
- Long distance
  - Cellular 3G and 4G
- Local areas
  - Wi-Fi
- Short distance
  - Bluetooth, ZigBee

Future trends

- LTE-Advanced and gigabit Wi-Fi now being deployed
- Machine-to-machine communications
  - The "Internet of Things"
  - Devices interact with each other
    - Healthcare, disaster recovery, energy savings, security and surveillance, environmental awareness, education, manufacturing, and many others
  - Information dissemination
    - Data mining and decision support
  - Automated adaptation and control
    - Home sensors collaborate with home appliances, HVAC systems, lighting systems, electric vehicle charging stations, and utility companies.
  - Eventually could interact in their own forms of social networking

Future trends

- Machine-to-machine communications

  - 100-fold increase in the number of devices

  - Type of communication would involve many short messages

  - Control applications will have real-time delay requirements

    - Much more stringent than for human interaction

Future trends

- Future networks
  - 1000-fold increase in data traffic by 2020
  - 5G – Not defined but envisioned by 2020
- Technologies
  - Network densification – many small cells
  - Device-centric architectures - focus on what a device needs
  - Massive multiple-input multiple-output (MIMO) – 10s or 100s of antennas
    - To focus antenna beams toward intended devices
  - Millimeter wave (mmWave) - frequencies in the 30 GHz to 300 GHz bands
    - Have much available bandwidth.
    - But require more transmit power and have higher attenuation due to obstructions
  - Native support for machine to machine communication
    - Sustained low data rates, massive number of devices, and very low delays.

The trouble with wireless

- Wireless is convenient and less expensive, but not perfect
- Limitations and political and technical difficulties inhibit wireless technologies
- Wireless channel
  - Line-of-sight is best but not required
  - Signals can still be received
    - Transmission through objects
    - Reflections off of objects
    - Scattering of signals
    - Diffraction around edges of objects

The trouble with wireless

- Wireless channel
    - Reflections can cause multiple copies of the signal to arrive
        - At different times and attenuations
        - Creates the problem of *multipath fading*
        - Signals add together to degrade the final signal
    - Noise
    - Interference from other users
    - Doppler spread caused by movement

Combating problems

- Modulation – use a signal format to send as many bits as possible
- Error control coding – add extra bits so errors are detected/corrected.
- Adaptive modulation and coding – dynamically adjust modulation and coding to current channel conditions.
- Equalization – counteract the multipath effects of the channel.
- Multiple-input multiple-output systems – use multiple antennas
  - Point signals strongly in certain directions
  - Send parallel streams of data.
- Direct sequence spread spectrum – expand the signal bandwidth
- Orthogonal frequency division multiplexing – break a signal into many lower rate bit streams
  - Each is less susceptible to multipath problems.

Political difficulties

- Between companies
  - Need common standards so products interoperate
  - Some areas have well agreed-upon standards
    - Wi-Fi, LTE
    - Not true for Internet of Things technologies
- Spectrum regulations
  - Governments dictate how spectrum is used
    - Many different types of uses and users
  - Some frequencies have somewhat restrictive bandwidths and power levels
    - Others have much more bandwidth available

Electromagnetic Signal

- Function of time

- Can also be expressed as a function of frequency
  - Signal consists of components of different frequencies

Time-Domain Concepts

- Analog signal - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
- Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level
- Periodic signal - analog or digital signal pattern that repeats over time

$$s(t+T) = s(t) \quad -\infty < t < +\infty$$

  - where T is the period of the signal

Frequency-Domain Concepts

- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

(a) sin (2ϕft)

1.0

0.5

0.0

−0.5

−1.0

0.0T 0.5T 1.0T 1.5T 2.0T

(b) (1/3) sin (2ϕ(3f)t)

1.0
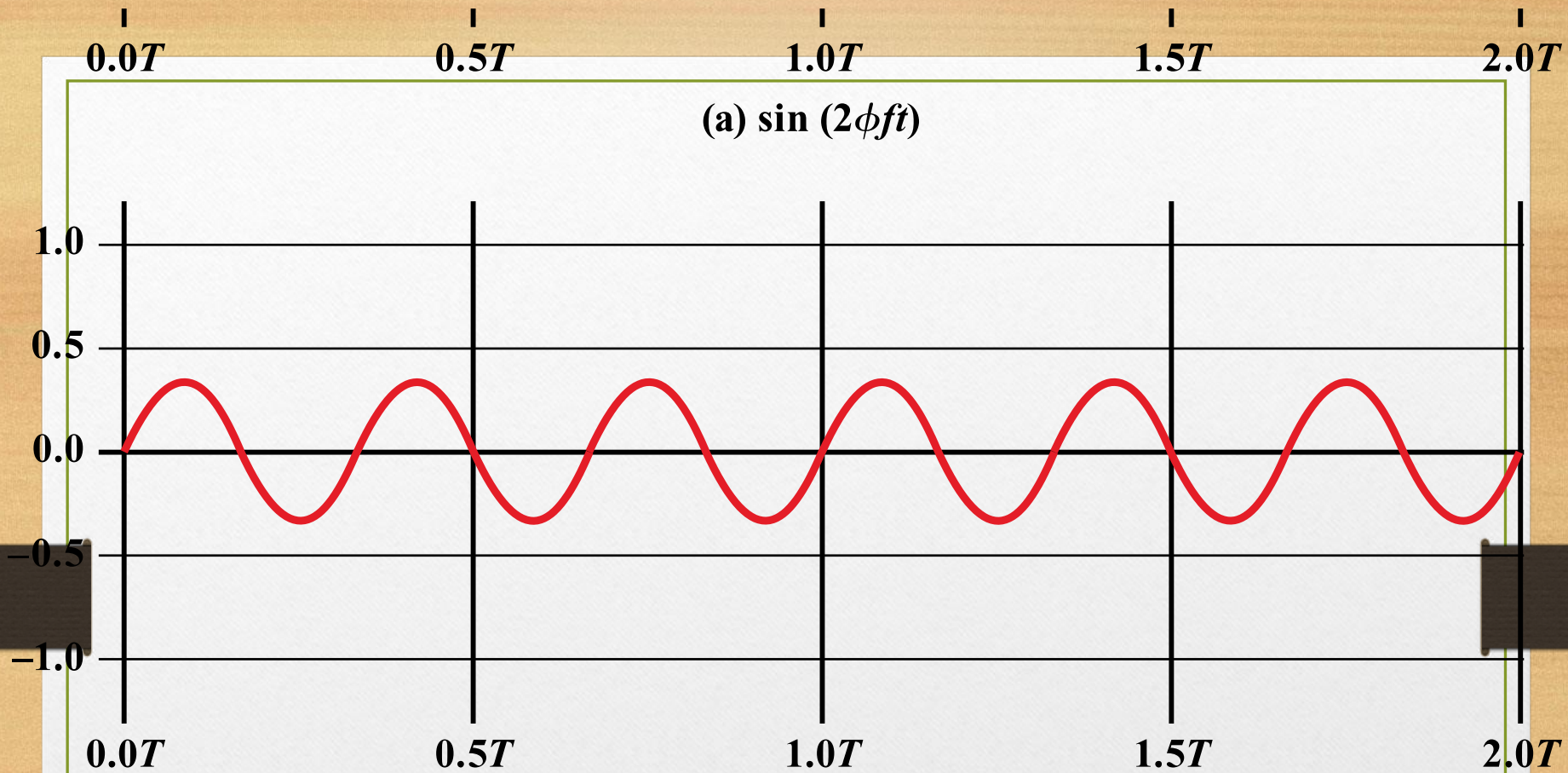
2.4 Addition of frequency Components(T = 1/f)

Frequency-Domain Concepts

- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases

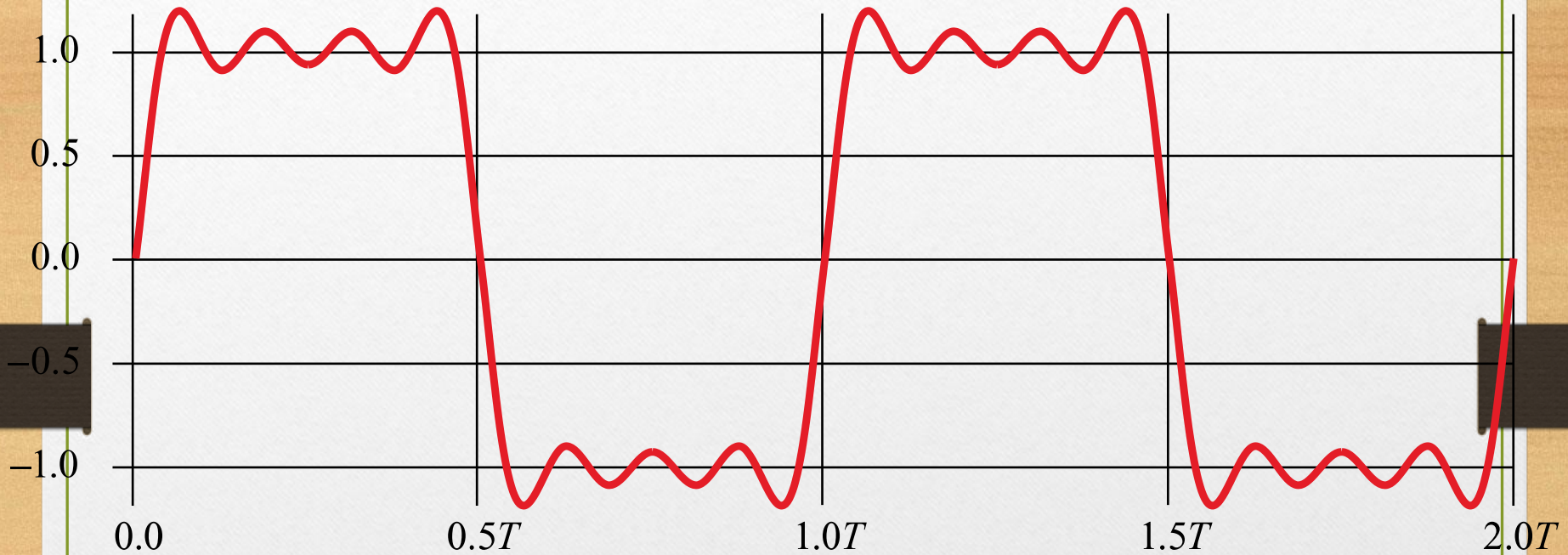- The period of the total signal is equal to the period of the fundamental frequency

(a) (4/φ) [sin (2φft) + (1/3) sin (2φ(3f)t) + (1/5) sin (2φ(5f)t)]

(b) (4/φ) [sin(2φft) + (1/3)sin(2φ(3f)t) + (1/5)sin(2φ(5f)t) + (1/7)sin(2φ(7f)t)]

2.5 Frequency Components of Square Wave

Relationship between Data Rate and Bandwidth

- The greater the bandwidth, the higher the information-carrying capacity

- Conclusions

  - Any digital waveform will have infinite bandwidth

  - BUT the transmission system will limit the bandwidth that can be transmitted

  - AND, for any given medium, the greater the bandwidth transmitted, the greater the cost

