Overview of Wireless Communications

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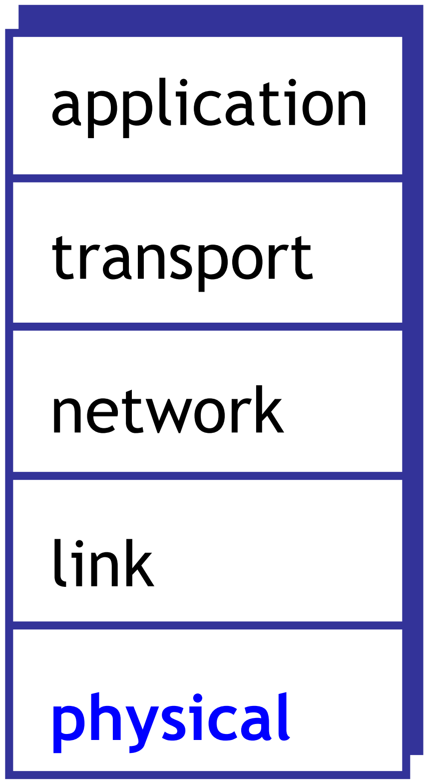
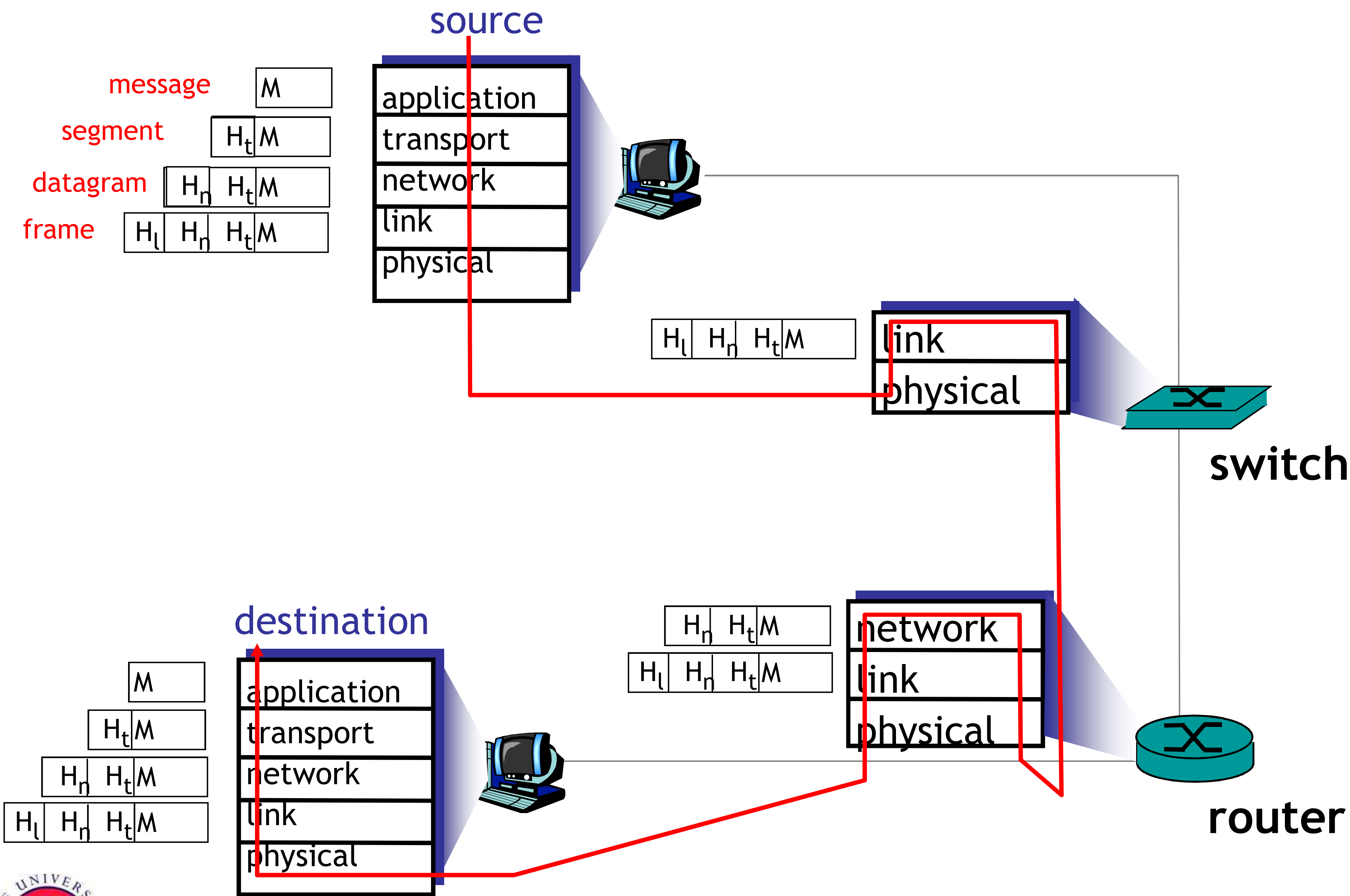
Plan

- Initially, focus on a single wireless link
  - Operating on a small slice of spectrum called a “channel”, defined by a centre frequency and channel width
- Then, multiple access

Internet Protocol Stack

- application: supporting network applications
  - FTP, SMTP, HTTP
- transport: process-process data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bit pipe





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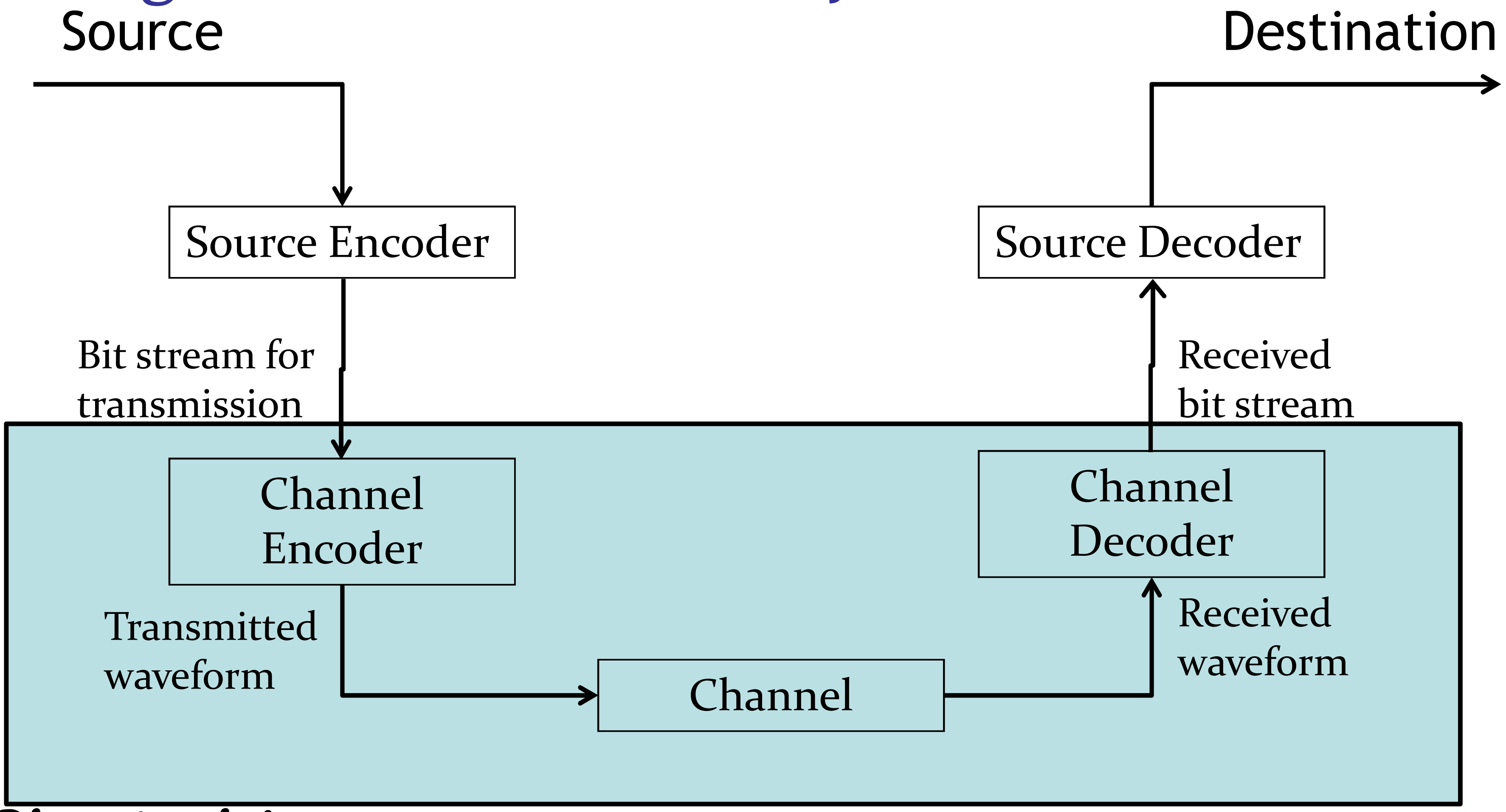
Digital Communication System



Physical Layer

Channel Encoder/Decoder Layers

1. Error Correction Coder/Decoder
2. Modulator/Demodulator (Baseband)
3. Frequency Conversion (Passband)

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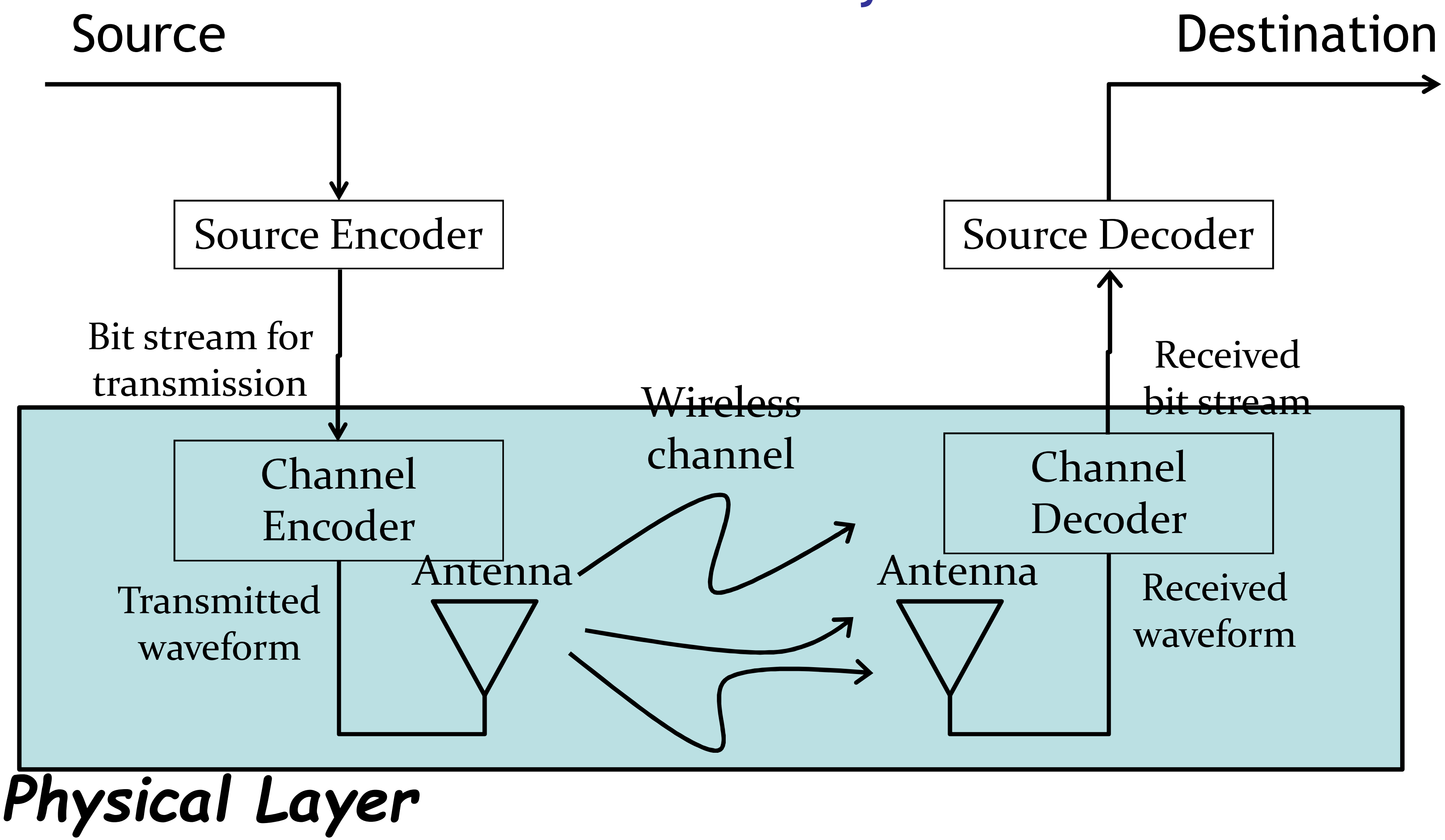
Wireless Communication System



Digression: Decibel Notation

Decibels

- Why use decibel units?
  - Signal strength often falls off exponentially, so loss easily expressed in terms of decibel (a logarithmic unit)
  - Net gain or loss via simple addition and subtraction

- Power ratio in decibels = $10\log_{10}(P/P_{ref})$
  - Power ratios $10^1 \rightarrow$ 10dB, $10^2 \rightarrow$ 20dB, $10^3 \rightarrow$ 30dB, …
  - Similarly, power ratios $10^{-1} \rightarrow$ -10dB, $10^{-2} \rightarrow$ -20dB, $10^{-3} \rightarrow$ -30dB, …
  - 3dB (power ratio = 2), -3dB (power ratio = ½)
  - Voltage ratio in decibels = $20\log_{10}(V/V_{ref})$, since $P = V^2/R$

Decibels (Contd.)

