EEEN3008J: Advance wireless communications

Wireless communications

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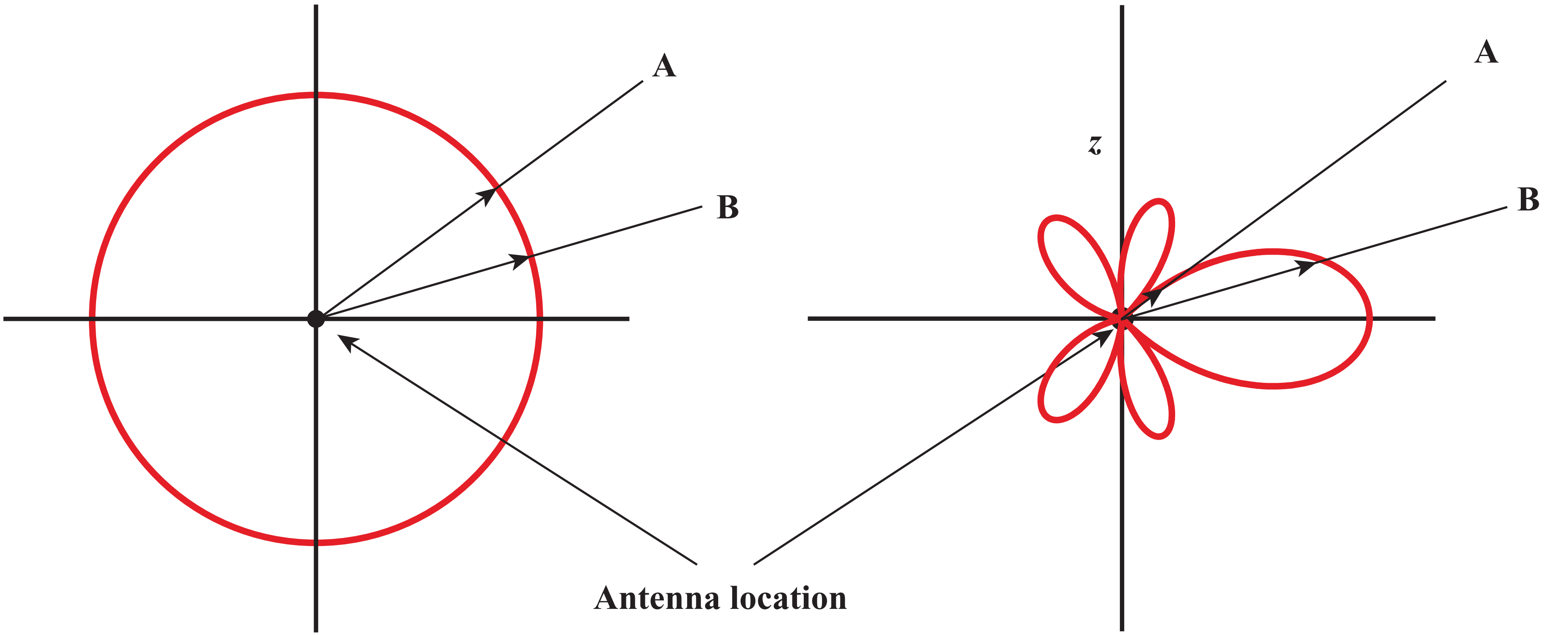
Antennas

- 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

Antenna Radiation Patterns



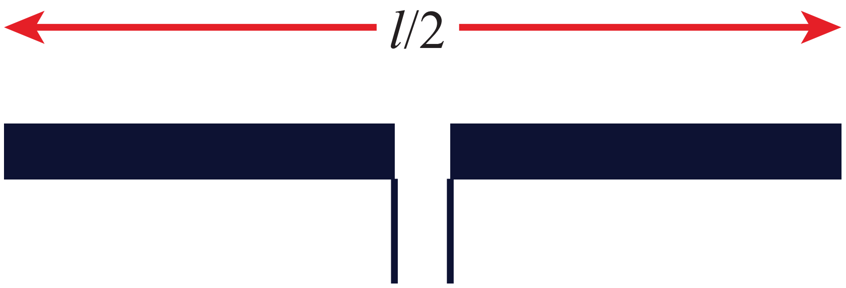
(a) Omnidirectional

(b) Directional

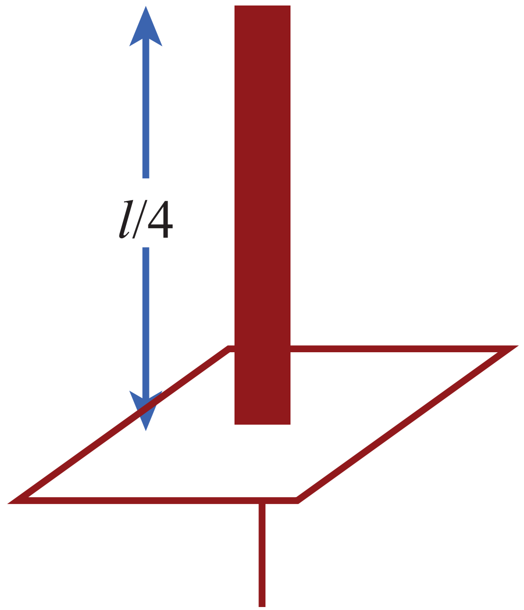
Types of Antennas

- Isotropic antenna (idealized)
  - Radiates power equally in all directions
- Dipole antennas
  - Half-wave dipole antenna (or Hertz antenna)
  - Quarter-wave vertical antenna (or Marconi antenna)
- Parabolic Reflective Antenna
- Directional Antennas
  - Arrays of antennas
    - In a linear array or other configuration
  - Signal amplitudes and phases to each antenna are adjusted to create a directional pattern
  - Very useful in modern systems

Simple Antennas

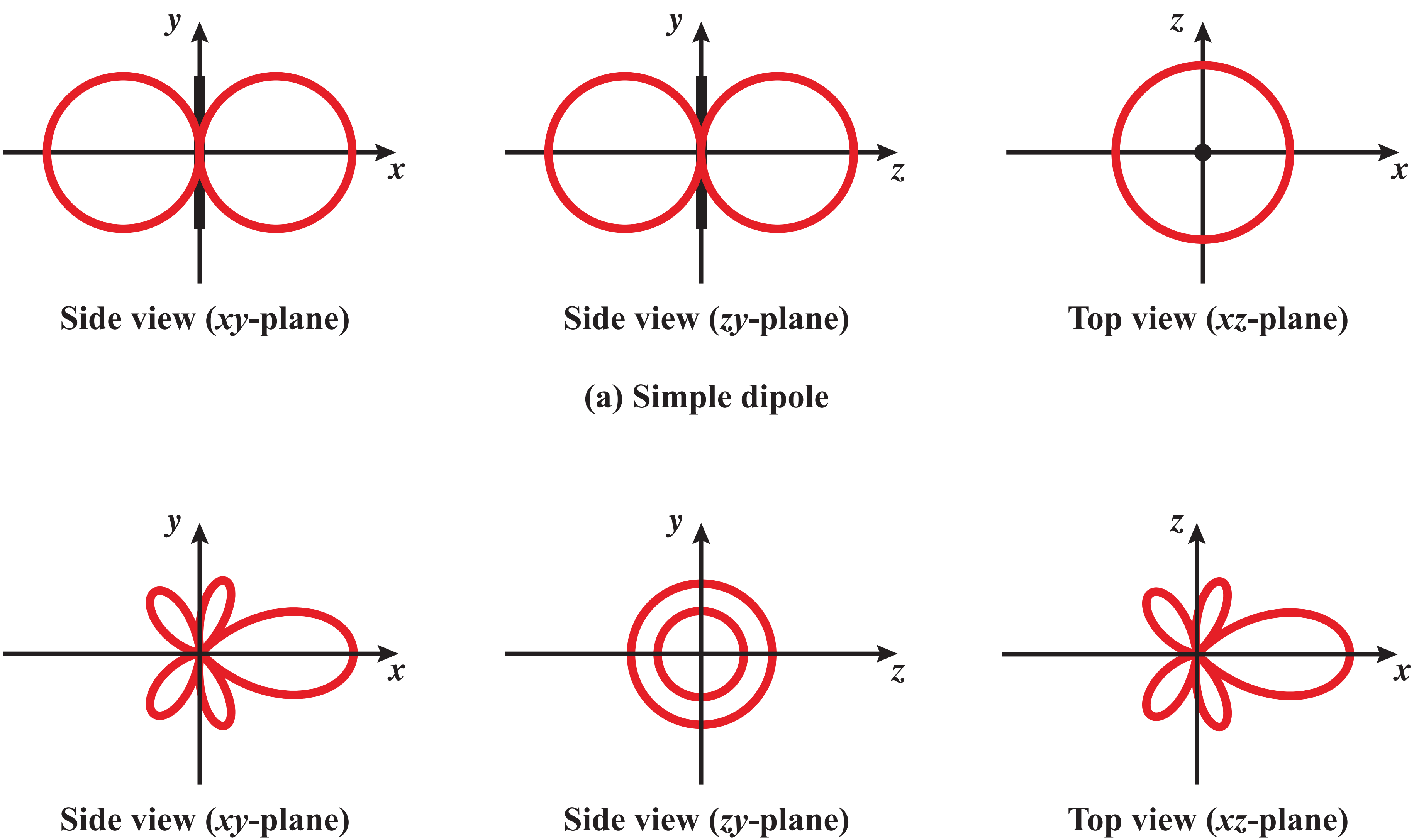


(a) Half-wave dipole



(b) Quarter-wave antenna

Radiation Patterns in Three Dimensions



(b) Directed antenna

Antenna Gain

- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- Effective area
  - Related to physical size and shape of antenna

Antenna Gain

- Relationship between antenna gain and effective area

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

- G = antenna gain
- A_e = effective area
- f = carrier frequency
- c = speed of light ($\approx 3 \times 10^8$ m/s)
- λ = carrier wavelength

