Overview of Wireless Communications

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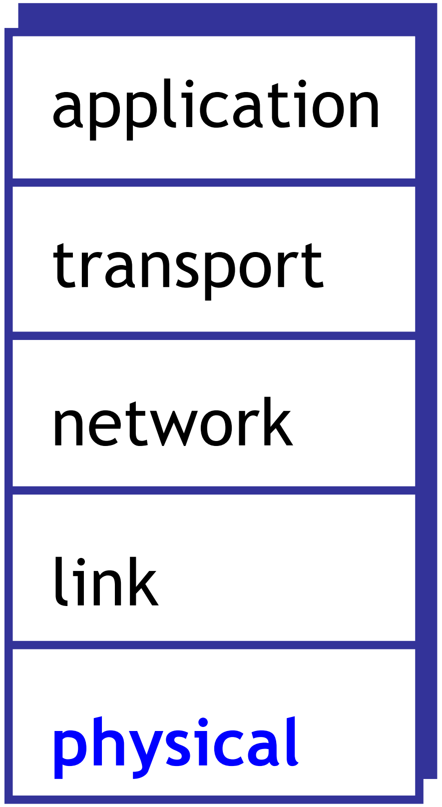
Plan

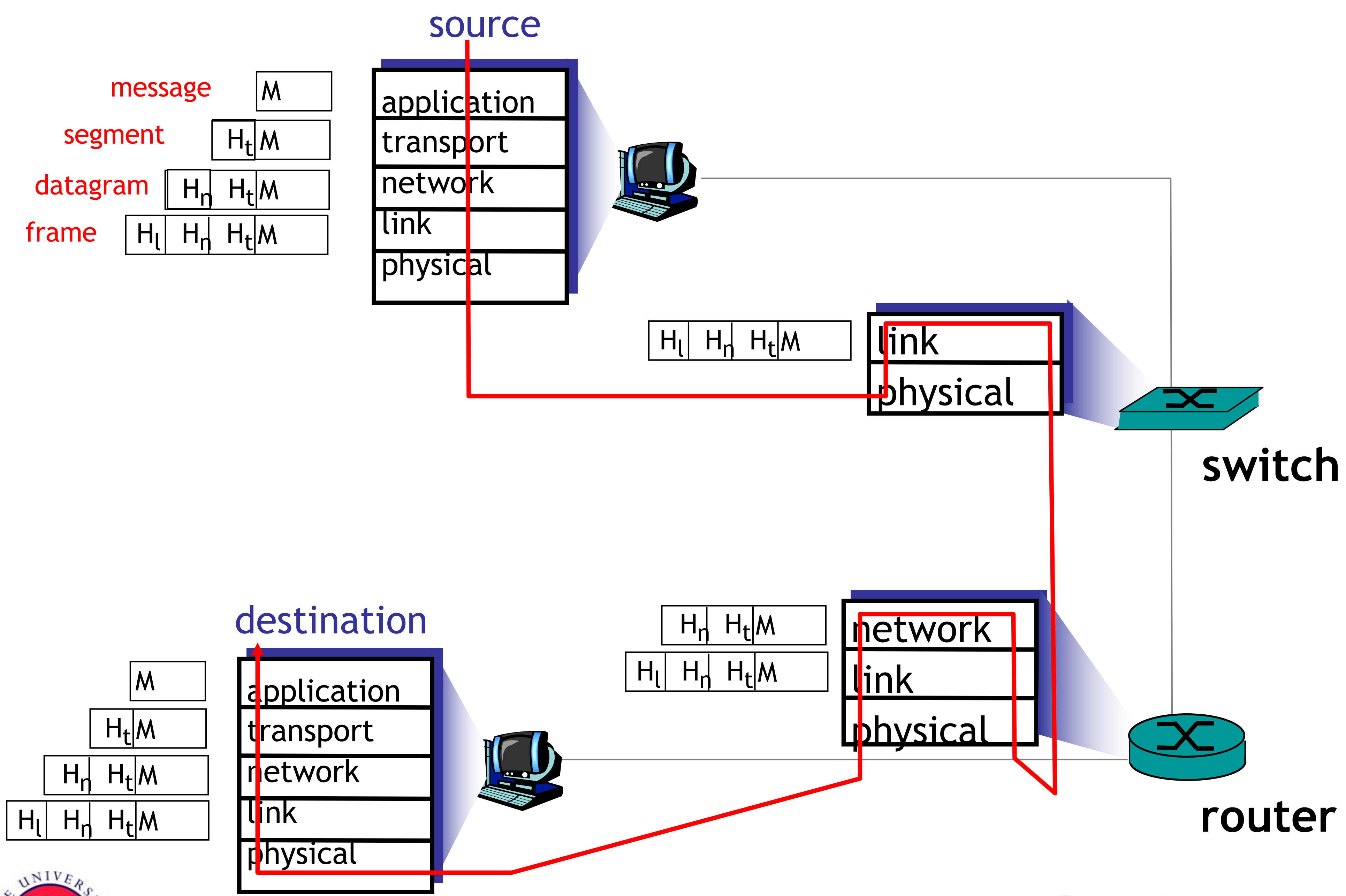
- Initially, focus on a single wireless link
  - Operating on a small slice of spectrum called a "channel", defined by a centre frequency and channel width

- 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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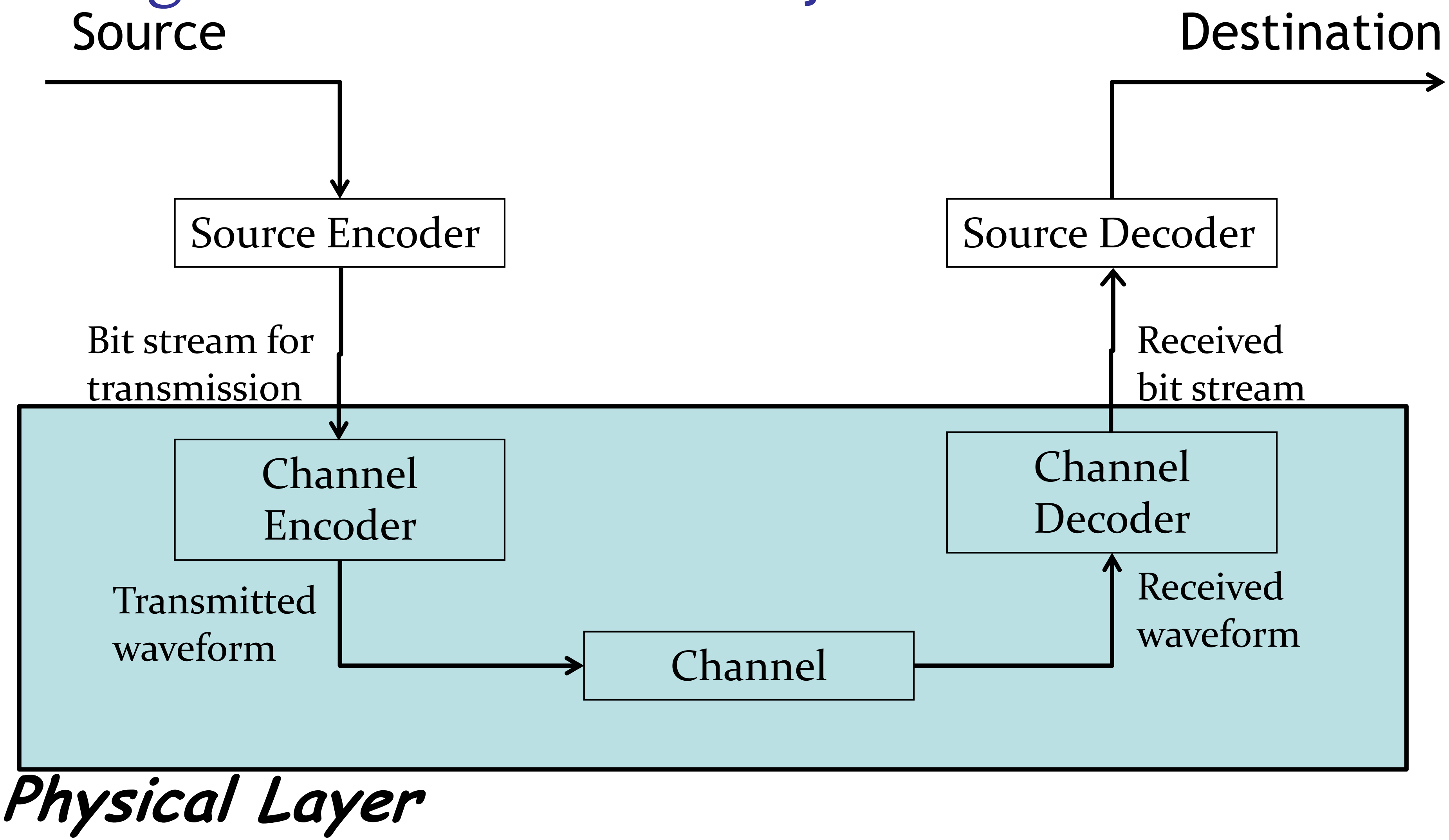
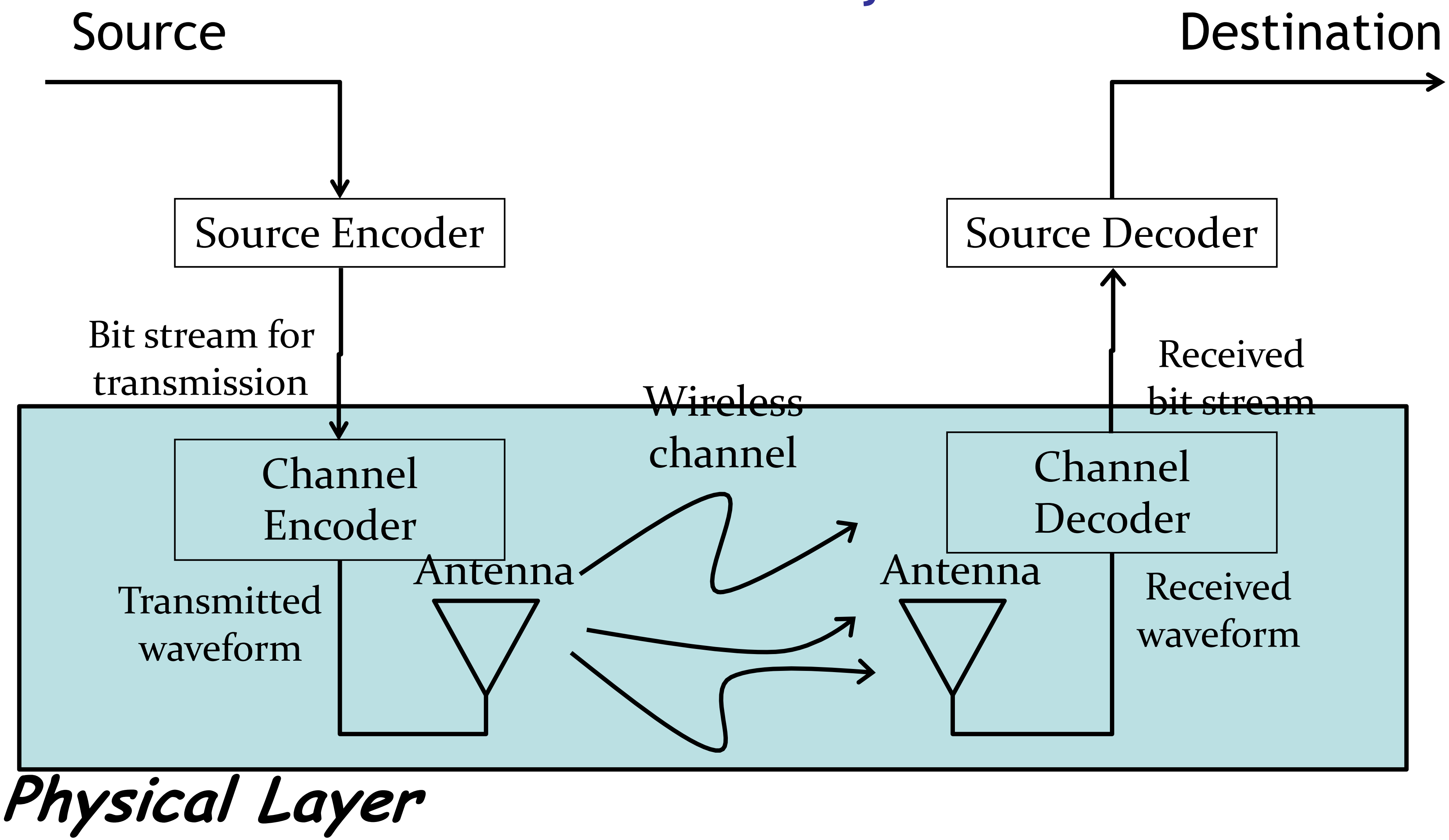
Digital Communication System



Channel Encoder/Decoder Layers

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

Wireless Communication System



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

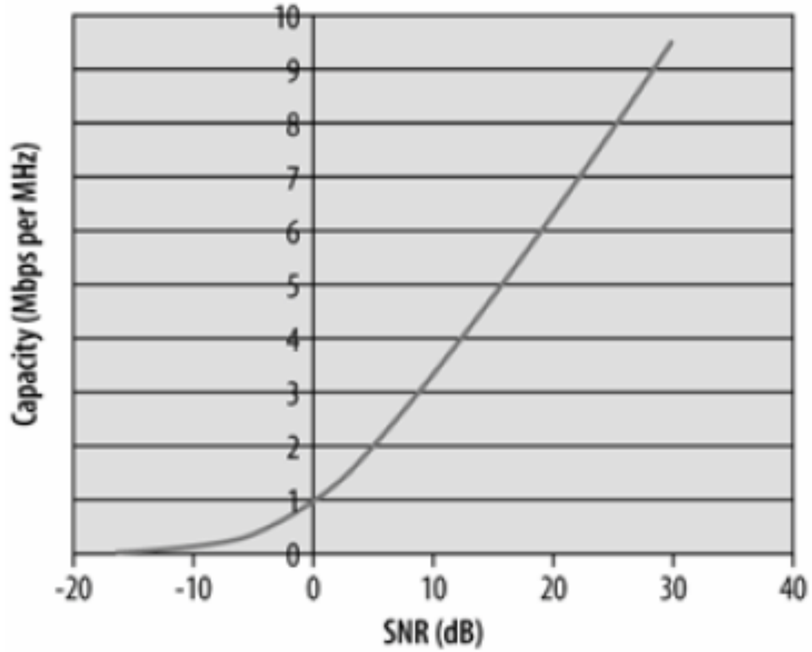
Decibels (Contd.)