  - HOWEVER, limiting the bandwidth creates distortions

Data Communication Terms

- Data - entities that convey meaning, or information

- Signals - electric or electromagnetic representations of data

- Transmission - communication of data by the propagation and processing of signals

Examples of Analog and Digital Data

- Analog
  - Video
  - Audio
- Digital
  - Text
  - Integers

Analog Signals

- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency

- Examples of media:

  - Copper wire media (twisted pair and coaxial cable)

  - Fiber optic cable

  - Atmosphere or space propagation

- Analog signals can propagate analog and digital data

Digital Signals

- A sequence of voltage pulses that may be transmitted over a copper wire medium

- Generally cheaper than analog signaling

- Less susceptible to noise interference

- Suffer more from attenuation

- Digital signals can propagate analog and digital data

Reasons for Choosing Data and Signal Combinations

- Digital data, digital signal
  - Equipment for encoding is less expensive than digital-to-analog equipment
- Analog data, digital signal
  - Conversion permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - Examples include optical fiber and satellite
- Analog data, analog signal
  - Analog data easily converted to analog signal

Telephone

Digital Data
(binary voltage pulses)

Modem

Analog Signal
(modulated on
carrier frequency)
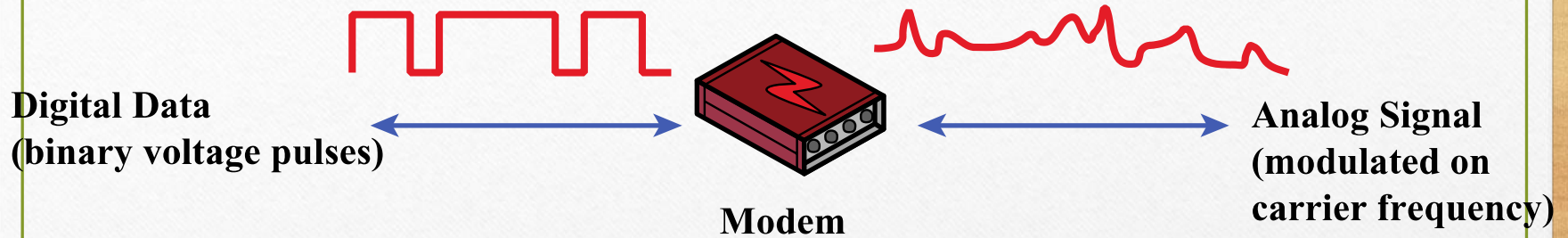
Digital Signals: Represent data with sequence
of voltage pulses

Analog Signal

Codec
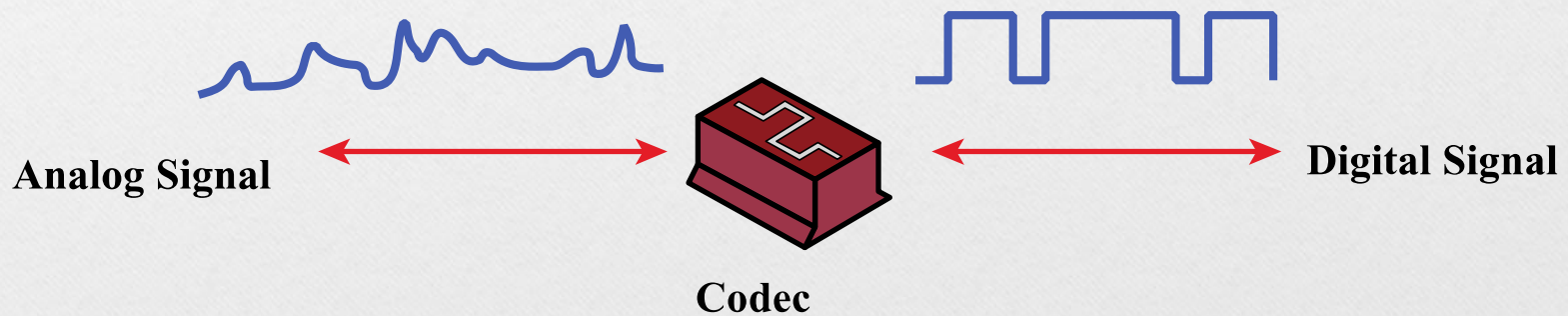
Digital Signal

2.8 Analog and Digital Signaling of Analog and Digital Data

Analog Transmission

- Transmit analog signals without regard to content

- Attenuation limits length of transmission link

- Cascaded amplifiers boost signal's energy for longer distances but cause distortion

  - Analog data can tolerate distortion

  - Introduces errors in digital data

Digital Transmission

- Concerned with the content of the signal
- Attenuation endangers integrity of data
- Digital Signal
  - Repeaters achieve greater distance
  - Repeaters recover the signal and retransmit
- Analog signal carrying digital data
  - Retransmission device recovers the digital data from analog signal
  - Generates new, clean analog signal

About Channel Capacity

- Impairments, such as noise, limit data rate that can be achieved

- For digital data, to what extent do impairments limit data rate?

- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions

Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated (bps)

- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)

- Noise - average level of noise over the communications path

- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

Classifications of Transmission Media

- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
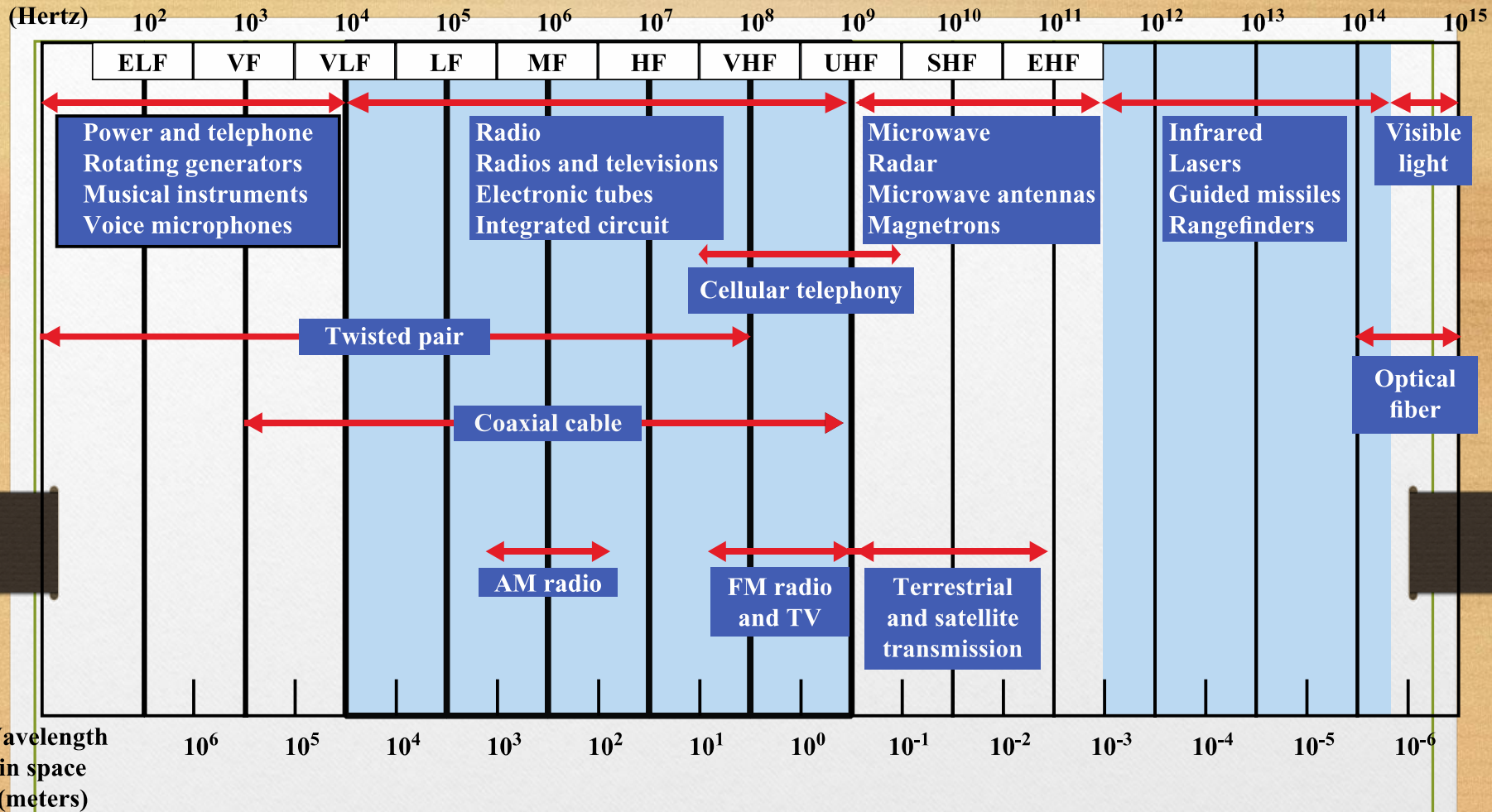 - E.g., atmosphere, outer space

Unguided Media

- Transmission and reception are achieved by means of an antenna

- Configurations for wireless transmission

  - Directional

  - Omnidirectional

TRANS
NS
MIS
SIO
N
FU
ND
AM
ENT
ALS
2-

Frequency (Hertz)

10^2 | 10^3 | 10^4 | 10^5 | 10^6 | 10^7 | 10^8 | 10^9 | 10^{10} | 10^{11} | 10^{12} | 10^{13} | 10^{14} | 10^{15}

| ELF | VF | VLF | LF | MF | HF | VHF | UHF | SHF | EHF |

Power and telephone
Rotating generators
Musical instruments
Voice microphones

Radio
Radios and televisions
Electronic tubes
Integrated circuit

Microwave
Radar
Microwave antennas
Magnetrons

Infrared
Lasers
Guided missiles
Rangefinders

Visible light

Cellular telephony

Twisted pair

Optical fiber

Coaxial cable

AM radio

FM radio and TV

Terrestrial and satellite transmission

Wavelength in space (meters)

10^6 | 10^5 | 10^4 | 10^3 | 10^2 | 10^1 | 10^0 | 10^{-1} | 10^{-2} | 10^{-3} | 10^{-4} | 10^{-5} | 10^{-6}

ELF = Extremely low frequency   MF = Medium frequency   UHF = Ultrahigh frequency
VF = Voice frequency   HF = High frequency   SHF = Superhigh frequency
VLF = Very low frequency   VHF = Very high frequency   EHF = Extremely high frequency
LF = Low frequency

2.10 Electromagnetic spectrum of Telecommunications

General Frequency Ranges

- Microwave frequency range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Infrared frequency range
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

Terrestrial Microwave

- Description of common microwave antenna
  - Parabolic "dish", 3 m in diameter
  - Fixed rigidly and focuses a narrow beam
  - Achieves line-of-sight transmission to receiving antenna
  - Located at substantial heights above ground level
- Applications
  - Long haul telecommunications service
  - Short point-to-point links between buildings

Satellite Microwave

- Description of communication satellite
  - Microwave relay station
  - Used to link two or more ground-based microwave transmitter/receivers
  - Receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink)
- Applications
  - Television distribution
  - Long-distance telephone transmission
  - Private business networks