- Absolute power with respect to standard reference power in decibels: dBW (P_{ref} = 1W) and dBm (P_{ref} = 1mW)
  - 1W = 0 dBW = +30 dBm; 1mW = 0 dBm = -30 dBW

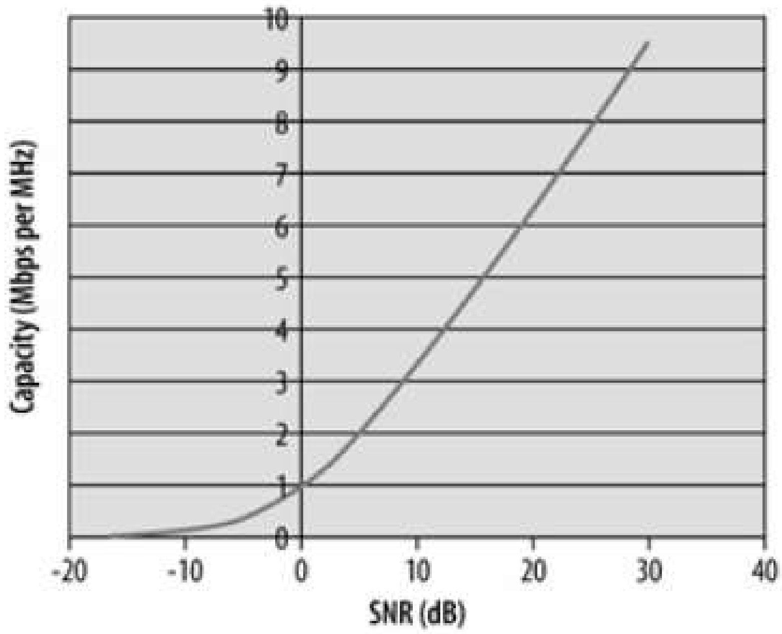
- Antenna gains: dBi (P_{ref} is power radiated by an isotropic reference antenna) and dBd (P_{ref} is power radiated by a half-wave dipole)
  - 0 dBd = 2.15 dBi

- dB for gains and losses (e.g., path loss, SNR)

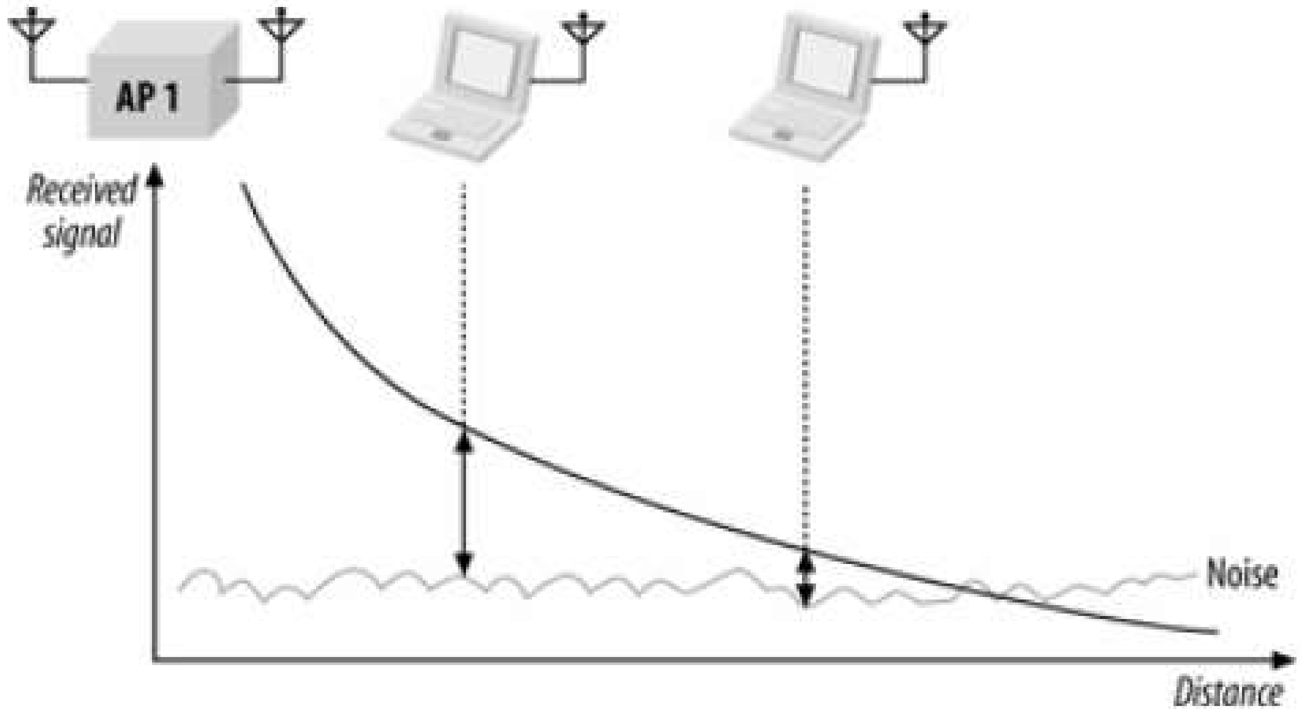
End of Digression

Signal-to-Noise Ratio (SNR)

- Crucial factor determining wireless transmission quality
- Shannon's Channel Capacity Theorem for band-limited additive white Gaussian noise (AWGN) channel: $C = W \log_2(1+SNR)$
  - C, channel capacity in bits per second
  - W, channel bandwidth in Hz
  - SNR, signal-to-noise ratio
- So long as data rate below C, error probability can made arbitrarily lower with the use of more sophisticated coding (error correction) schemes

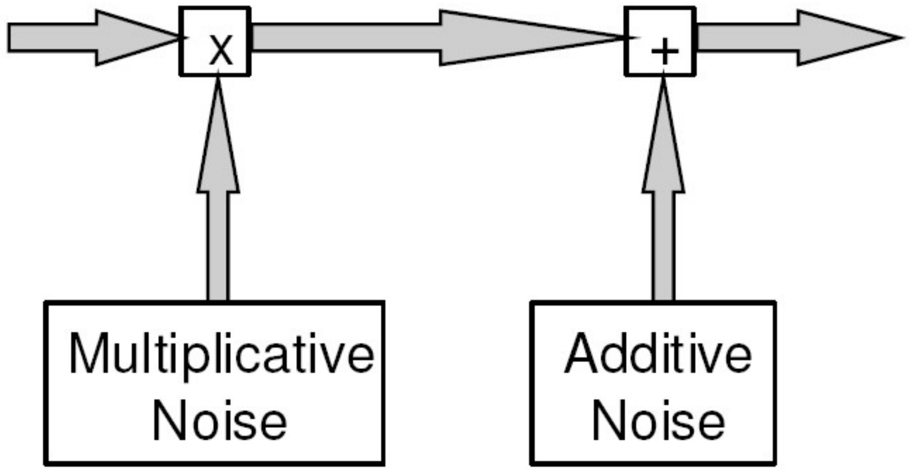


SNR versus Distance



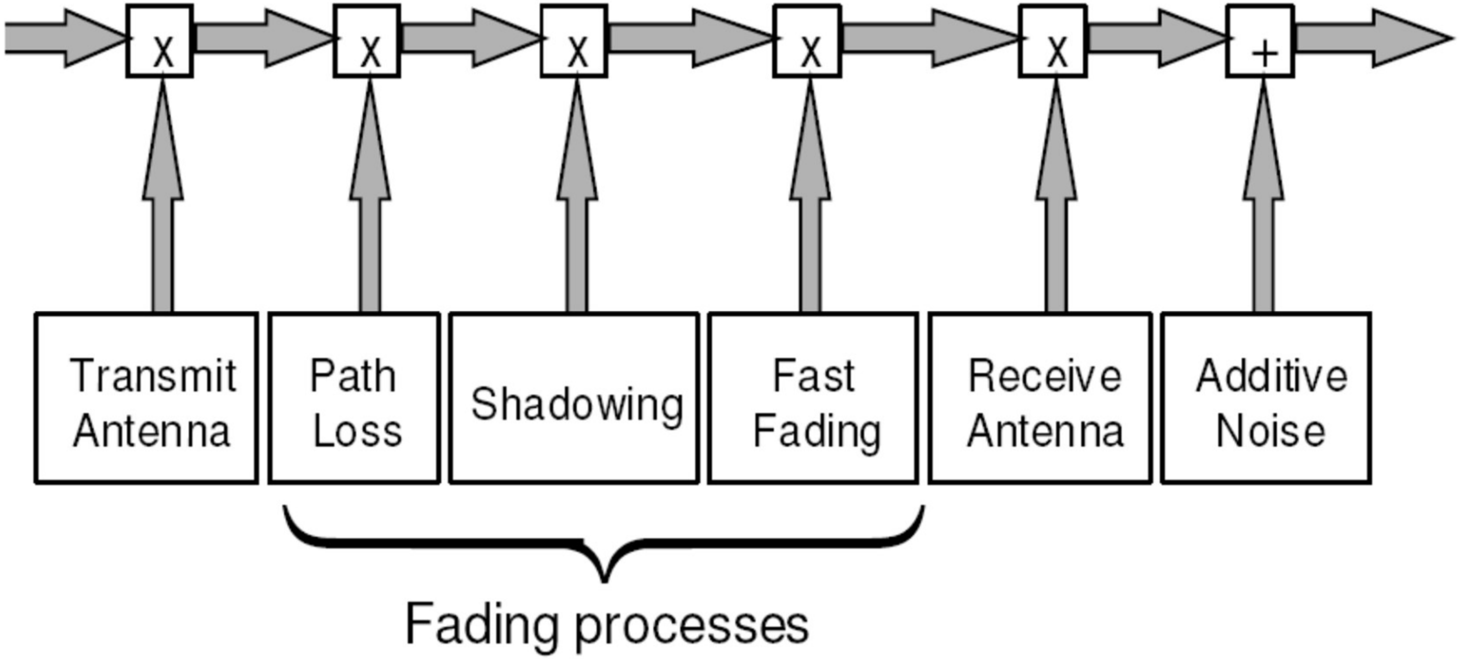
Wireless Channel

Noise Types in a Wireless Channel



- Multiplicative
  - Antenna directionality
  - Attenuation from absorption (walls, trees, atmosphere)
  - Shadowing
  - Reflection (smooth surfaces)
  - Scattering (rough surfaces and small objects)
  - Diffraction (edges of buildings and hills)
  - Refraction (atmospheric layers, layered/graded materials)
- Additive
  - Internal sources within the receiver (e.g., thermal noise)
  - External sources (e.g., interference from other transmitters and appliances)