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

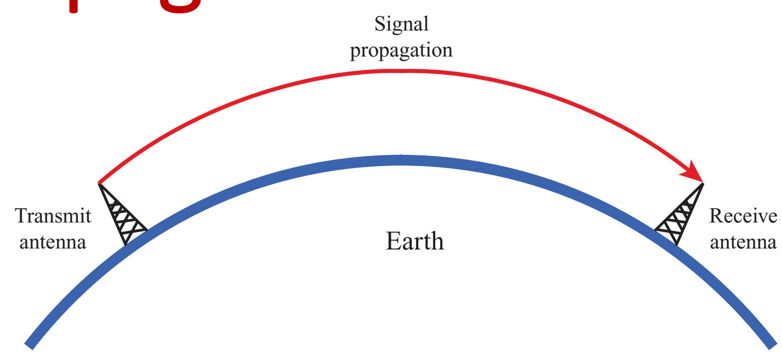
Spectrum considerations

- 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

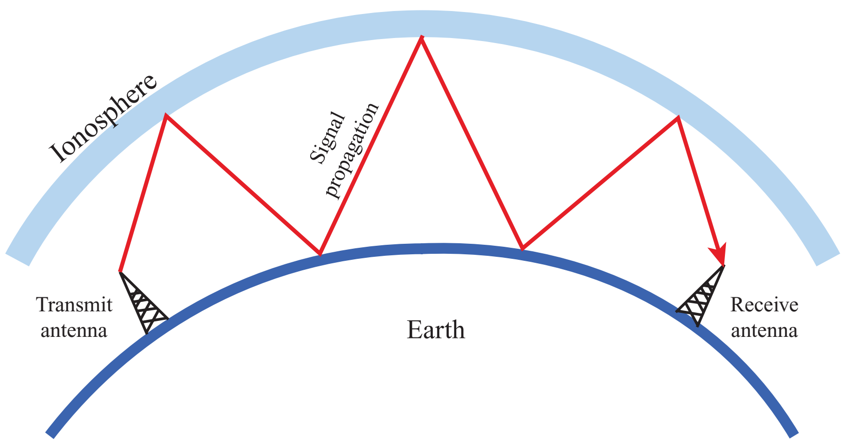
Propagation Modes

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation

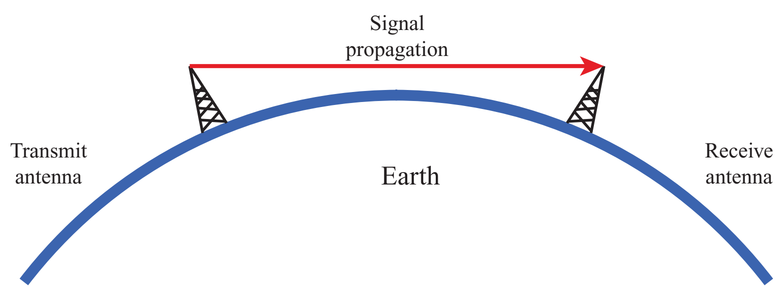
Wireless Propagation Modes



(a) Ground wave propagation (below 2 MHz)



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



(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

Line-of-Sight Equations

- Optical line of sight

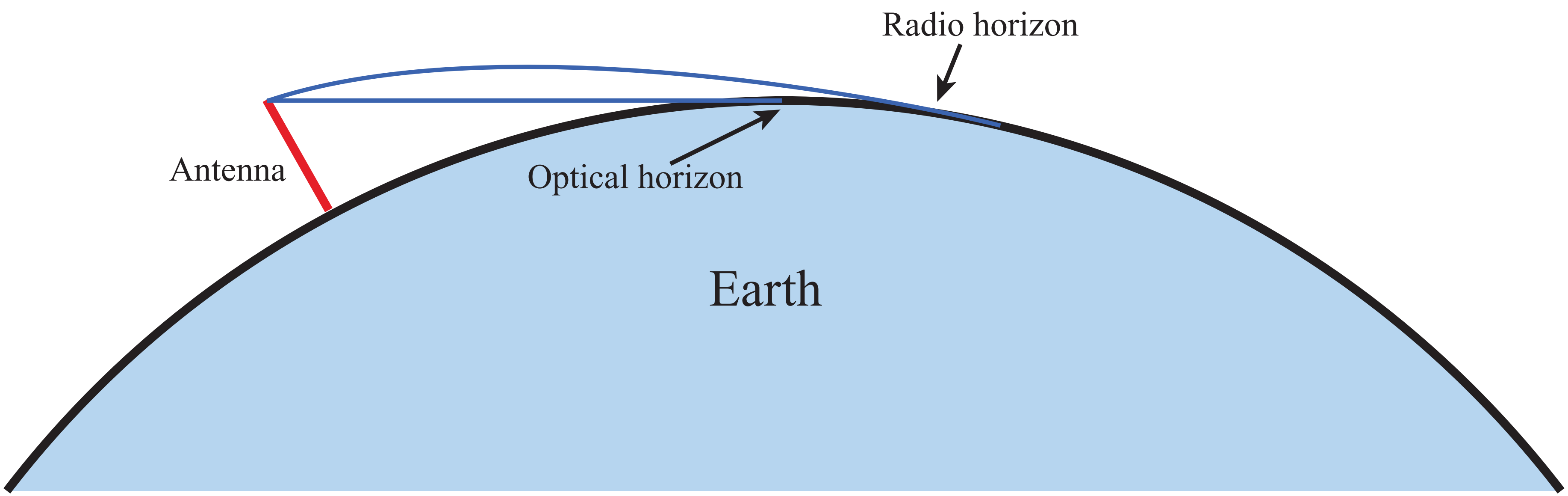
$$d = 3.57\sqrt{h}$$

- Effective, or radio, line of sight

$$d = 3.57\sqrt{\mathrm{K}h}$$

  - *d* = distance between antenna and horizon (km)
  - *h* = antenna height (m)
  - K = adjustment factor to account for refraction, rule of thumb K = 4/3

Optical and Radio Horizons



Line-of-Sight Equations

- Maximum distance between two antennas for LOS propagation:

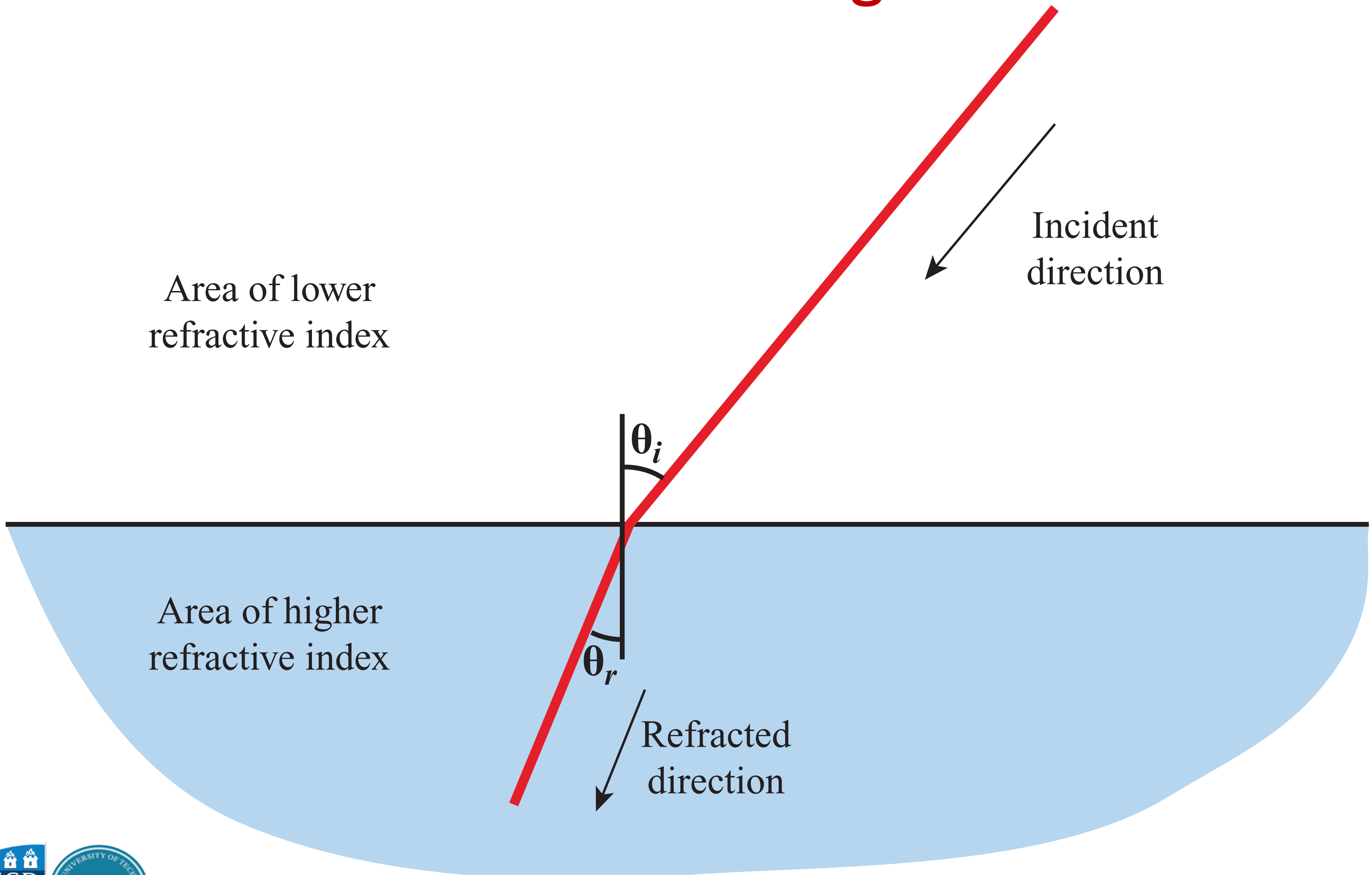
$$3.57\left(\sqrt{\mathrm{K}h_1}+\sqrt{\mathrm{K}h_2}\right)$$

  - h_1 = height of first antenna
  - h_2 = height of second antenna

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

Refraction of an Electromagnetic Wave



LOS Wireless Transmission Impairments

- Attenuation and attenuation distortion
- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction
- Thermal noise

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

Free Space Loss

- Free space loss, ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

- P_t = signal power at transmitting antenna
- P_r = signal power at receiving antenna
- λ = carrier wavelength
- d = propagation distance between antennas
- c = speed of light (3×10^8 m/s)

where d and λ are in the same units (e.g., meters)

