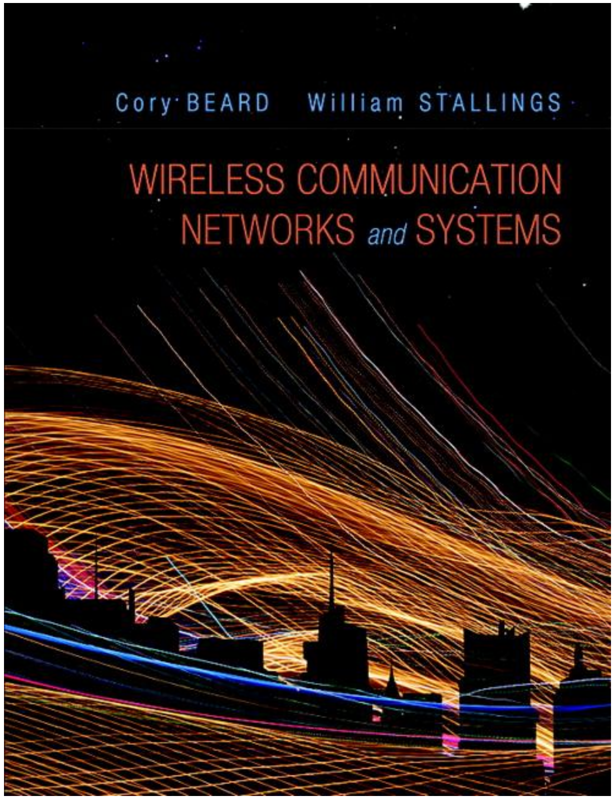
CHAPTER 1 INTRODUCTION



Wireless Communication Networks and Systems

1st edition

Cory Beard, William Stallings

Wireless Comes of Age

- Guglielmo Marconi invented the wireless telegraph in 1896
  - Communication by encoding alphanumeric characters in analog signal
  - Sent telegraphic signals across the Atlantic Ocean
- Communications satellites launched in 1960s
- Advances in wireless technology
  - Radio, television, mobile telephone, mobile data, communication satellites
- More recently
  - Wireless networking, cellular technology, mobile apps, Internet of Things

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

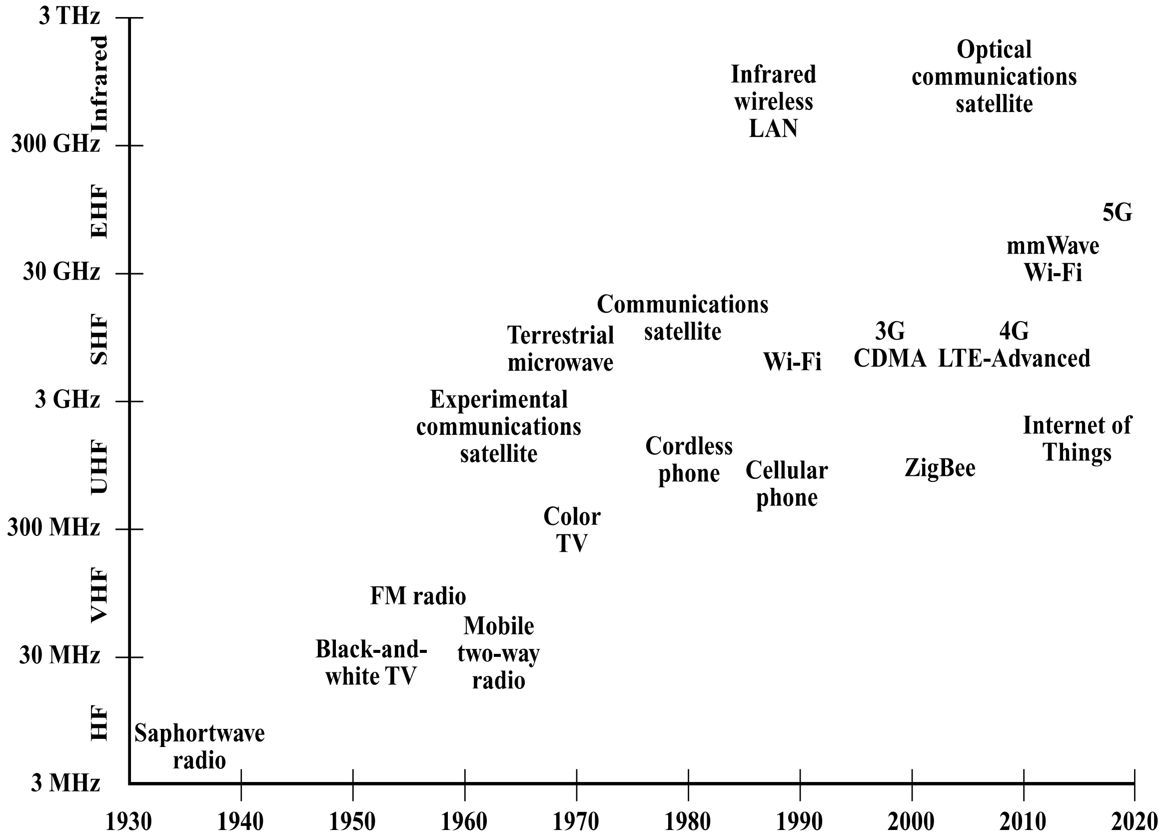


Figure 1.1 Some Milestones in Wireless Communications

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

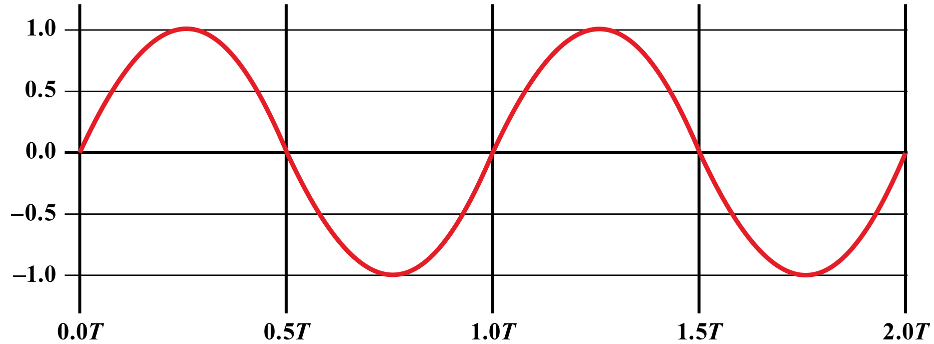
- Analog signal - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
- Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level
- Periodic signal - analog or digital signal pattern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

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

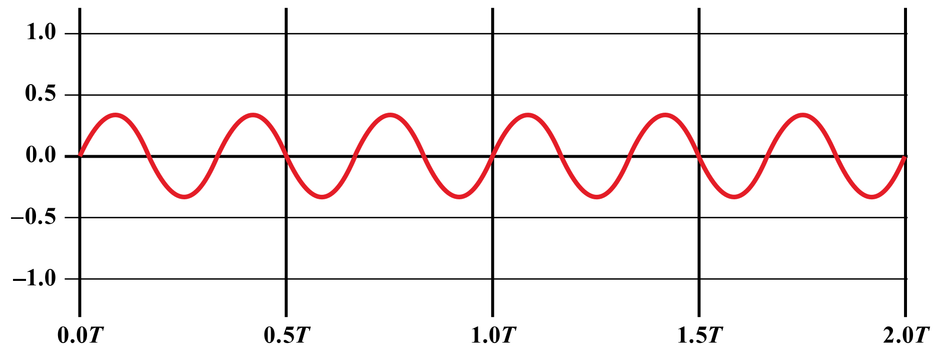
  - where T is the period of the signal

Frequency-Domain Concepts

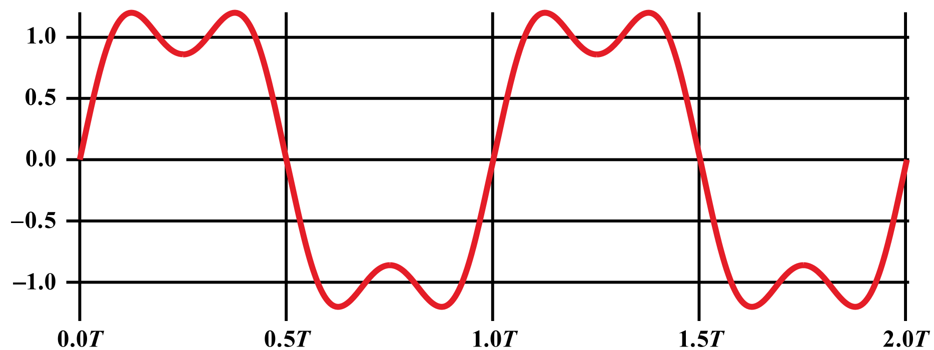
- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth)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