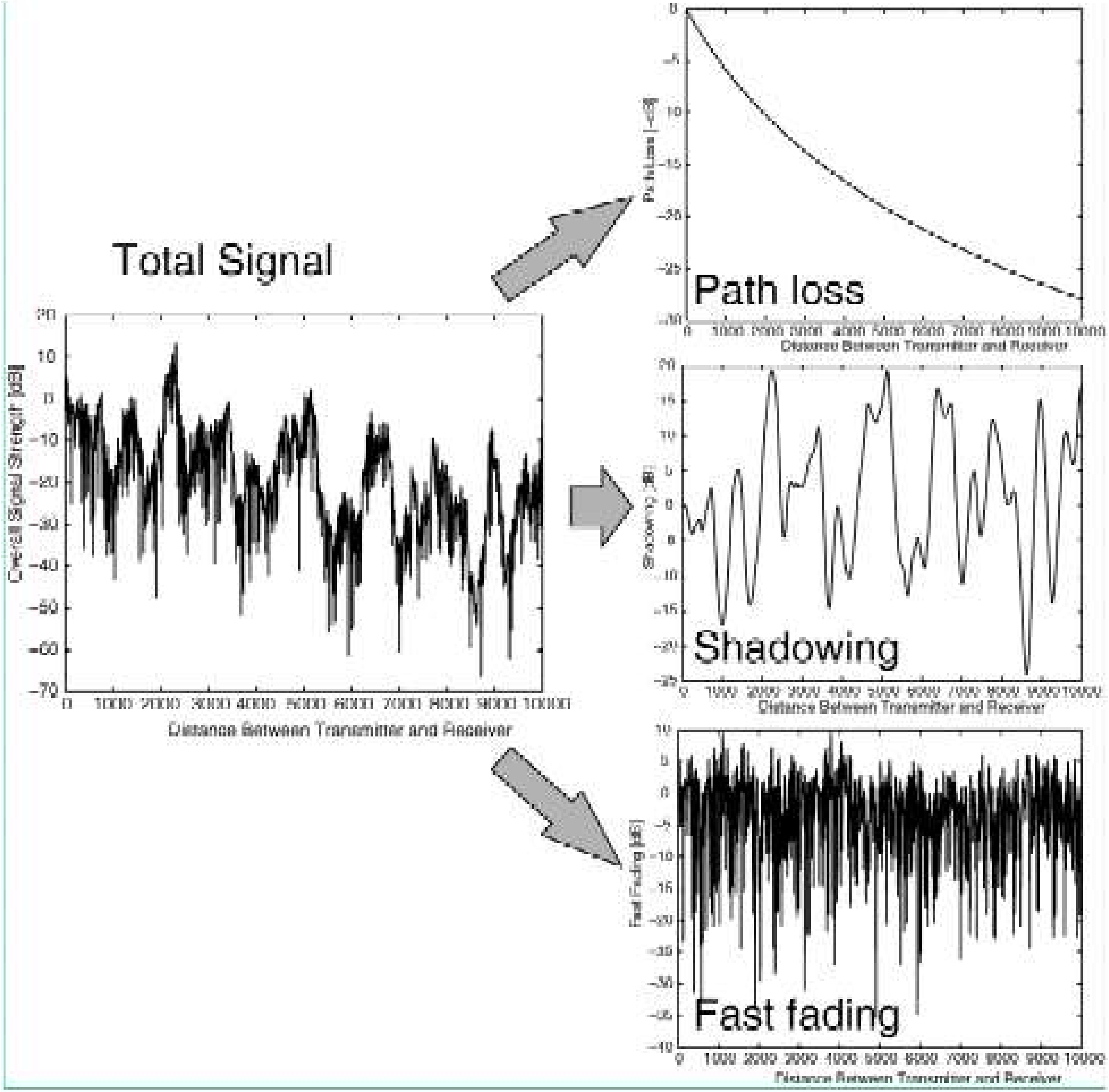
Three Scales of Multiplicative Noise



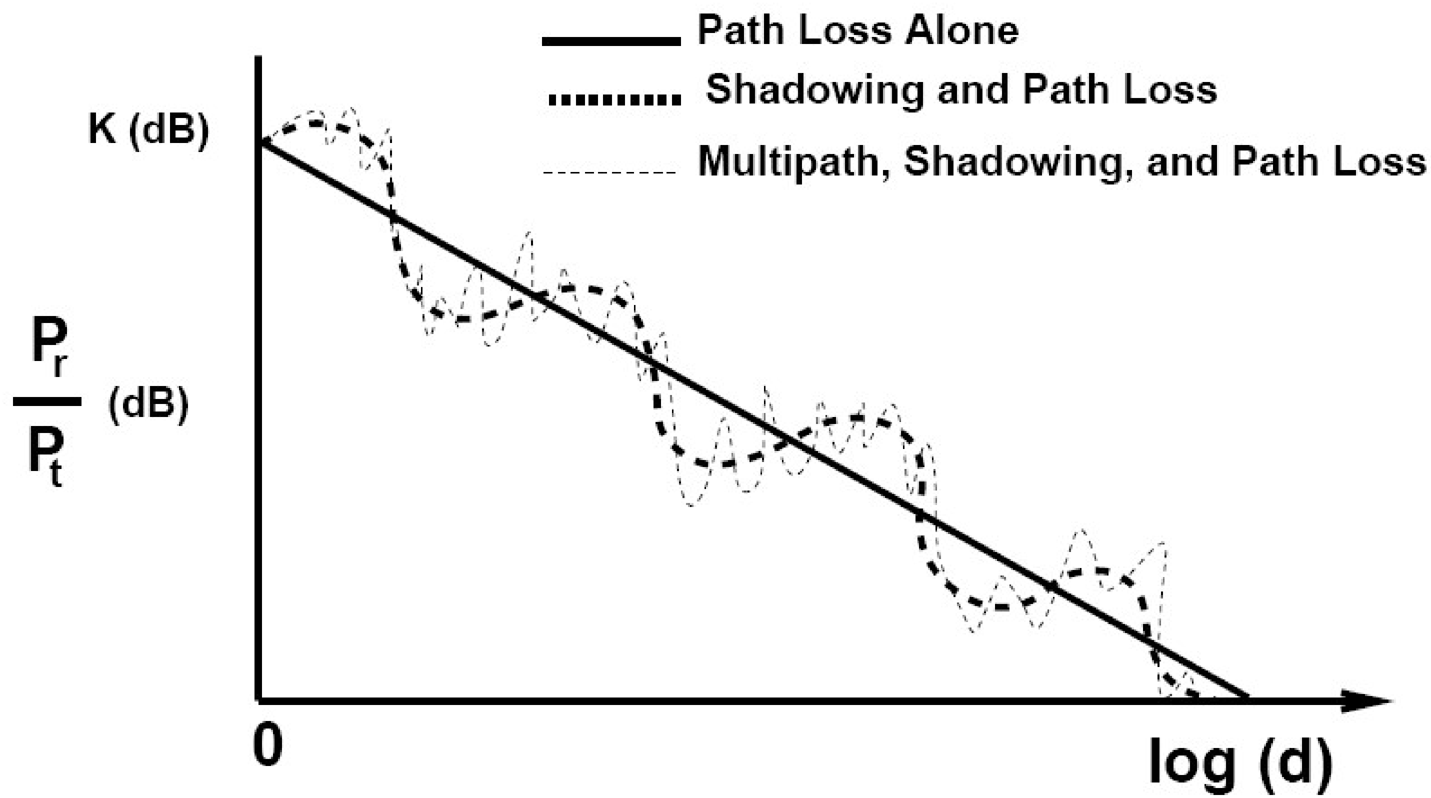
- Large and medium scale propagation effects
  - Path loss
  - Shadowing leads to variations over distances in the order of metres
    - ➢ Could be over 10s or 100s of metres in outdoor environments

- Small-scale fading (or multipath fading): causes variations of over very short distances in the order of the signal wavelength

Fading Processes Illustrated



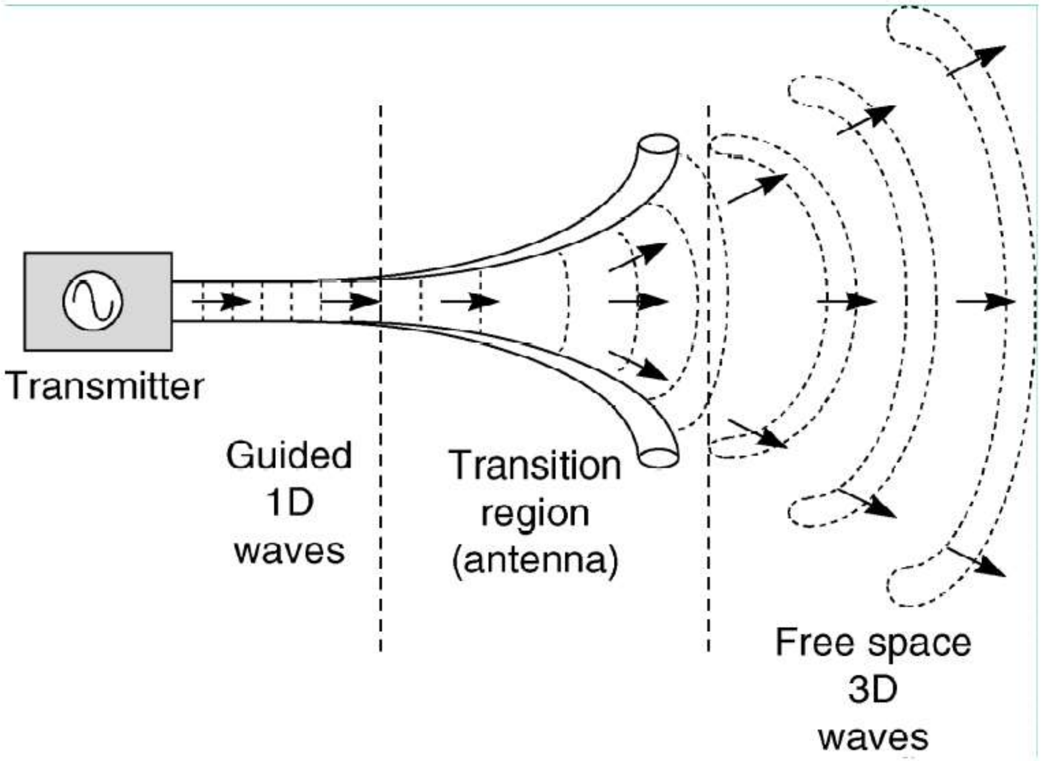
Another Illustration of Path Loss, Shadowing and Multipath Fading



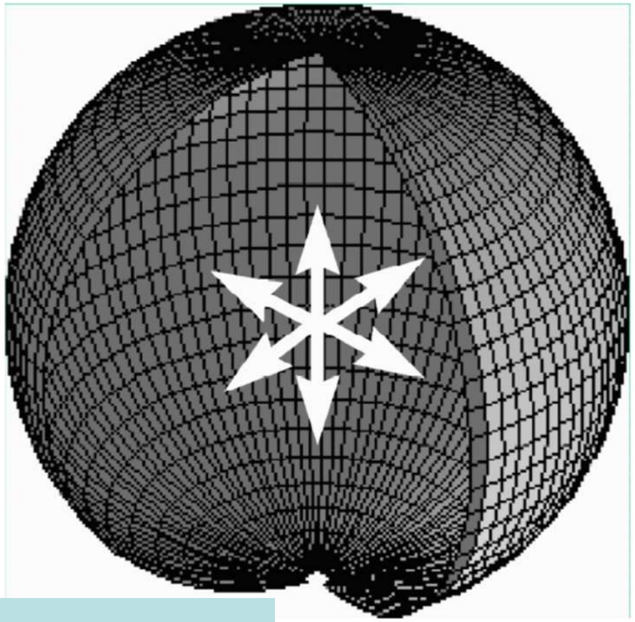
Antennas

Antenna Design Goal

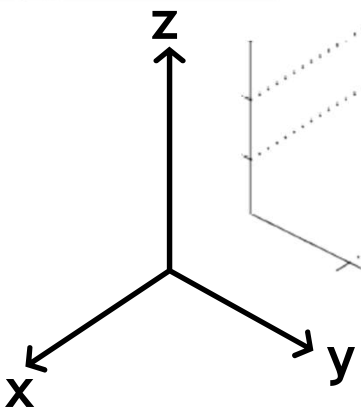
- Ensure the process of conversion between electrical signal and electromagnetic wave is efficient, i.e., direct as much power as possible in "useful" directions

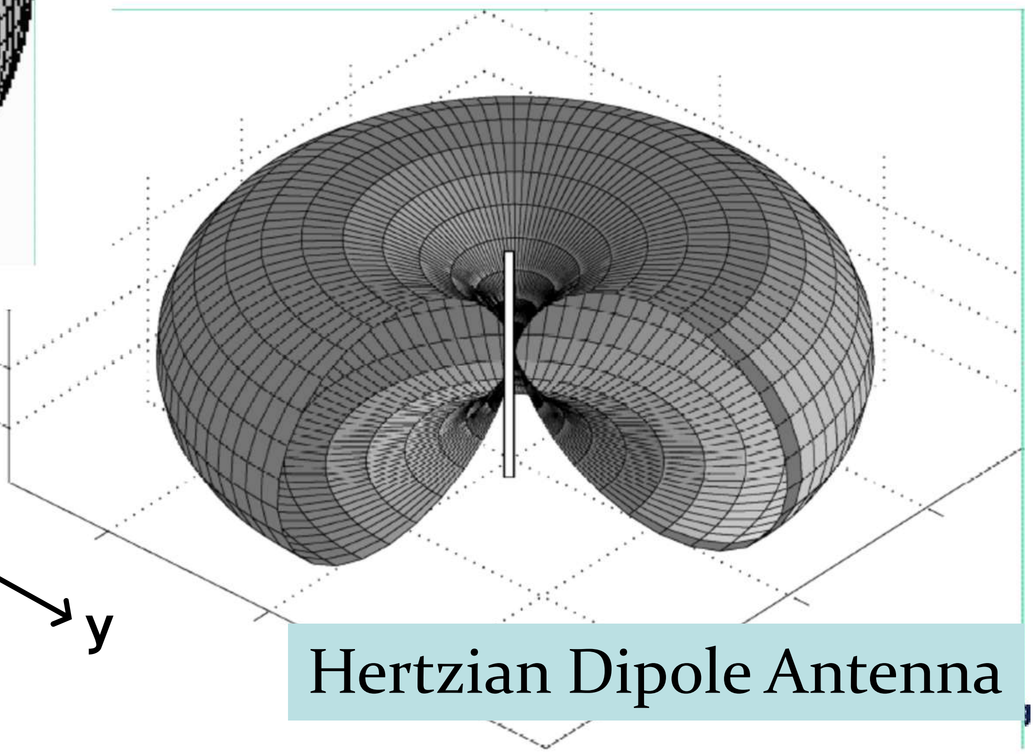


Antenna Radiation Pattern



Isotropic Antenna





Hertzian Dipole Antenna

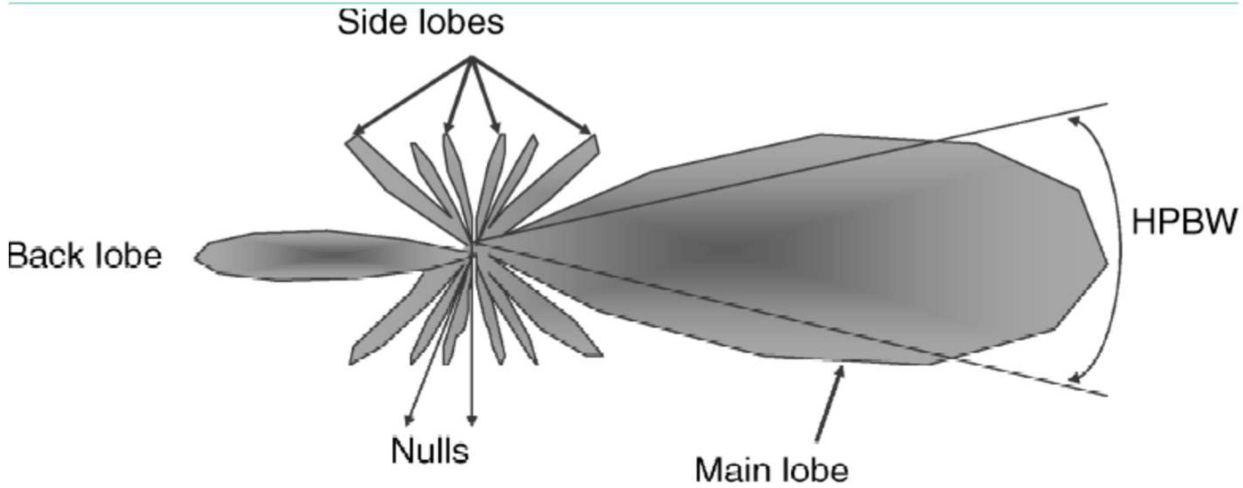
Antenna Radiation Pattern (contd.)