Free Space Loss

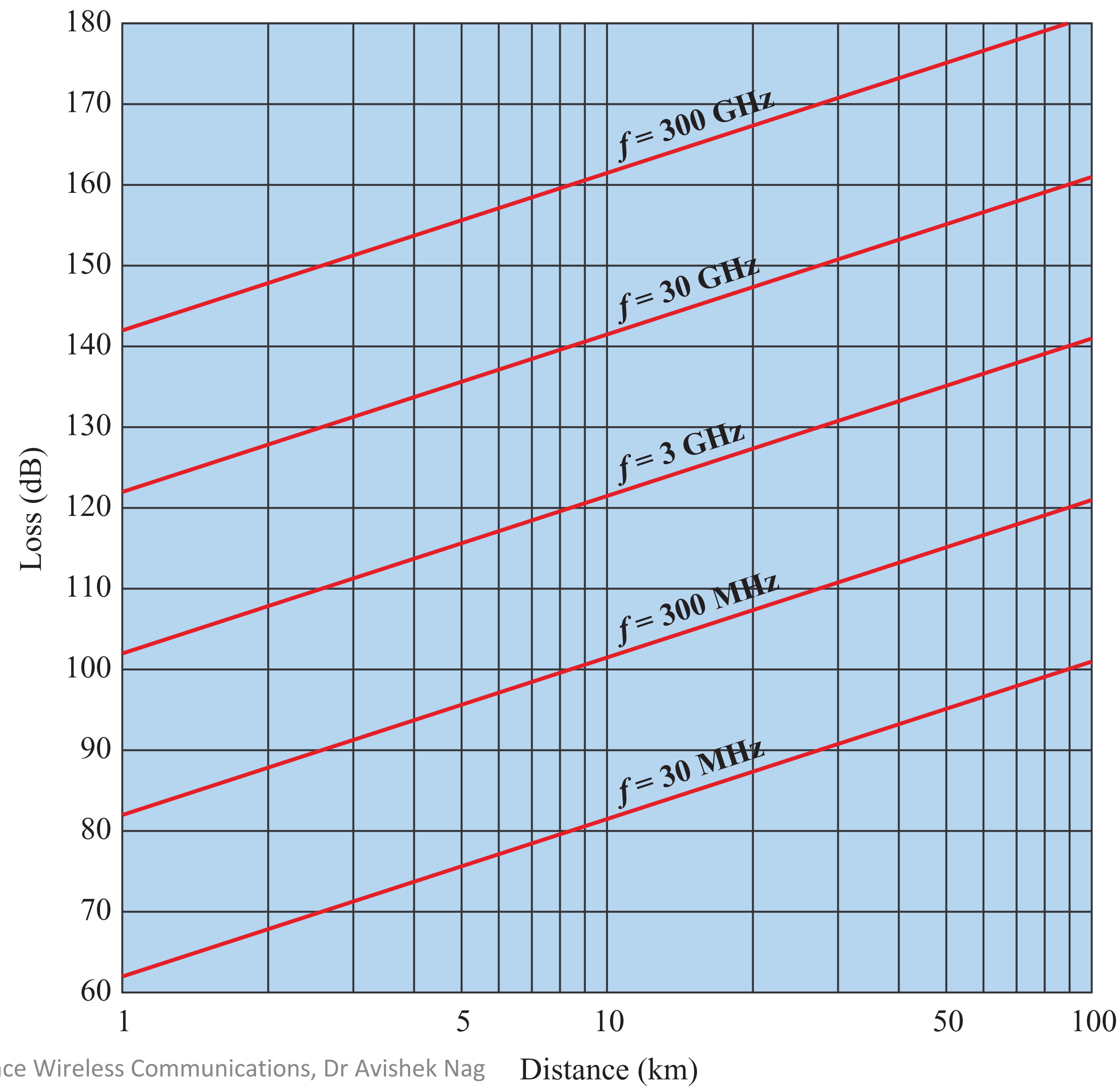
- Free space loss equation can be recast:

$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\,\text{dB}$$

$$= 20\log\left(\frac{4\pi f d}{c}\right) = 20\log(f) + 20\log(d) - 147.56\,\text{dB}$$

Free Space Loss



Path Loss Exponent in practical systems

- Practical systems – reflections, scattering, etc.
- Beyond a certain distance, received power decreases logarithmically with distance
  - Based on many measurement studies

$$\frac{P_t}{P_r} = \left(\frac{4\pi}{\lambda}\right)^2 d^n = \left(\frac{4\pi f}{c}\right)^2 d^n$$

$$L_{dB} = 20\log(f) + 10n\log(d) - 147.56 \text{ dB}$$

Path Loss Exponent in practical systems

Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

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

Class Exercise

For radio transmission in free space, signal power is reduced in proportion to the square of the distance from the source, whereas in wire transmission, the attenuation is a fixed number of dB per kilometer. The following table is used to show the dB reduction relative to some reference for free space radio and uniform wire. Fill in the missing numbers to complete the table.

Distance (km)	Radio (dB)	Wire (dB)
1	-6	-3
2		
4		
8		
16		

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

Thermal Noise

- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = \mathrm{k}T\left(\mathrm{W/Hz}\right)$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in Kelvins (absolute temperature)

Thermal Noise

- Noise is assumed to be independent of frequency
- Thermal noise present in a bandwidth of *B* Hertz (in watts):

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$N = 10\log \mathrm{k} + 10\log T + 10\log B$$

$$= -228.6\,\mathrm{dBW} + 10\log T + 10\log B$$

Noise Terminology

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

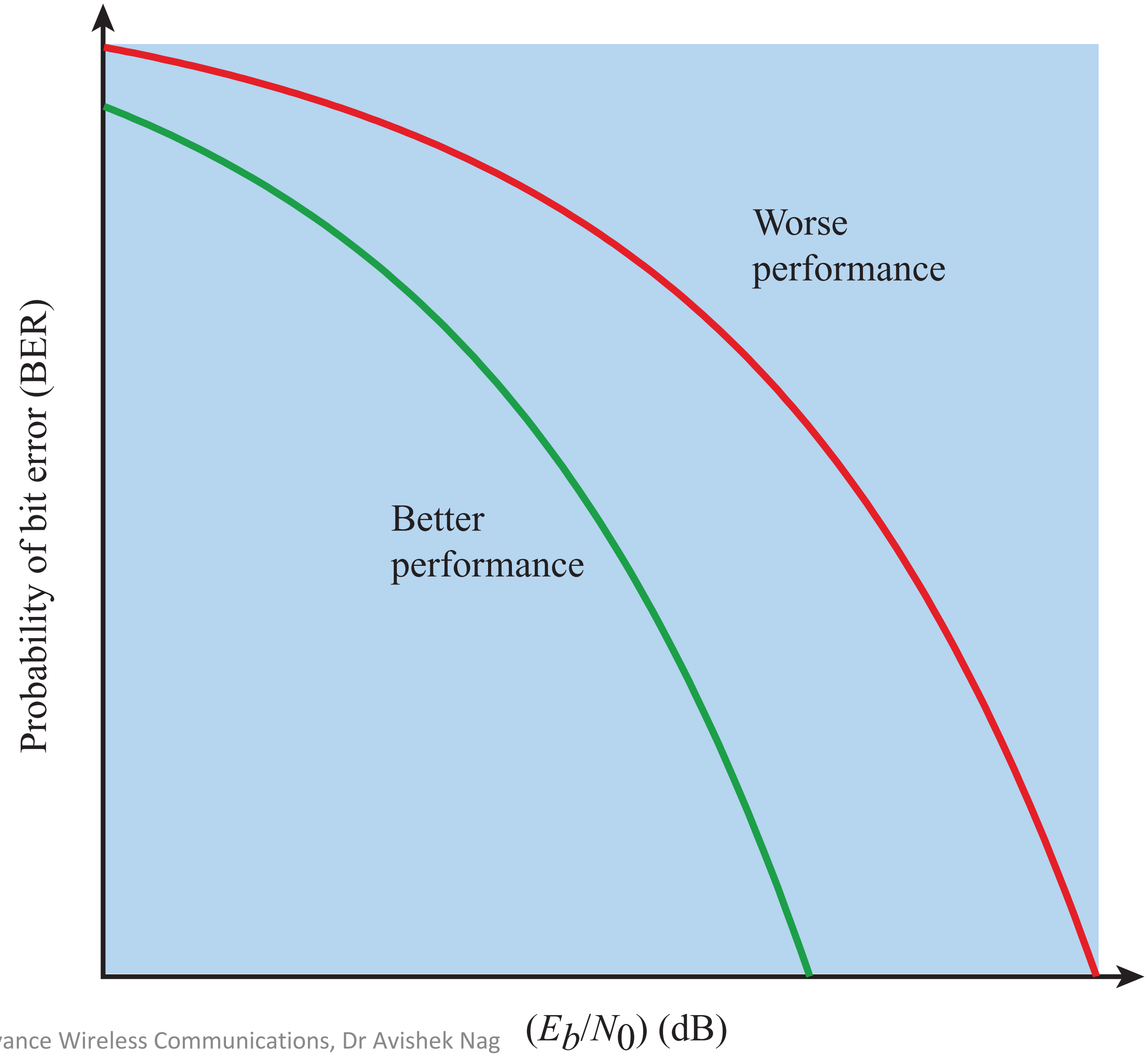
Expression E_b/N_0

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

- The bit error rate (i.e., bit error probability) for digital data is a function of E_b/N_0
  - Given a value for E_b/N_0 to achieve a desired error rate, parameters of this formula can be selected
  - As bit rate R increases, transmitted signal power must increase to maintain required E_b/N_0