Broadcast Radio

- Description of broadcast radio antennas
  - Omnidirectional
  - Antennas not required to be dish-shaped
  - Antennas need not be rigidly mounted to a precise alignment
- Applications
  - Broadcast radio
    - VHF and part of the UHF band; 30 MHZ to 1GHz
    - Covers FM radio and UHF and VHF television

Multiplexing

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal

- Multiplexing - carrying multiple signals on a single medium

  - More efficient use of transmission medium

1 link, n channels

Reasons for Widespread Use of Multiplexing

- Cost per kbps of transmission facility declines with an increase in the data rate

- Cost of transmission and receiving equipment declines with increased data rate

- Most individual data communicating devices require relatively modest data rate support

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal

- Time-division multiplexing (TDM)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal

Time

Channel f_1 f_2 f_3 f_4 f_5 f_6

f_1 f_2 f_3 f_4 f_5
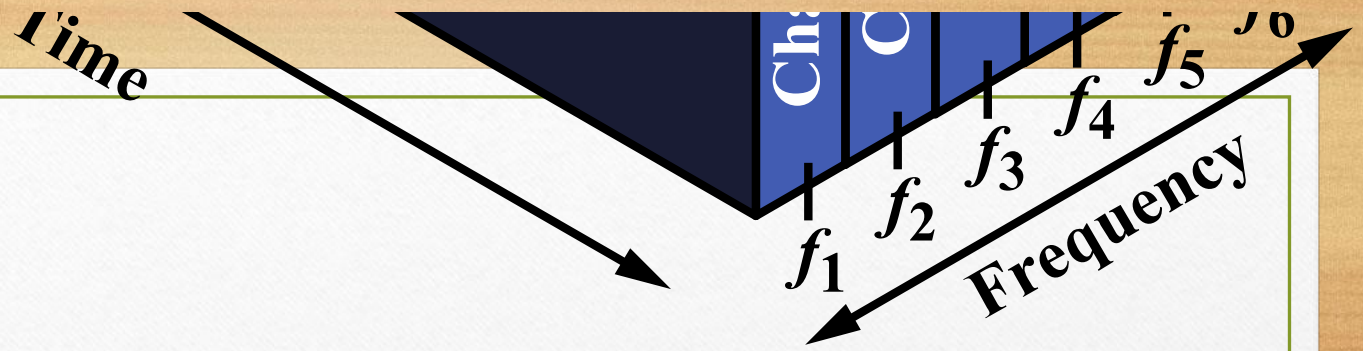
Frequency

(a) Frequency division multiplexing
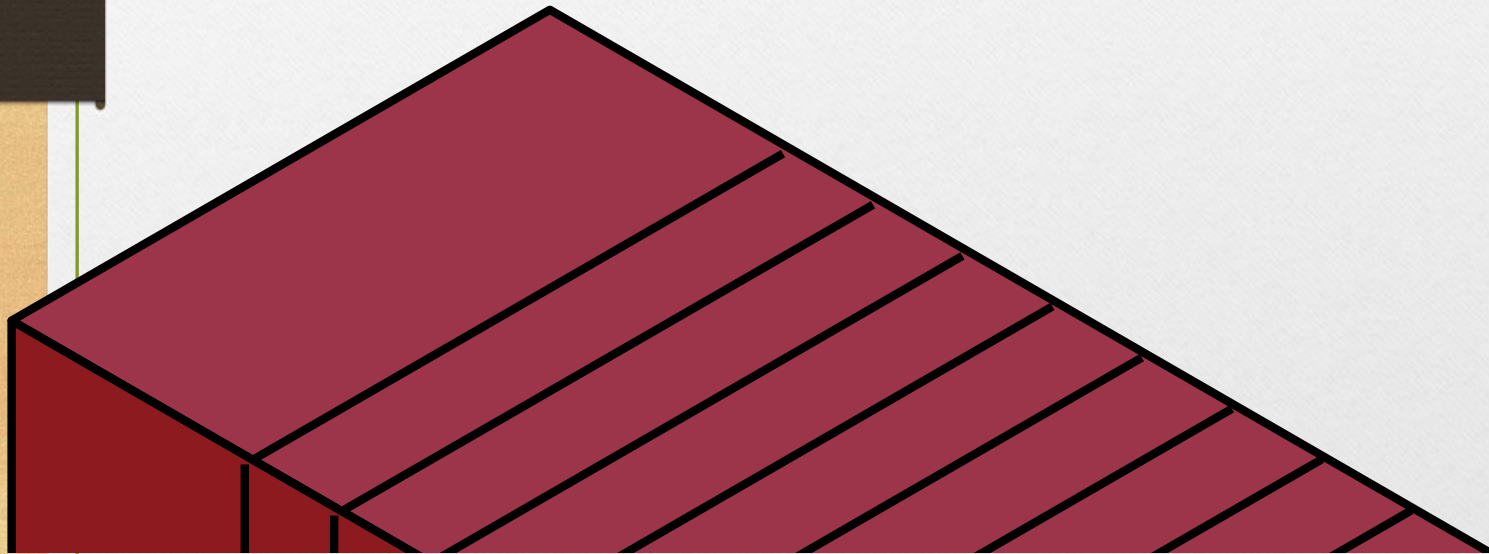
2.12 FDM and TDM

Spectrum considerations

- Controlled by regulatory bodies
  - Carrier frequency
  - Signal Power
  - Multiple Access Scheme
    - Divide into time slots –Time Division Multiple Access (TDMA)
    - Divide into frequency bands – Frequency Division Multiple Access (FDMA)
    - Different signal encodings – Code Division Multiple Access (CDMA)

Spectrum considerations

- Federal Communications Commission (FCC) in the United States regulates spectrum
  - Military
  - Broadcasting
  - Public Safety
  - Mobile
  - Amateur
  - Government exclusive, non-government exclusive, or both
  - Many other categories
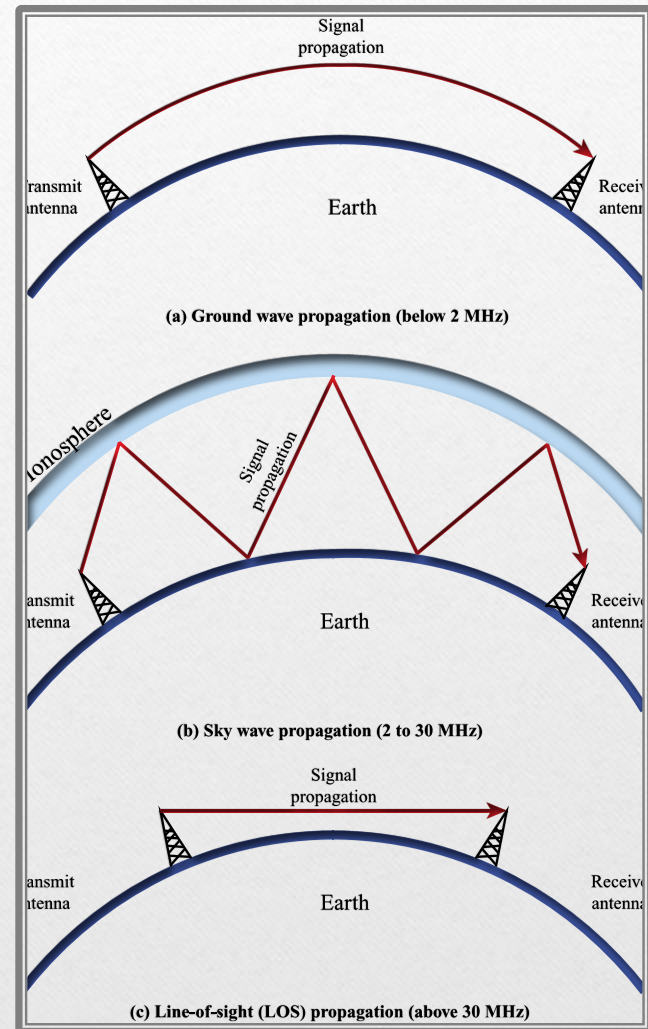
Spectrum considerations

- Industrial, Scientific, and Medical (ISM) bands
  - Can be used without a license
  - As long as power and spread spectrum regulations are followed
- ISM bands are used for
  - WLANs
  - Wireless Personal Area networks
  - Internet of Things

Propagation Modes

- Ground-wave propagation

- Sky-wave propagation

- Line-of-sight propagation

5.1 Wireless Propagation Modes

Signal propagation

Transmit antenna

Earth

Receive antenna

(a) Ground wave propagation (below 2 MHz)

Ionosphere

Signal propagation

Transmit antenna

Earth

Receive antenna

(b) Sky wave propagation (2 to 30 MHz)

Signal propagation

Transmit antenna

Earth

Receive antenna

(c) Line-of-sight (LOS) propagation (above 30 MHz)

Ground Wave Propagation

- Follows contour of the earth

- Can propagate considerable distances

- Frequencies up to 2 MHz

- Example

  - AM radio

Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth

- Signal can travel a number of hops, back and forth between ionosphere and earth's surface

- Reflection effect caused by refraction

- Examples

  - Amateur radio

  - CB radio

Line-of-Sight Propagation

- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within *effective* line of site due to refraction
- Refraction – bending of microwaves by the atmosphere
  - Velocity of electromagnetic wave is a function of the density of the medium
  - When wave changes medium, speed changes
  - Wave bends at the boundary between mediums

Five basic propagation mechanisms

1. Free-space propagation
2. Transmission
   - Through a medium
   - Refraction occurs at boundaries
3. Reflections
   - Waves impinge upon surfaces that are large compared to the signal wavelength
4. Diffraction
   - Secondary waves behind objects with sharp edges
5. Scattering
   - Interactions between small objects or rough surfaces

antennas

- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

Radiation Patterns

- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
- Beam width (or half-power beam width)
  - Measure of directivity of antenna
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern
- Sidelobes
  - Extra energy in directions outside the mainlobe
- Nulls
  - Very low energy in between mainlobe and sidelobes