- Plot of far-field radiation from the antenna
  - Radiation intensity, U: power radiated from an antenna per unit solid angle

- Azimuth plane (x-y plane), Elevation plane (x-z plane)

- Different types of antennas have different radiation patterns
  - An ideal isotropic antenna has a spherical pattern
  - Omnidirectional (e.g., hertzian dipole) antenna has a donut shaped pattern
  - Directional antennas radiate power along a direction

Radiation Pattern of a Generic Directional Antenna



- Half-power beamwidth (HPBW): angle subtended by the half-power points of the main lobe
- Front-back ratio: ratio between peak amplitudes of main and back lobes
- Side lobe level: amplitude of the biggest side lobe

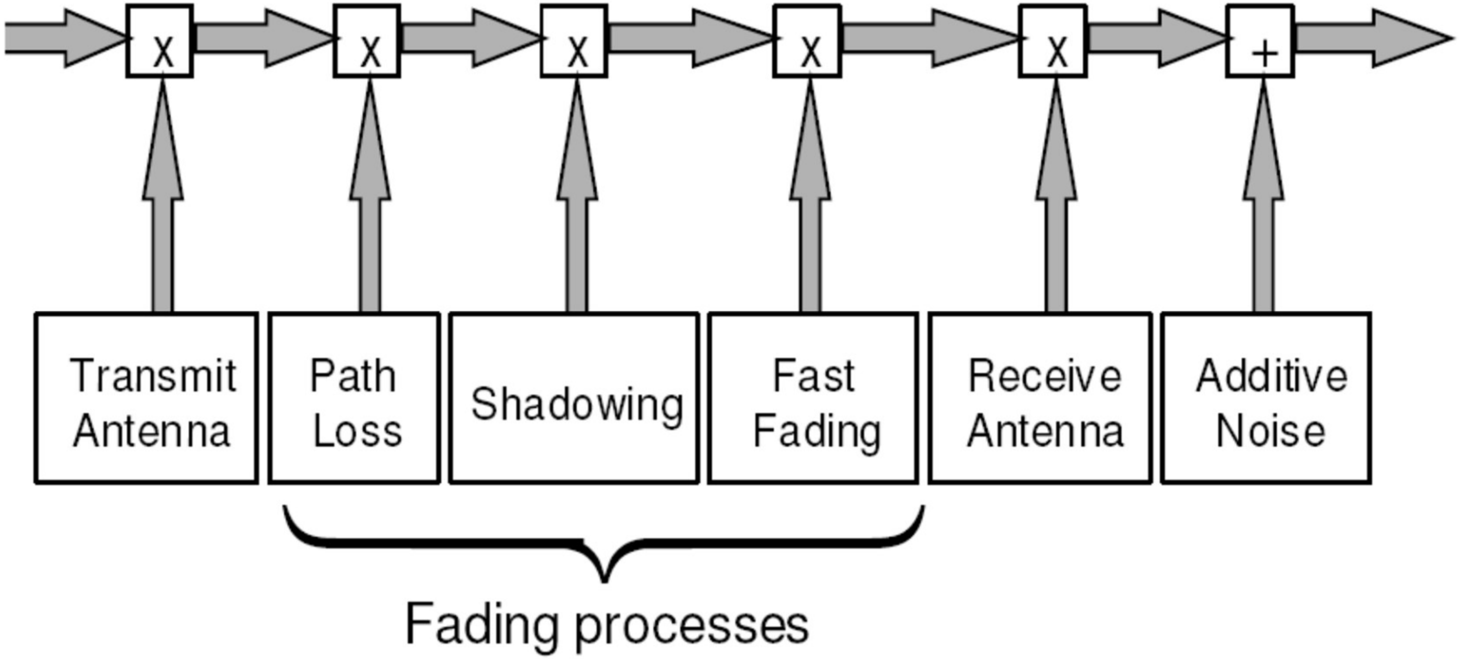
Gain and Other Antenna Characteristics

- **Directivity, D:** ratio of max radiation intensity of antenna to radiation intensity of isotropic antenna radiating the same total power

  $D = \sim 41{,}000/\Theta^{o}_{HP}\varphi^{o}_{HP}$; Θ^{o}_{HP} (φ^{o}_{HP}) are vertical (horizontal) plane half-power beamwidths in degrees

- **Radiation Efficiency, e:** ratio of radiated power to power accepted by antenna
  - Sometimes specified via Voltage Standing Wave Ratio (VSWR)
- **Antenna Gain, G = e * D**
  - Effective area of an antenna is a related concept we will see later
- Antenna polarization: orientation of the electric field of an electromagnetic wave relative to the earth
  - Linear (vertical/horizontal) vs. Circular antenna polarizations

Three Scales of Multiplicative Noise



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  - Path loss
  - Shadowing leads to variations over distances in the order of metres
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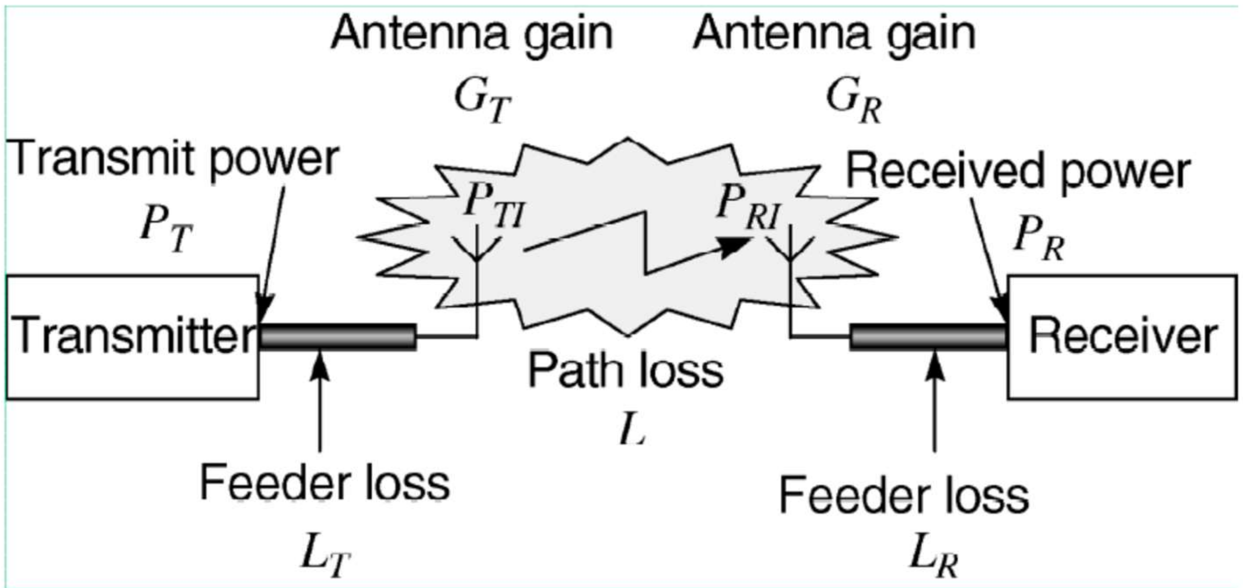
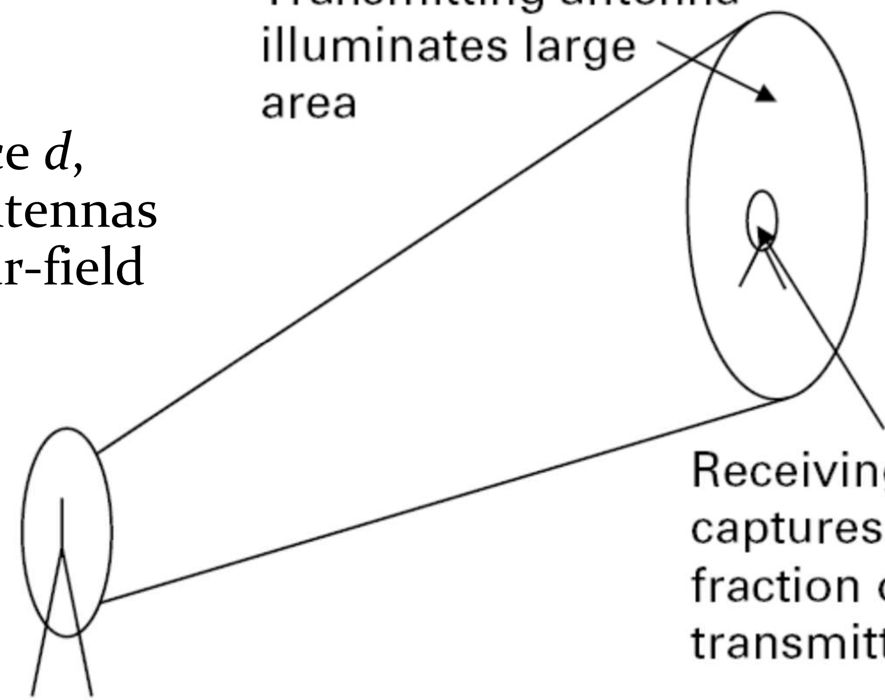
Path Loss

- Output power at transmit antenna, $P_{TI} = P_T G_T / L_T$
  - P_{TI} also called **Effective Isotropic Radiated Power (EIRP)**
- P_{RI}: Input power at receive antenna
- Received power, $P_R = P_{RI} G_R / L_R$
- Path loss, $L = P_{TI}/P_{RI} = P_T G_T G_R / P_R L_T L_R$
- Received power, $P_R = P_T G_T G_R / L_T L L_R$



Free-Space (or Spreading) Loss
Illustration on a Point-to-Point Wireless Link

- Assume antennas T and R
  - Arranged such that their directions of maximum gain are aligned
  - With matching polarizations
  - Separated by distance *d*, large enough that antennas are in each other's far-field regions



Free-Space Loss

- P_T: transmit power
- For simplicity, assume no feeder losses, i.e., $L_T = L_R = 1$
- S: power density incident on receiver antenna = $P_T G_T / 4\Pi d^2$
- Receiver antenna effective area (aperture), $A_{eR} = G_R\, \lambda^2 / 4\Pi$
- Receiver input power, $P_R = S\, A_{eR}$

➢ **Friss transmission formula:** $P_R/P_T = G_T G_R (\lambda / 4\Pi d)^2$
  - Note that this formula is valid only for values of d in the far-field region of transmit antenna

➢ **Propagation loss in free space,** $L_F = P_T G_T G_R / P_R = (4\Pi d/\lambda)^2 = (4\Pi df/c)^2$, where c is speed of light (3×10^5 Km per second)
  - ➢ $L_F\ (dB) = 32.4 + 20\log(d) + 20\log(f)$, $d\ (> 1)$ in Km and f in MHz
  - ➢ Free space loss increases by 6dB whenever either frequency or distance is doubled.