General Shape of BER Versus E_b/N_0 Curves



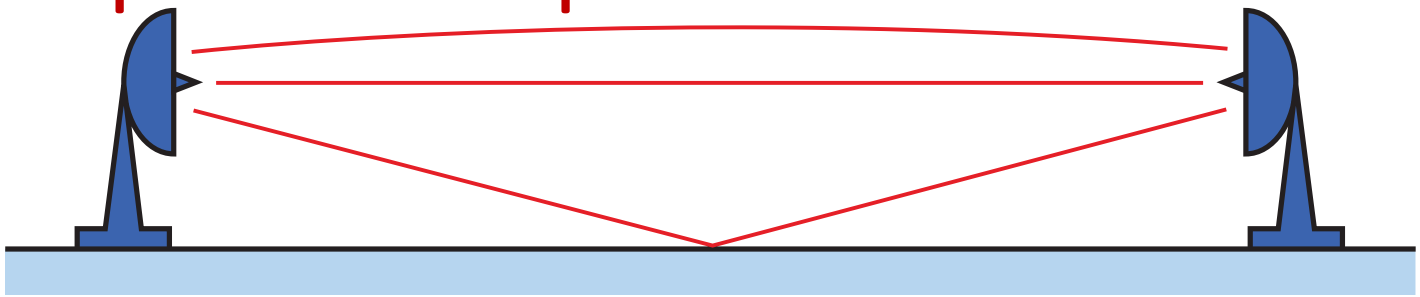
Other Impairments

- 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

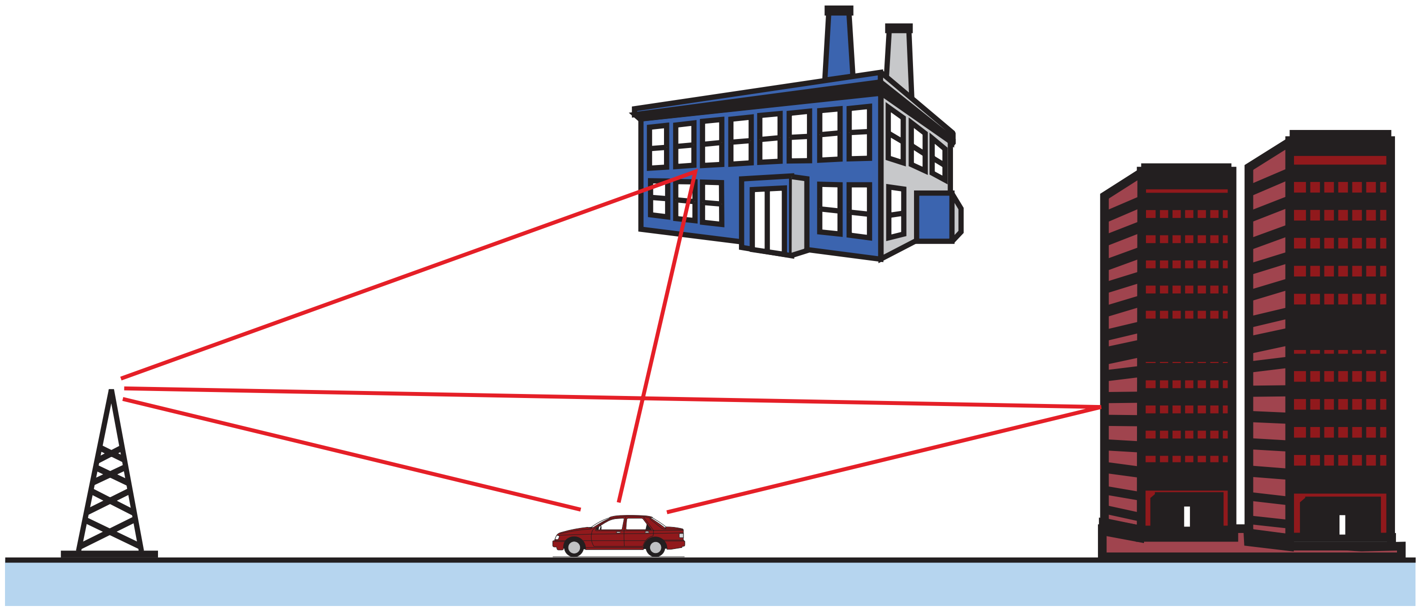
The Effects of Multipath Propagation

- 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

Example of Multipath Interference

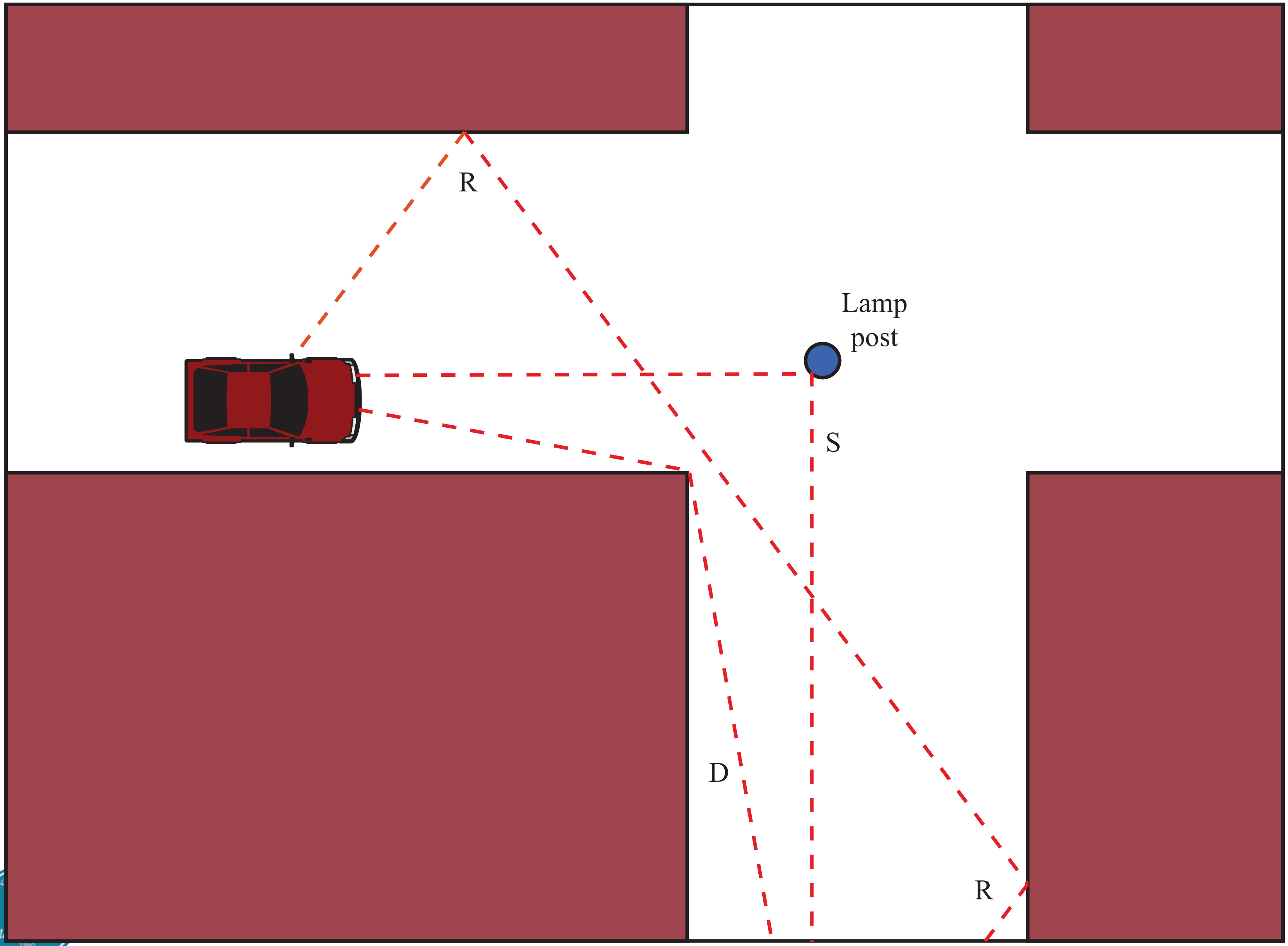


(a) Microwave line of sight

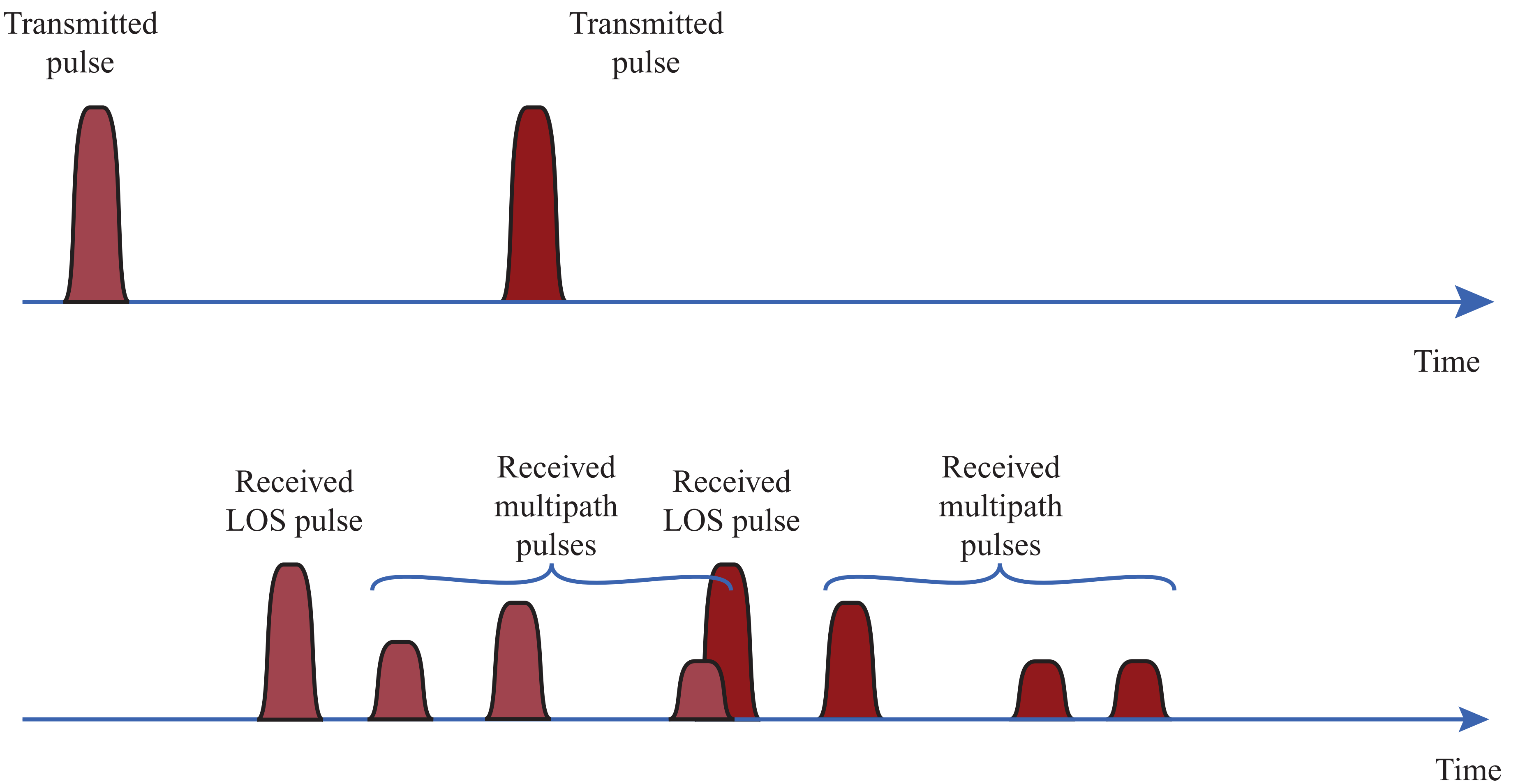


(b) Mobile radio

Sketch of Three Important Propagation Mechanism



Two Pulses in Time-Variant Multipath

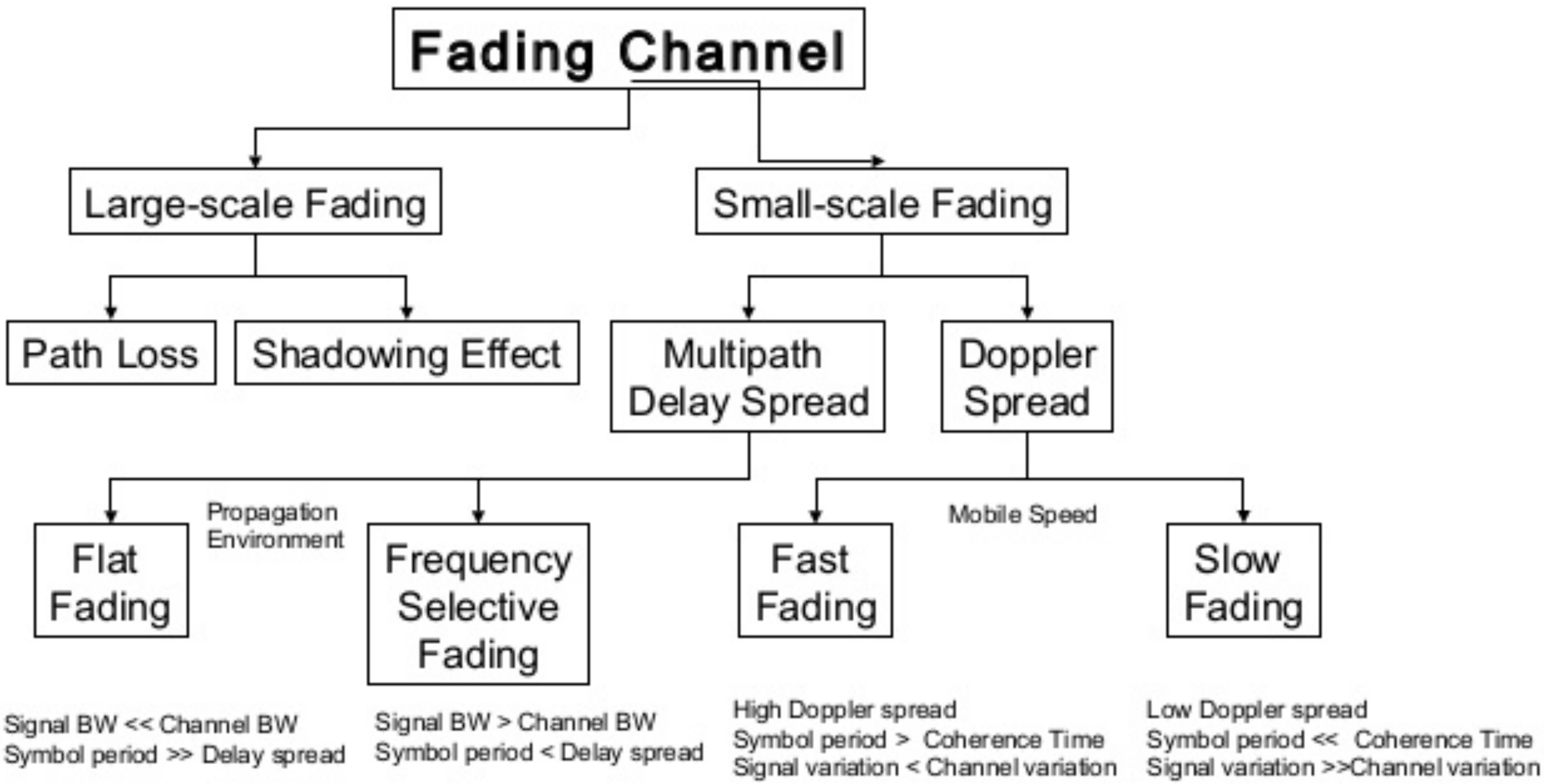


Outline of the Last Lecture

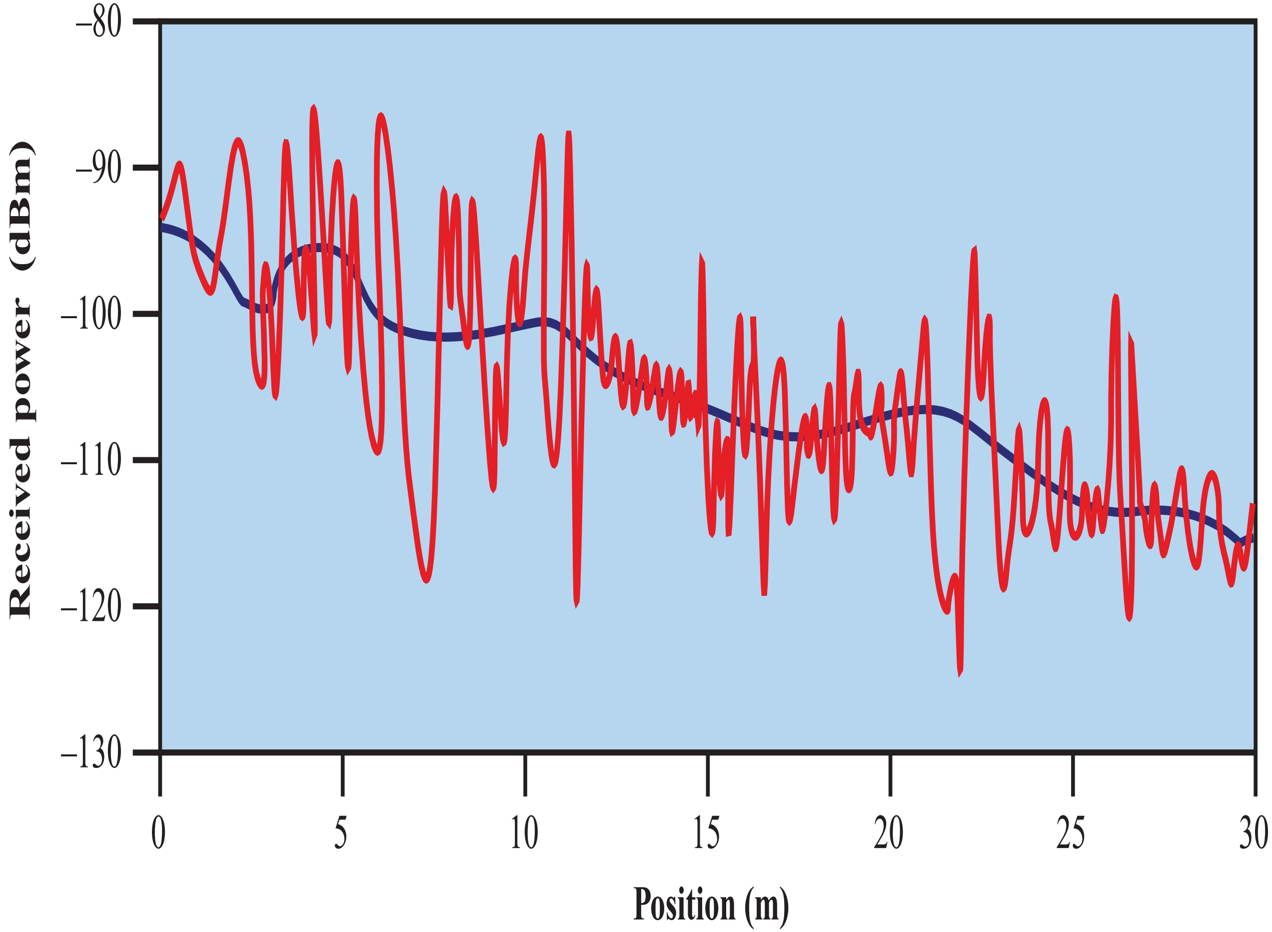
- Antennas
  - Omnidirectional
  - Directional
  - Radiation Patterns
- Spectrum Considerations
- Propagation Modes
  - Skywave, Groundwave, LoS
- Propagation Mechanisms