- 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)

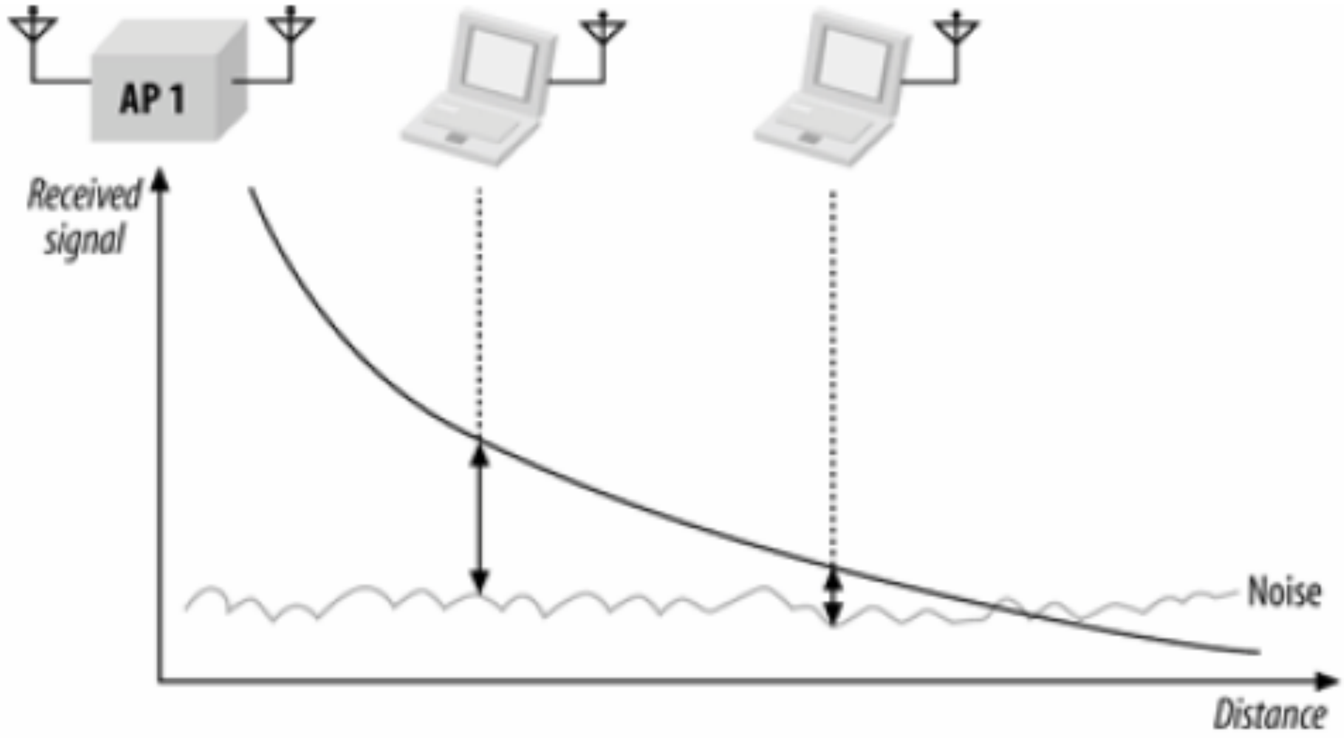
End of Digression

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

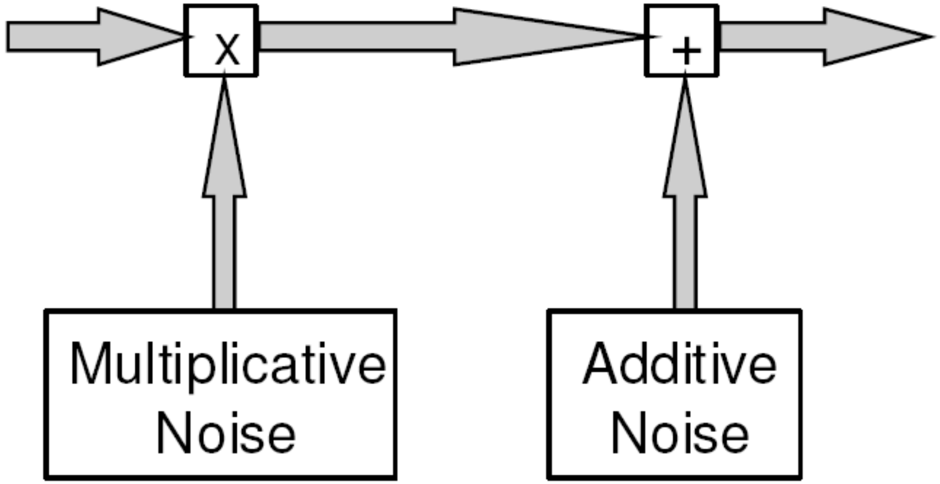


SNR versus Distance



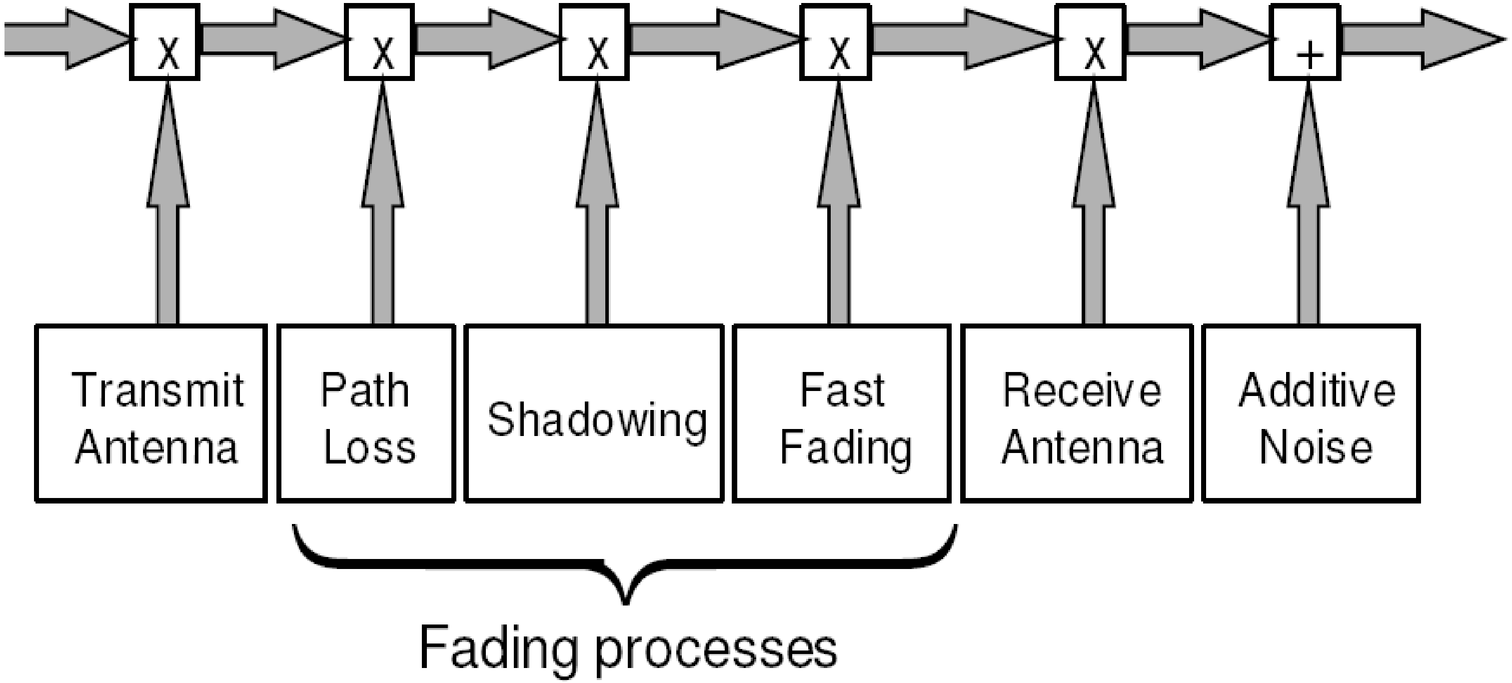
Wireless Channel

Noise Types in a Wireless Channel



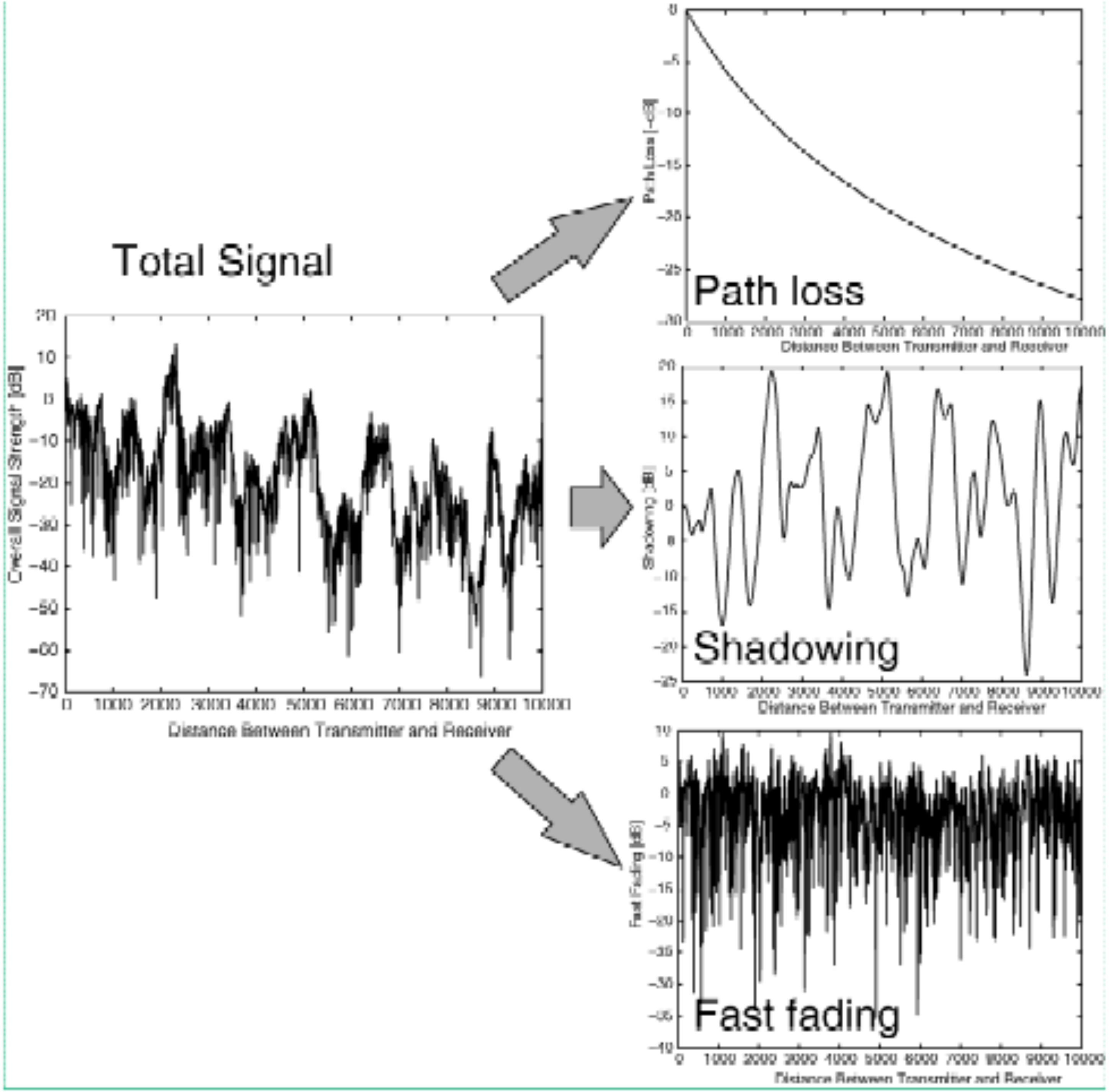
- Multiplicative
  - Antenna directionality
  - Attenuation from absorption (walls, trees, atmosphere)
  - Shadowing
  - Reflection (smooth surfaces)
  - Scattering (rough surfaces and small objects)
  - Diffraction (edges of buildings and hills)
  - Refraction (atmospheric layers, layered/graded materials)
- 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