(a) $\sin(2\phi f t)$



(b) $(1/3)\sin(2\phi(3f)t)$

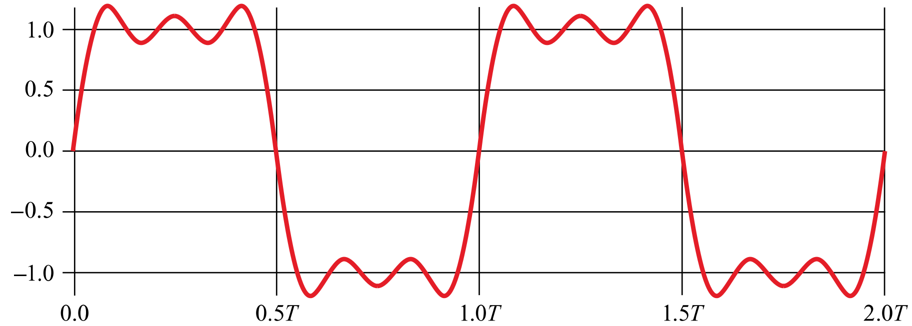


(c) $(4/\phi)\,[\sin(2\phi f t) + (1/3)\sin(2\phi(3f)t)]$

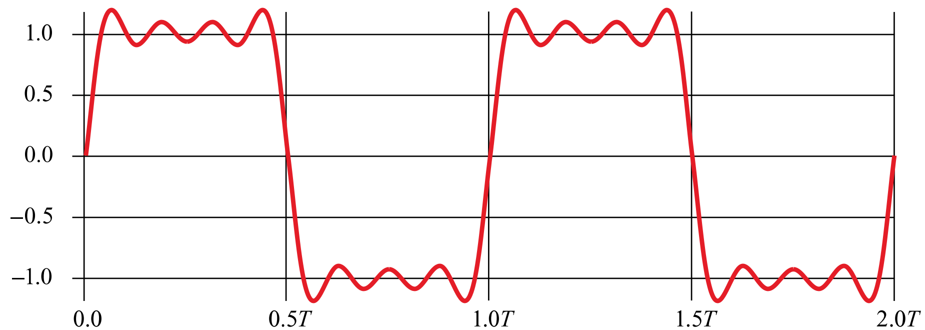
2.4 Addition of frequency Components($T = 1/f$)

Frequency-Domain Concepts

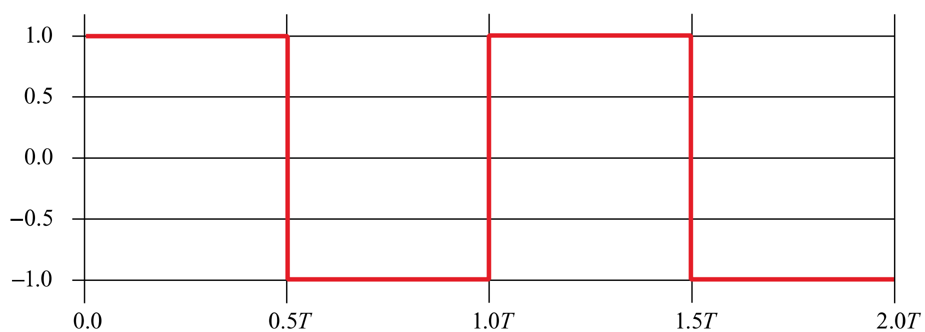
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases
- The period of the total signal is equal to the period of the fundamental frequency



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



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



(c) (4/ϕ) Σ(1/*k*) sin (2ϕ(*kf*)*t*), for *k* odd

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

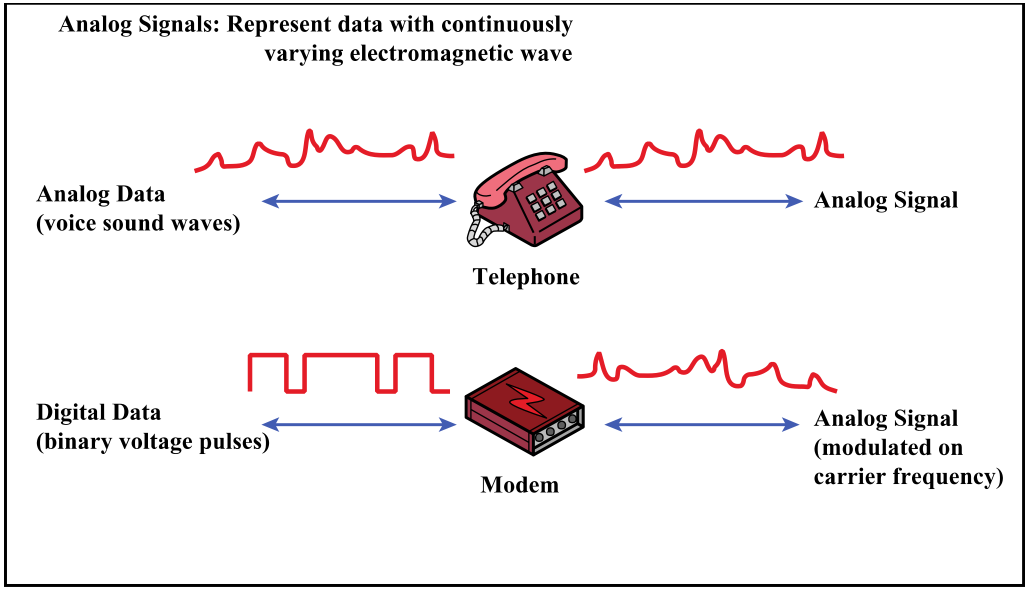
- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable
  - Atmosphere or space propagation
- Analog signals can propagate analog and digital data

