04832250 – Computer Networks (Honor Track)

A Data Communication and Device Networking Perspective

Module 2: PHY Concepts and Wireless Fundamentals

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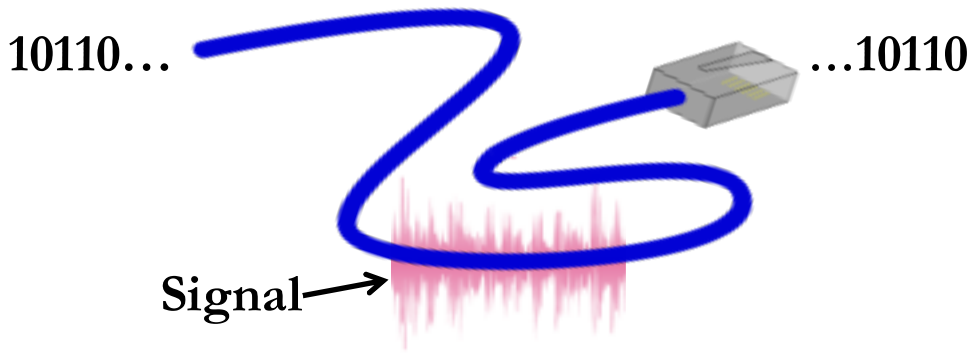
Context of Physical layer

- Beginning to work our way up starting with the Physical layer

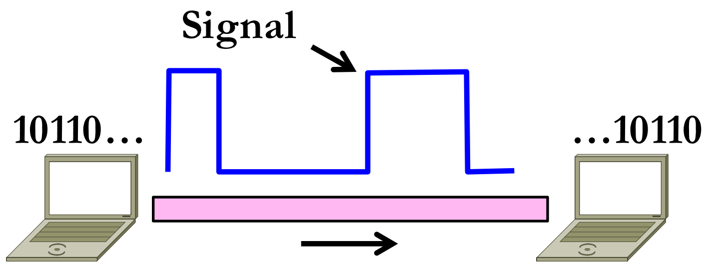
Application
Transport
Network
Link
Physical

- Concerns how signals are used to transfer message bits over a link
  - Wire etc. carry analog signals
  - We want to send digital bits



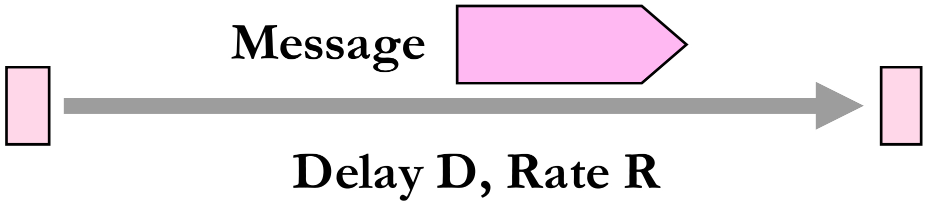
Topics

- Properties of media
  - Wires, fiber optics, wireless
- Signal propagation and wireless basics
  - Bandwidth, channel model, and multipath effect
- Coding, modulation, and multiplexing
  - Representing and communicating bits
- Advanced wireless transmission techniques
  - MIMO, OFDM, Spread spectrum, CDMA



Simple Link Model (in Computer Science) and Message Latency

- Abstraction of a physical channel
  - Rate (or bandwidth in CS, capacity, speed) in bits/second
  - Delay in seconds, related to length



- Use powers of 10 for rates, 2 for storage
  - 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
- Other important properties:
  - Whether the channel is broadcast, wireless

- Latency: the delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"
    - T-delay = M (bits) / Rate (bits/sec) = M/R seconds
  - Propagation delay: time for bits to propagate across the wire
    - P-delay = Length / speed of signals = L/(⅔)c = D seconds
  - Combining the two terms we have: Latency = M/R + D
- Examples:
  - "Dialup" with a telephone modem:
    - D = 5 ms, R = 56 kbps, M = 1250 bytes
    - L = 5 ms + (1250 x 8)/(56 x 10^3) sec = 184 ms!
  - Broadband cross-country link:
    - D = 50ms, R = 10 Mbps, M = 1250 bytes
    - L = 50ms + (1250 x 8) / (10 x 10^6) sec = 51ms

A long link or a slow rate means high latency!

Bandwidth-Delay Product

- Messages take space on the wire!

- The amount of data in flight is the <u>bandwidth-delay (BD) product</u>
  - Measure in bits, or in messages
  - Small for LANs, big for “long fat” pipes

Dina Katabi, Mark Handley, and Charlie Rohrs.
Congestion control for high bandwidth-delay product networks.
In *Proc. of ACM SIGCOMM, 2002*

- Fiber at home, cross-country

R = 40 Mbps, D = 50ms

BD = $40 \times 10^6 \times 50 \times 10^{-3}$ bits

= 2000 Kbit

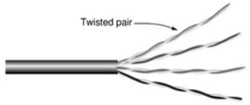
= 250 KB

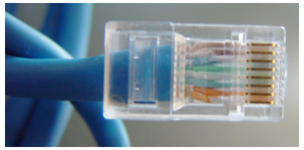
- That’s quite a lot of data “in the network”!