5.2 Antenna Radiation Patterns

A

B

Antenna location
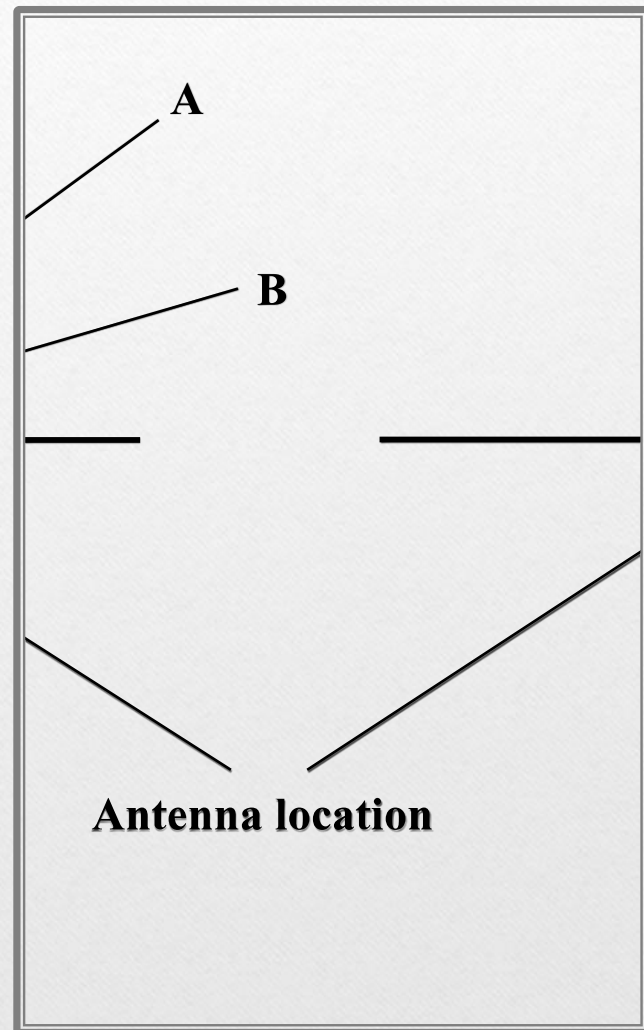
Attenuation

- Strength of signal falls off with distance over transmission medium

- Attenuation factors for unguided media:

  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal

  - Signal must maintain a level sufficiently higher than noise to be received without error

  - Attenuation is greater at higher frequencies, causing distortion

Models Derived from Empirical Measurements

- Need to design systems based on empirical data applied to a particular environment
  - To determine power levels, tower heights, height of mobile antennas
- Okumura developed a model, later refined by Hata
  - Detailed measurement and analysis of the Tokyo area
  - Among the best accuracy in a wide variety of situations
- Predicts path loss for typical environments
  - Urban
  - Small, medium sized city
  - Large city
  - Suburban
  - Rural

Categories of Noise

- Thermal Noise

- Intermodulation noise

- Crosstalk

- Impulse Noise

Thermal Noise

- Thermal noise due to agitation of electrons

- Present in all electronic devices and transmission media

- Cannot be eliminated

- Function of temperature

- Particularly significant for satellite communication

Noise Terminology

- Intermodulation noise – occurs if signals with different frequencies share the same medium

  - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies

- Crosstalk – unwanted coupling between signal paths

- Impulse noise – irregular pulses or noise spikes

  - Short duration and of relatively high amplitude

  - Caused by external electromagnetic disturbances, or faults and flaws in the communications system

Other Impairments

- Atmospheric absorption – water vapor and oxygen contribute to attenuation

- Multipath – obstacles reflect signals so that multiple copies with varying delays are received

- Refraction – bending of radio waves as they propagate through the atmosphere

The Effects of Multipath Propagation

- Reflection, diffraction, and scattering
- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit
- Rapid signal fluctuations
  - Over a few centimeters

5.5 Sketch of Three Important Propagation Mechanisms

R

Lamp post

S

D
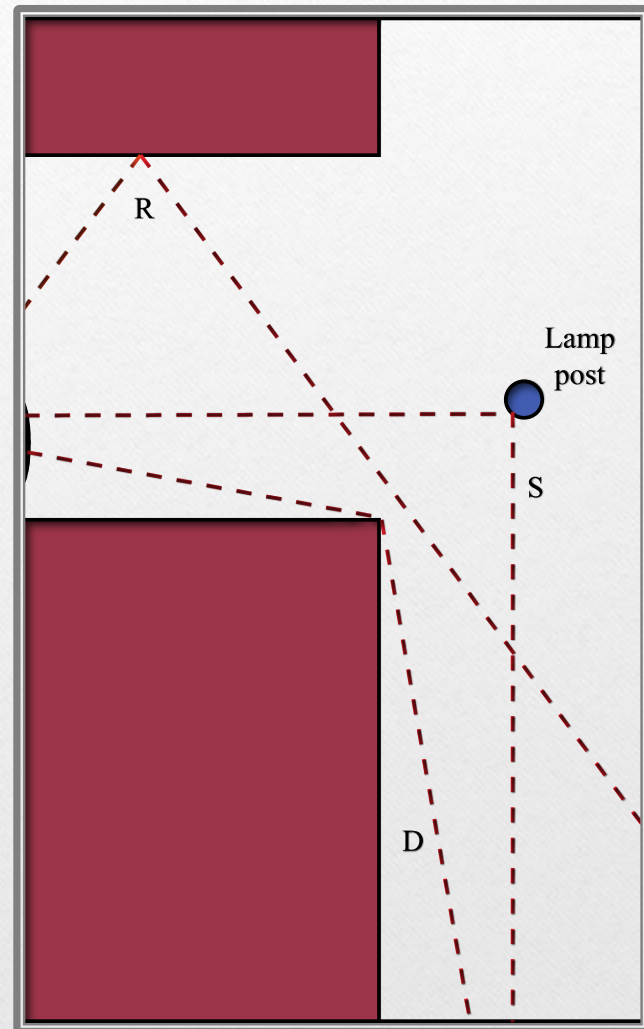
Types of Fading

- Large-scale fading
  - Signal variations over large distances
  - Path loss L_{dB} as we have seen already
  - Shadowing
- Statistical variations
  - Rayleigh fading
  - Ricean fading

Types of fading

- Doppler Spread
  - Frequency fluctuations caused by movement
  - Coherence time T_c characterizes Doppler shift
    - How long a channel remains the same
  - Coherence time $T_c \gg T_b$ bit time → *slow fading*
    - The channel does not change during the bit time
  - Otherwise *fast fading*
- Example 6.11: T_c = 70 ms, bit rate r_b = 100 kbs
  - Bit time $T_b = 1/100 \times 10^3 = 10$ μs
  - $T_c \gg T_b$? 70 ms $\gg$ 10 μs?
  - True, so *slow fading*

Types of fading

- Multipath fading
  - Multiple signals arrive at the receiver
  - Coherence bandwidth B_c characterizes multipath
    - Bandwidth over which the channel response remains relatively constant
    - Related to delay spread, the spread in time of the arrivals of multipath signals
  - Signal bandwidth B_s is proportional to the bit rate
  - If $B_c \gg B_s$, then *flat fading*
    - The signal bandwidth fits well within the channel bandwidth
  - Otherwise, *frequency selective fading*
- Example 6.11: $B_c = 150$ kHz, bit rate $r_b = 100$ kbs
  - Assume signal bandwidth $B_s \approx r_b$, $B_s = 100\ kHz$
  - $B_c \gg B_s$? 150 kHz $\gg$ 100 kHz?
  - Using a factor of 10 for "$\gg$", 150 kHz is not more than 10×100 kHz
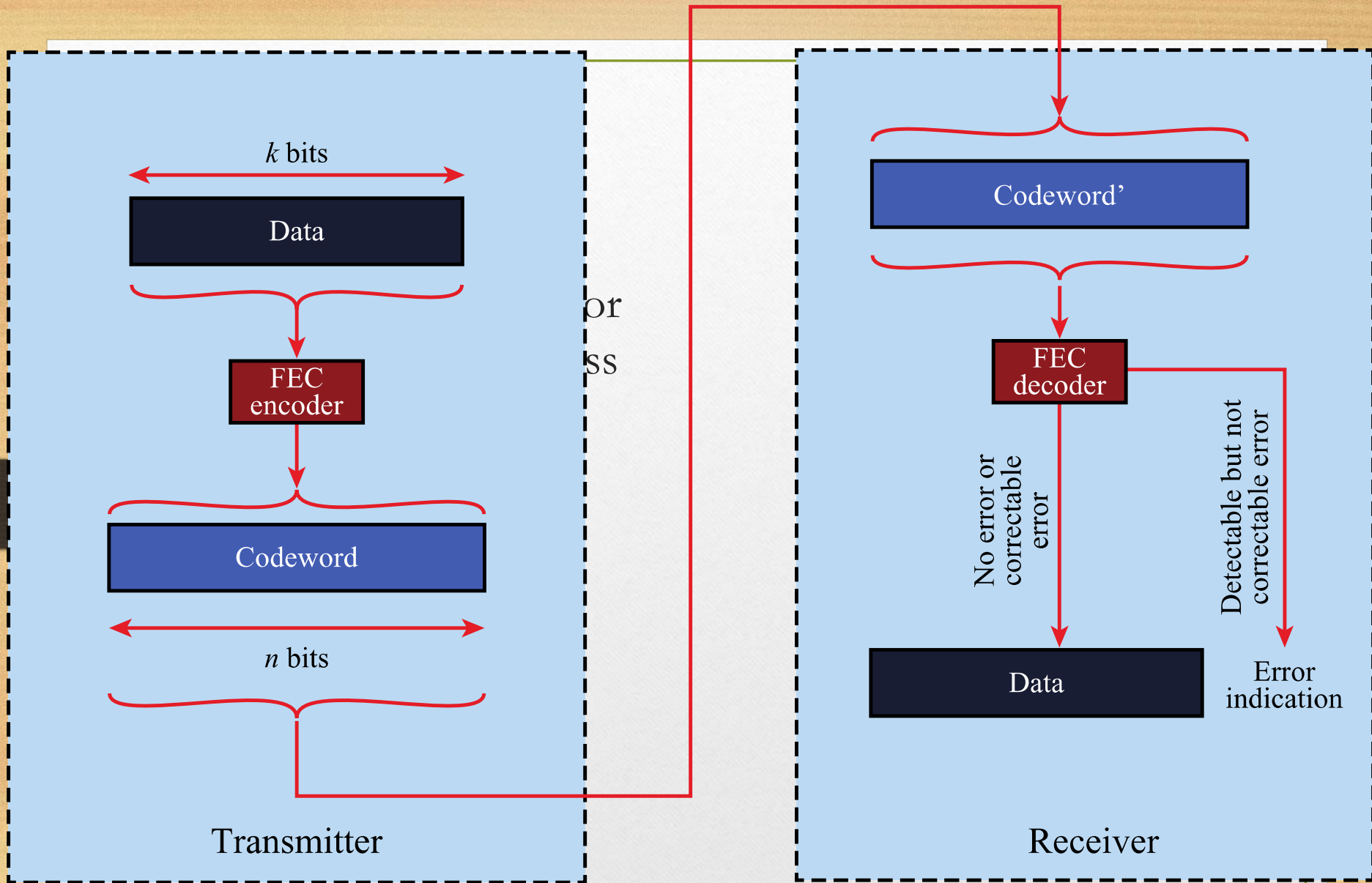 - False, so *frequency selective fading*

Channel correction Mechanisms

- Forward error correction
- Adaptive equalization
- Adaptive modulation and coding
- Diversity techniques and MIMO
- OFDM
- Spread sprectrum
- Bandwidth expansion

Forward Error Correction

- Transmitter adds error-correcting code to data block
  - Code is a function of the data bits
- Receiver calculates error-correcting code from incoming data bits
  - If calculated code matches incoming code, no error occurred
  - If error-correcting codes don't match, receiver attempts to determine bits in error and correct
- Subject of Chapter 10

k bits

Data

FEC encoder

Codeword

n bits

or ss

Codeword'