Path Loss Exponent (α)

- Free-space loss is the minimum path loss for a given distance
- Path loss in practice much higher (includes average shadowing) because of attenuation due to signal encounters with the environment
- Path loss exponent, α: a term used to indicate how fast signal power degrades with distance
  - $\alpha = 2$ in free space; typically, $2 \leq \alpha \leq 5$

Log-Distance Path Loss Model

$PL_d = PL_{do} + 10\ \alpha\ log10(d/do)$

- PL_d: Path Loss (in dB) at distance d (m)
- PL_{do}: Path Loss (in dB) at reference distance do, typically 1m for indoor environment and 1km for outdoor environment
- α: Path Loss Exponent

Path Loss Models

- Useful for network design (coverage and/or capacity), handoff optimization, power level adjustments, antenna placements, etc.
- Types of models
  - Empirical vs. analytical
  - Deterministic vs. statistical
- Some examples
  - Free-space propagation model
  - Okumura/Hata model
  - Cost 231 model
  - IMT-2000 models
  - Indoor path loss models
  - Ray tracing based

Shadowing

- Represents medium-scale fluctuations of the received signal power occurring over distances from few metres to tens or hundreds of meters
  - Due to signal encounters with terrain obstructions such as hills or man-made obstructions (e.g., buildings, trees)
  - Can be season dependant
- Received signal power may differ substantially at different locations even though at the same radial distance from transmitter
- Usually modelled as a zero-mean Gaussian (normal) random variable, X_σ, with standard deviation, σ (dB)
  - A typical value of σ is 8dB

Combined Effect of Path Loss and Shadowing

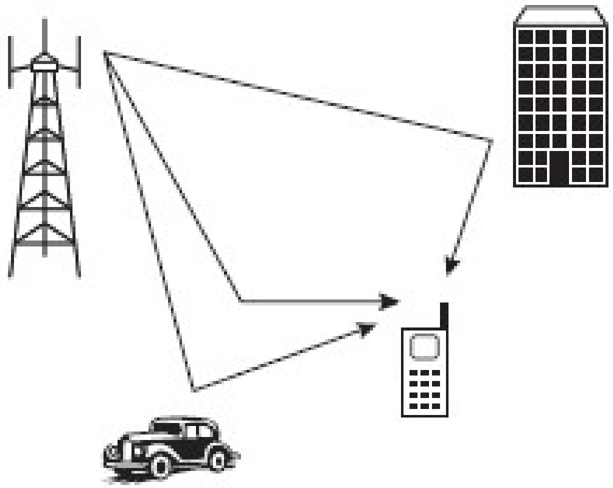
$$PL_d = PL_{do} + 10\ \alpha\ \log10(d/do) + \boxed{X_\sigma}$$

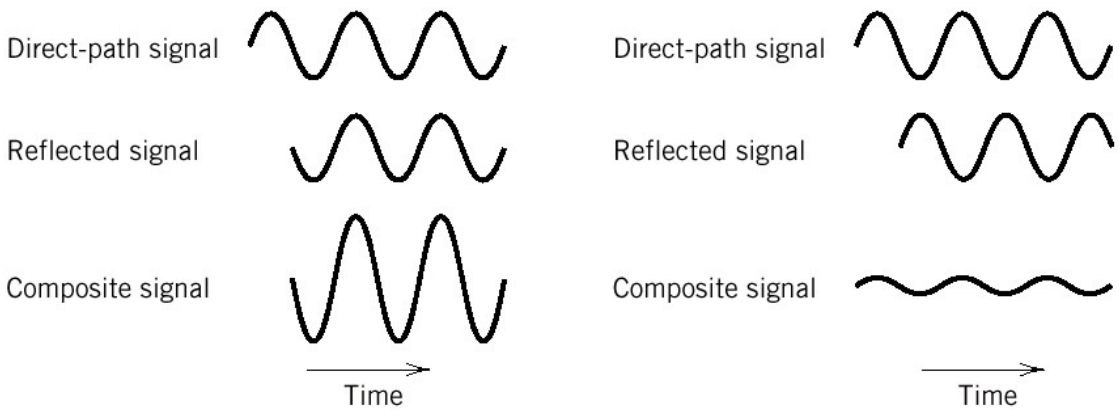
- PL_d: Path Loss (in dB) at distance *d* (m)
- PL_{do}: Path Loss (in dB) at reference distance *do*, typically 1m for indoor environment and 1km for outdoor environment
- α: Path Loss Exponent
- X_σ: shadowing related variation

Multipath (or Small-Scale or Fast) Fading

- Effects
  - Rapid changes in signal strength over a small physical distance or time interval
  - Time dispersion (echoes) caused by multipath propagation delays
  - Random frequency modulation due to Doppler shifts on different multipath signals
- Influencing Factors
  - Multipath propagation
  - The transmission bandwidth of the signal
  - Movement of transmitter, receiver and surrounding objects

Multipath Propagation





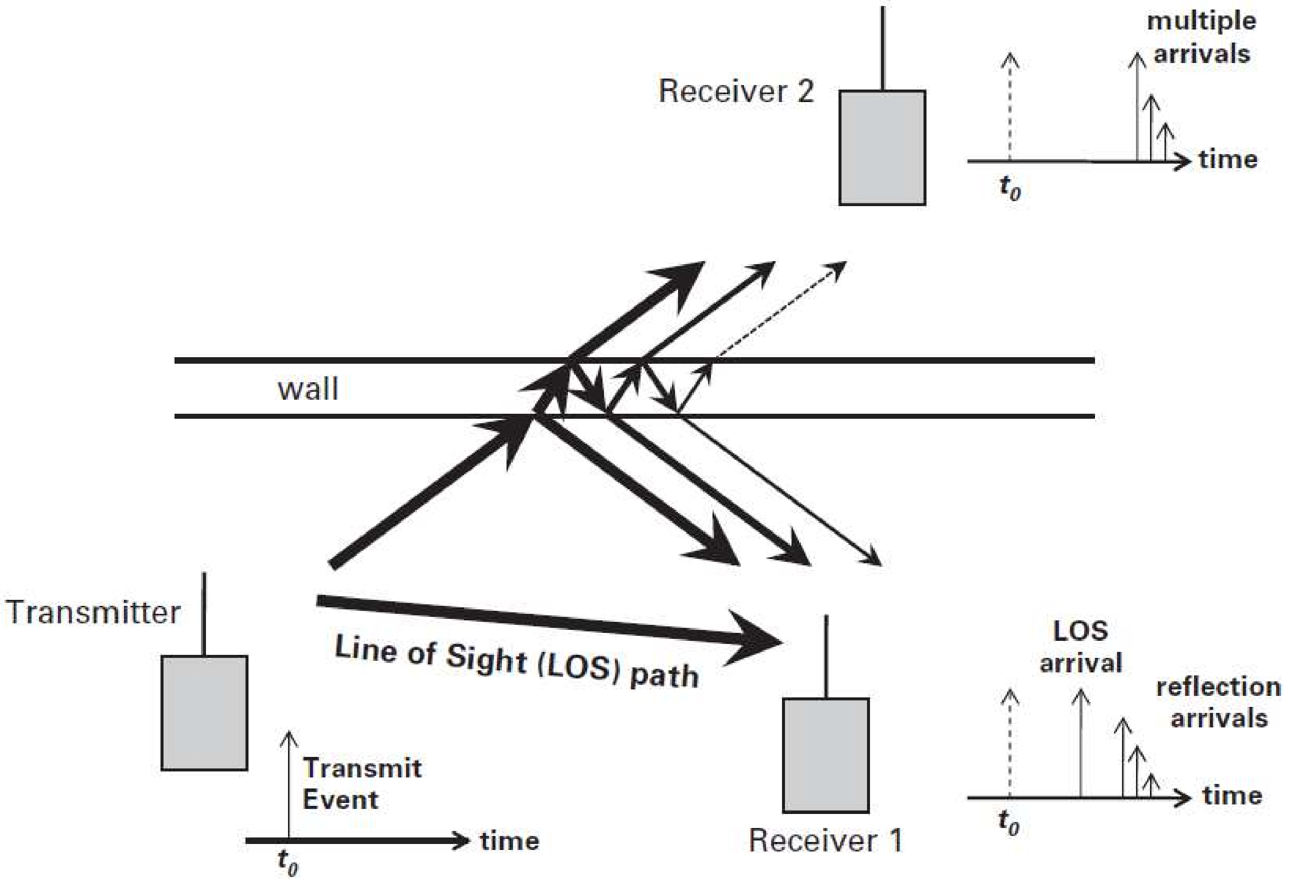
(a) (b)

(a) constructive phase interference

(b) destructive phase interference

Delay Spread or Time Dispersion

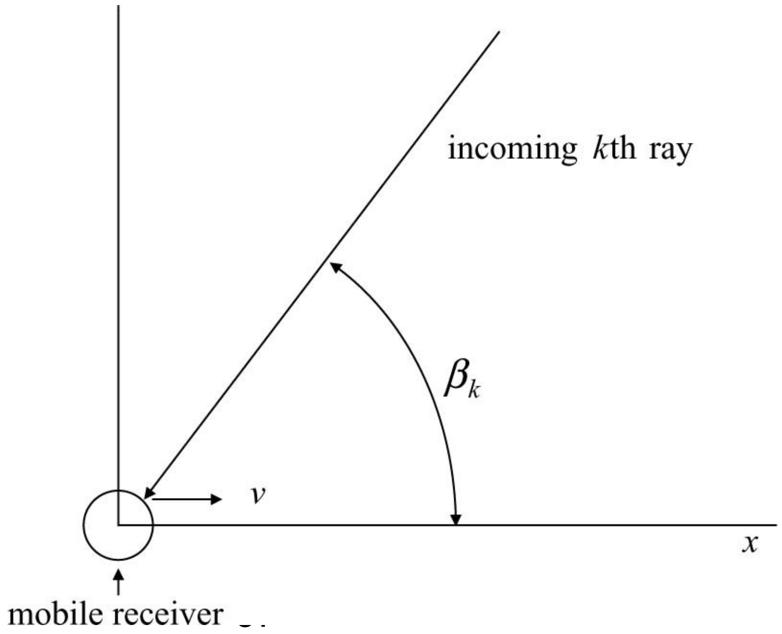
- Depends on the environment
  - Typically around 40-70ns in indoor office environments, can go up to 200ns in some cases
- Can cause inter-symbol interference (ISI)



Doppler Shift or Frequency Dispersion

- Receiver motion with respect to the incoming ray introduces a doppler frequency shift, $f_k = v \cos\beta_k/\lambda$ Hz

- Frequency of received signal with doppler shift = $f_c + f_k$, where f_c is carrier frequency



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Multipath Channel Parameters

- **Delay spread (τ_t)** and **coherence bandwidth (B_c)** describe the time dispersive (frequency-selective) nature of the channel due to delays between different propagation paths

  $T_t \propto 1/B_c$

- **Doppler spread (B_D)** and **coherence time (T_C)** describe the frequency dispersive (time-varying) nature of the channel due to relative motion of transmitter and receiver or movement of surrounding objects

  $T_C \propto 1/B_D$

Types of Small-Scale Fading

Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading

1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading

1. BW of signal > BW of channel
2. Delay spread > Symbol period

Small-Scale Fading
(Based on Doppler spread)

Fast Fading

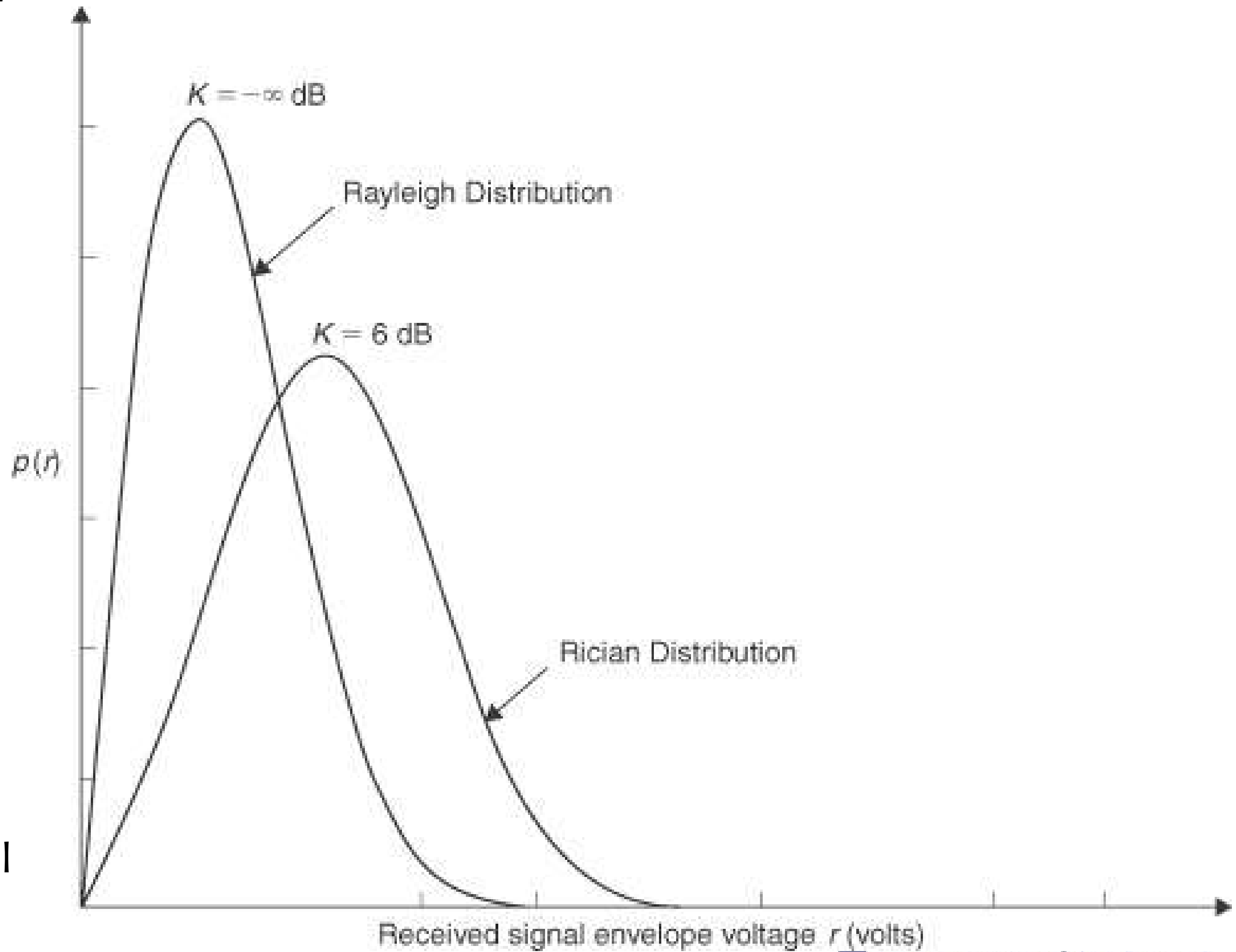
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than base-band signal variations

Slow Fading

1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Rayleigh and Rician Distributions

- Used to model small-scale fading
- Rayleigh: a common model in which we assume that the rays reach the receiver in the horizontal plane and equally from all angles
- Rician: when there is a dominant signal component such as line-of-sight (LOS) path
  - Rayleigh is a special case of Rician



Mitigating Multipath Fading

- Coding techniques for error detection and correction
- Diversity techniques (space, frequency, time and polarization dimensions)
- Equalization to mitigate frequency-selective fading
- Orthogonal frequency division multiplexing (OFDM) also to mitigate frequency-selective fading
- Interleaving for combating fast fading

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
- 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 (contd.)