  - Free-Space, Guided, Reflection, Diffraction, Scattering
- Transmission Impairments
  - Attenuation, Path Loss, Noise, Atmospheric Absorption, Refraction, Multipath

Multipath Fading

The term *fading* refers to the time variation of received signal power caused by changes in the transmission medium or path(s). In a fixed environment, fading is affected by changes in atmospheric conditions, such as rainfall. But in a mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.



Slide Courtesy: Ajal AJ, FISAT


–80
–90
–100
–110
–120
–130
Received power (dBm)
0
5
10
15
20
25
30
Position (m)

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

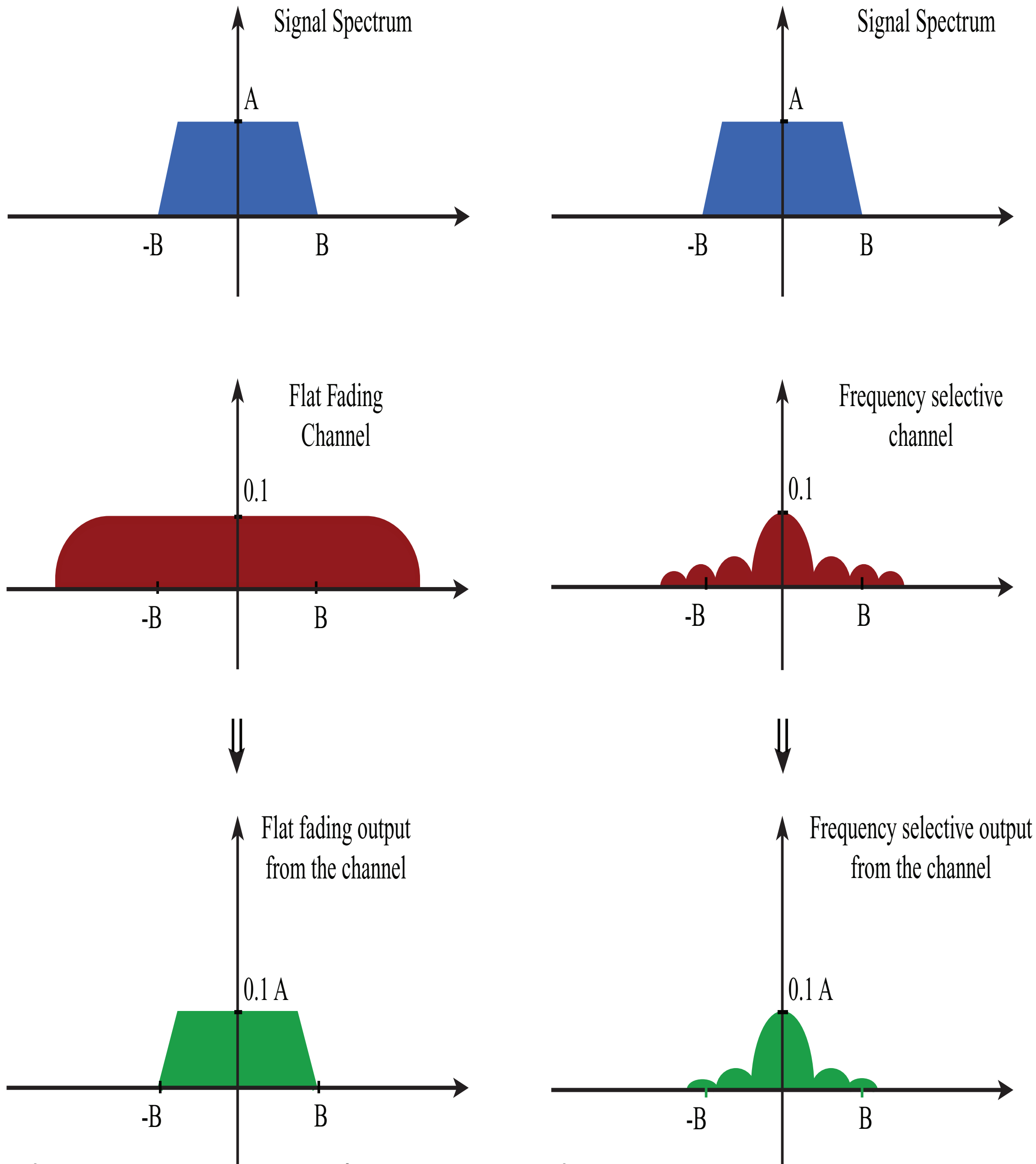
Types of fading

- 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: 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