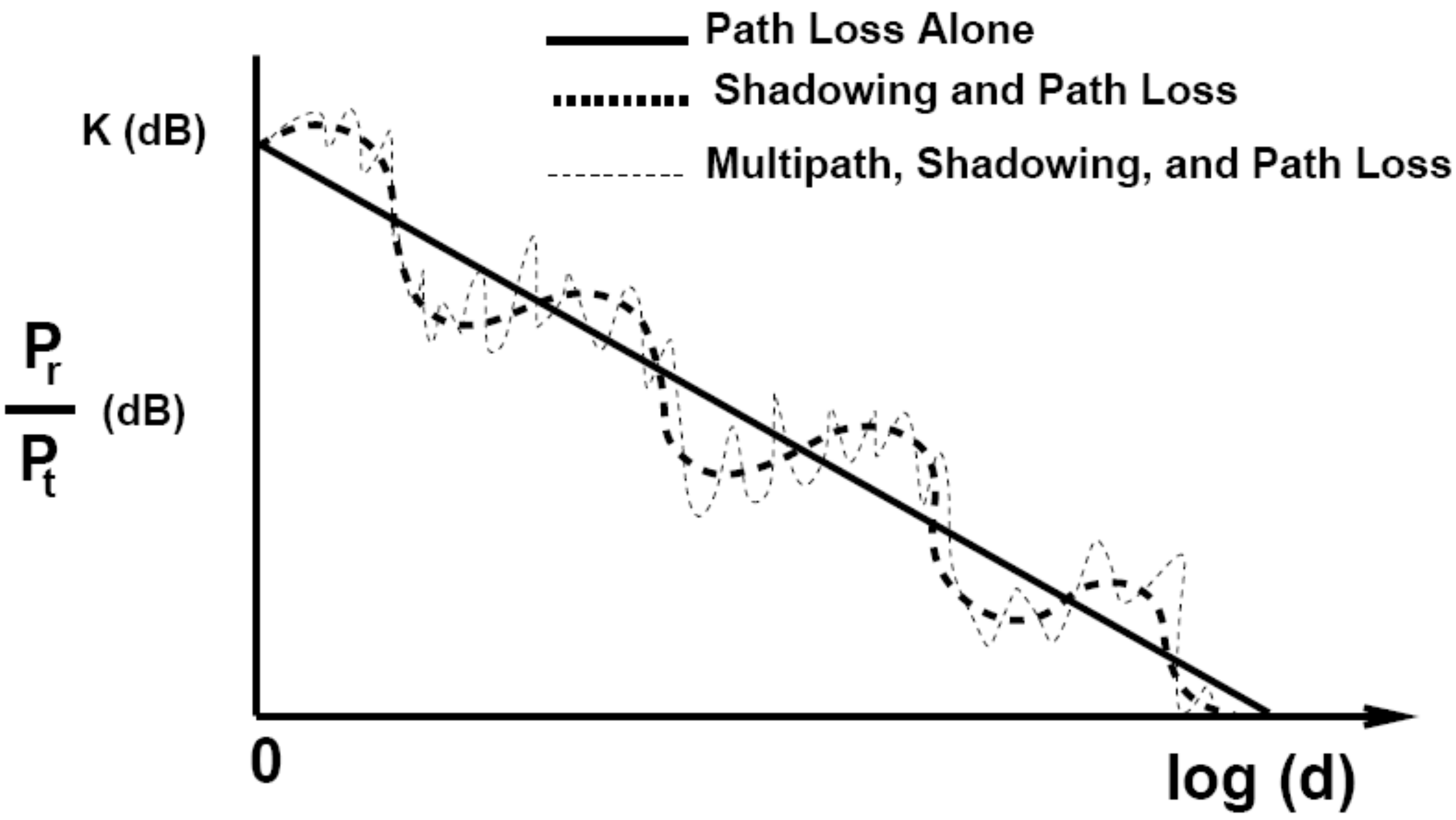


- Large and medium scale propagation effects
  - Path loss
  - Shadowing leads to variations over distances in the order of metres
    - Could be over 10s or 100s of metres in outdoor environments
- Small-scale fading (or multipath fading): causes variations of over very short distances in the order of the signal wavelength

Fading Processes Illustrated



Another Illustration of Path Loss, Shadowing and Multipath Fading



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Recap from last week

- Prominent examples of wireless networks
- Benefits and characteristics/challenges of wireless networks
- Common wireless network model
- Different categorisations of wireless networks
- Spectrum regulation and access models
- Standards
- Building blocks of a wireless communication system
- Decibel notation
- Intuitive understanding of Signal-to-Noise Ratio (SNR) and its relationship with data rate of a wireless link
- Types and scales of noise in wireless systems

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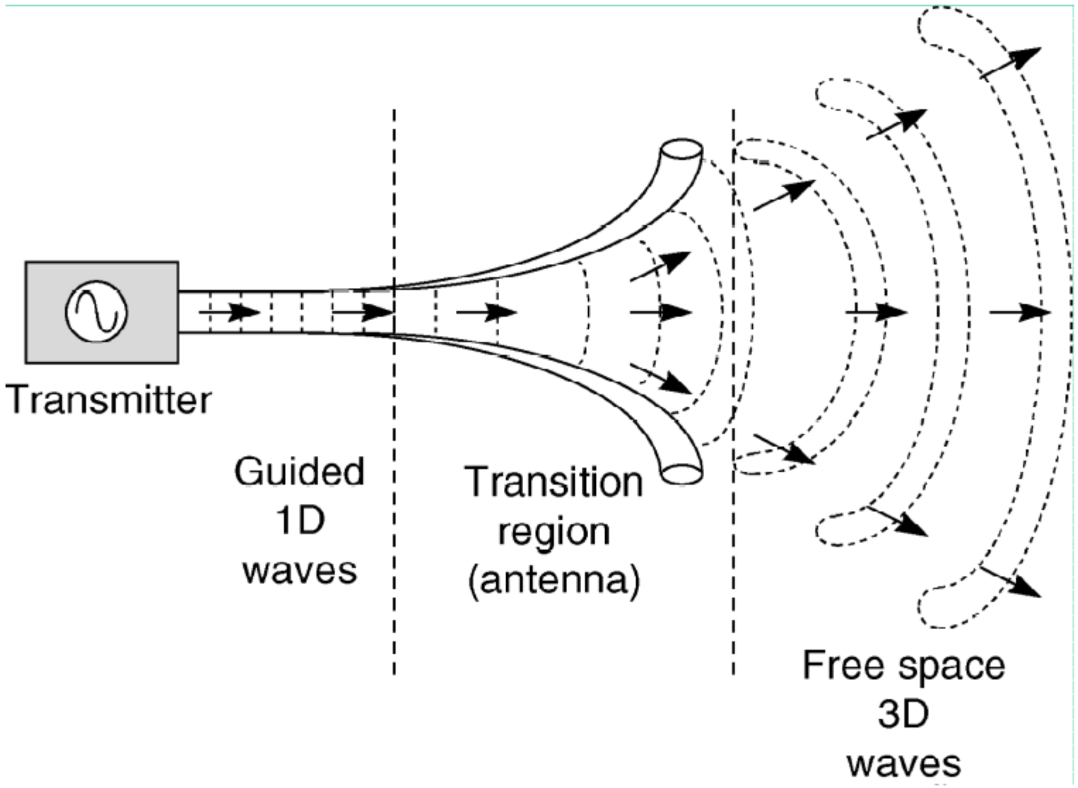
Antennas

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



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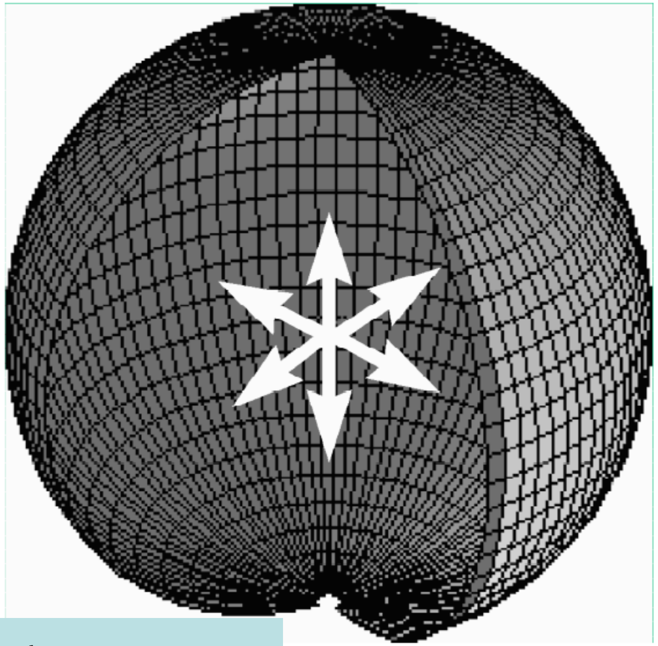
Antenna Radiation Pattern

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

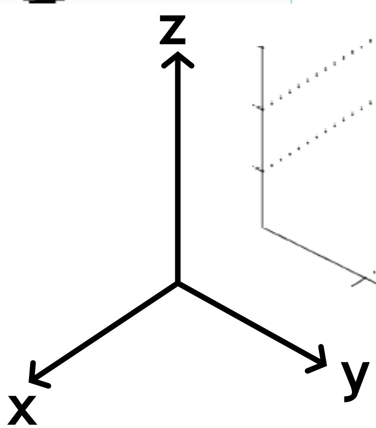
- Azimuth plane (x-y plane), Elevation plane (x-z plane)

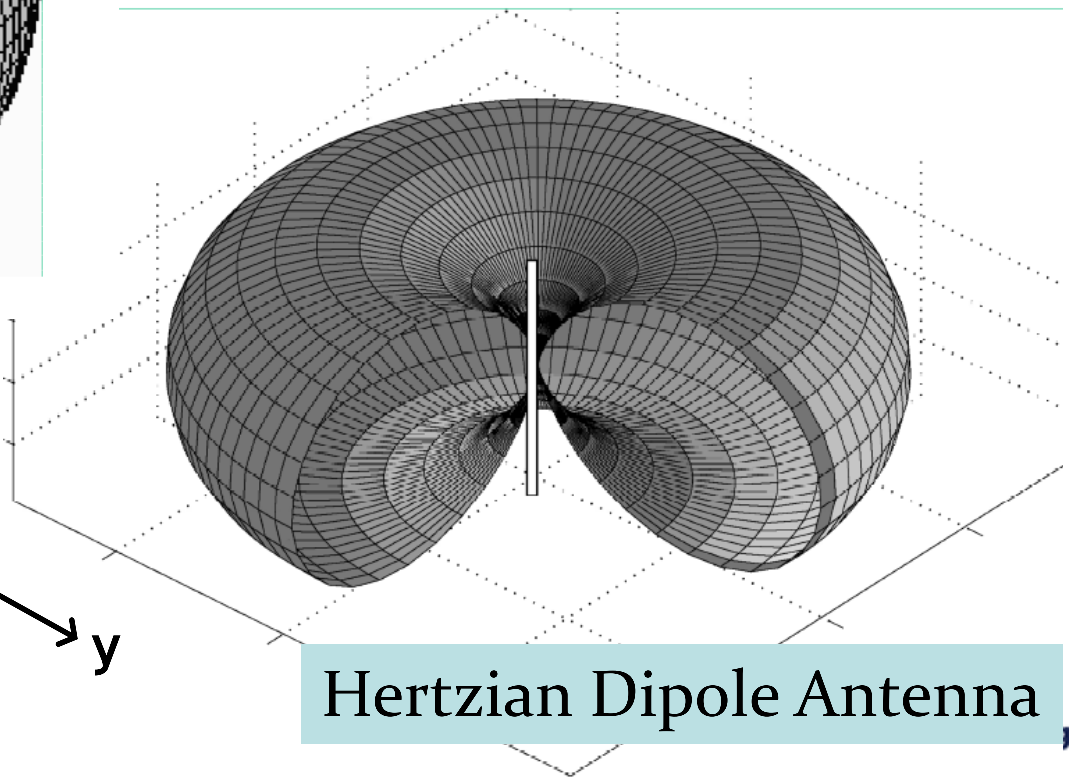
- Different types of antennas have different radiation patterns
  - An ideal isotropic antenna has a spherical pattern
  - Omnidirectional (e.g., hertzian dipole) antenna has a donut shaped pattern
  - Directional antennas radiate power along a direction

Antenna Radiation Pattern (contd.)