- 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 (dBW)

$$\begin{aligned} N &= 10\log \mathrm{k} + 10\log T + 10\log B \\ &= -228.6\,\mathrm{dBW} + 10\log T + 10\log B \end{aligned}$$

Receiver Sensitivity

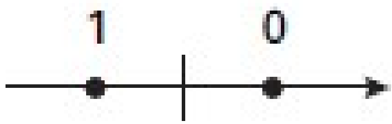
- Defined as the lowest received power level, P_R^{min}, at which just acceptable communication quality
  - Assuming only thermal noise in the receiver electronic circuitry
  - For a given transmission bit-rate (i.e., physical layer data rate or modulation & coding scheme)

- Determines the maximum communication range

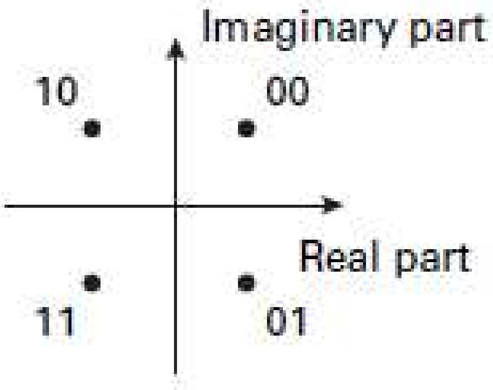
- Path loss corresponding to P_R^{min} is called *maximum acceptable path loss*

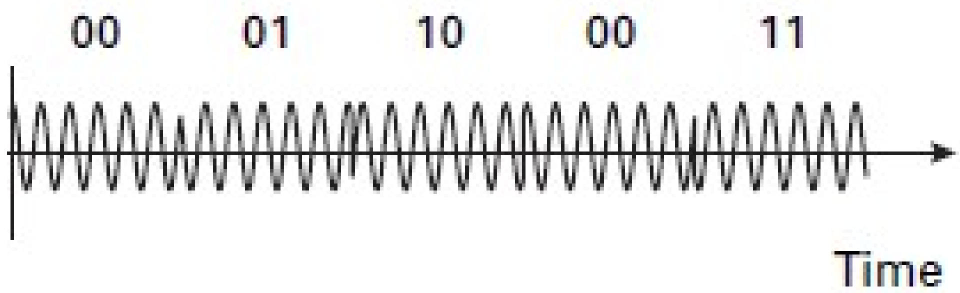
Modulated Waveforms

- Use symbols to modify a sinusoidal waveform (carrier) for transmission to receiver
- Binary Phase Shift Keying (BPSK)
  - Phase modulation using symbol phases of 0 deg and 180 deg.



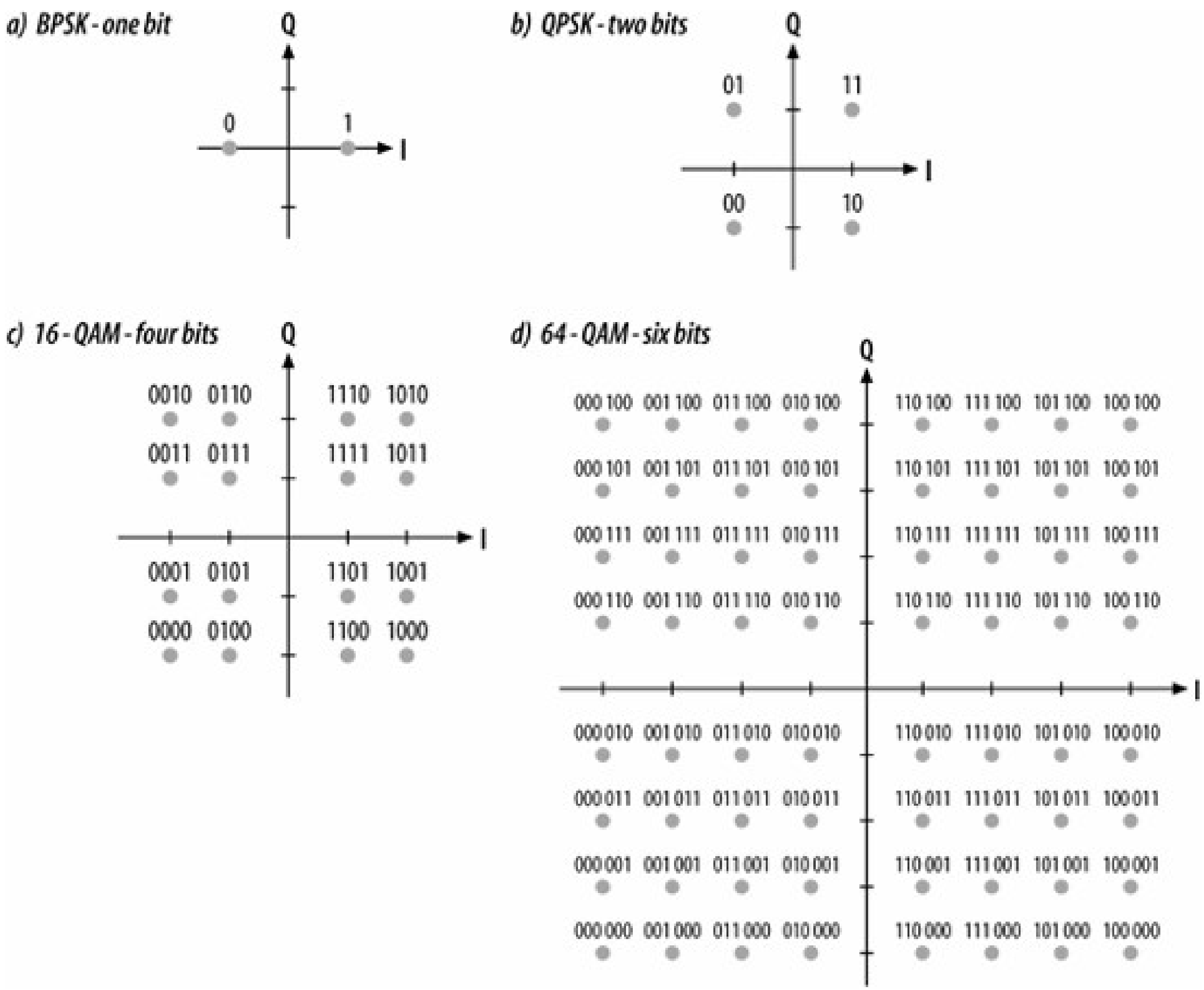
- Quadrature Phase Shift Keying (QPSK)
  - Phase modulation using symbol phases of 45 deg, 135 deg, 225 deg and 315 deg.
  - Can also be seen as amplitude modulation with symbols as complex numbers with values +/- 1 +/- i, where i is square root of -1.





Modulation Schemes and Constellations

- Bits to symbols
  - E.g., in BPSK, bits 0 and 1 are mapped onto symbols +1 and -1, respectively.
  - Real and imaginary parts are often known as in-phase (I) and quadrature (Q) components of the signal.
- The minimum distance between any two values in a constellation determines the least amount of noise that would result in a bit-error
  - denser constellations require a higher signal-to-noise ratio (S/N) to ensure they can decode every symbol correctly.
  - Distances between them represent mean energy per data bit



Error Correction Coding and Coding Rate (R)

- Information bits ←→ codewords (typically with 2-3 times as many bits)

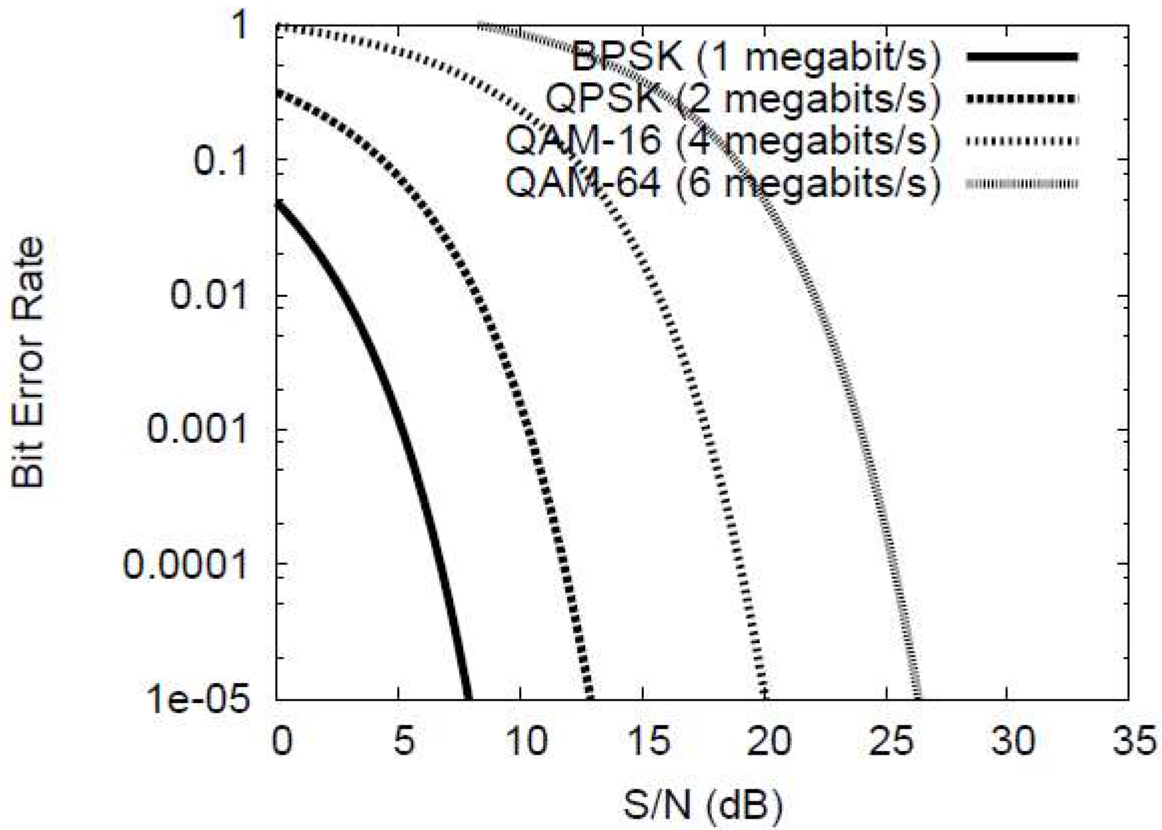
- Coding rate:
  - Determines the number of redundant bits added
  - Ratio of number of data bits transmitted to the number of coded bits
  - If K redundant bits are added for every N data bits transmitted, then $R = N / (N+K)$

Wireless Link Throughput

- Modulation and coding scheme (MCS) used determines the *transmission bit-rate*
- Use of a MCS also implies a relationship between SNR and bit-error rate (BER)