FEC decoder

No error or correctable error

Detectable but not correctable error

Data

Error indication

Transmitter

Receiver

Adaptive Equalization

- Can be applied to transmissions that carry analog or digital information
  - Analog voice or video
  - Digital data, digitized voice or video
- Used to combat intersymbol interference
- Involves gathering dispersed symbol energy back into its original time interval
- Techniques
  - Lumped analog circuits
  - Sophisticated digital signal processing algorithms

Diversity Techniques

- Diversity is based on the fact that individual channels experience independent fading events

- Space diversity – techniques involving physical transmission path, spacing antennas

- Frequency diversity – techniques where the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers

- Time diversity – techniques aimed at spreading the data out over time

- Use of diversity
  - Selection diversity – select the best signal
  - Combining diversity – combine the signals

MULTIPLE INPUT MULTIPLE OUTPUT (MIMO) ANTENNAS

- Use antenna arrays for
  - Diversity – different signals from different antennas
  - Multiple streams – parallel data streams
  - Beamforming – directional antennas
  - Multi-user MIMO – directional beams to multiple simultaneous users
- Modern systems
  - 4 × 4 (4 transmitter and 4 reciever antennas)
  - 8 × 8
  - Two dimensional arrays of 64 antennas
  - Future: Massive MIMO with many more antennas

Adaptive modulation and coding (AMC)

- The modulation process formats the signal to best transmit bits
  - To overcome noise
  - To transmit as many bits as possible
- Coding detects and corrects errors
- AMC adapts to channel conditions
  - 100's of times per second
  - Measures channel conditions
 - Sends messages between transmitter and receiver to coordinate changes

Bandwidth expansion

- A signal can only provide a limited bps/Hz
    - More bandwidth is needed
- Carrier aggregation
    - Combine multiple channels
        - Example: Fourth-generation LTE combines third-generation carriers
- Frequency reuse
    - Limit propagation range to an area
    - Use the same frequencies again when sufficiently far away
    - Use large coverage areas (macro cells) and smaller coverage areas (outdoor picocells or relays and indoor femtocells)
- Millimeter wave (mmWave)
    - Higher carrier frequencies have more bandwidth available
    - 30 to 300 GHz bands with millimeter wavelengths
    - Yet these are expensive to use and have problems with obstructions

Figure 14.14 LTE Carrier Aggregation

(a) Logical view of carrier aggregation

(b) Types of carrier aggregation
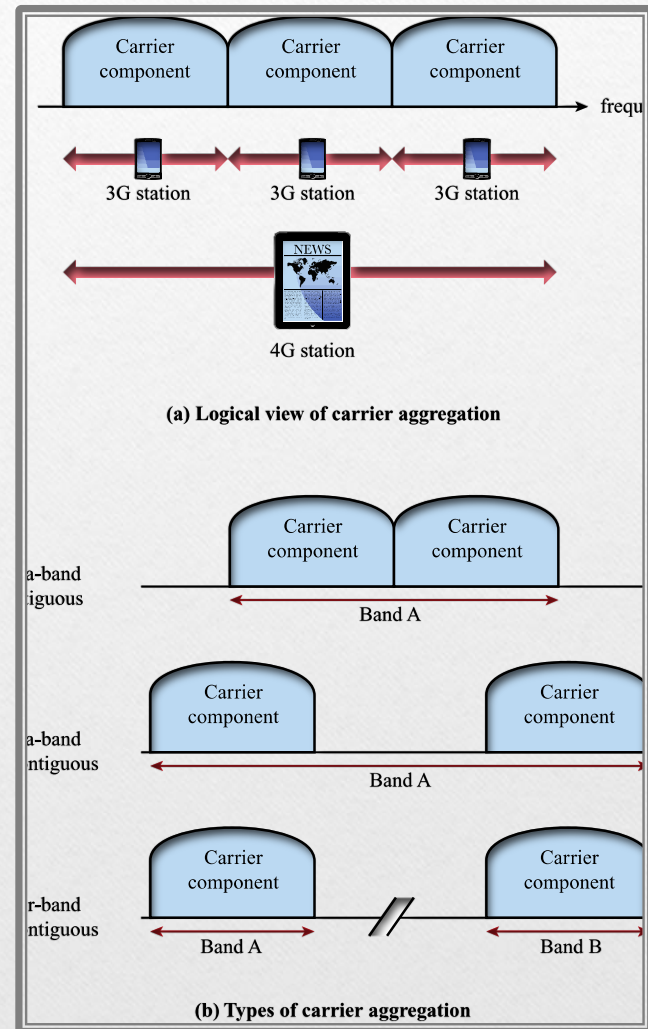
signal Encoding Techniques

- Digital data to analog signal
  - Amplitude-shift keying (ASK)
    - Amplitude difference of carrier frequency
  - Frequency-shift keying (FSK)
    - Frequency difference near carrier frequency
  - Phase-shift keying (PSK)
    - Phase of carrier signal shifted

5.10 Modulation of Analog Signals for Digital Data
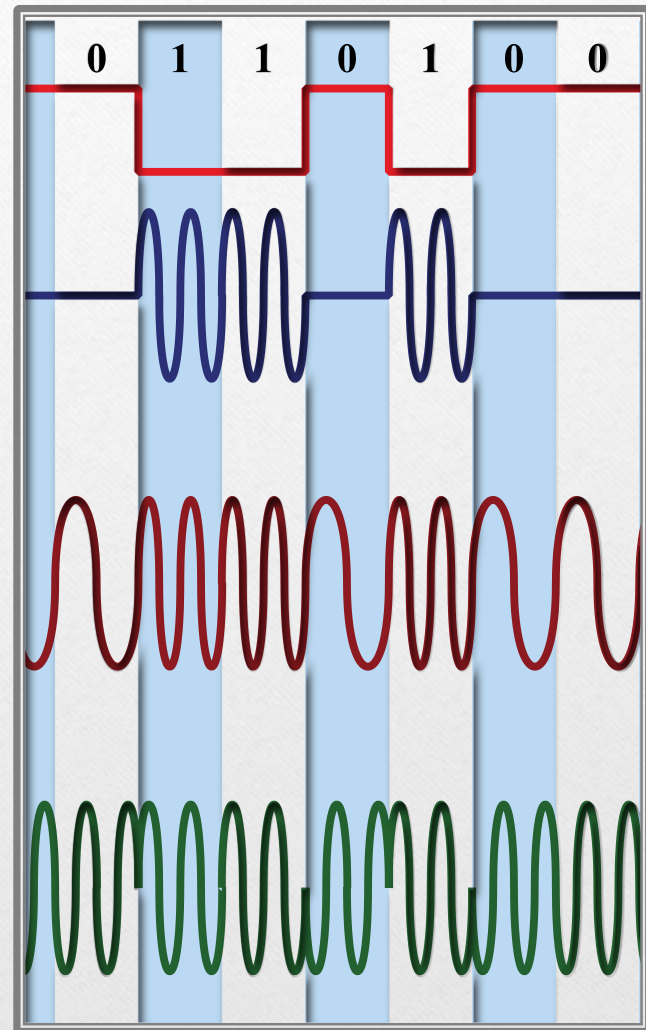
Amplitude-Shift Keying

- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

$$s(t) = \begin{cases} A\cos\left(2\rho f_c t\right) & \text{binary 1} \\ 0 & \text{binary 0} \end{cases}$$

- where the carrier signal is $A\cos(2\pi f_c t)$

Amplitude-Shift Keying

- Susceptible to sudden gain changes

- Inefficient modulation technique

- Used to transmit digital data over optical fiber

Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} A\cos\left(2\rho f_1 t\right) & \text{binary 1} \\ A\cos\left(2\rho f_2 t\right) & \text{binary 0} \end{cases}$$

- where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts f_d

Binary Frequency-Shift Keying (BFSK)

- Less susceptible to error than ASK

- Used for high-frequency (3 to 30 MHz) radio transmission

- Can be used at higher frequencies on LANs that use coaxial cable

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i\left(t\right) = A\cos 2\rho f_i t \qquad 1 \pounds i \pounds M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- f_c = the carrier frequency
- f_d = the difference frequency
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

$$s(t) = \begin{cases} A\cos\left(2\rho f_c t\right) & \text{binary 1} \\ A\cos\left(2\rho f_c t + \rho\right) & \text{binary 0} \end{cases}$$

$$= \begin{cases} A\cos\left(2\rho f_c t\right) & \text{binary 1} \\ -A\cos\left(2\rho f_c t\right) & \text{binary 0} \end{cases}$$

Quadrature Phase-Shift Keying (PSK)

- Four-level PSK (QPSK)
  - Each element represents more than one bit

$$s(t) = \begin{cases} A\cos\left(2\rho f_c t + \dfrac{\rho}{4}\right) & 11 \\[2em] A\cos\left(2\rho f_c t + \dfrac{3\rho}{4}\right) & 01 \\[2em] A\cos\left(2\rho f_c t - \dfrac{3\rho}{4}\right) & 00 \\[2em] A\cos\left(2\rho f_c t - \dfrac{\rho}{4}\right) & 10 \end{cases}$$

CODING AND ERROR CONTROL

- 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 Process

- Transmitter
  - For a given frame, an error-detecting code (check bits) is calculated from data bits
  - Check bits are appended to data bits

- Receiver
  - Separates incoming frame into data bits and check bits
  - Calculates check bits from received data bits
  - Compares calculated check bits against received check bits
  - Detected error occurs if mismatch

Transmitter

k bits

Data

E = f(Data)

Data

$n - k$ bits

n bits

Receiver

Data'