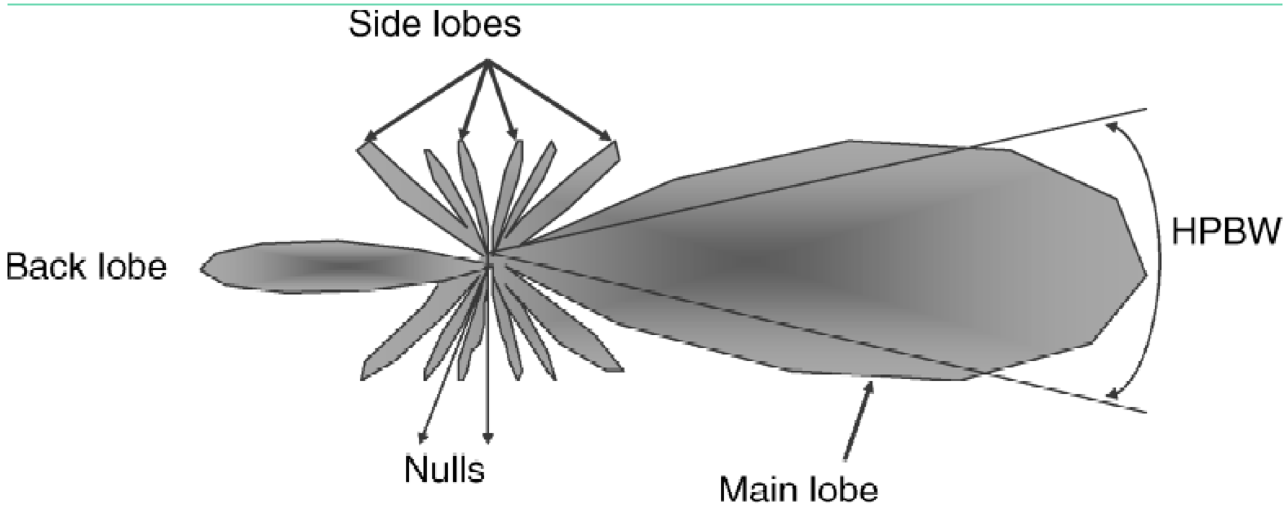
Isotropic Antenna





Hertzian Dipole Antenna

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

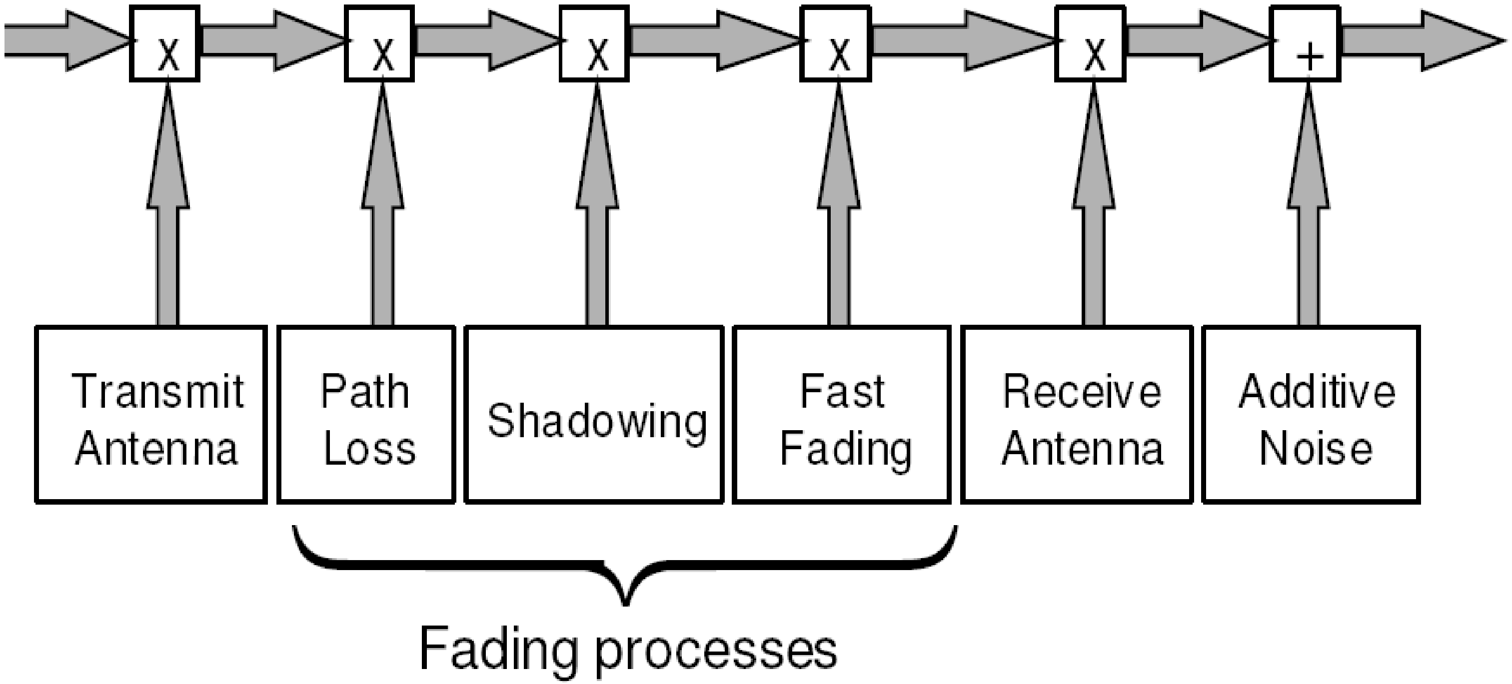
Gain and Other Antenna Characteristics

- **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
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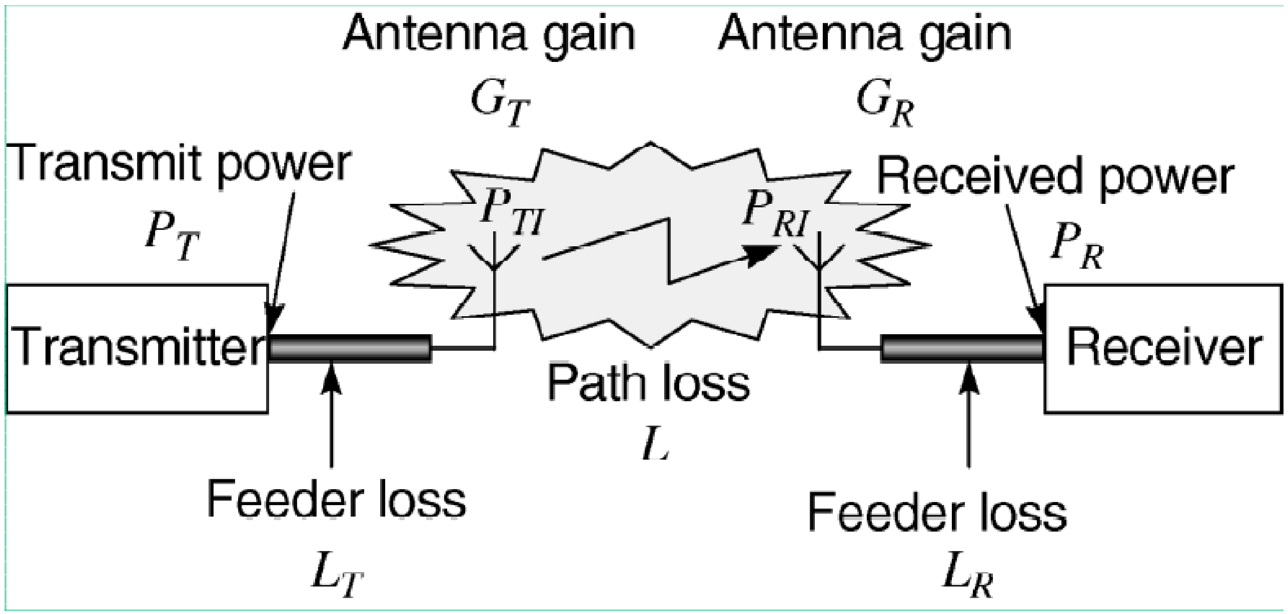
Path Loss

- 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 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

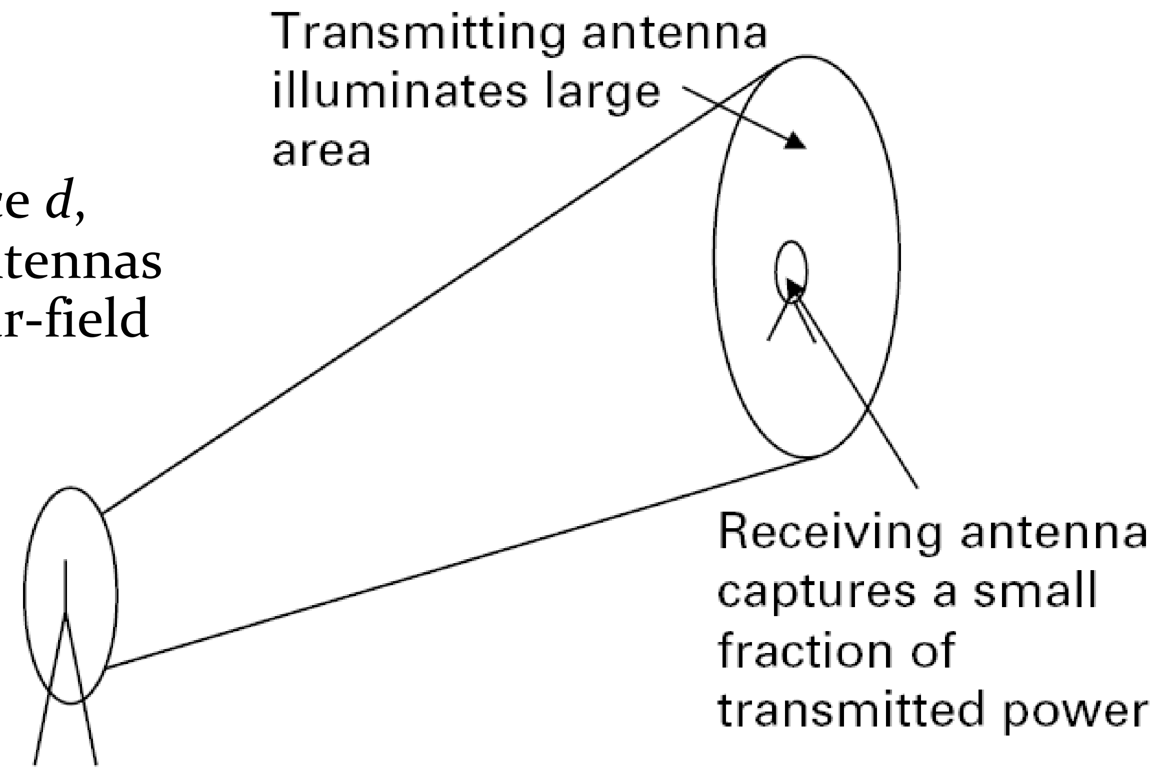
➢ **Propagation loss in free space,** $L_F = P_T G_T G_R / P_R = (4\Pi d/\lambda)^2 = (4\Pi df/c)^2$, where c is speed of light (3×10^5 Km per second)

  ➢ $L_F\,(dB) = 32.4 + 20log(d) + 20log(f)$, $d\ (> 1)$ in Km and f in MHz

  ➢ Free space loss increases by 6dB whenever either frequency or distance is doubled.