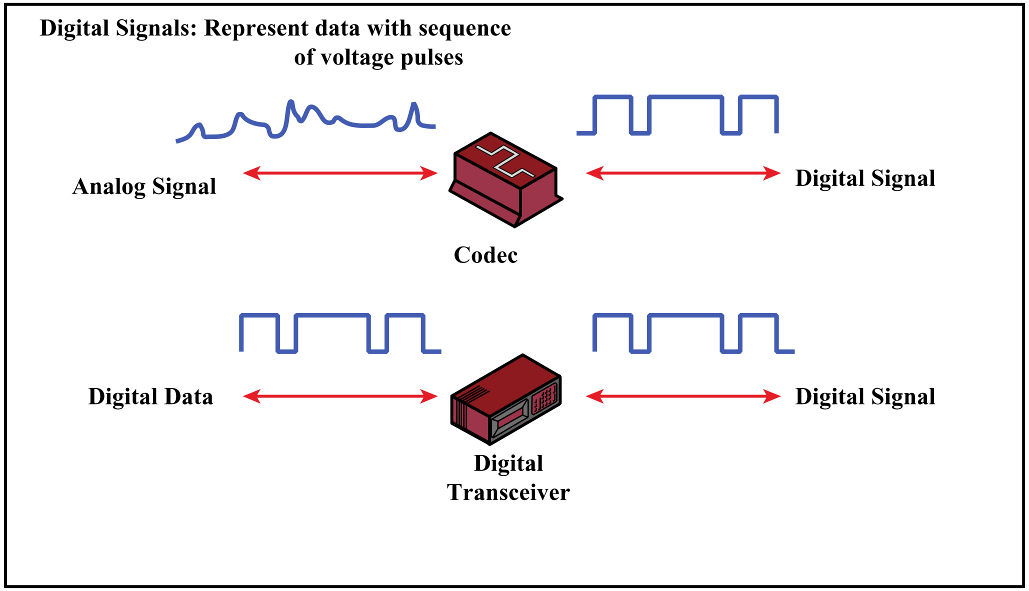
Digital Signals

- 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





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

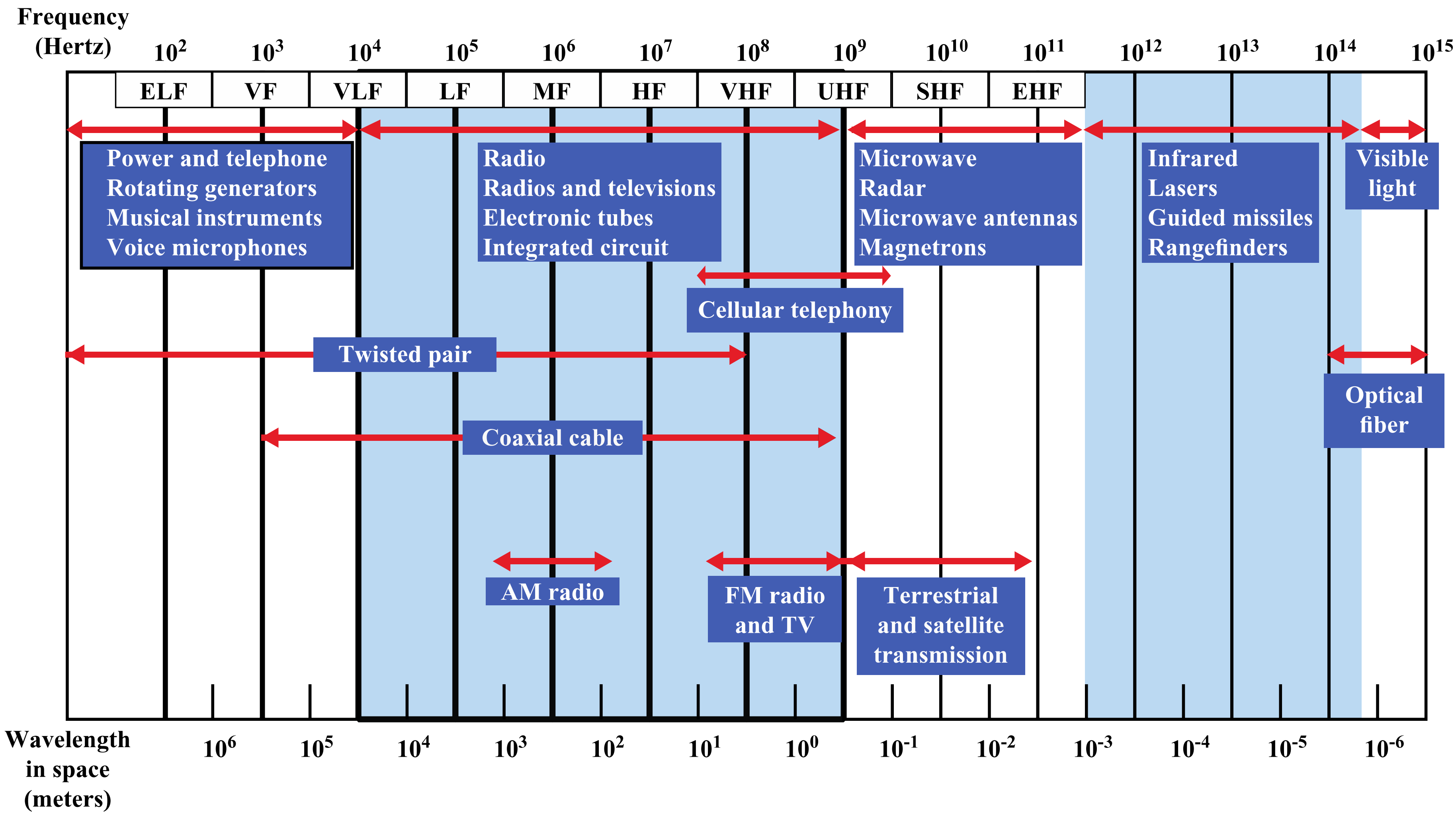
- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - 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



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, $3x10^{11}$ to $2x10^{14}$ 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

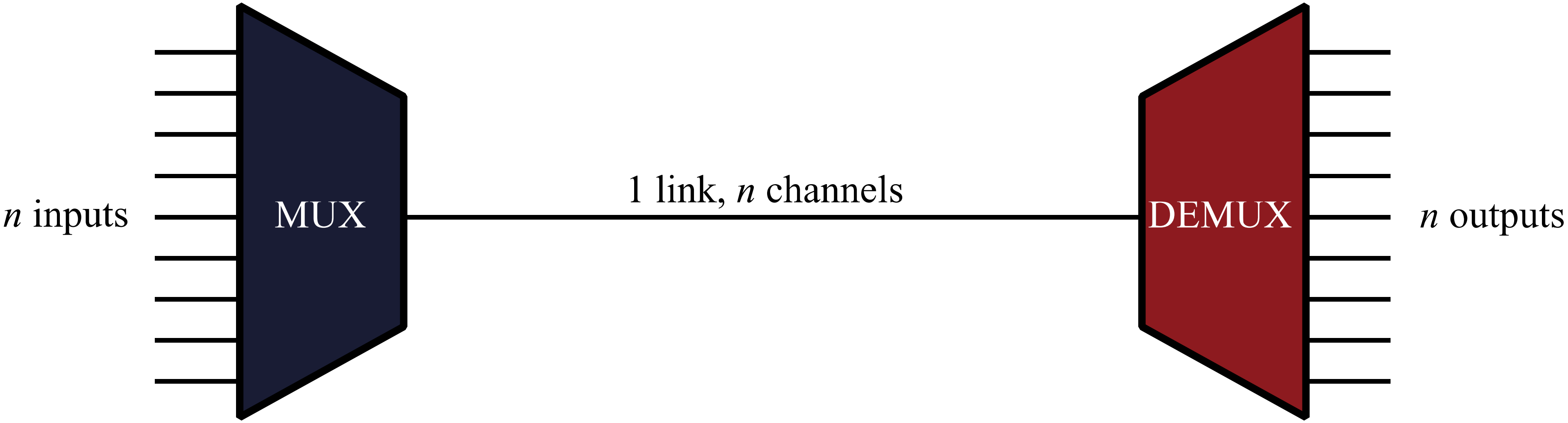
- Description of communication satellite
  - Microwave relay station
  - Used to link two or more ground-based microwave transmitter/receivers
  - Receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink)
- Applications
 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



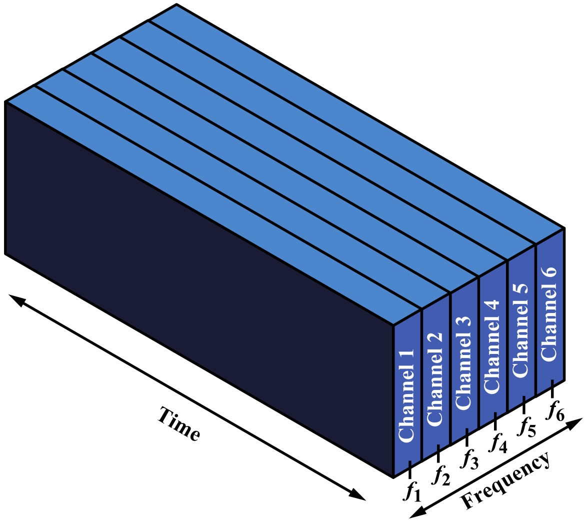
2.11 Multiplexing

Reasons for Widespread Use of Multiplexing

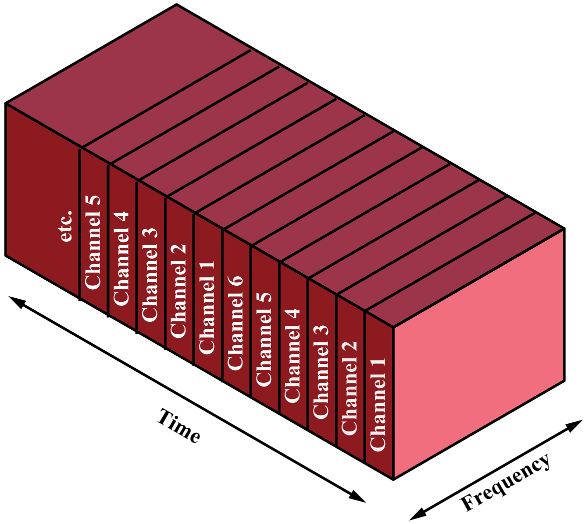
- Cost per kbps of transmission facility declines with an increase in the data rate
- Cost of transmission and receiving equipment declines with increased data rate
- Most individual data communicating devices require relatively modest data rate support