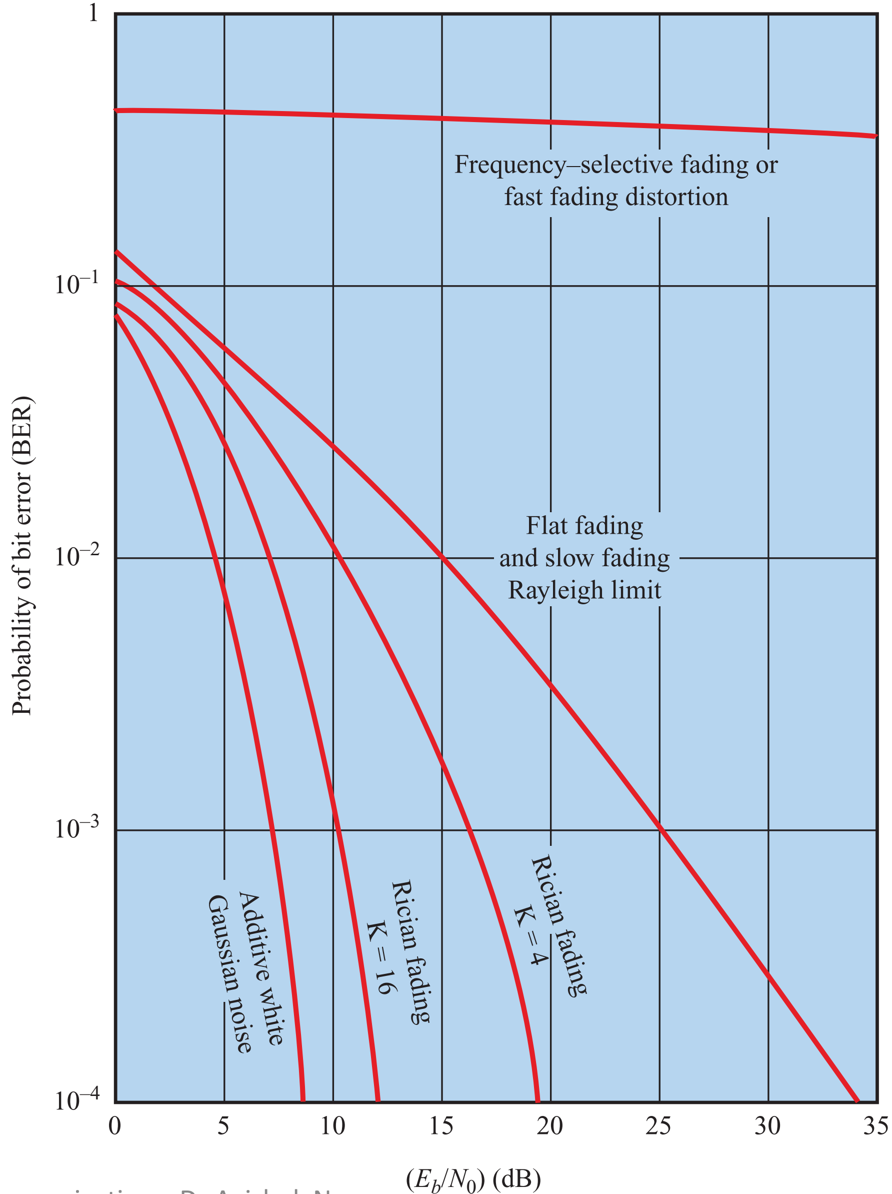
- Multipath fading
  - Multiple signals arrive at the receiver
  - Coherence bandwidth B_c characterizes multipath
    - Bandwidth over which the channel response remains relatively constant
    - Related to delay spread, the spread in time of the arrivals of multipath signals
  - Signal bandwidth B_s 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: B_c = 150 kHz, bit rate r_b = 100 kbps
  - 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*



Flat and Frequency Selective Fading

BER for Various Fading Conditions



Class Exercise

A multipath fading channel has a multipath spread of $T_m = 1$ s and a Doppler spread $B_d = 0.01$ Hz. The total channel bandwidth at bandpass available for signal transmission is $W = 5$ Hz. To reduce the effects of intersymbol interference, the signal designer selects a pulse duration $T = 10$ s.

a. Determine the coherence bandwidth and the coherence time.

b. Is the channel frequency selective? Explain.

c. Is the channel fading slowly or rapidly? Explain.

(a)

$$T_m = 1 \text{ sec} \Rightarrow (\Delta f)_c \approx \frac{1}{T_m} = 1\ Hz$$
$$B_d = 0.01\ Hz \Rightarrow (\Delta t)_c \approx \frac{1}{B_d} = 100 \text{ sec}$$

(b) Since $W = 5\ Hz$ and $(\Delta f)_c \approx 1\ Hz$, the channel is frequency selective.

(c) Since T=10 sec $<$ $(\Delta t)_c$, the channel is slowly fading.

Class Exercise

Three-Ray Multipath Consider a 980 MHz signal signal experiencing three-ray multipath. The tranmitted signal is $s(t)$. The received signal is

$$r(t) = A_0 s(t) + A_1 s(t - \tau_1) + A_2 s(t - \tau_2)$$

where

$$A_0 = 0.4$$
$$A_1 = 1.0,\ \tau_1 = 5.125\ \mu\text{sec}$$
$$A_2 = 0.7,\ \tau_2 = 8.334\ \mu\text{sec}$$

a. What is the distance in meters between the longest and shortest path?

b. If the transmitted signal is a cosine, what are the relative phase angles between the three multipath components?

(a) The longest delay is τ_2. Therefore, the distance is $d = c\tau_2 = 3 \times 10^8 \times 8334 \times 10^{-6} \approx 2500$ metres.

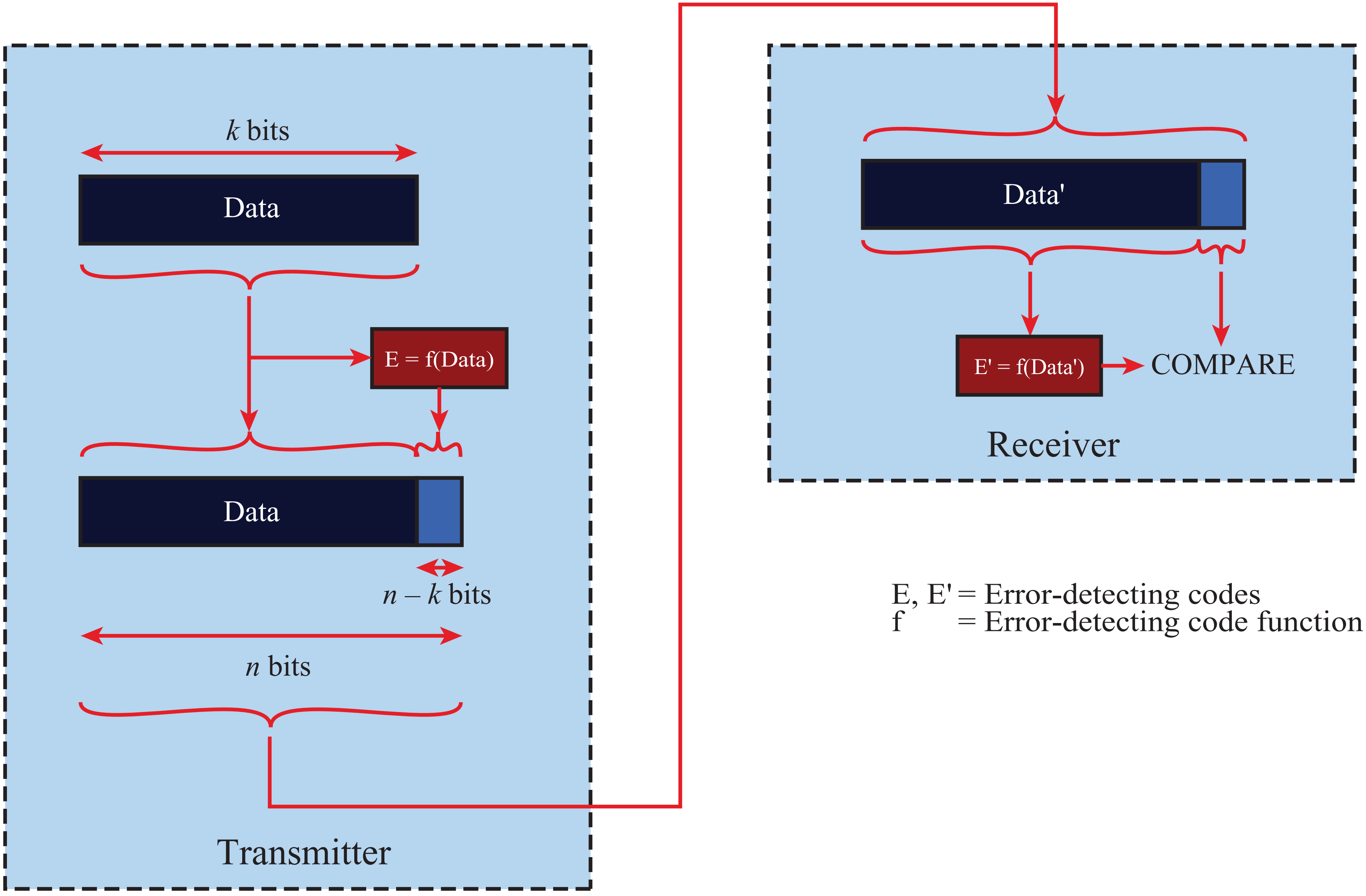
(b) If $s(t) = \cos(2\pi f_c t)$, then
$r(t) = A_0 \cos(2\pi f_c t) + A_1 \cos(2\pi f_c (t - \tau_1)) + A_2 \cos(2\pi f_c (t - \tau_2))$
or $r(t) = A_0 \cos(2\pi f_c t) + A_1 \cos(2\pi f_c t + \phi_1) + A_2 \cos(2\pi f_c t + \phi_2)$
where, $\phi_1 = -2\pi f_c \tau_1$ and $\phi_2 = -2\pi f_c \tau_2$. Calculating we have, $\phi_1 =\approx -31557$ radians and $\phi_2 \approx -51317$ radians.