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



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

$$PL_d = PL_{d0} + 10\ \alpha\ \log10(d/d0)$$

- PL_d: Path Loss (in dB) at distance *d* (m)
- PL_{d0}: Path Loss (in dB) at reference distance *d0*, 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
  - Analytical vs. empirical
  - 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

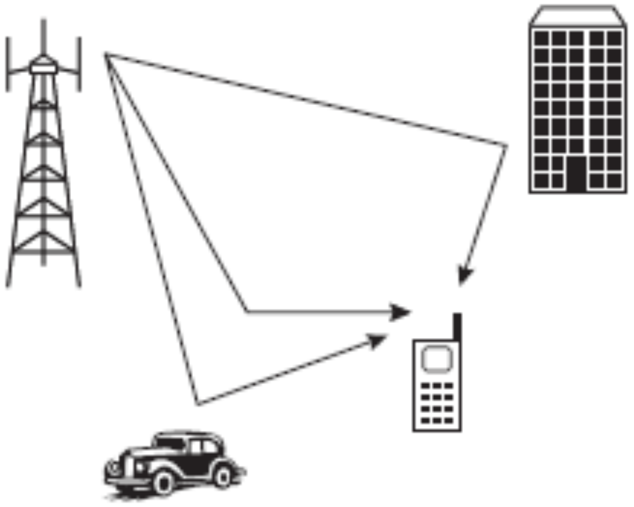
$$PL_d = PL_{d0} + 10\,\alpha\,\log10(d/d0) + X_\sigma$$

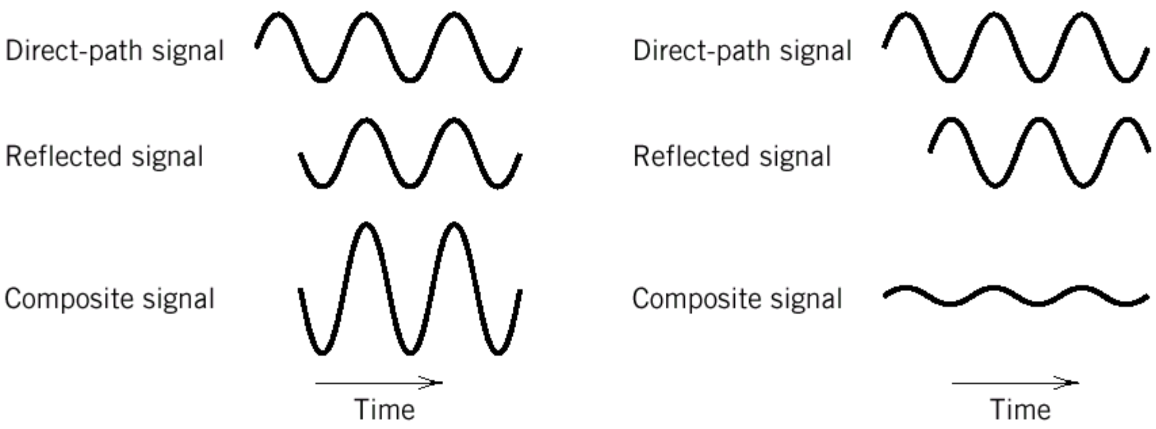
- PL_d: Path Loss (in dB) at distance *d* (m)
- PL_{d0}: Path Loss (in dB) at reference distance *d0*, typically 1m for indoor environment and 1km for outdoor environment
- α: Path Loss Exponent
- X_σ: shadowing related variation

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





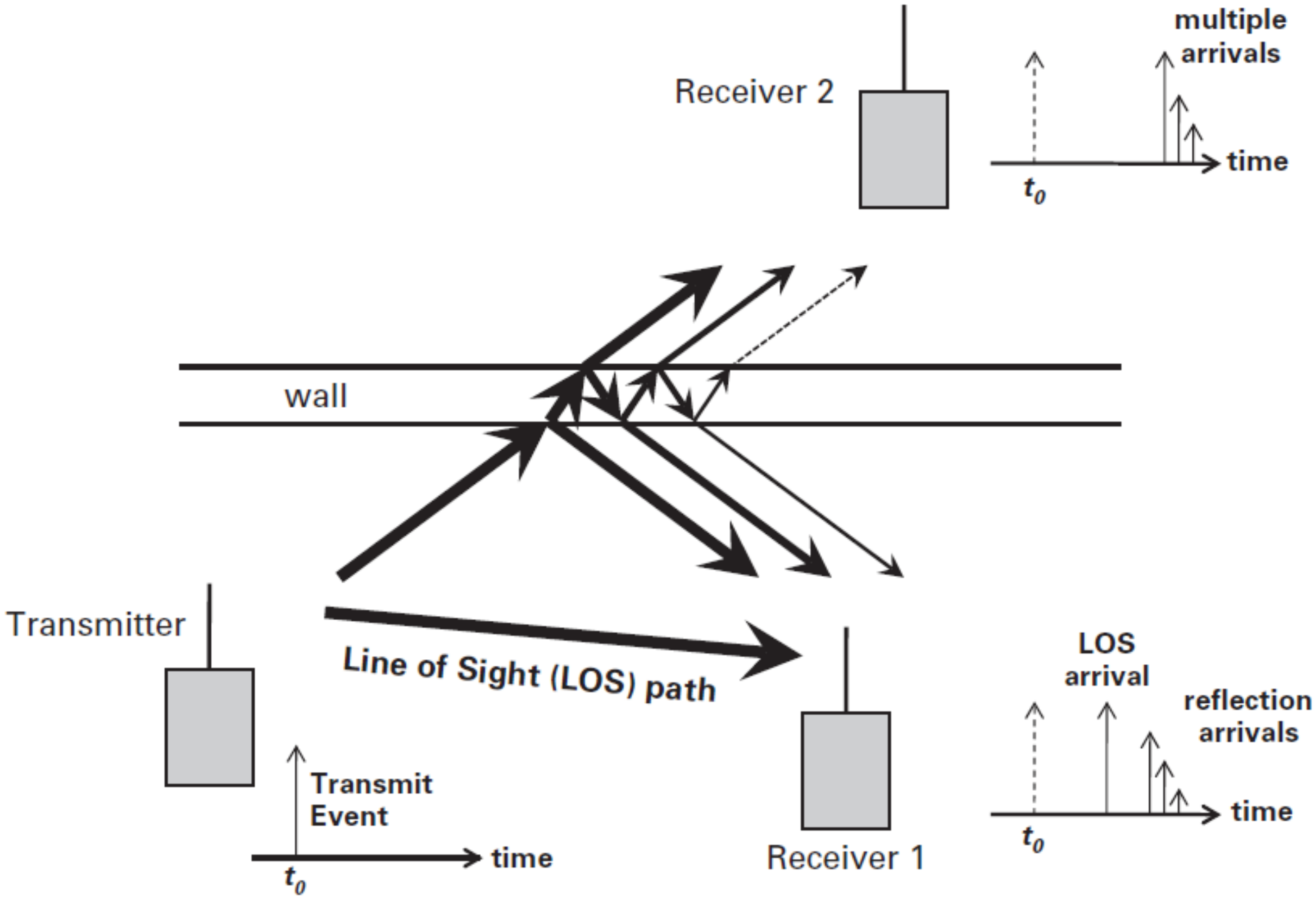
(*a*) (*b*)

(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)



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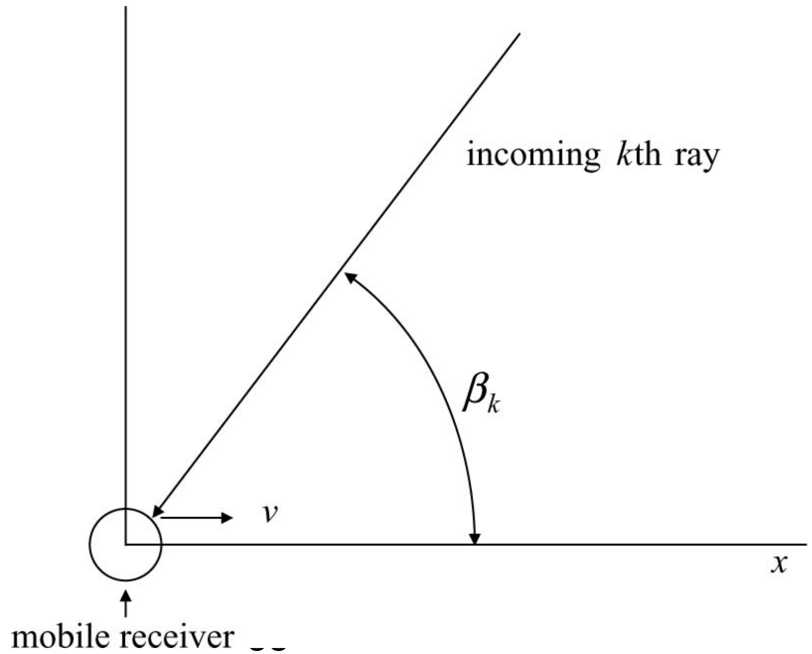
Doppler Shift or Frequency Dispersion

- 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



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

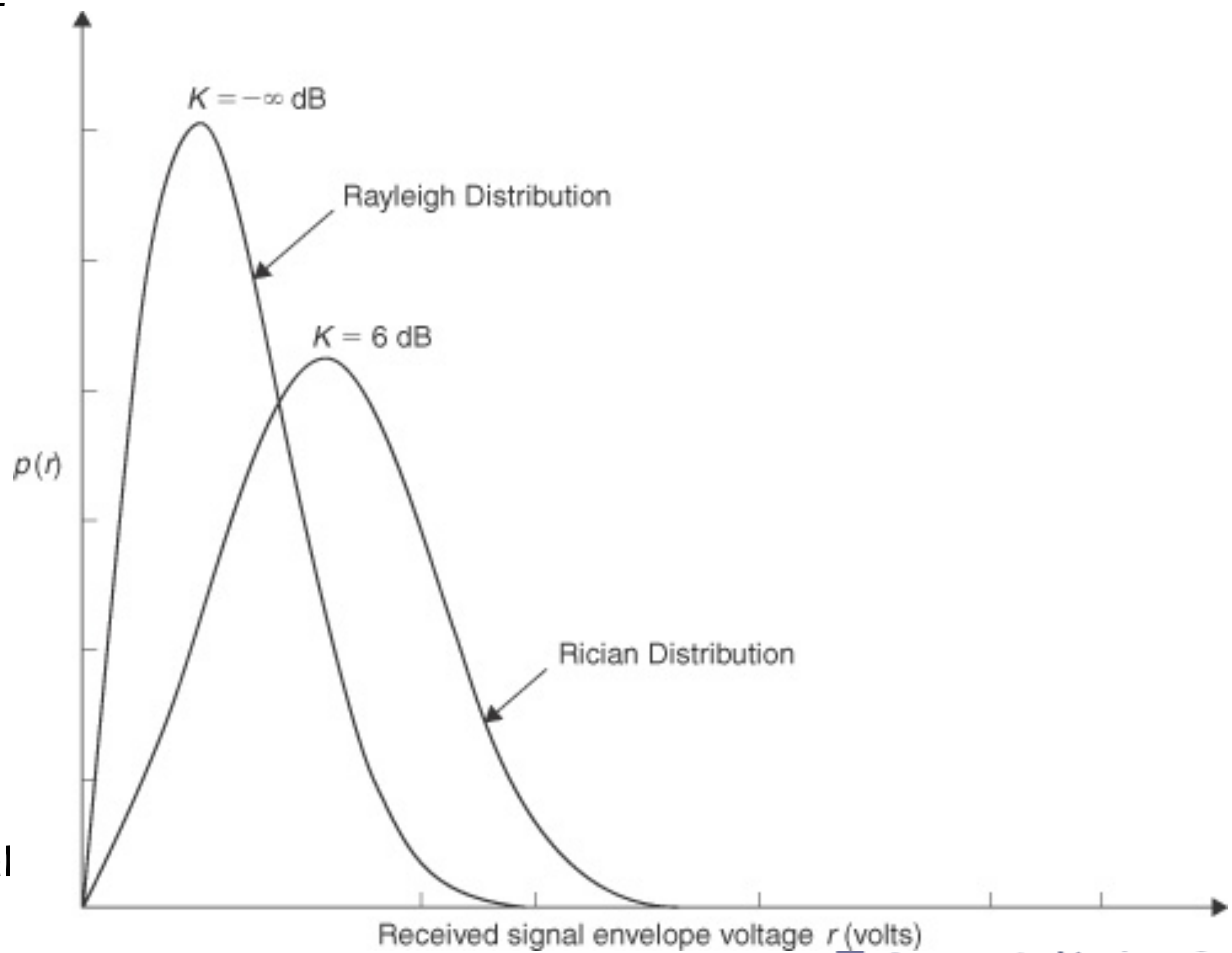
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than base-band signal variations

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

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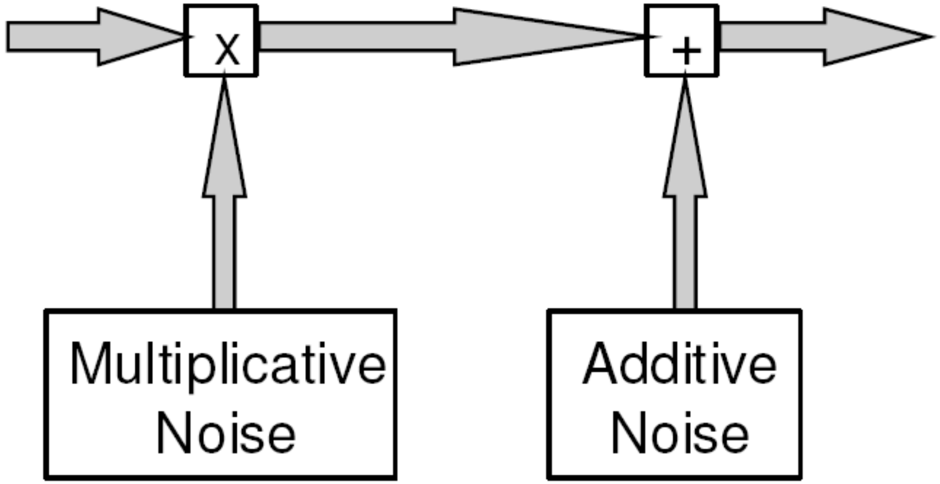
Noise Types in a Wireless Channel



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  - 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)

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Thermal Noise

- Also referred to as **white 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.)