E' = f(Data') → COMPARE
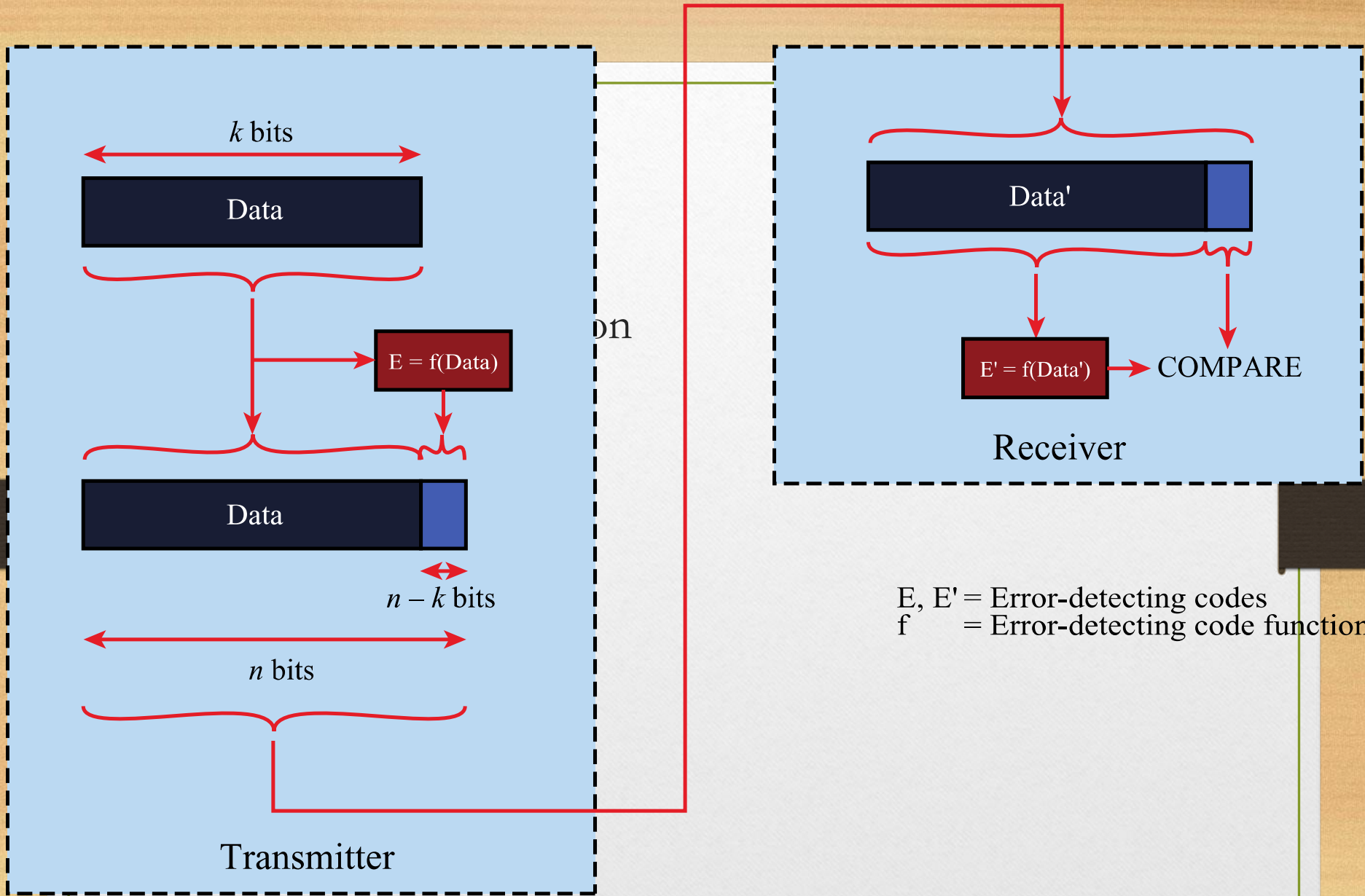
E, E' = Error-detecting codes
f   = Error-detecting code function

Parity Check

- Parity bit appended to a block of data
- Even parity
  - Added bit ensures an even number of 1s
- Odd parity
  - Added   bit ensures an odd number of 1s
- Example, 7-bit character [1110001]
  - Even parity [11100010]
  - Odd parity [11100011]

Cyclic Redundancy Check (CRC)

- Transmitter
  - For a k-bit block, transmitter generates an $(n-k)$-bit frame check sequence (FCS)
  - Resulting frame of n bits is exactly divisible by predetermined number

- Receiver
  - Divides incoming frame by predetermined number
  - If no remainder, assumes no error
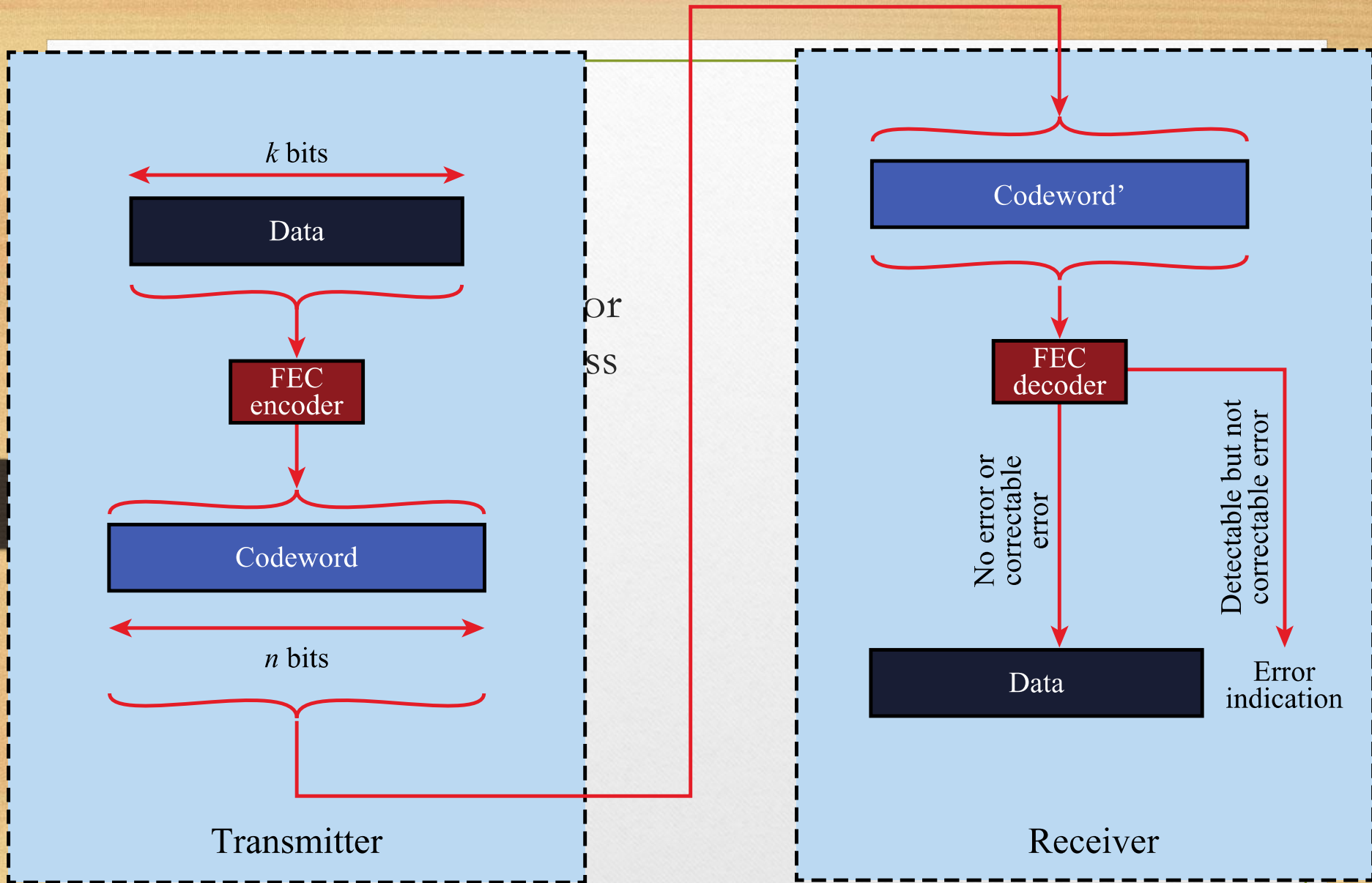
Wireless Transmission Errors

- Error detection requires retransmission

- Detection inadequate for wireless applications

  - Error rate on wireless link can be high, results in a large number of retransmissions

  - Long propagation delay compared to transmission time

Block Error Correction Codes

- Transmitter
  - Forward error correction (FEC) encoder maps each k-bit block into an n-bit block codeword
  - Codeword is transmitted; analog for wireless transmission
- Receiver
  - Incoming signal is demodulated
  - Block passed through an FEC decoder

Transmitter

k bits

Data

FEC encoder

Codeword

n bits

or ss

Receiver

Codeword'

FEC decoder

No error or correctable error

Detectable but not correctable error

Data

Error indication

FEC Decoder Outcomes

- No errors present
  - Codeword produced by decoder matches original codeword
- Decoder detects and corrects bit errors
- Decoder detects but cannot correct bit errors; reports uncorrectable error
- Decoder incorrectly corrects bit errors
  - Error pattern looks like a different block of data was sent
- Decoder detects no bit errors, though errors are present

Block Code Principles

- Hamming distance – for 2 n-bit binary sequences, the number of different bits

  - E.g., v_1=011011; v_2=110001; $d(v1, v_2)$=3

- Redundancy – ratio of redundant bits to data bits

- Code rate – ratio of data bits to total bits

- Coding gain – the reduction in the required E_b/N_0 to achieve a specified BER of an error-correcting coded system

Decoding process

Data block	Codeword
00	00000
01	00111
10	11001
11	11110

-

- Received: 00100
    - Not valid, error is detected
    - Correction?
        - One bit away from 00000
        - Two bits away from 00111
        - Three bits away from 11110
        - Four bits away from 11110
    - Most likely 00000 was sent, assume data was 00
        - But others could have been sent, albeit much less likely

Decoding process

- Received: 01100
  - Two bits from 00000
  - Two bits from 11110
  - No other codes closer
  - Cannot decode. Only know bit errors are detected
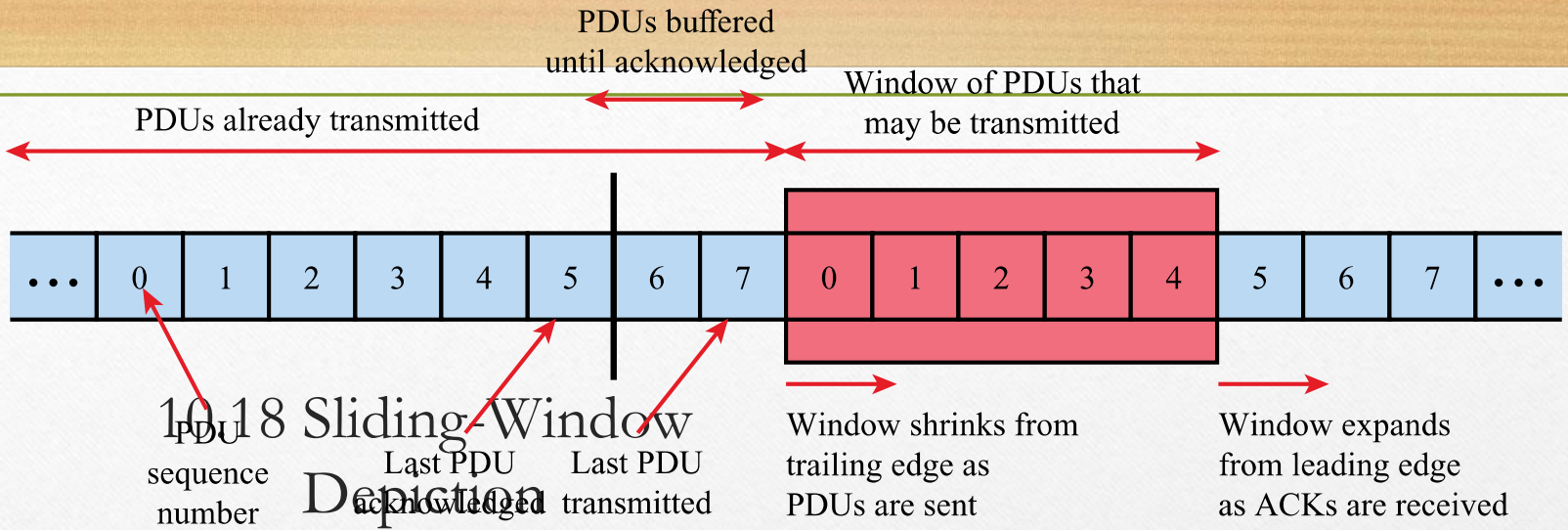
Automatic Repeat Request