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



(a) Frequency division multiplexing



(b) Time 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

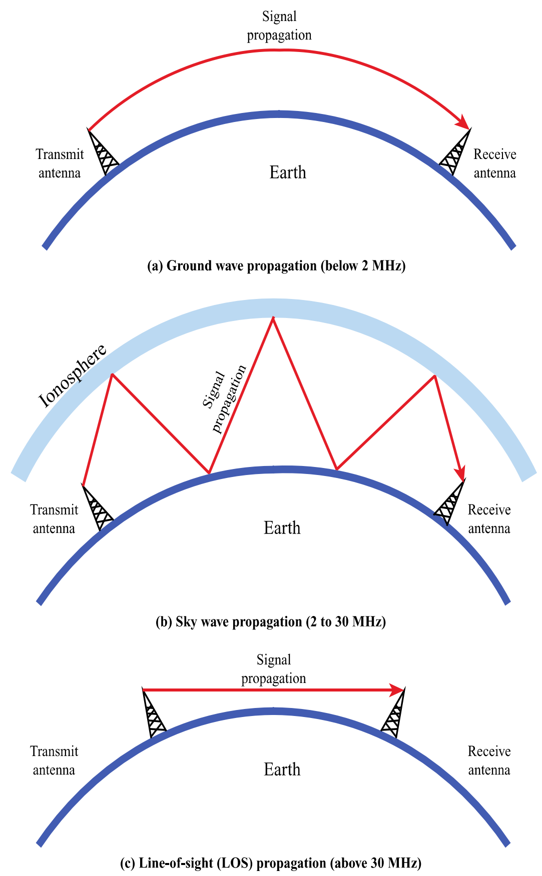
- Federal Communications Commission (FCC) in the United States regulates spectrum
  - Military
  - Broadcasting
  - Public Safety
  - Mobile
  - Amateur
  - Government exclusive, non-government exclusive, or both
  - Many other categories

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

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

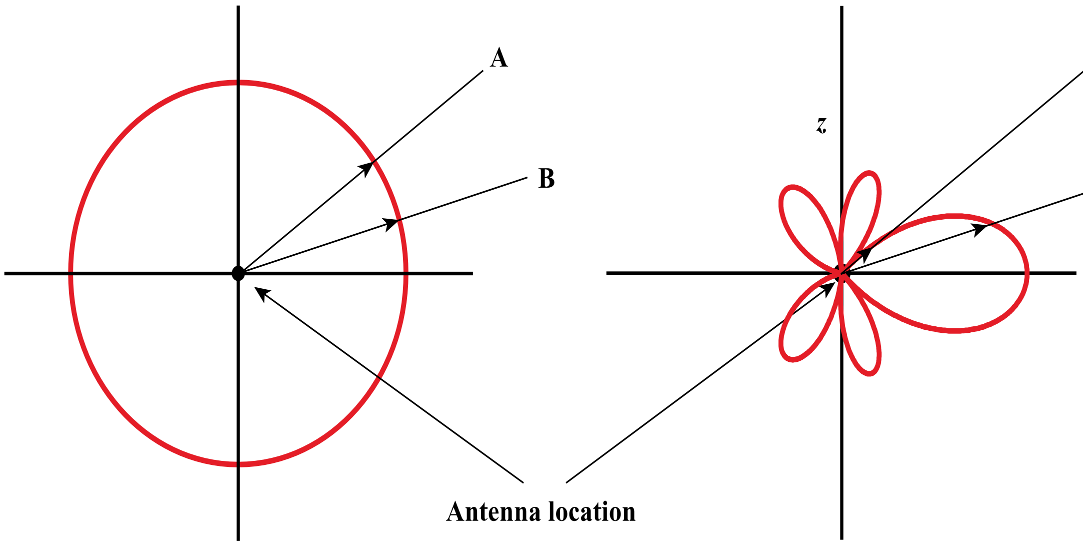
1. Free-space propagation
2. Transmission
   – Through a medium
   – Refraction occurs at boundaries
3. Reflections
   – Waves impinge upon surfaces that are large compared to the signal wavelength
4. Diffraction
   – Secondary waves behind objects with sharp edges
5. Scattering
   – Interactions between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



(a) Omnidirectional (b) Directional

5.2 Antenna Radiation Patterns

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

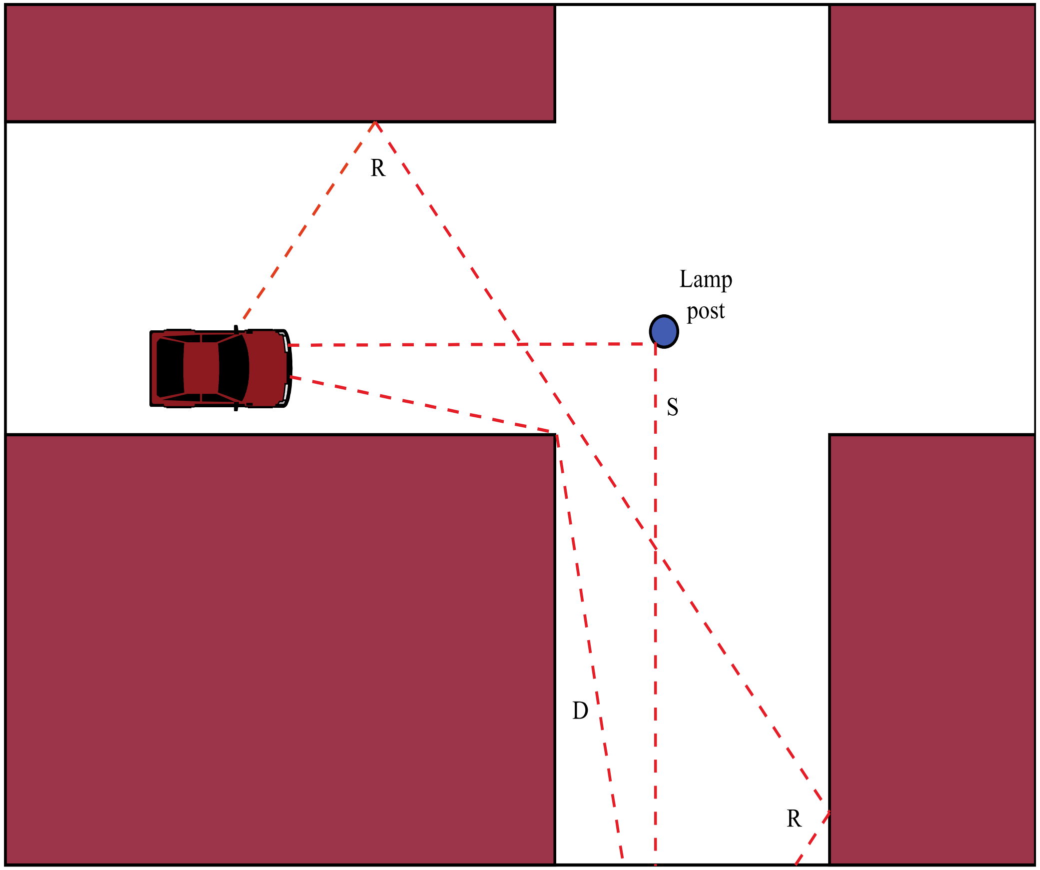
- Intermodulation noise – occurs if signals with different frequencies share the same medium
  - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies
- Crosstalk – unwanted coupling between signal paths
- Impulse noise – irregular pulses or noise 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

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 $T_c >> T_b$ 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 $T_b = 1/100 \times 10^3 = 10\ \mu s$
  - $T_c >> T_b$? 70 ms >> 10 μs?
  - True, so *slow fading*