- Uniformly distributed across the frequency spectrum so 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)

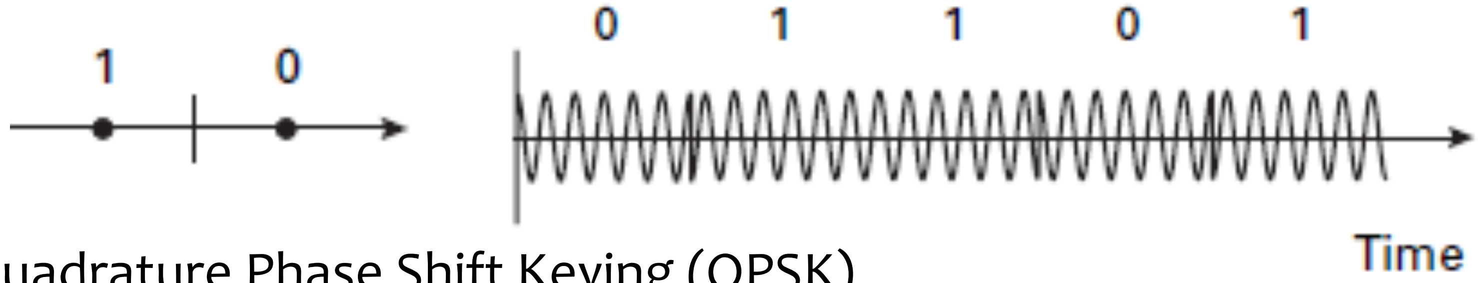
$$\begin{aligned} N &= 10 \log \mathrm{k} + 10 \log T + 10 \log B \\ &= -228.6\ \mathrm{dBW} + 10 \log T + 10 \log B \end{aligned}$$

Receiver Sensitivity

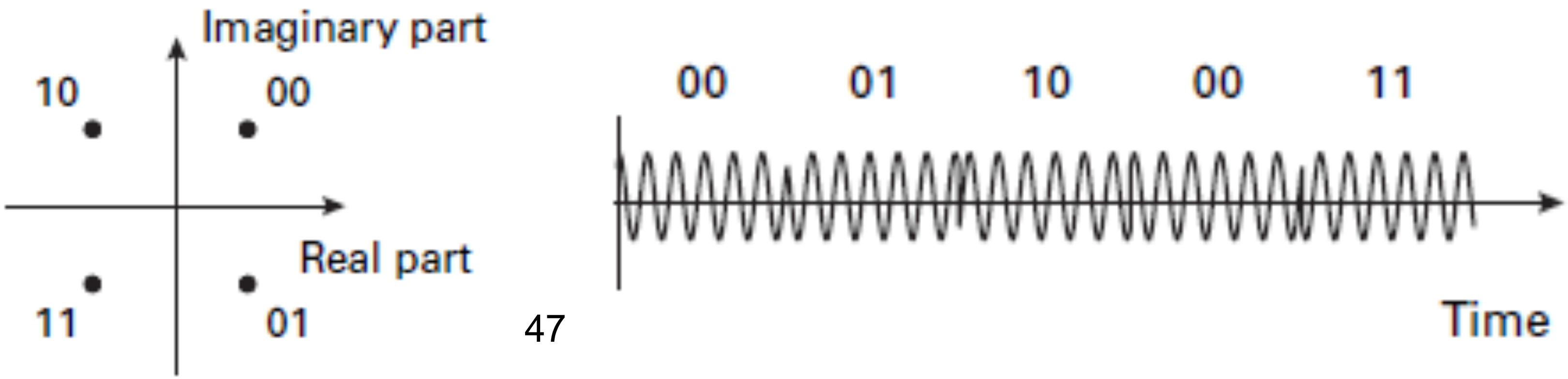
- Defined as the lowest received power level, P_R^{min}, at which just acceptable communication quality
  - Assuming only thermal noise in the receiver electronic circuitry
  - For a given transmission bit-rate (i.e., physical layer data rate or modulation & coding scheme)
- Determines the maximum communication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

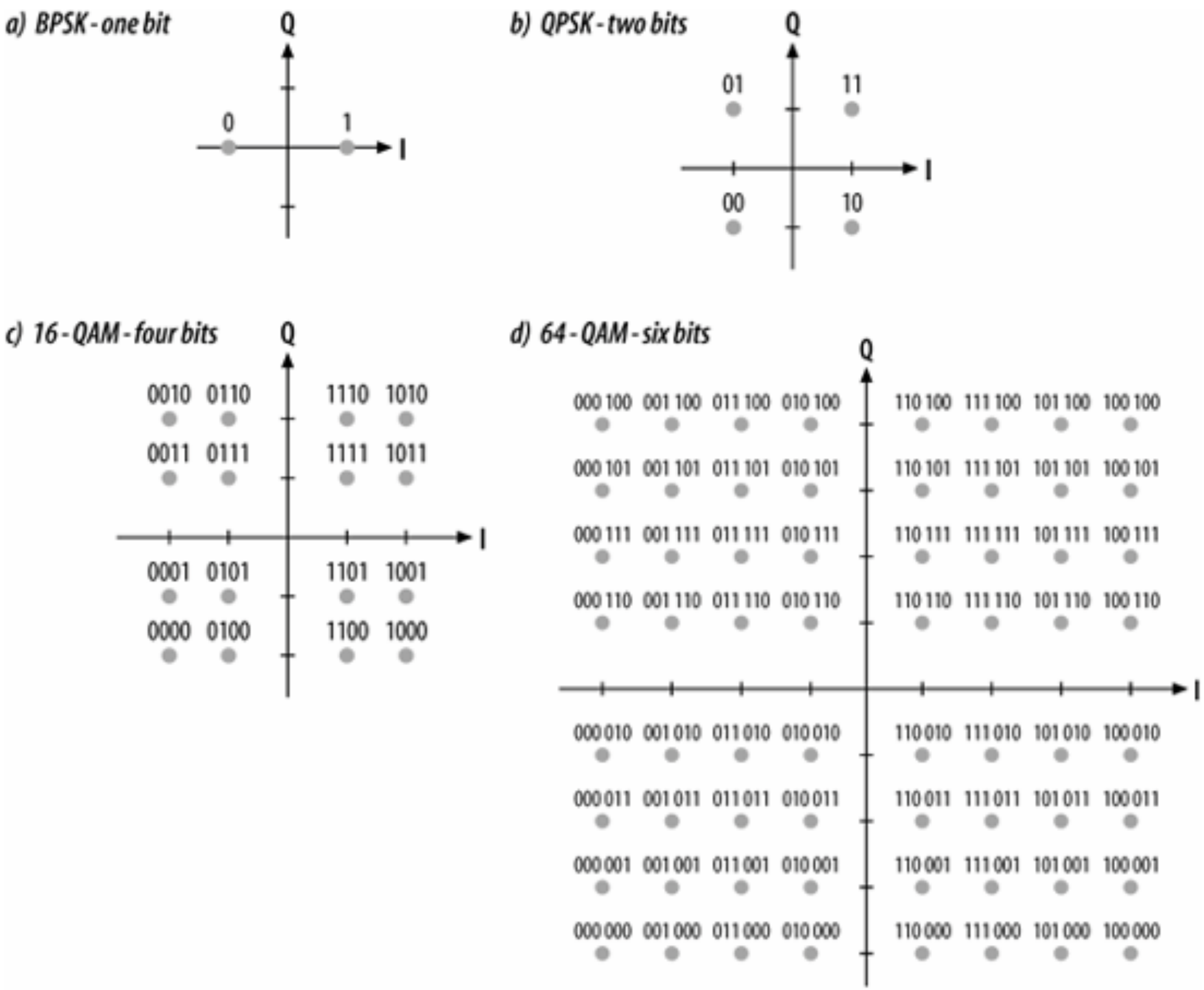


- Quadrature Phase Shift Keying (QPSK)
  - Phase modulation using symbol phases of 45 deg, 135 deg, 225 deg and 315 deg
  - Can also be seen as amplitude modulation with symbols as complex numbers with values +/- 1 +/- i, where i is square root of -1



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)

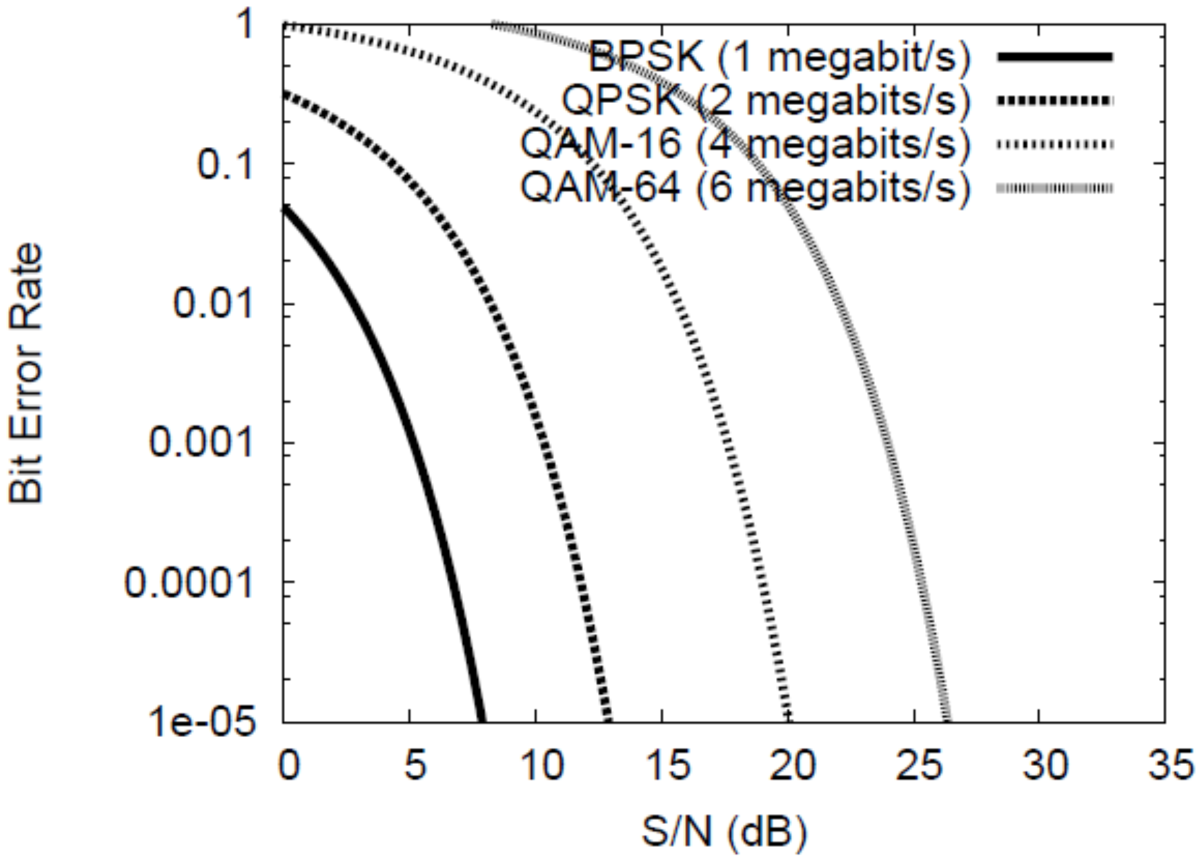
- Coding rate:
  - Determines the number of redundant bits added
  - Ratio of number of data bits transmitted to the number of coded bits
  - If K redundant bits are added for every N data bits transmitted, then $R = N / (N+K)$

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 additive white gaussian noise (AWGN) channel