- Mechanism used in data link control and transport protocols

- Relies on use of an error detection code (such as CRC)
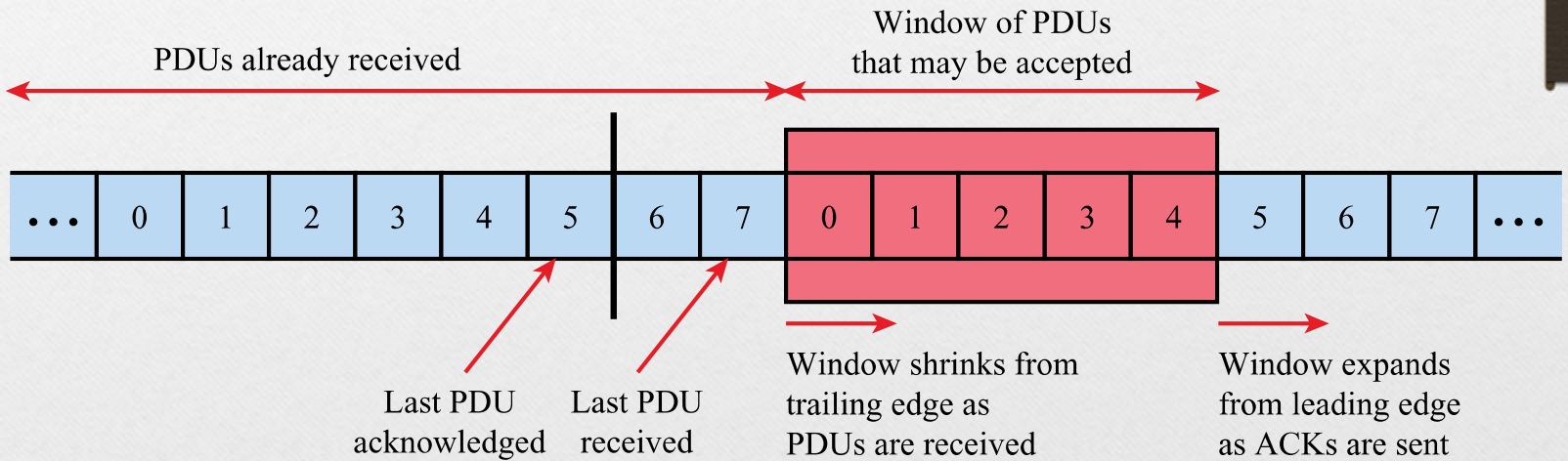
- Flow Control

- Error Control

Flow Control

- Assures that transmitting entity does not overwhelm a receiving entity with data
- Protocols with flow control mechanism allow multiple PDUs in transit at the same time
- PDUs arrive in same order they're sent
- Sliding-window flow control
  - Transmitter maintains list (window) of sequence numbers allowed to send
  - Receiver maintains list allowed to receive

10.18 Sliding Window Depiction
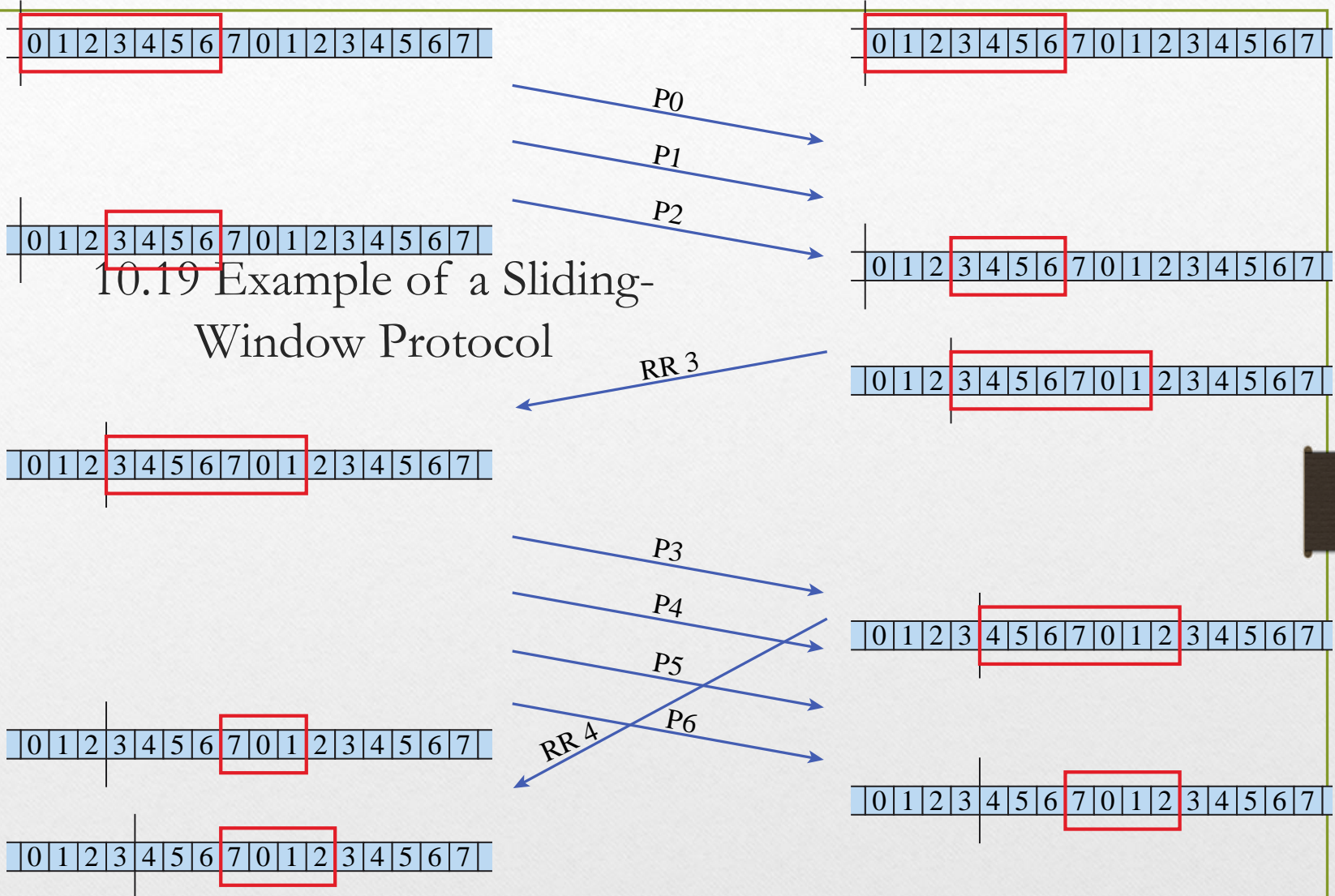
PDUs buffered until acknowledged

PDUs already transmitted

Window of PDUs that may be transmitted

| ··· | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ··· |

PDU sequence number

Last PDU acknowledged

Last PDU transmitted

Window shrinks from trailing edge as PDUs are sent

Window expands from leading edge as ACKs are received

(a) Sender's perspective

PDUs already received

Window of PDUs that may be accepted

| ··· | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | ··· |

Last PDU acknowledged

Last PDU received

Window shrinks from trailing edge as PDUs are received

Window expands from leading edge as ACKs are sent

(b) Receiver's perspective

10.19 Example of a Sliding-Window Protocol

Flow Control

- Reasons for breaking up a block of data before transmitting:

    - Limited buffer size of receiver

    - Retransmission of PDU due to error requires smaller amounts of data to be retransmitted

    - On shared medium, larger PDUs occupy medium for extended period, causing delays at other sending stations

Error Control
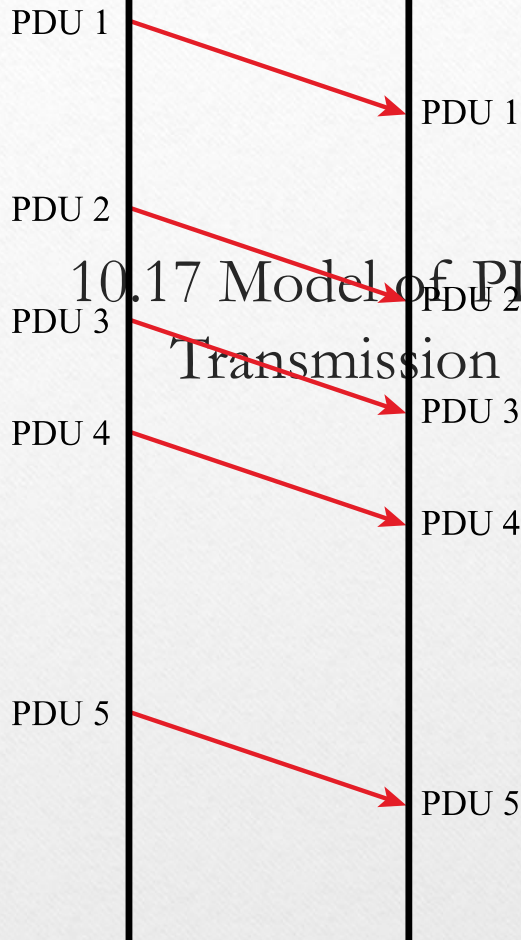
- Mechanisms to detect and correct transmission errors

- Types of errors:

  - Lost PDU : a PDU fails to arrive

  - Damaged PDU : PDU arrives with errors
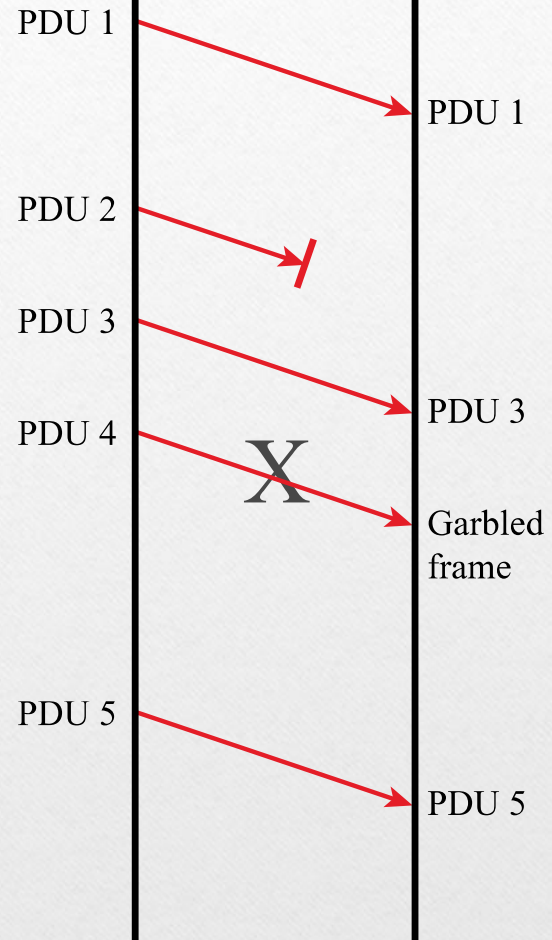
10.17 Model of PDU Transmission