Types of fading

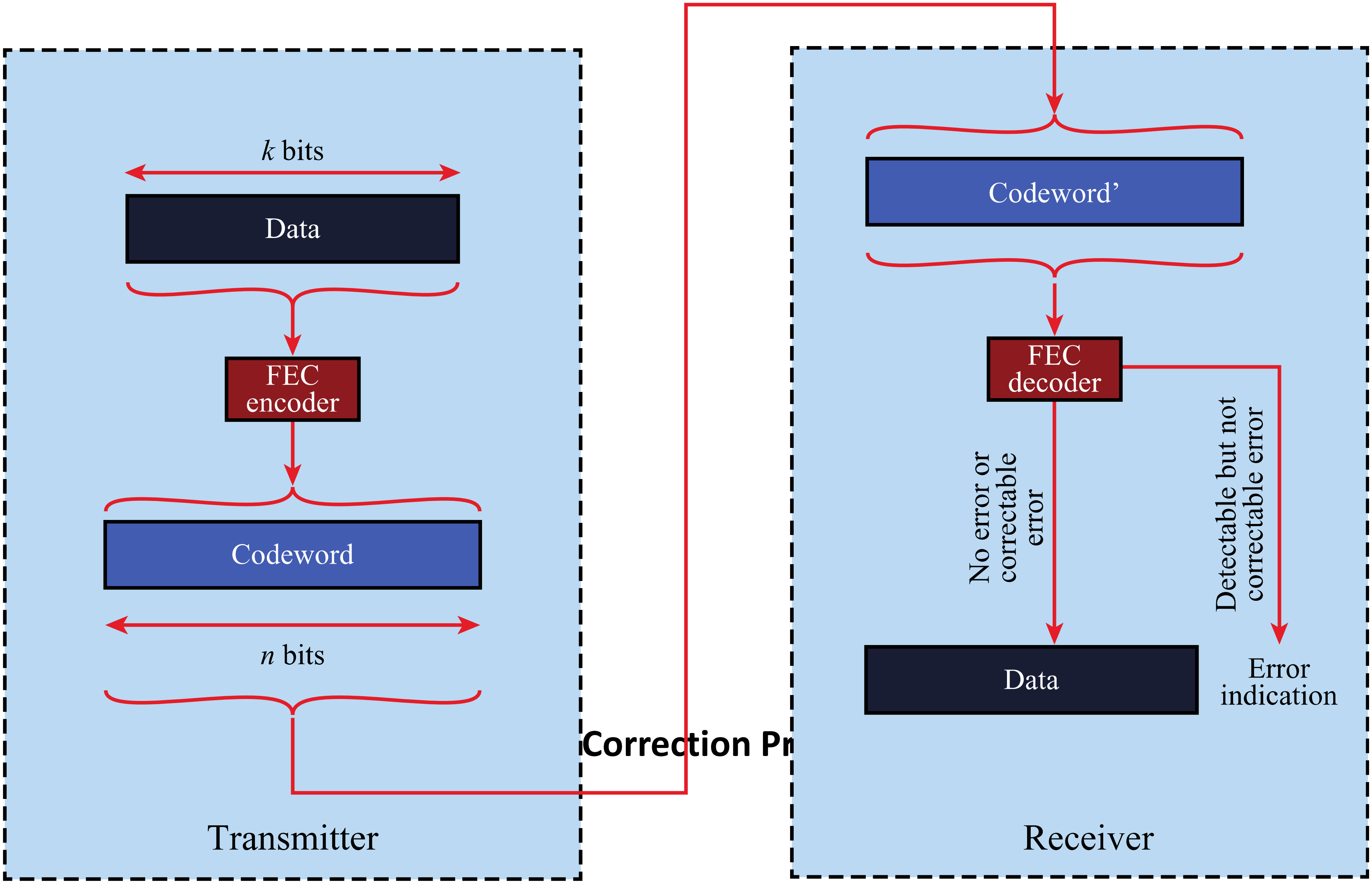
- Multipath fading
  - Multiple signals arrive at the receiver
  - Coherence bandwidth B_c characterizes multipath
    - Bandwidth over which the channel response remains relatively constant
    - Related to delay spread, the spread in time of the arrivals of multipath signals
  - Signal bandwidth B_s is proportional to the bit rate
  - If $B_c >> B_s$, 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*
  - $B_c >> B_s$? 150 kHz >> 100 kHz?
  - Using a factor of 10 for “>>”, 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



Correction Pr

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

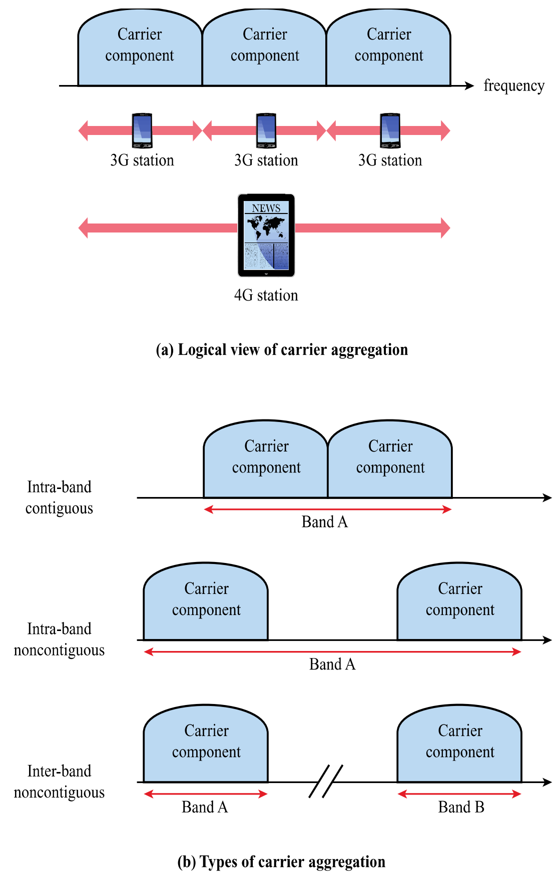
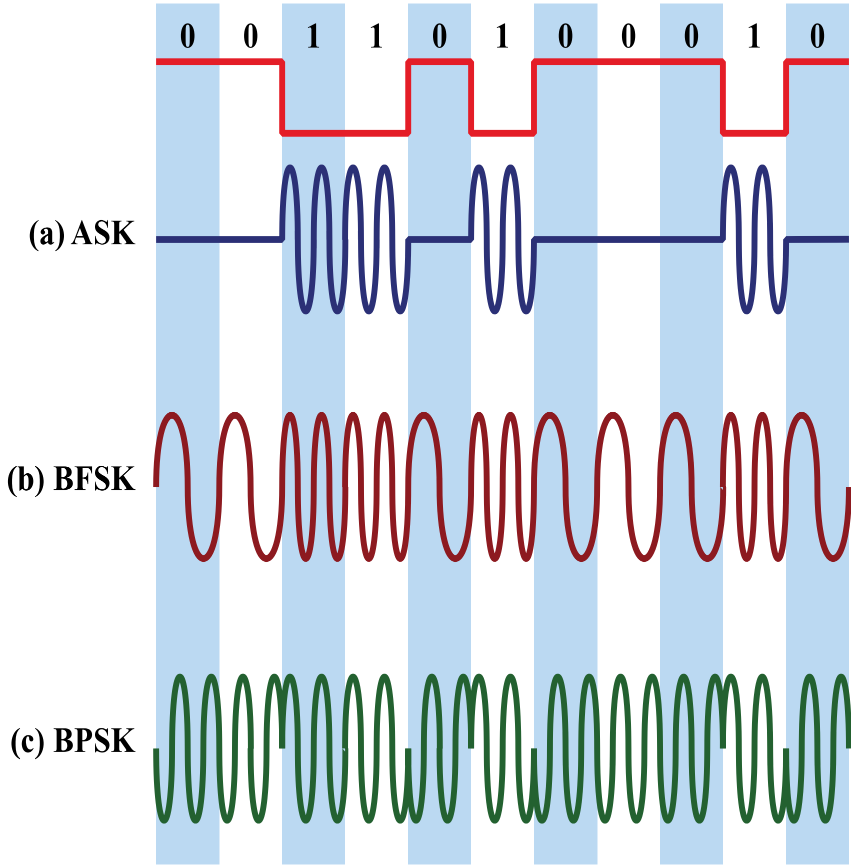


Figure 14.14 LTE Carrier Aggregation

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

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

- 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

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

  - 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

$$s_i(t) = A\cos 2pf_i t \qquad 1 \pounds i \pounds M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- 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

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

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

Quadrature Phase-Shift Keying (PSK)