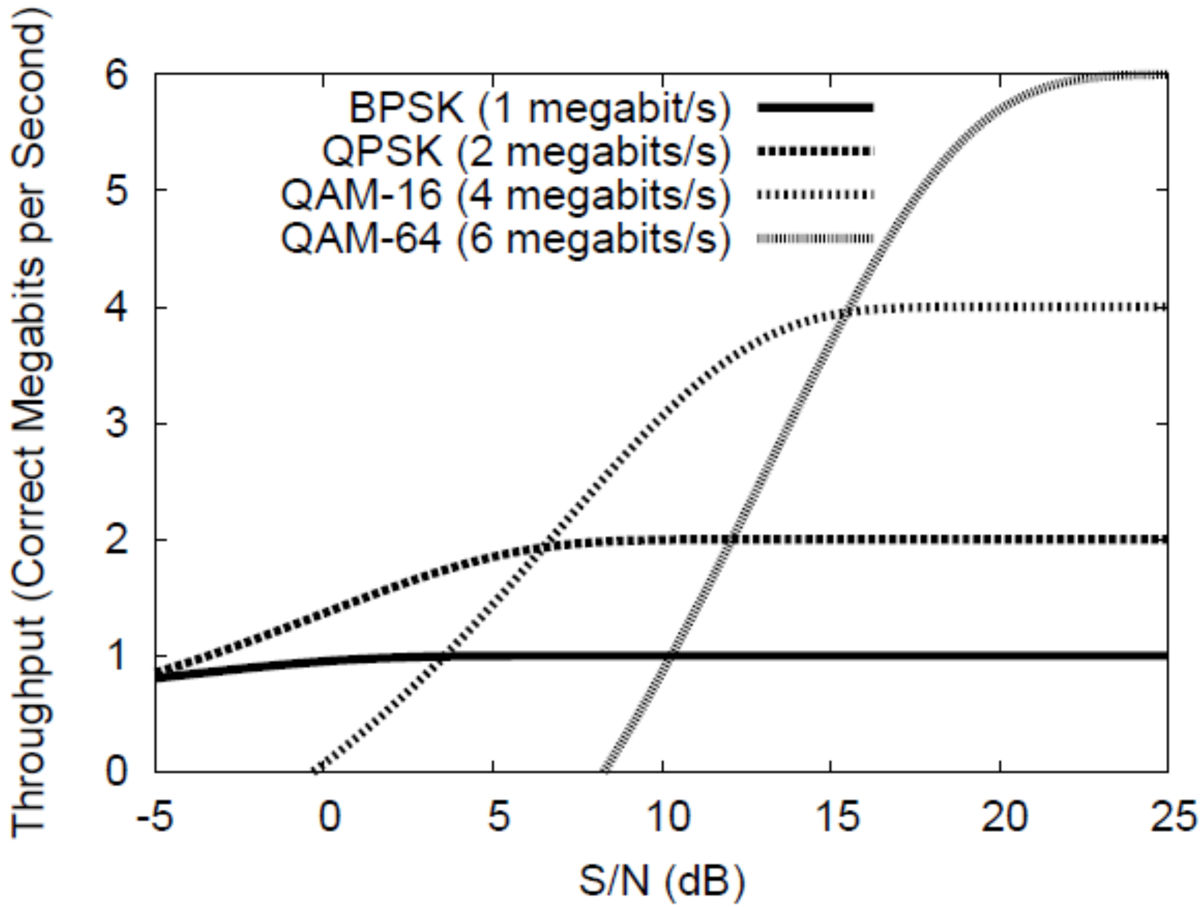


Wireless Link Throughput

- 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) = $1 - (1 - BER)^L$

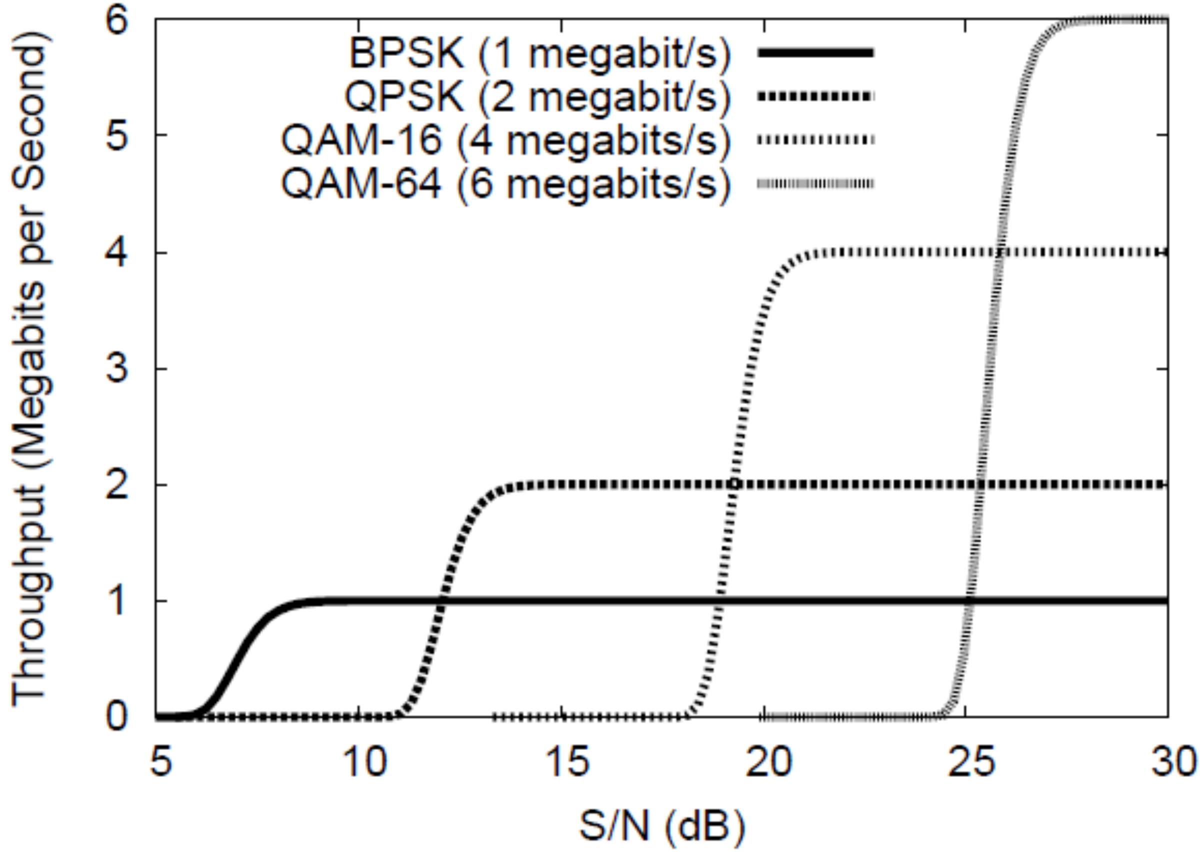
  L, frame length
- Throughput = bit-rate * (1-FER) = bit-rate * $(1 - BER)^L$
- The above two equations assume that no error correction used

Bit-Level Throughput versus SNR



Frame-Level Throughput versus SNR

- Assuming 1500 byte frames and no error correction coding



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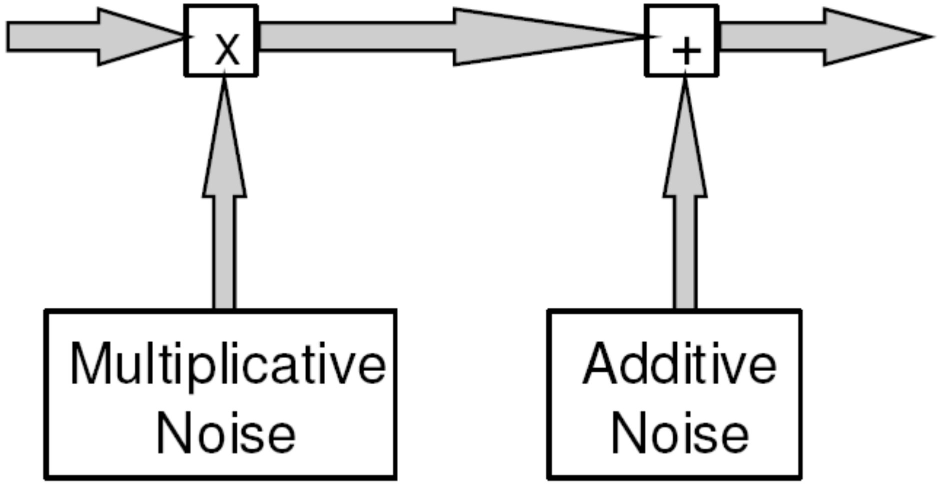

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Multiple Access

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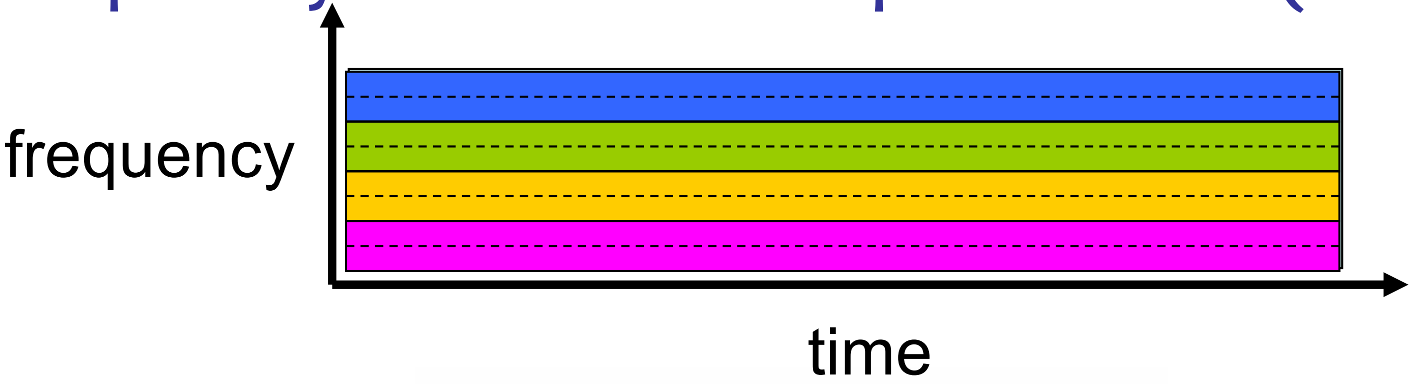
(Common) Multiple Access Techniques

- Frequency Division Multiple Access (FDMA)

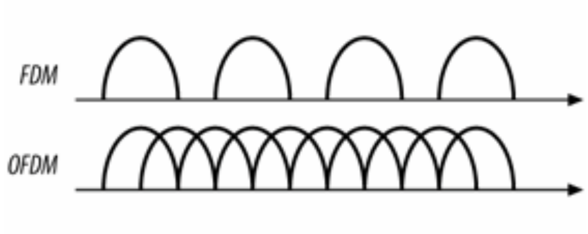
- Time Division Multiple Access (TDMA)
  - Packet mode Multiple Access

- Code Division Multiple Access (CDMA)

Frequency Division Multiple Access (FDMA)

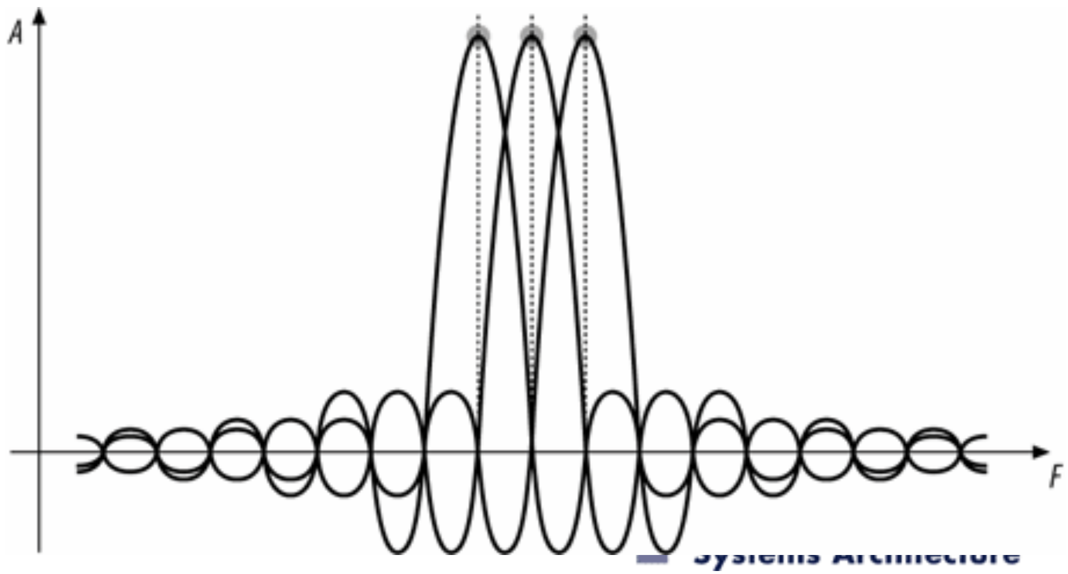


- Early cellular systems were based on FDMA
- Used for AM radio broadcasting and in telephone networks
- OFDM (and OFDMA) similar to FDMA except that
  - Frequency division fine-grained (i.e., closer frequency spacing) with no guard bands
  - Dynamic allocation of subcarriers (in 4G/LTE and WiMAX)

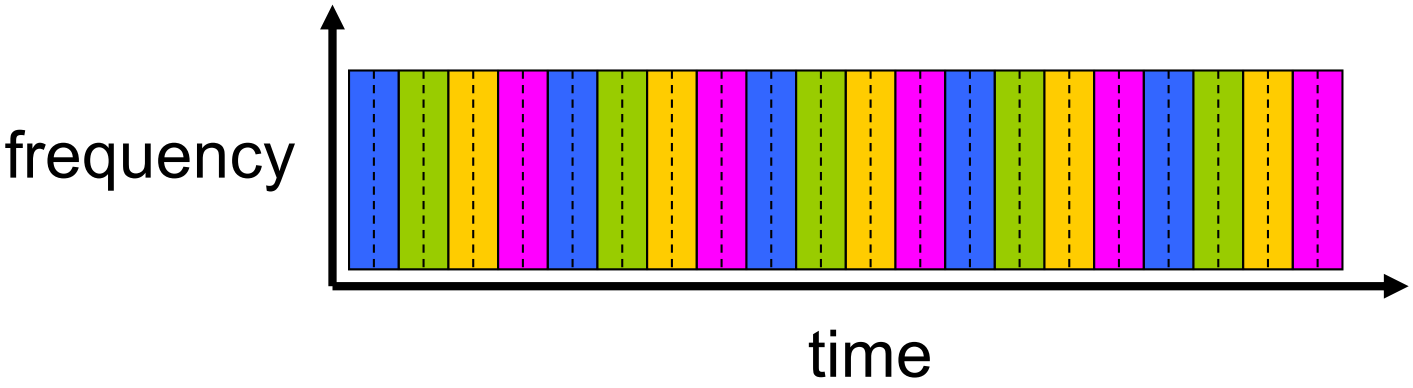


Orthogonal Frequency Division Multiplexing (OFDM)

- 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 modern Wi-Fi (802.11a/g/n/ac) and cellular (from 4G/LTE) based on OFDM



Time Division Multiple Access (TDMA)