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
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)

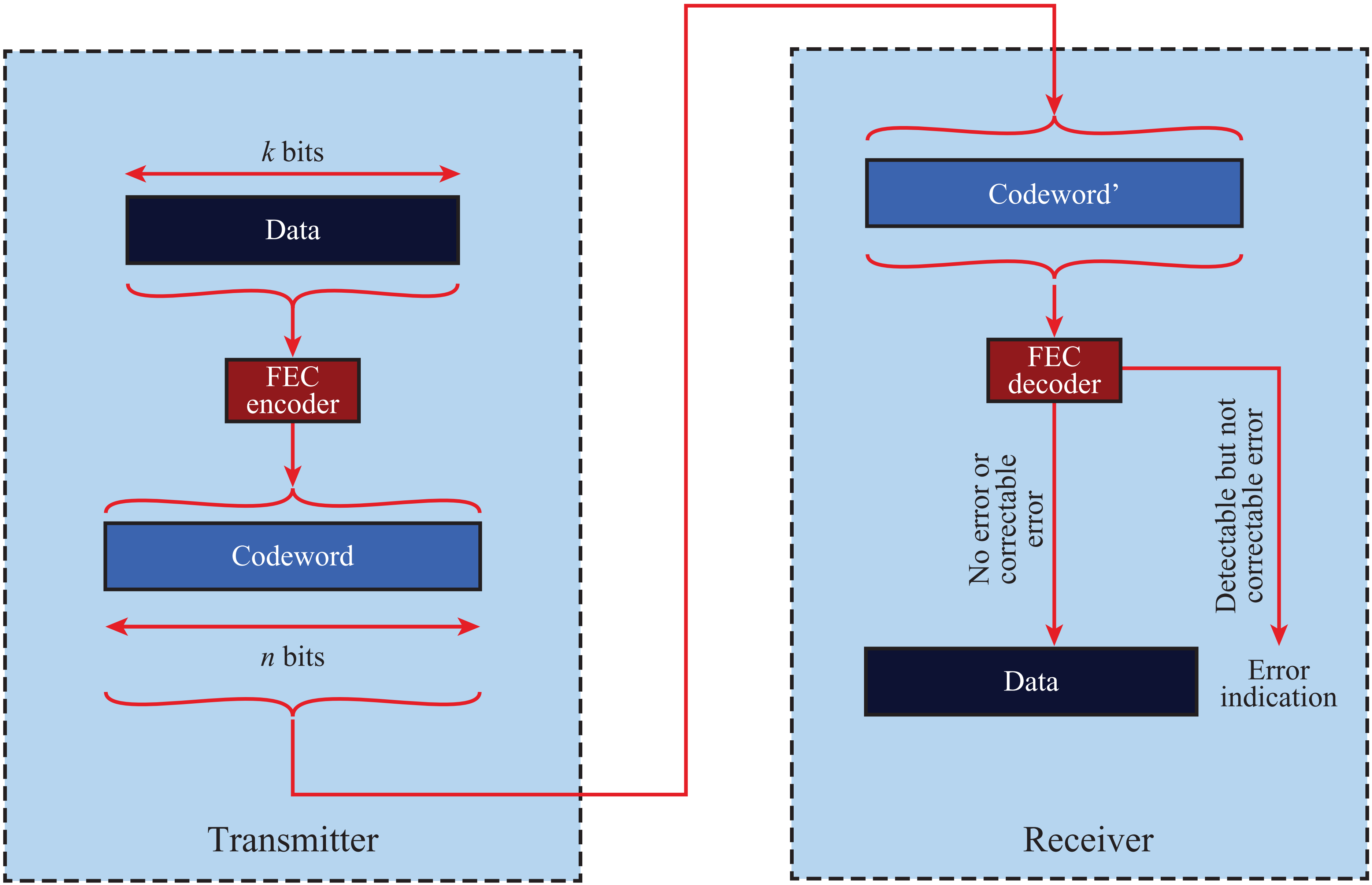
- Transmitter
  - For a *k*-bit block, transmitter generates an (*n*-*k*)-bit frame check sequence (FCS)
  - Resulting frame of *n* bits is exactly divisible by predetermined number
- Receiver
  - Divides incoming frame by predetermined number
  - If no remainder, assumes no error

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

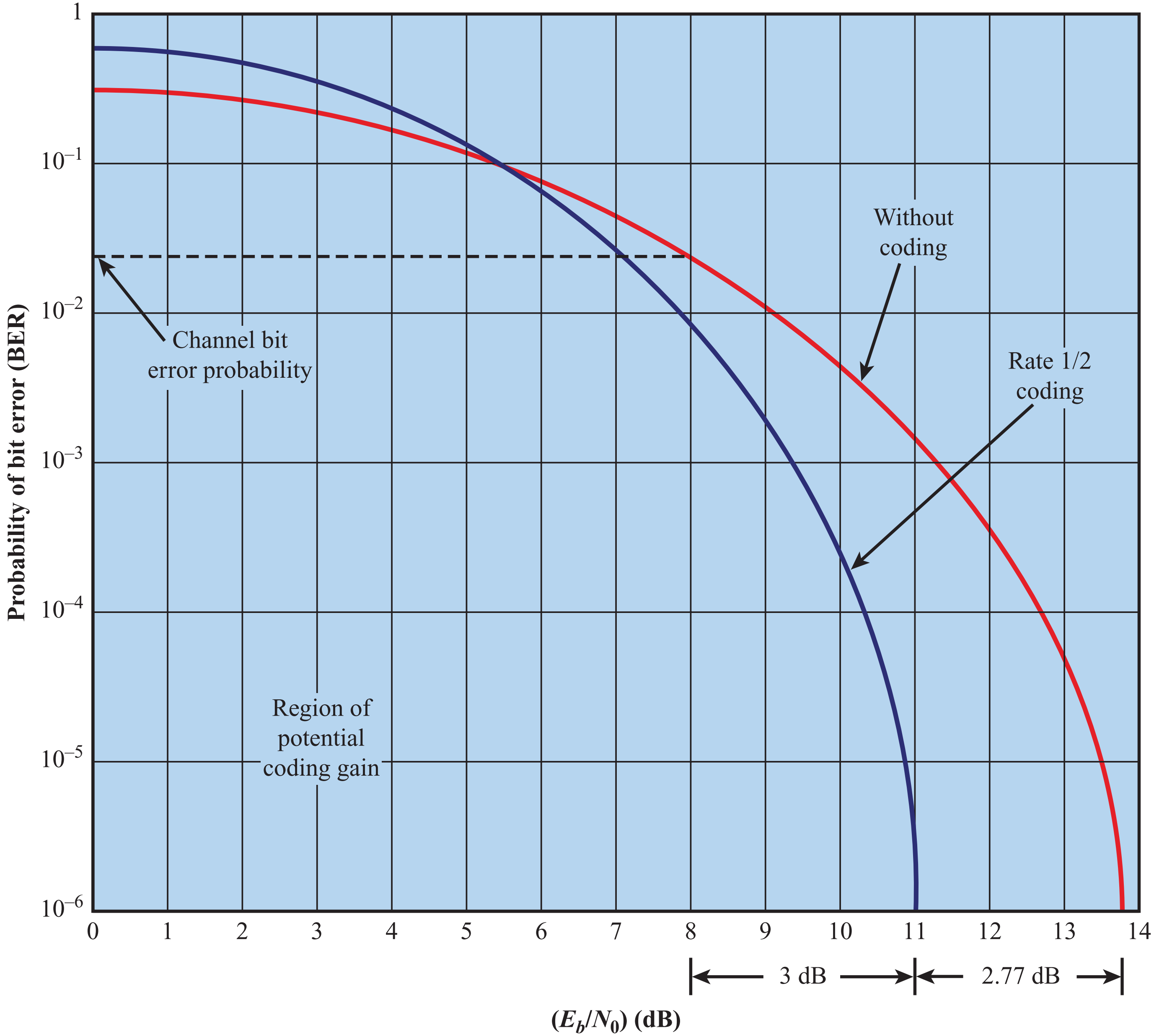

k bits
Data
FEC
encoder
Codeword
n bits
Transmitter
Codeword'
FEC
decoder
No error or
correctable
error
Detectable but not
correctable error
Data
Error
indication
Receiver

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; $d(v_1, v_2)$=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