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

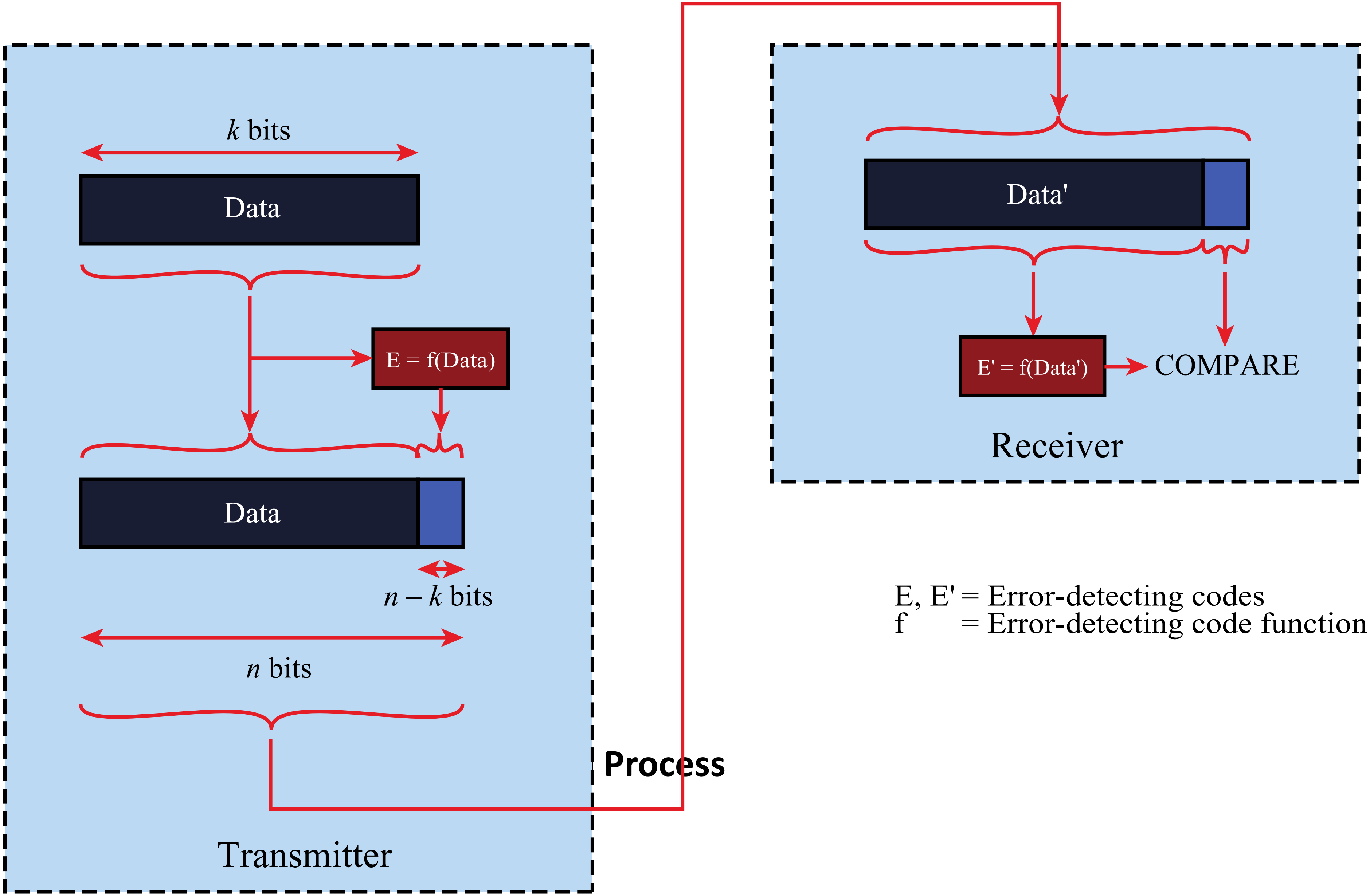
$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

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


k bits
Data
E = f(Data)
Data
n − k bits
n bits
Transmitter
Process
Data'
E' = f(Data')
COMPARE
Receiver
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