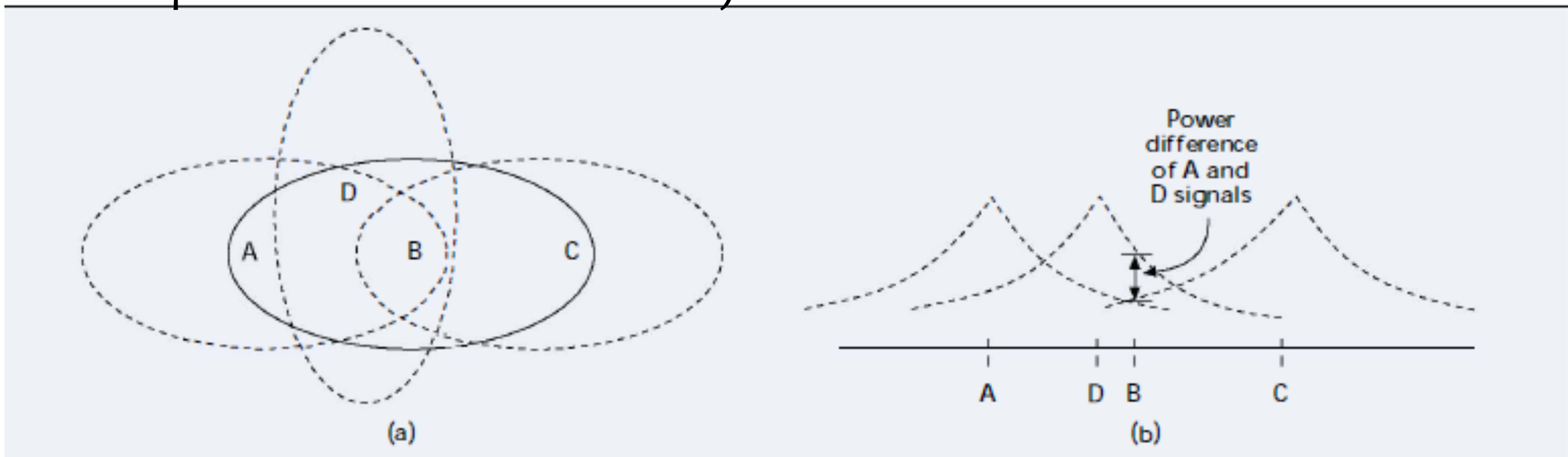
- Used in telephone and 2G cellular networks
- More difficult to implement than FDMA since the users must be time-synchronized
  - Guard time to cope with timing variations
- But easier to dynamically accommodate multiple data rates with TDMA than classical FDMA because multiple timeslots can be assigned 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; Carrier Sense Multiple Access (CSMA); CSMA with Collision Detection (CSMA/CD) used in classical Ethernet; CSMA with Collision Avoidance (CSMA/CA) on which Wi-Fi is based
- Token Passing
  - Token ring, Token bus
- Polling
- Scheduled
  - Dynamic TDMA, etc.

Wireless Random Multiple Access Issues

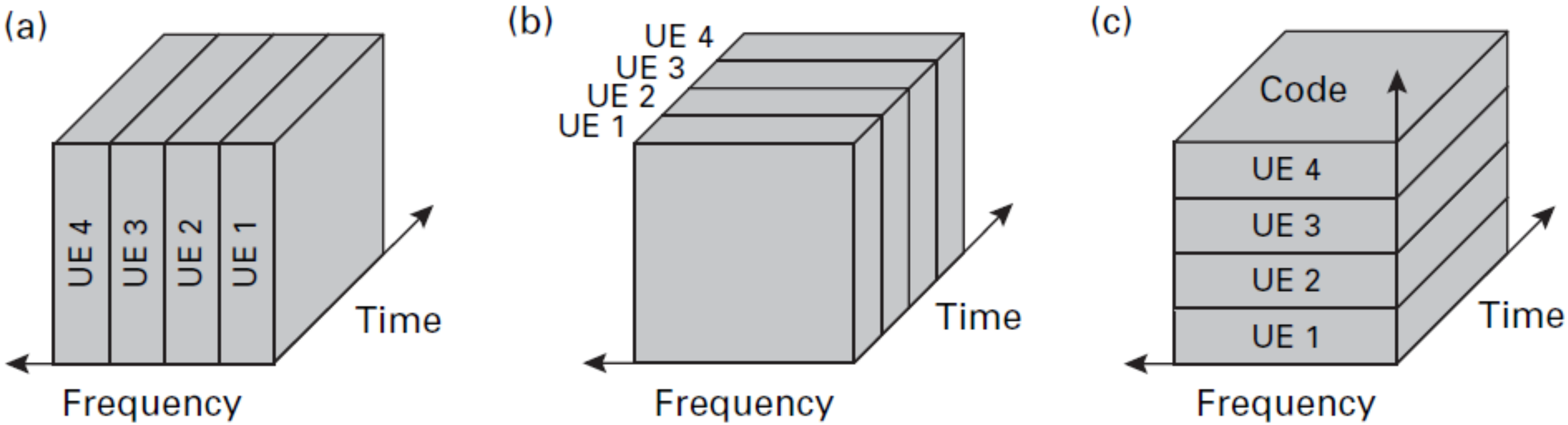
- **Receiver side interference** (collisions occur at receiver, detection at transmitter difficult) and **half-duplex operation** (transmit or receive but not both simultaneously)
- Carrier sensing is location dependent. As a result:
  - **Hidden terminals** (e.g., A and C are hidden from each other ➔ 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)

- Here UE refers to User Equipment, the term for a user device in 3G/4G/5G mobile cellular networks

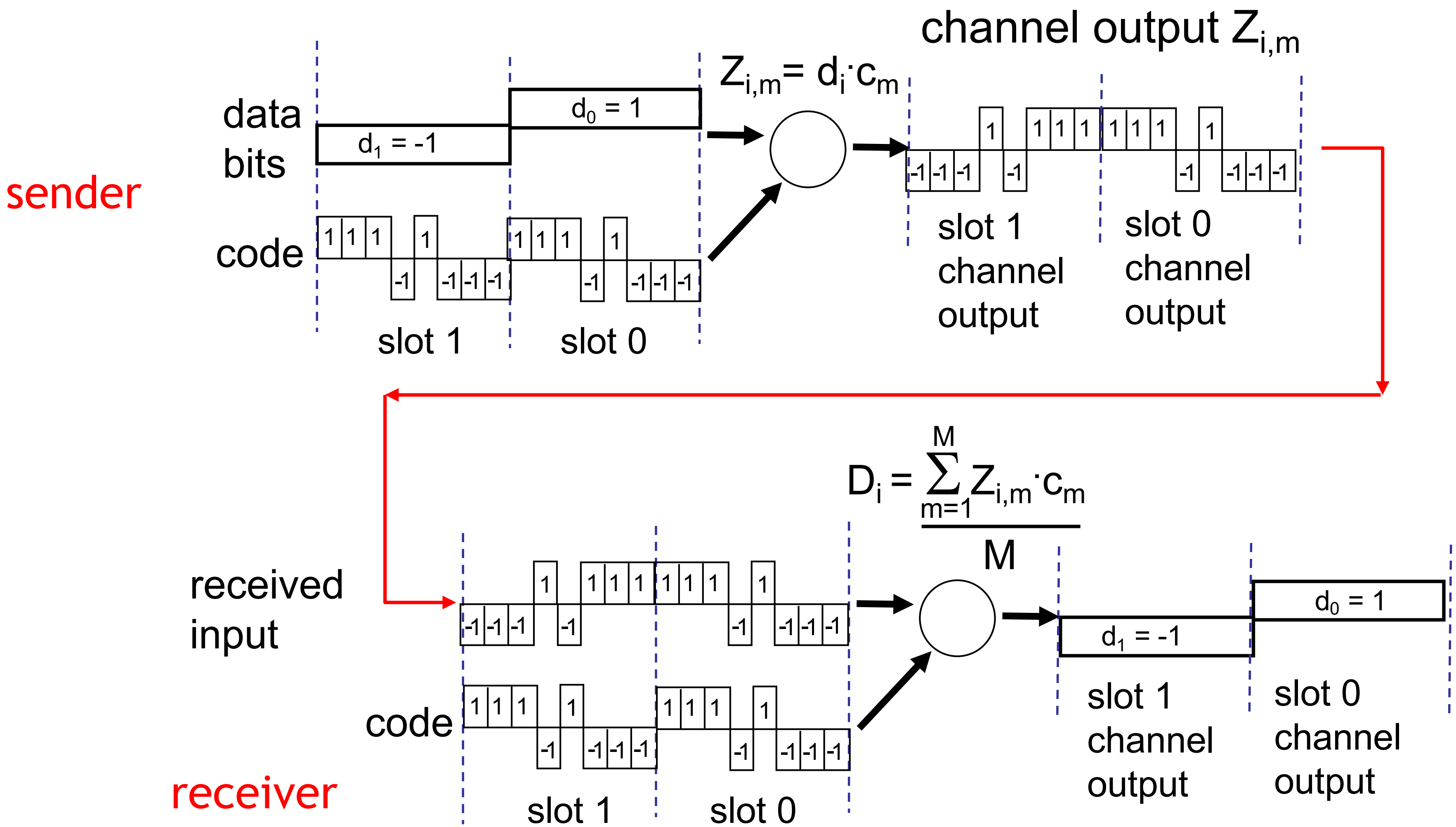


(a) FDMA, (b) TDMA, (c) CDMA.

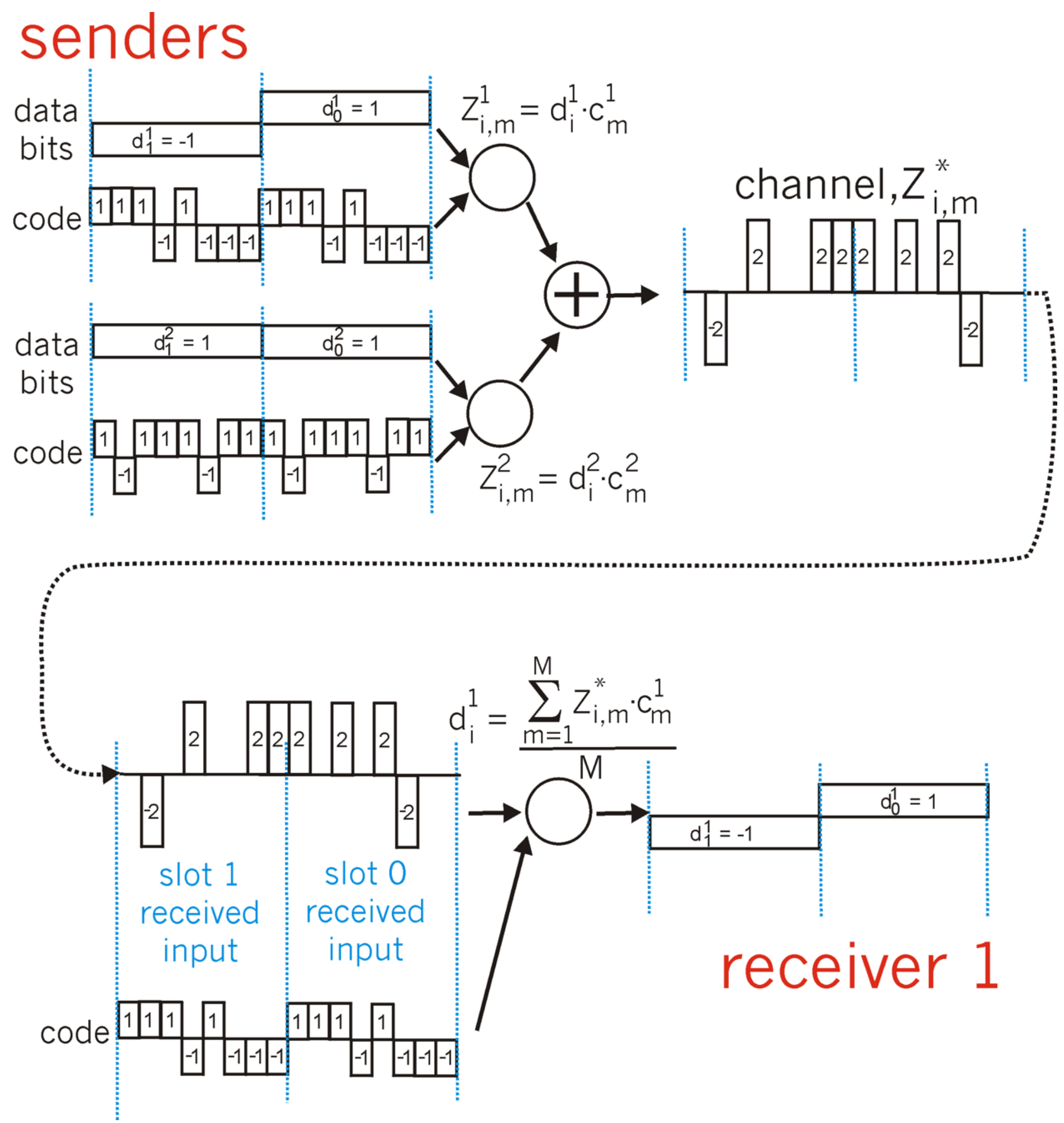
CDMA

- 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



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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 wireless networks (cellular, Wi-Fi, ..)