How Coding Improves System Performance

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

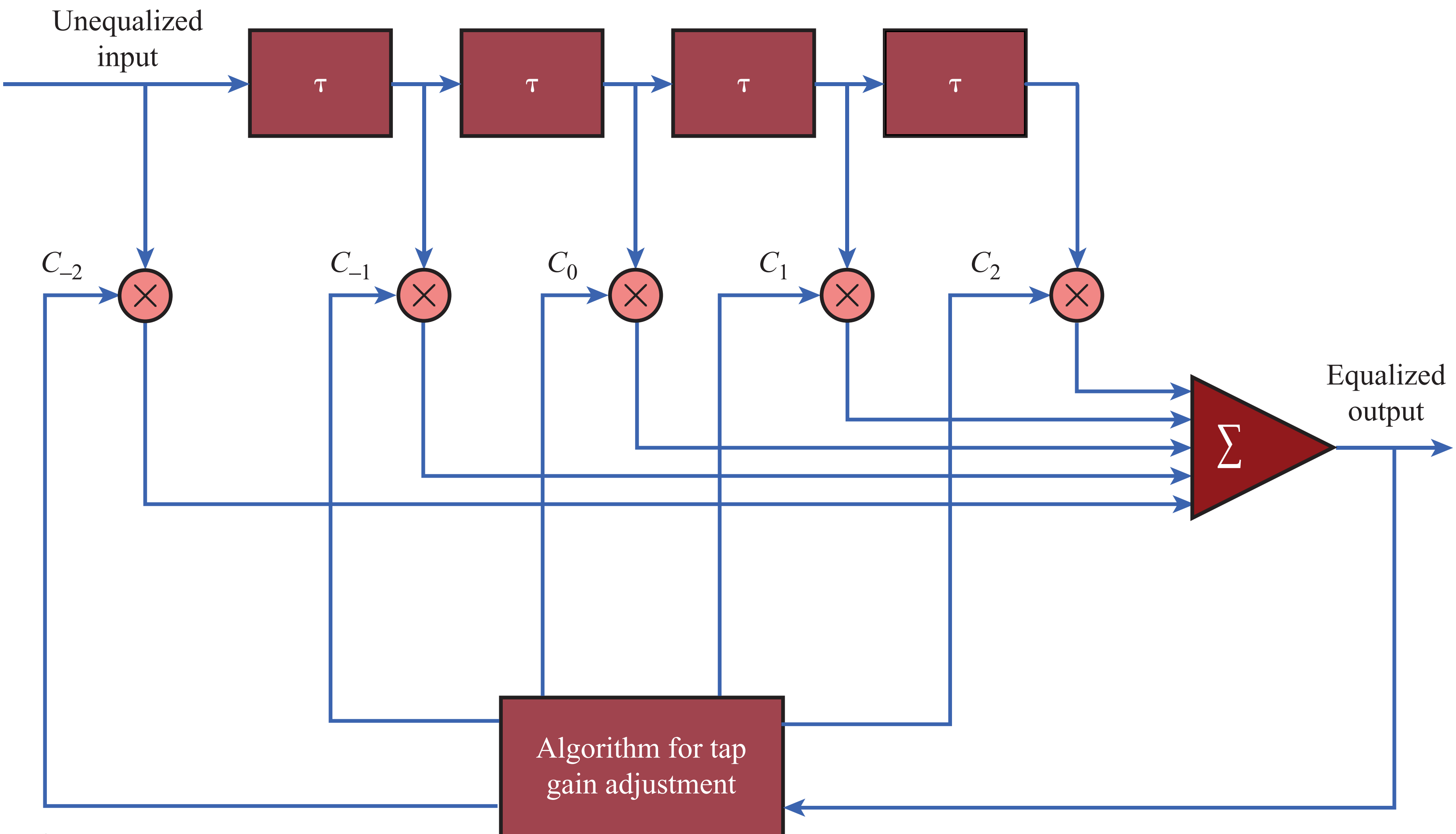
Decoding process

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

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

Linear Equalizer Circuit



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

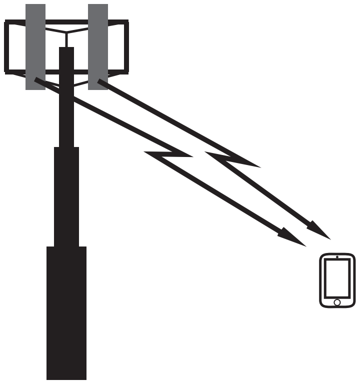
Diversity Techniques

- 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

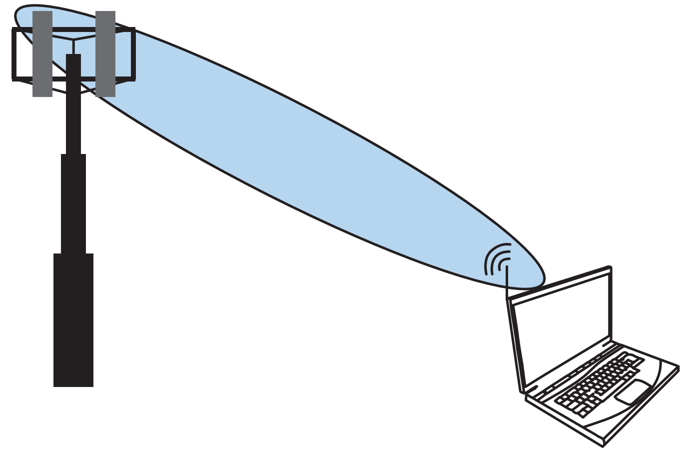
MULTIPLE INPUT MULTIPLE OUTPUT (MIMO) ANTENNAS

- 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

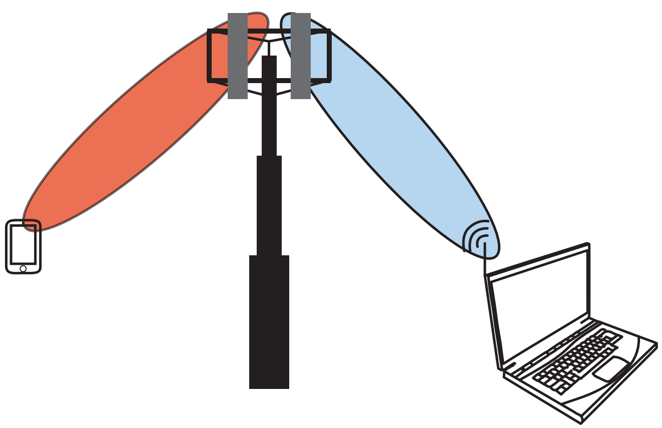
Four Uses of MIMO



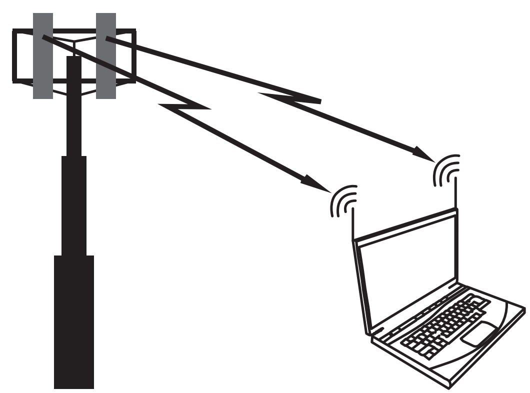
Diversity for improved
system performance



Beam-forming for improved coverage
(less cells to cover a given area)

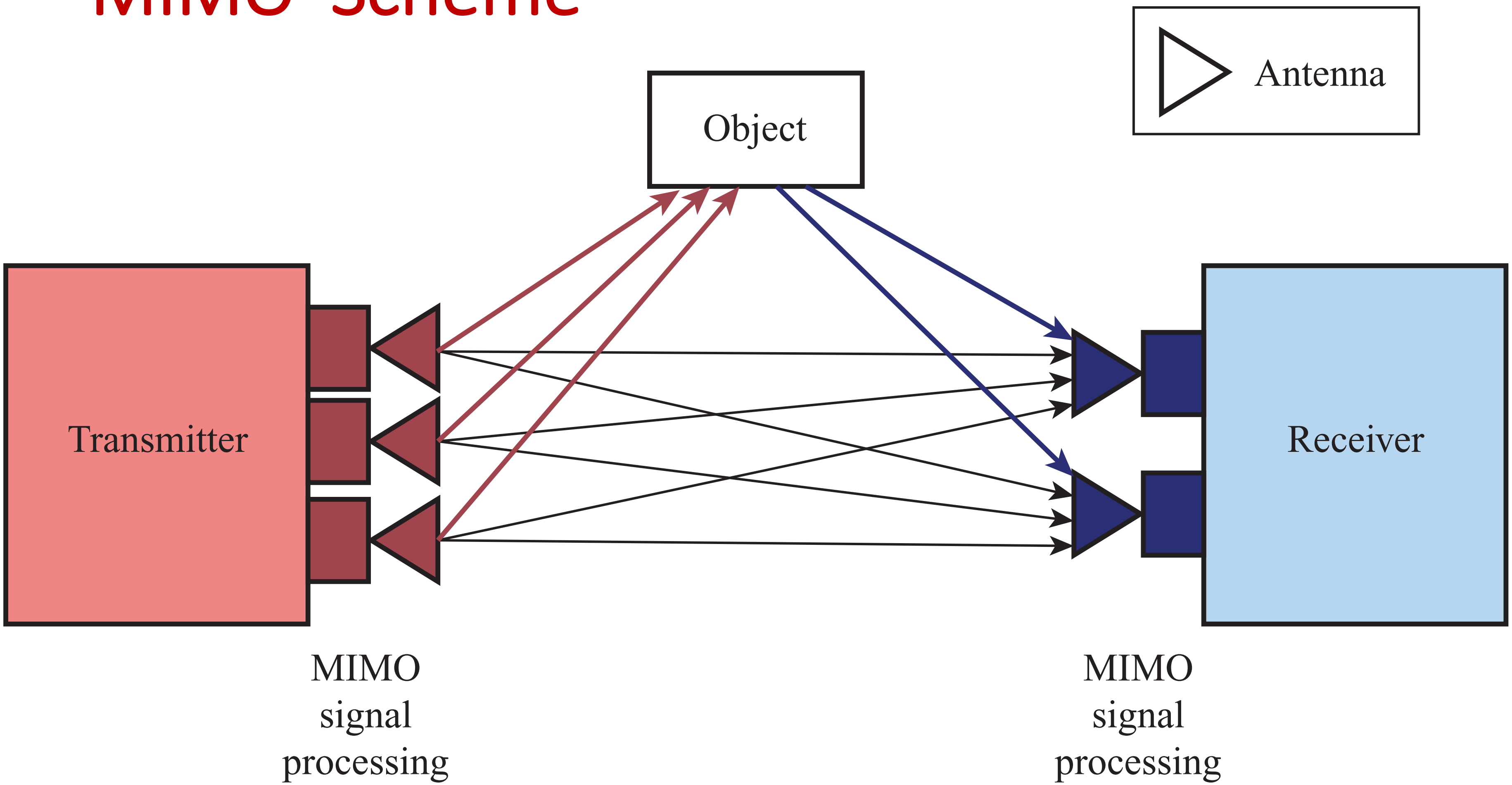


Spatial division multiple access
("MU-MIMO") for improved capacity
(more user per cell)



Multi layer transmission
("SU-MIMO") for higher data rates
in a given bandwidth

MIMO Scheme


Object
Antenna
Transmitter
Receiver
MIMO
signal
processing
MIMO
signal
processing

Channel correction mechanisms

- Orthogonal Frequency Division Multiplexing (OFDM)
  - Splits signal into many lower bit rate streams called subcarriers
  - Overcomes frequency selectivity from multipath
  - Spaces subcarriers apart in overlapping yet orthogonal carrier frequencies
- Spread spectrum
  - Expand a signal to 100 times its bandwidth
  - An alternative method to overcome frequency selectivity
  - Users can share the channel by using different spreading codes
    - ➢ Code Division Multiple Access (CDMA)

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