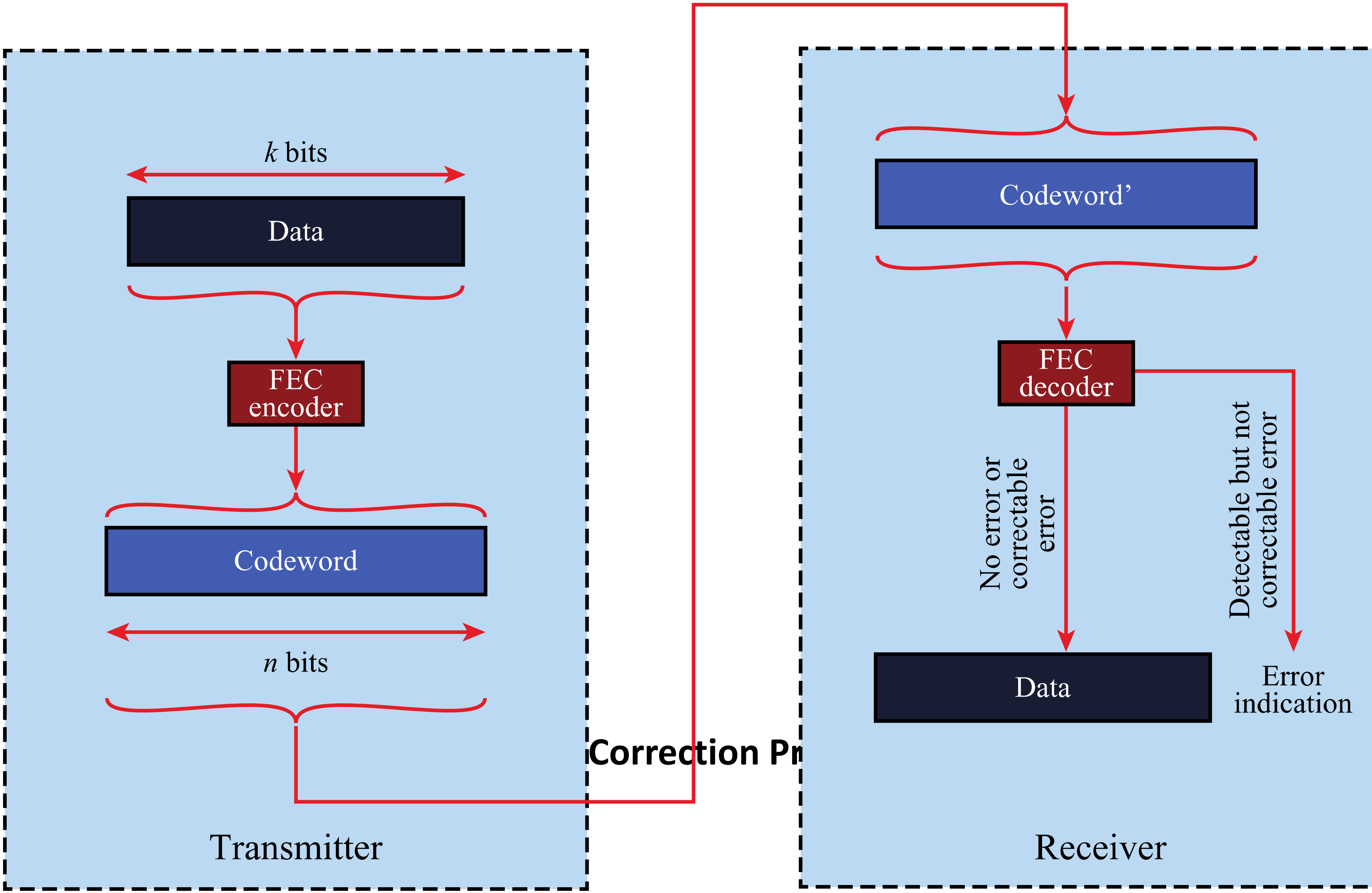
Wireless Transmission Errors

- 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

Correction Pr



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

- Coding table

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

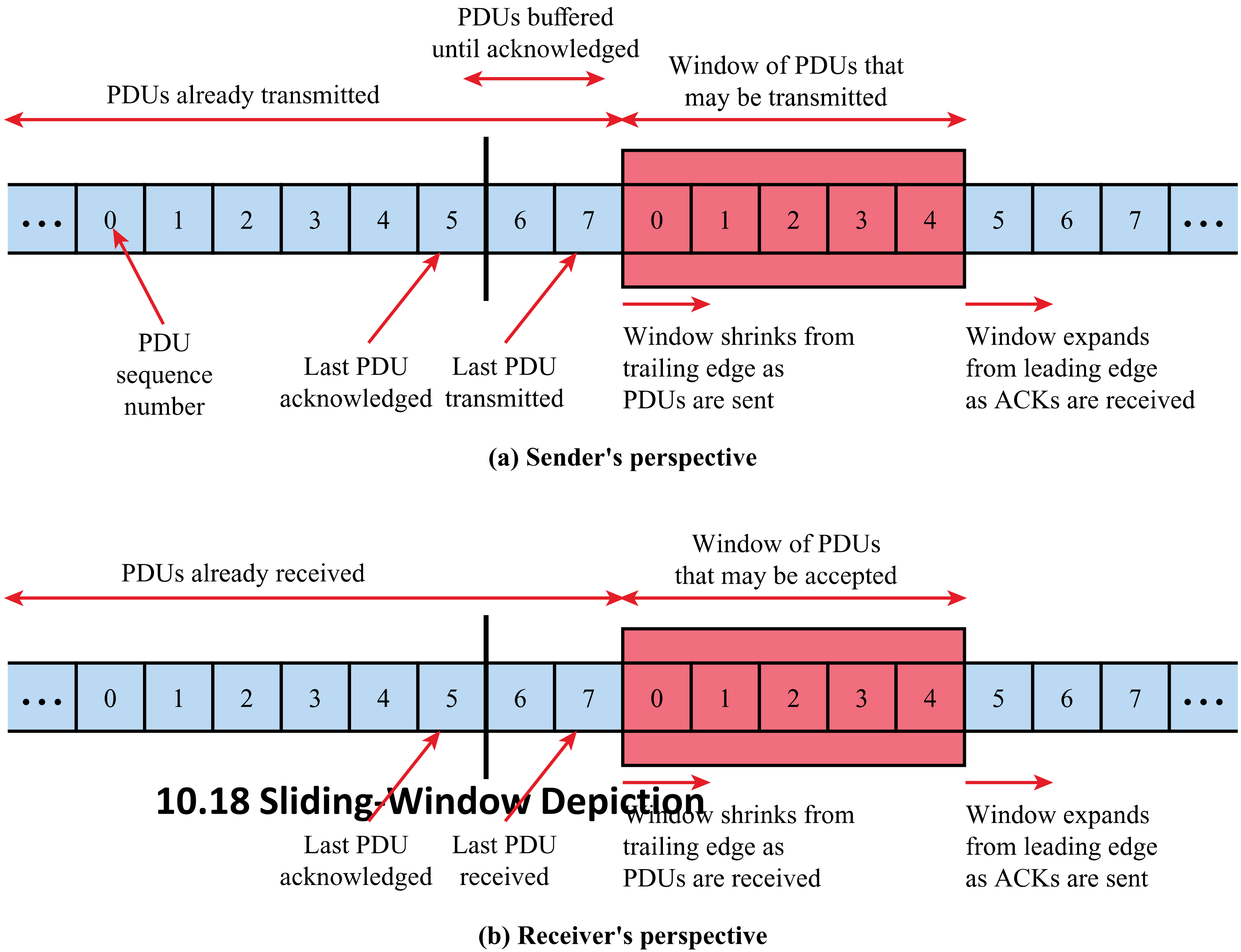
Automatic Repeat Request

- Mechanism used in data link control and transport protocols
- Relies on use of an error detection code (such as CRC)
- Flow Control
- Error Control