(a) Error-free transmission

(b) Transmission with losses and errors

Error Control Requirements

- Error detection
  - Receiver detects errors and discards PDUs
- Positive acknowledgement
  - Destination returns acknowledgment of received, error-free PDUs
- Retransmission after timeout
  - Source retransmits unacknowledged PDU
- Negative acknowledgement and retransmission
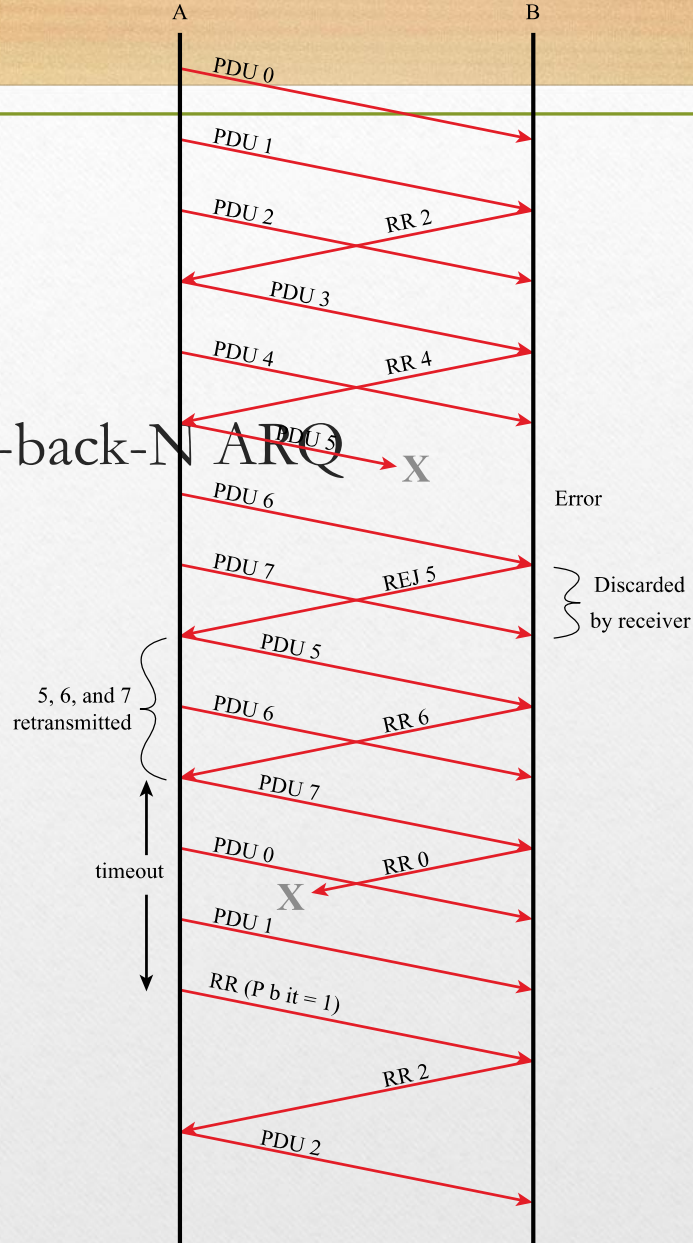 - Destination returns negative acknowledgment to PDUs in error

Go-back-N ARQ

- Acknowledgments

  - RR = receive ready (no errors occur)

  - REJ = reject (error detected)

- Contingencies

  - Damaged PDU

  - Damaged RR

  - Damaged REJ

10.20 Go-back-N ARQ

A   B

PDU 0

PDU 1

PDU 2   RR 2

PDU 3

PDU 4   RR 4

PDU 5   **X**

PDU 6   Error

PDU 7   REJ 5   Discarded
                             by receiver

PDU 5

5, 6, and 7   PDU 6   RR 6
retransmitted

PDU 7

PDU 0   RR 0

timeout   **X**

PDU 1

RR (P b it = 1)

RR 2

PDU 2

HYBRID ARQ

- Hybrid Automatic Repeat Request (HARQ)
  - Neither FEC or ARQ is adequate in practical situations
    - FEC may add unnecessary redundancy
    - ARQ may cause excessive delays from retransmissions
  - HARQ is widely used
  - Uses combination of FEC and ARQ

orthogonal frequency division multiplexing (ofdm)

- OFDM created great expansion in wireless networks
  - Greater efficiency in bps/Hz
- Main air interface in the change from 3G to 4G
  - Also expanded 802.11 rates
- Critical technology for broadband wireless access
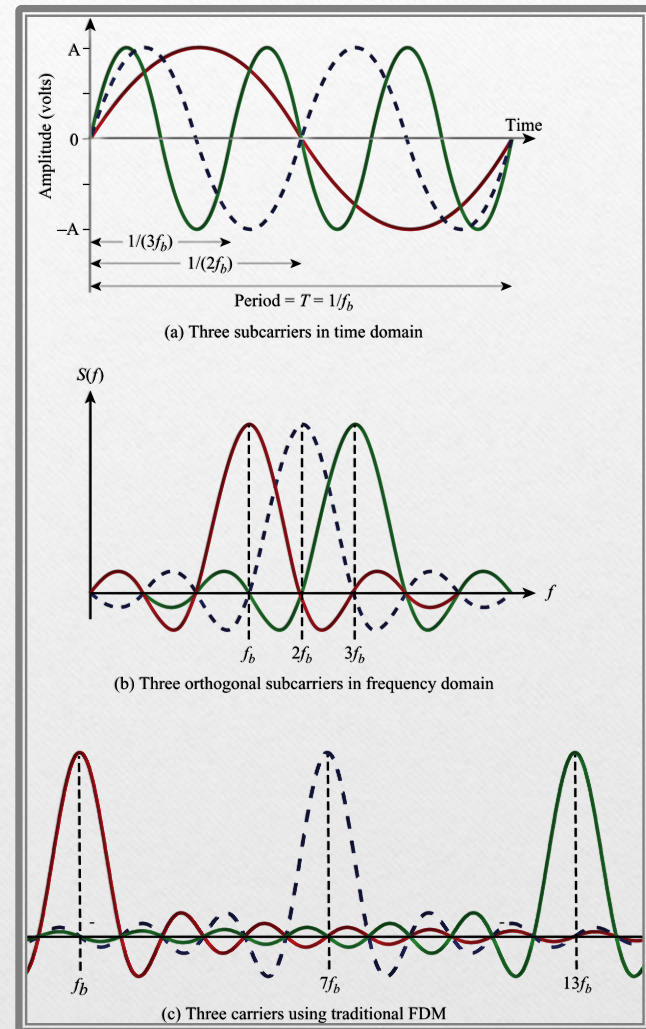 - WiMAX

How OFDM works

- Also called multicarrier modulation
- Start with a data stream of R bps
  - Could be sent with bandwidth Nf_b
  - With bit duration $1/R$
- OFDM splits into N parallel data streams
  - Called *subcarriers*
  - Each with bandwidth f_b
  - And data rate R/N (bit time N/R)

Orthogonality

- The spacing of the f_b frequencies allows tight packing of signals
  - Actually with overlap between the signals
  - Signals at spacing of f_b ,$2f_b$, $3f_b$,etc.
- The choice of f_b is related to the bit rate to make the signals *orthogonal*
- Traditional FDM makes signals completely avoid frequency overlap
  - OFDM allows overlap which greatly increases capacity

Figure 5.24 Illustration of Orthogonality of OFDM

(a) Three subcarriers in time domain

(b) Three orthogonal subcarriers in frequency domain

(c) Three carriers using traditional FDM

Benefits of OFDM

- Frequency selective fading only affects some subcarriers
- More importantly, OFDM overcomes intersymbol 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
    - OFDM's long bit times eliminate most of the ISI
    - OFDM also uses a *cyclic prefix* (CP) to overcome the residual ISI
        - Adds additional time to the OFDM symbol before the real data is sent
        - Called the *guard interval*
        - ISI diminishes before the data starts

OFDMA

- Orthogonal Frequency Division Multiple Access (OFDMA) uses OFDM to share the wireless channel
  - Different users can have different slices of time and different groups of subcarriers
  - Subcarriers are allocated in groups
    - Called subchannels or resource blocks
    - Too much computation to allocate every subcarrier separately
- Single-carrier FDMA (SC-FDMA)
  - Similar structure and performance to OFDMA
  - Lower peak to average power ratio than OFMDA
  - Mobile user benefits – battery life, power efficiency, lower cost
    - Good for uplinks
  - Multiple access is not possible
    - At one time, all subcarriers must be dedicated to one user

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
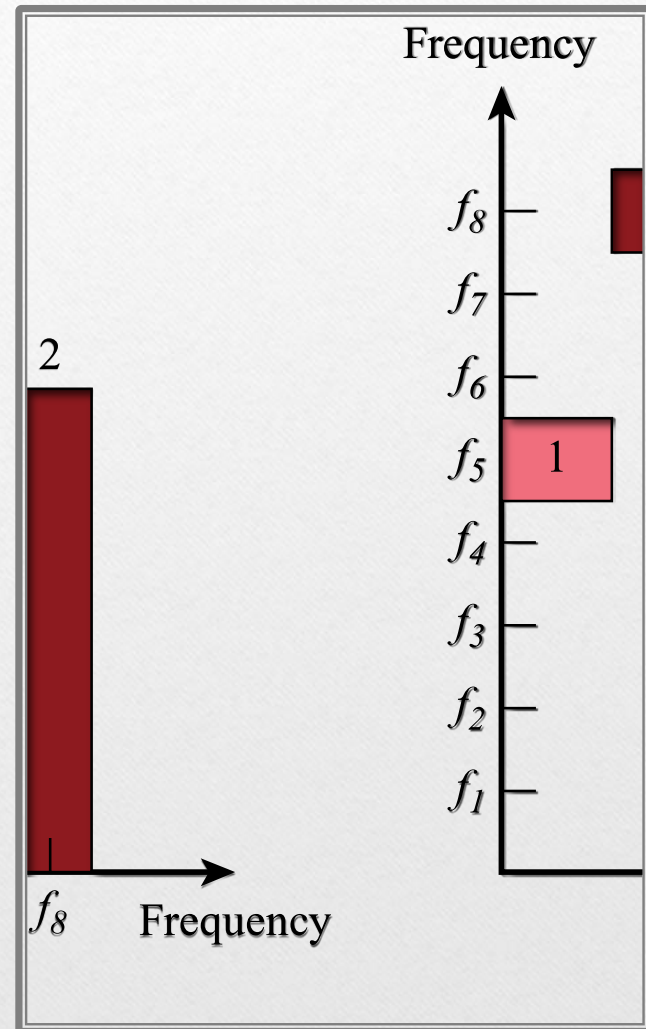
Spread Spectrum

- On receiving end, digital sequence is used to demodulate the spread spectrum signal

- Signal is fed into a channel decoder to recover data

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

5.28 Frequency Hopping Example

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 5.30)

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
- Each user encodes with a different spreading code