BER versus SNR

- Assume a symbol rate of 1M symbols per second and AWGN channel

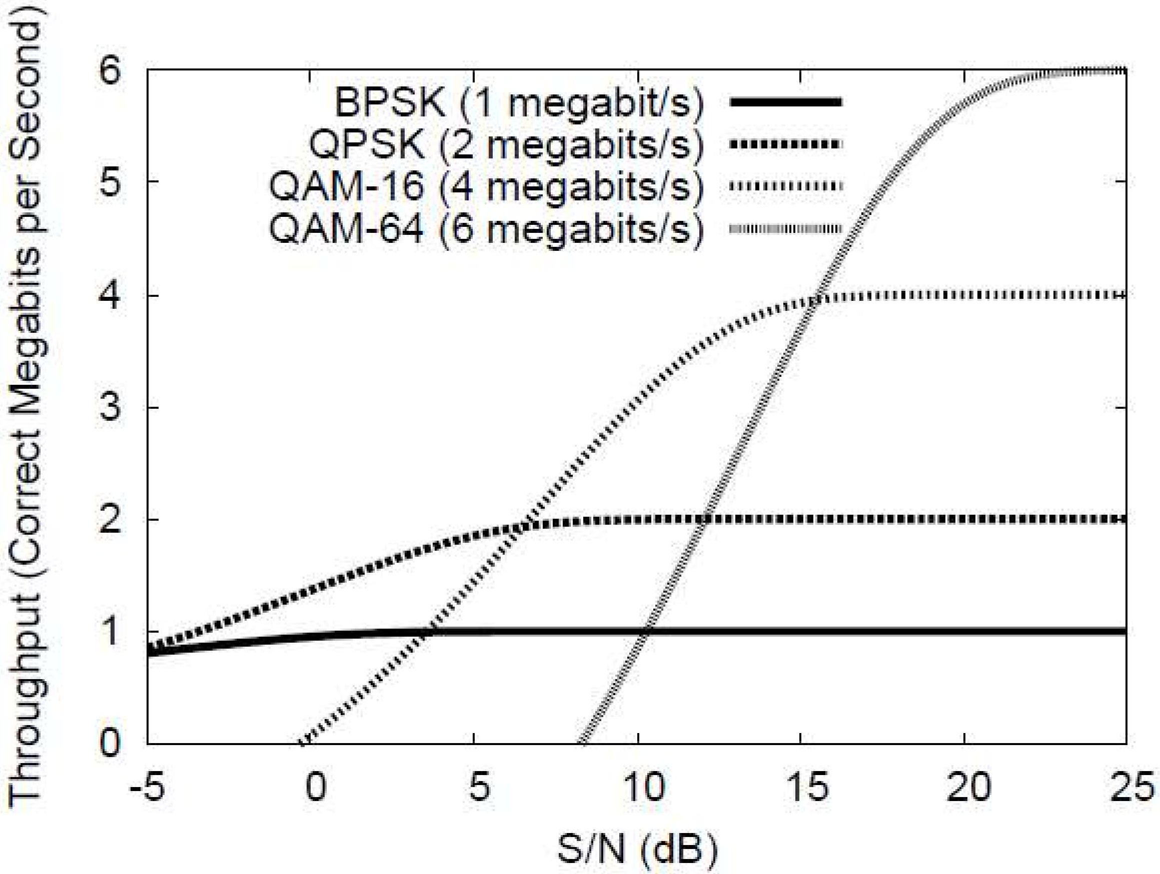


Wireless Link Throughput

- Modulation and coding scheme (MCS) used determines the *transmission bit-rate*
- Use of a MCS also implies a relationship between SNR and bit-error rate (BER)
- Frame error rate (FER) = $1 – (1\text{- BER})^L$

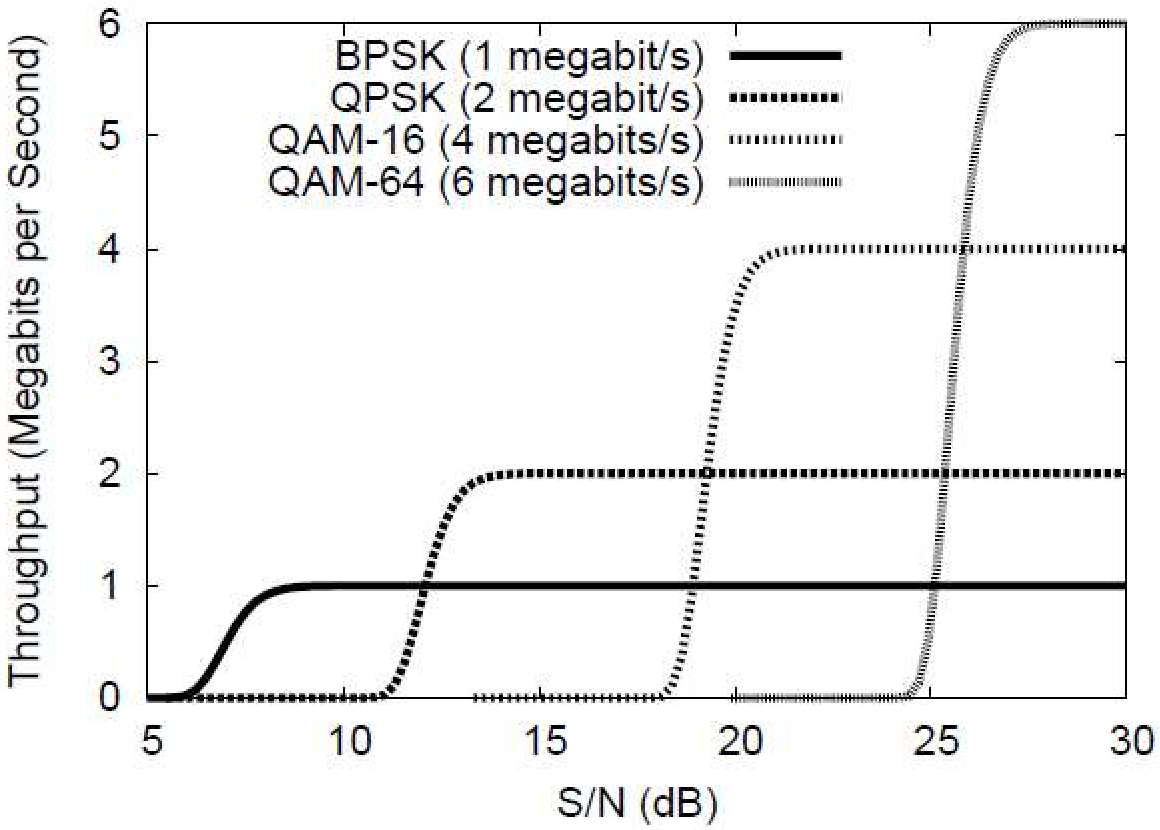
  L, frame length
- Throughput = bit-rate * (1-FER) = bit-rate * $(1\text{- BER})^L$
- The above two equations assume that no error correction used

Bit-Level Throughput versus SNR



Frame-Level Throughput versus SNR

- Assuming 1500 byte frames



Multiple Access

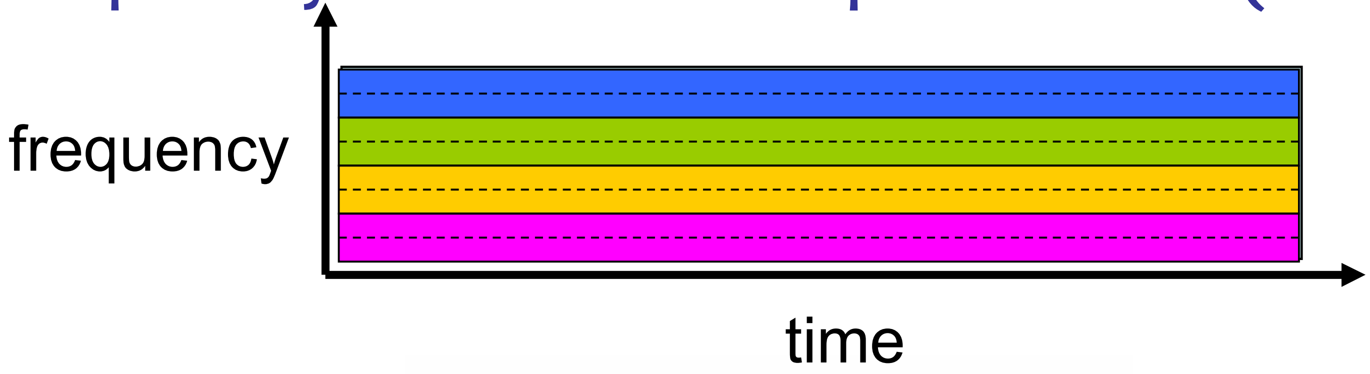
(Common) Multiple Access Techniques

- Frequency Division Multiple Access (FDMA)

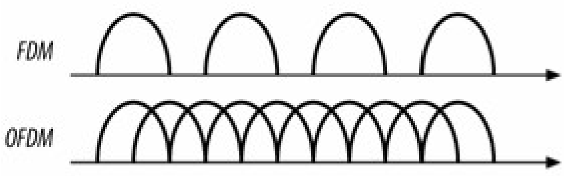
- Time Division Multiple Access (TDMA)
  - Packet mode Multiple Access

- Code Division Multiple Access (CDMA)

Frequency Division Multiple Access (FDMA)

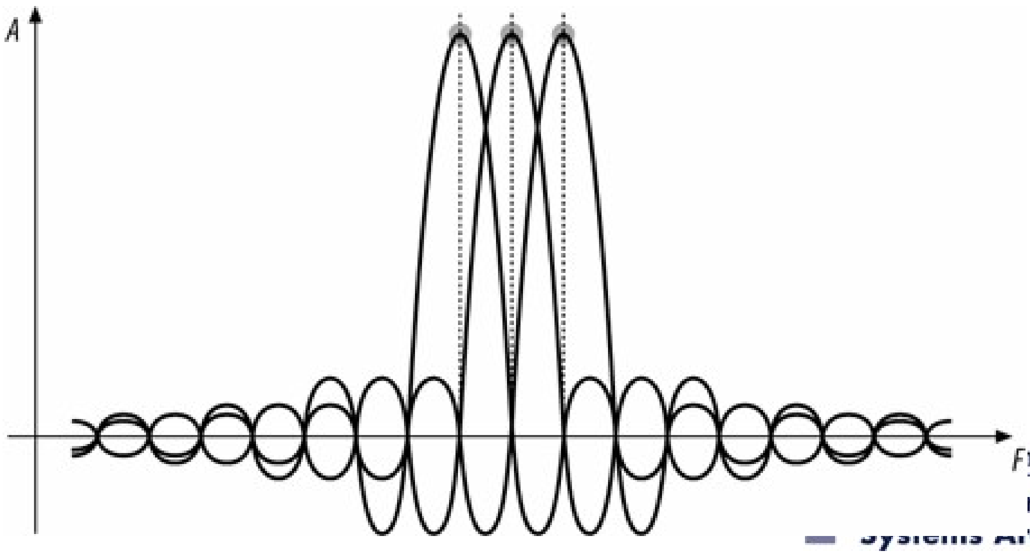


- Early cellular systems were based on FDMA
- Used for AM radio broadcasting and in telephone networks
- OFDM (and OFDMA) similar to FDMA except that
  - Frequency division fine-grained (i.e., closer frequency spacing) with no guard bands
  - Dynamic allocation of subcarriers (in WiMAX and 4G/LTE)

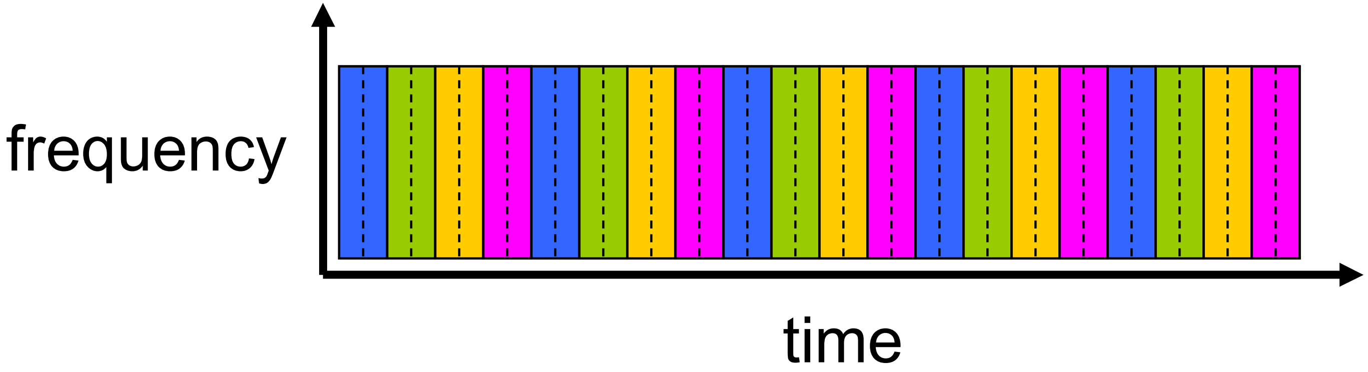


Orthogonal Frequency Division Multiplexing (OFDM)

- A wide channel is divided into several component "orthogonal" subcarriers that do not interfere with each other
  - Use multiple subcarriers in parallel for a single transmission by multiplexing data over all of them
  - Guard time needed but with much less overhead than guard bands with classic FDM
- Similar to the discrete multi-tone (DMT) in DSL systems
- Used in cable networks and power line networking
- Physical layer in 802.11a/g is based on OFDM; also used in 4G/LTE cellular systems



Time Division Multiple Access (TDMA)



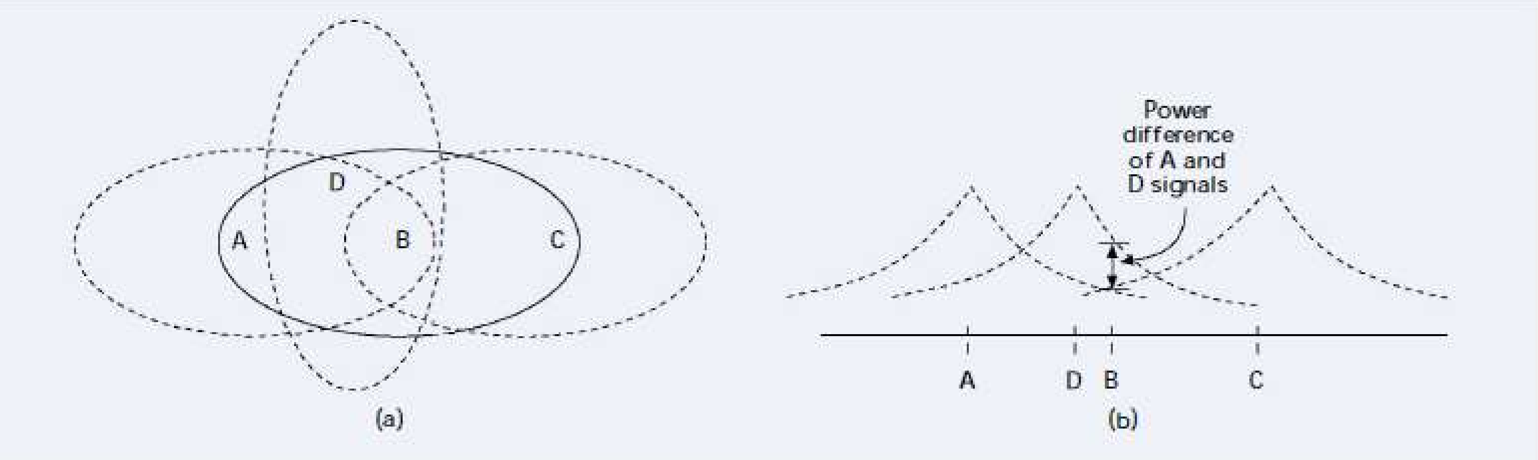
- Used in telephone and 2G cellular networks
- More difficult to implement than FDMA since the users must be time-synchronized
  - Guard time to cope with timing variations
- But easier to accommodate multiple data rates with TDMA because multiple timeslots can be assigned to a given user

Packet mode Multiple Access

- Also based on time-domain multiplexing like TDMA
- But dynamic to adapt allocation based on traffic demands, so a statistical multiplexing technique
- Contention based Random Multiple Access
  - ALOHA, Slotted ALOHA, CSMA, CSMA/CD (Ethernet), CSMA/CA (WiFi)
- Token Passing
  - Token ring, Token bus
- Polling
- Scheduled
  - Dynamic TDMA, etc.