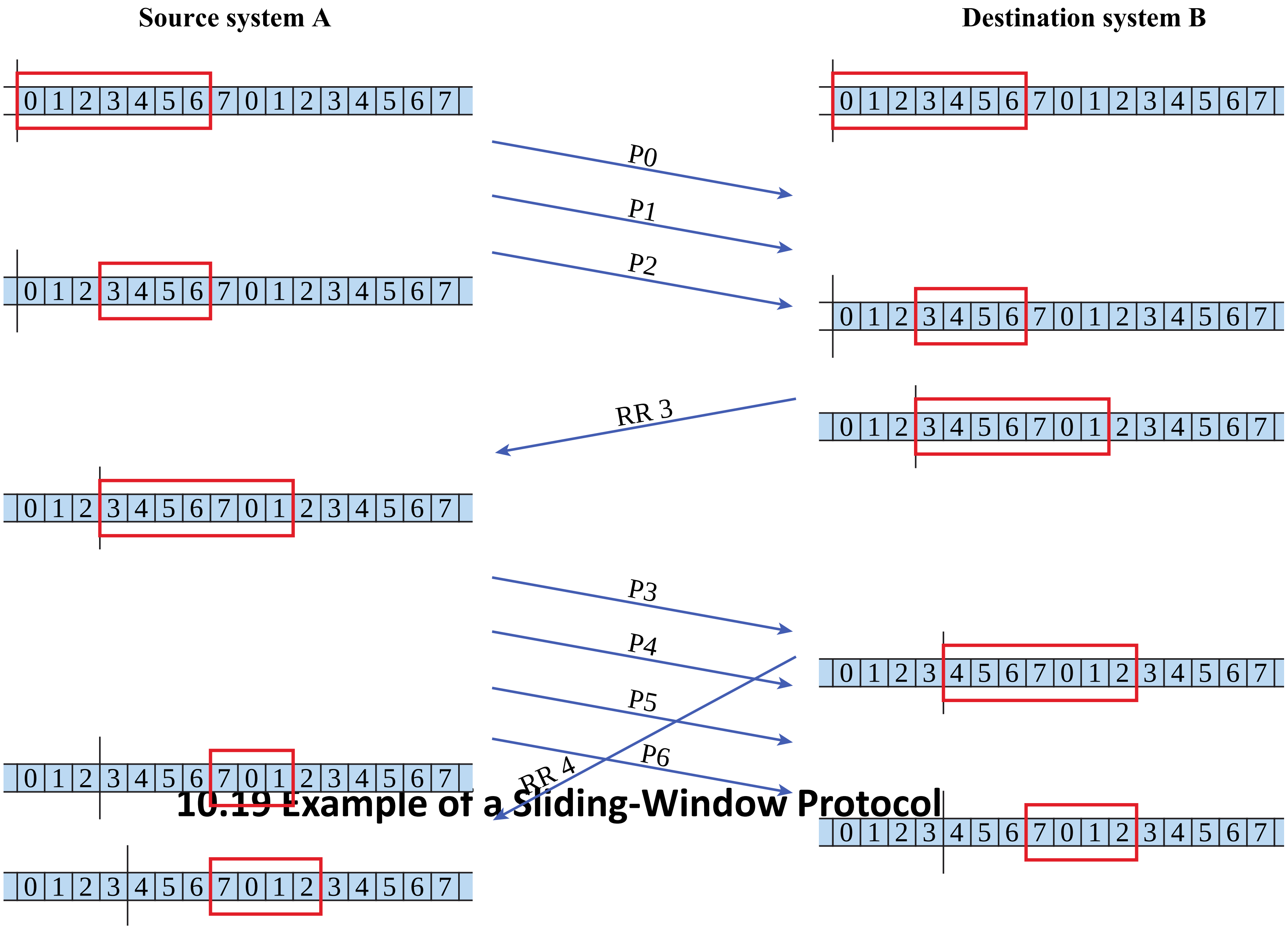
Flow Control

- 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



10.19 Example of a Sliding-Window Protocol



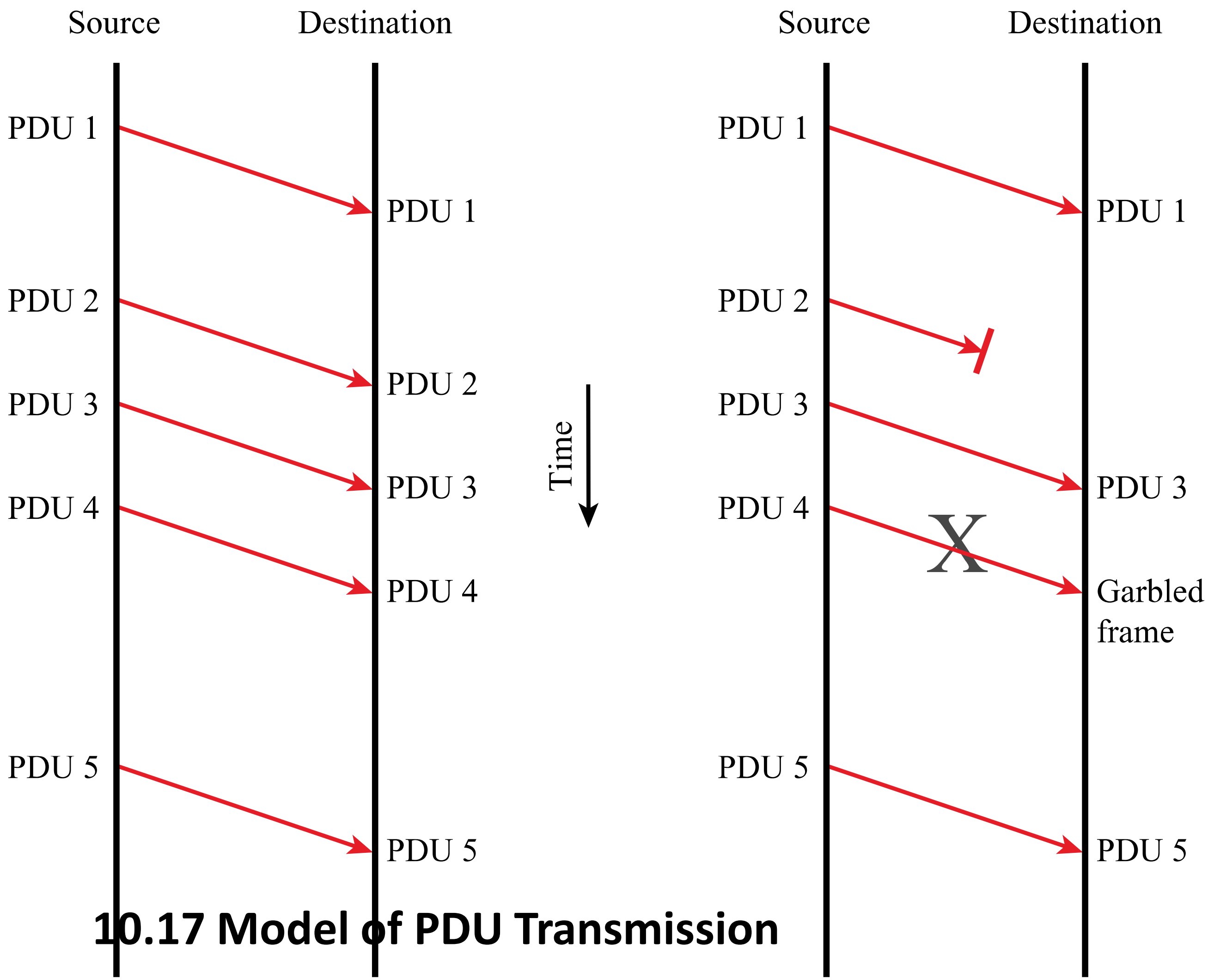
Flow Control

- 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

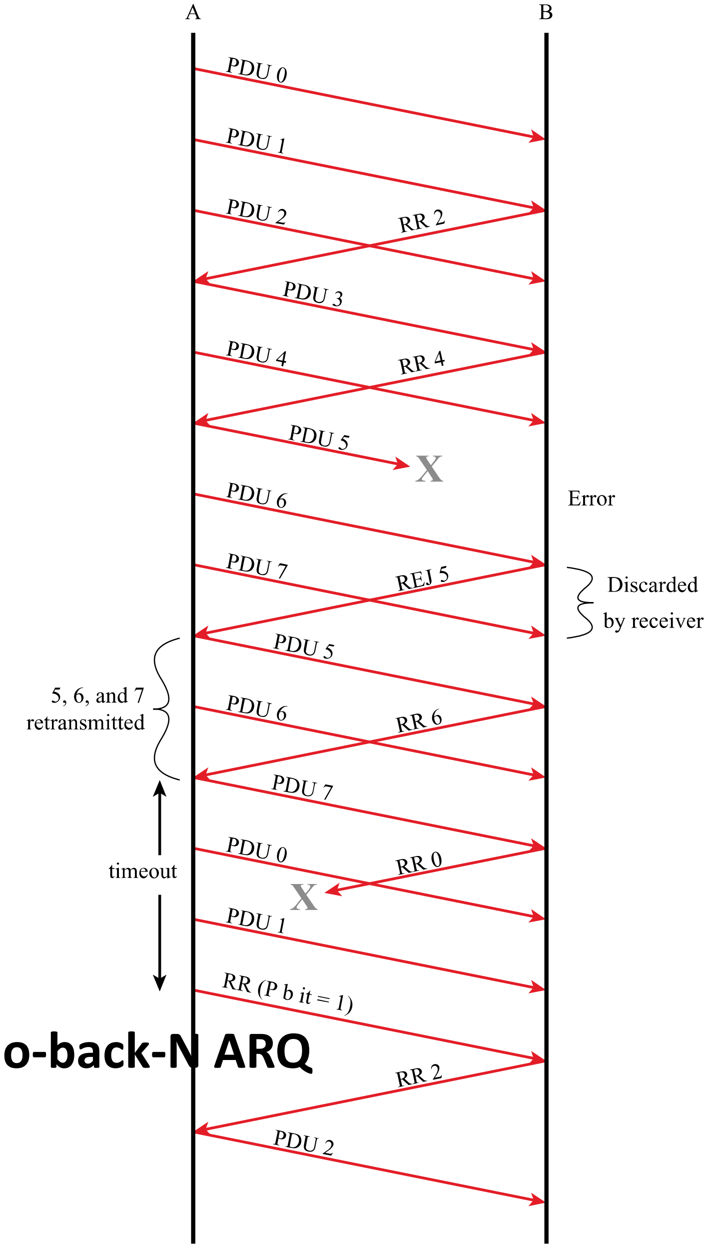
(b) Transmission with losses and errors

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

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

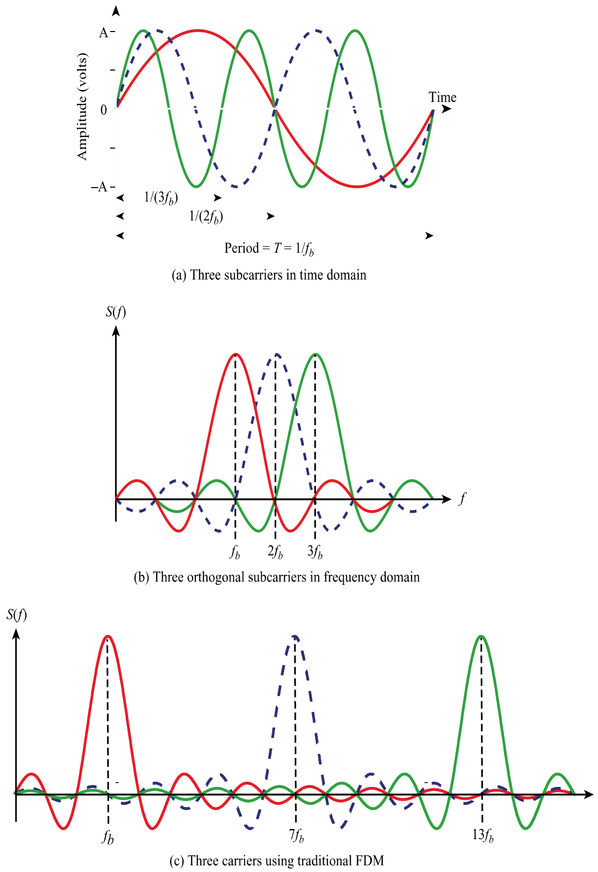


Figure 5.24 Illustration of Orthogonality of OFDM

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

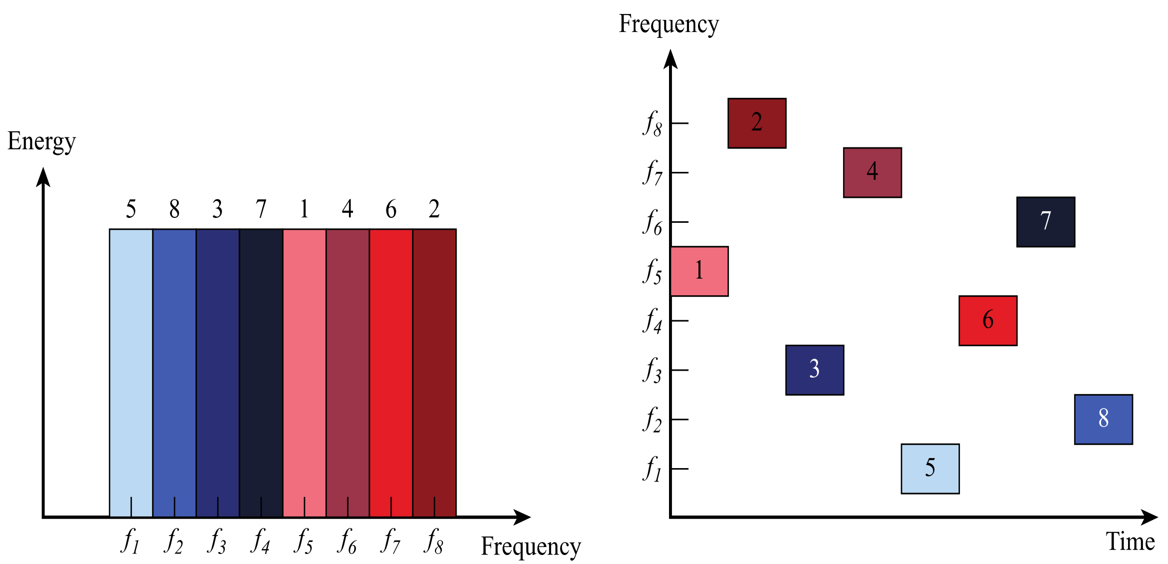
- Input is fed into a channel encoder
  - Produces analog signal with narrow bandwidth
- Signal is further modulated using sequence of digits
  - Spreading code or spreading sequence
  - Generated by pseudonoise, or pseudo-random number generator
- Effect of modulation is to increase bandwidth of signal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



(a) Channel assignment **(b) Channel use**

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