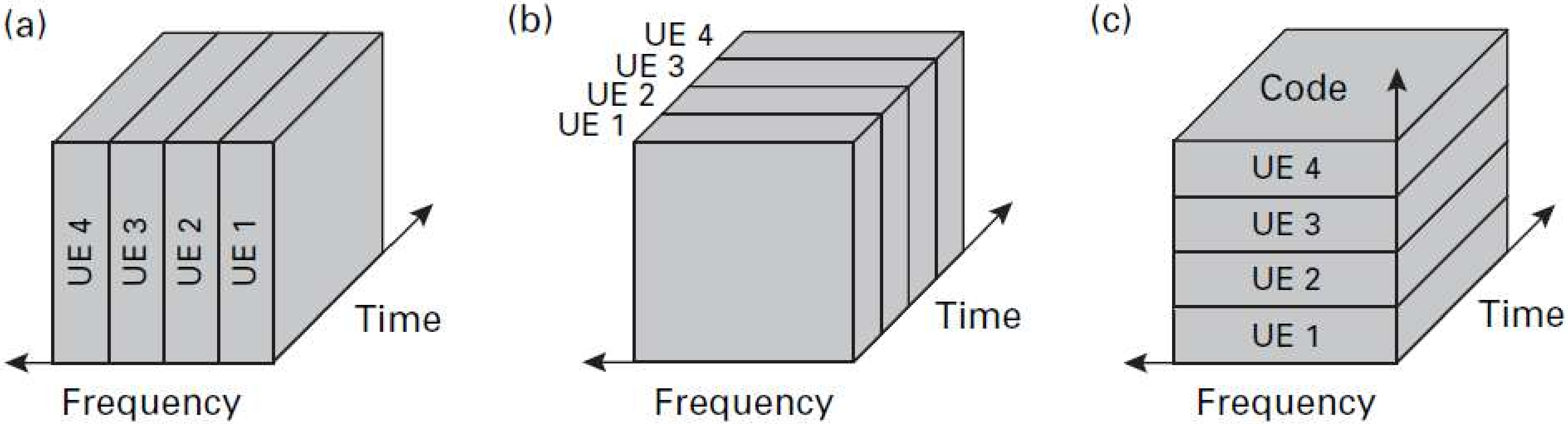
Wireless Random Multiple Access Issues

- Receiver side interference (collisions occur at receiver, detection at transmitter difficult) and half-duplex operation
- Location-dependent carrier sensing
  - Hidden terminals (e.g., A and C are hidden from each other ➔ colliding transmissions at B)
  - Exposed terminals (e.g., C is exposed to B's transmission to A and wastes a transmission opportunity since C could potentially transmit without causing interference to A)
  - Capture: a signal received at significantly higher power compared to other concurrently received signals can still be correctly decoded (e.g., D's transmission can capture A's transmission at B)



(a) Dotted/solid ellipses indicate node ranges; (b) shows signal decay with distance

Code Division Multiple Access (CDMA)

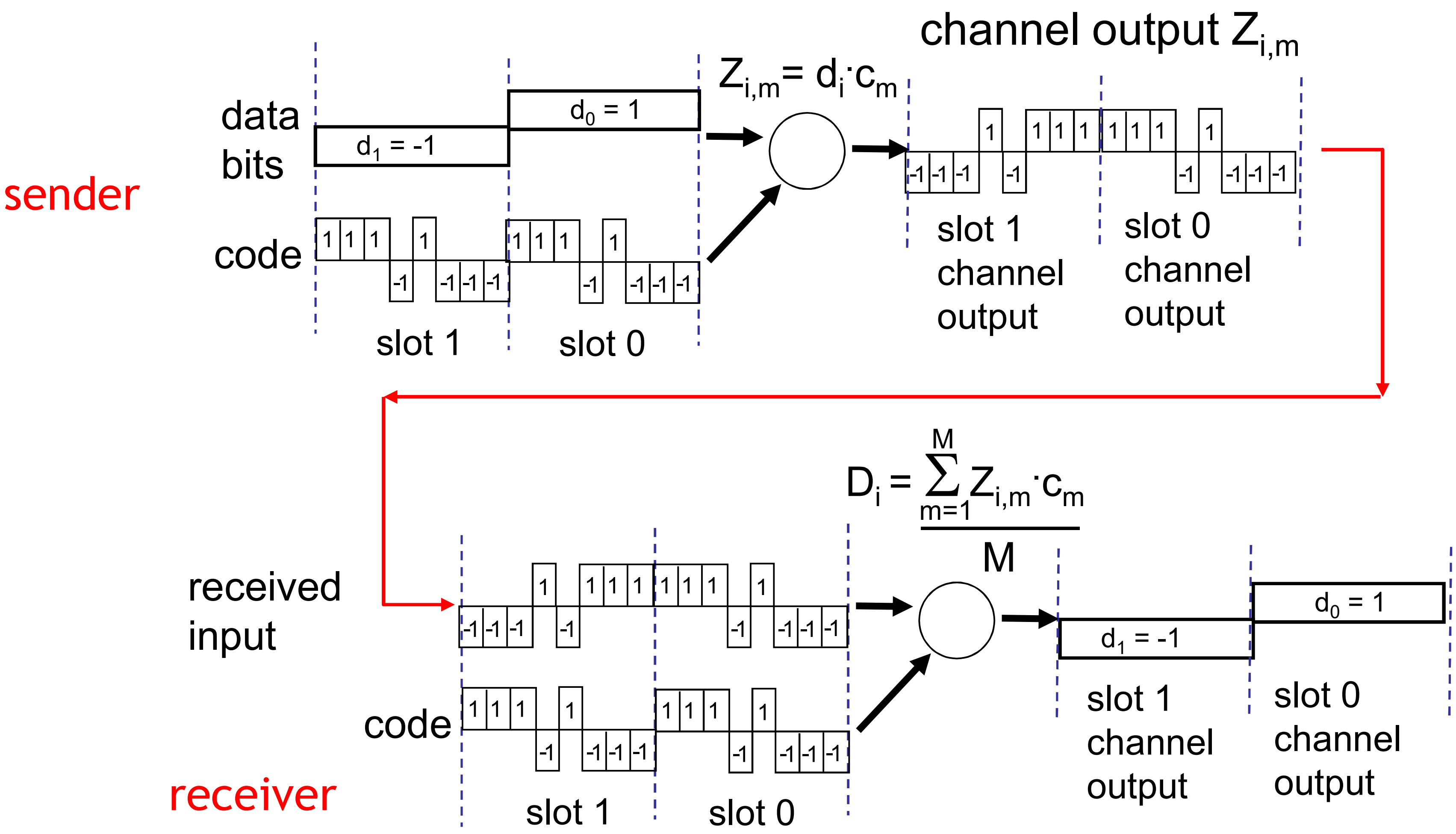


(a) FDMA, (b) TDMA, (c) CDMA.

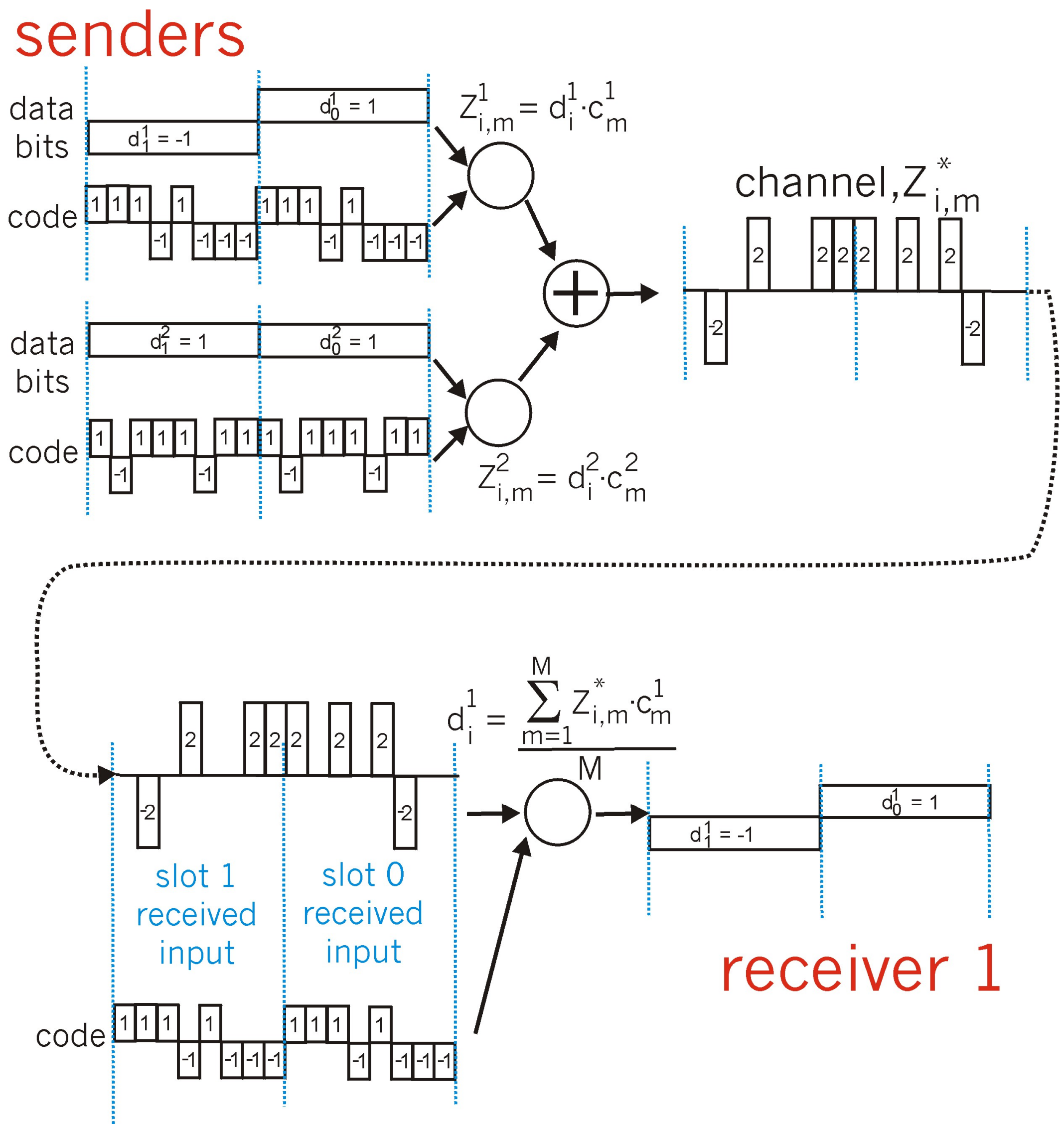
CDMA

- Unique "code" assigned to each user, i.e., code set partitioning
- All users share same frequency, but each user has own "chipping" sequence (code) to encode data
- Encoded signal = (original data) X (chipping sequence)
- Decoding: normalized inner-product of encoded signal and chipping sequence

CDMA Encode/Decode



CDMA with Two Senders



CDMA

- Used in 2G/3G cellular, satellite and cable networks

- Benefits:
  - Assuming codes are "orthogonal", allows multiple users to "coexist" and transmit simultaneously in the same frequency channel with minimal interference ➔ increased capacity
  - More resilient to narrowband interference (jamming)
  - Enables soft handoffs

- Issues:
  - code selection
  - time synchronization
  - near-far problem

(Common) Multiple Access Techniques

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
  - Packet mode Multiple Access
- Code Division Multiple Access (CDMA)
- Spatial Reuse
  - Can be used in conjunction with FDMA, TDMA or CDMA
  - Exploits signal propagation characteristics (e.g., signal decay with distance) to realise multiple concurrent transmissions in a given area
  - Key principle underlying modern cellular networks