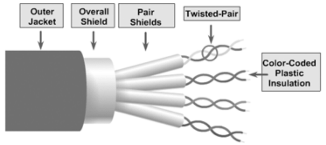
Media propagates signals that carry bits of information

- **Wires – Twisted pair**
  - Commonly used in LANs and telephone lines
    - Twists reduce radiated signal

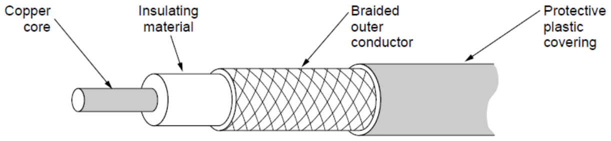
Category 5 UTP cable with four twisted pairs





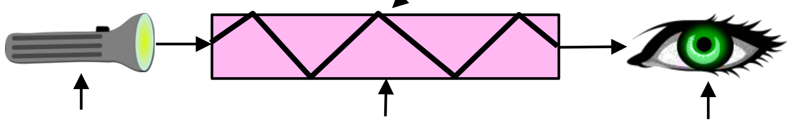


- **Wires – Coaxial Cable**
  - Better shielding for better performance



- **Fiber**
  - Long, thin, pure strands of glass
    - Enormous bandwidth over long distances

Optical fiber

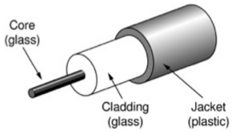


Light source (LED, laser)

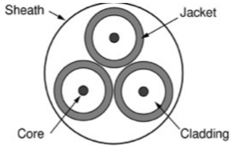
Light trapped by total internal reflection

Photo-detector

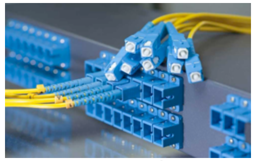
  - Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to ~100 km)



One fiber



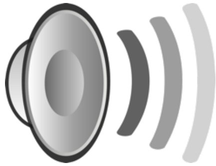
Fiber bundle in a cable



- **Wireless**
  - Sender radiates signal over a region
    - In many directions, unlike a wire, to potentially many receivers
    - Nearby signal (same freq.) <u>interfere</u> at a receiver, need to coordinate use

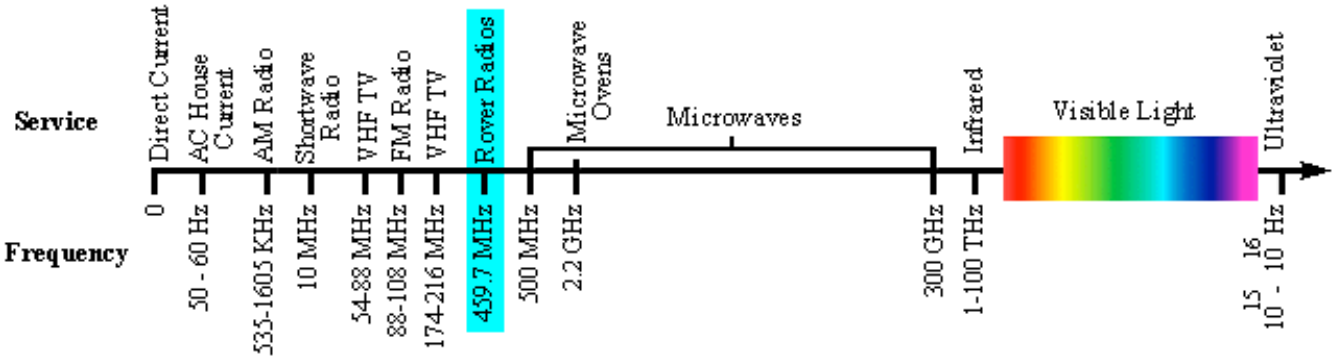
Radio Frequency

Visible Light and Infrared



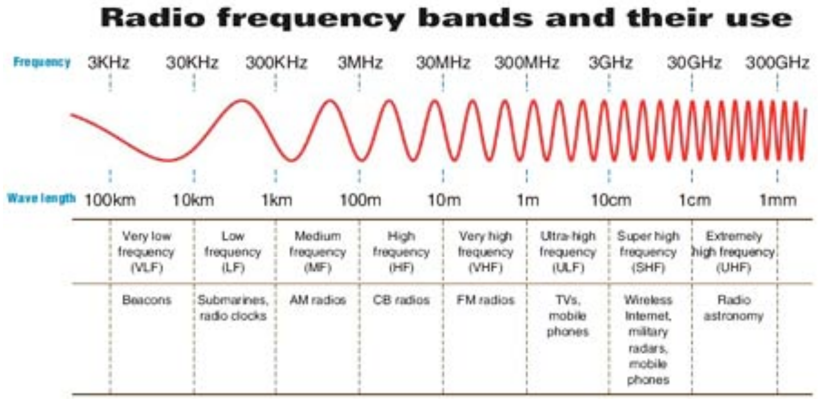
Ultrasonic

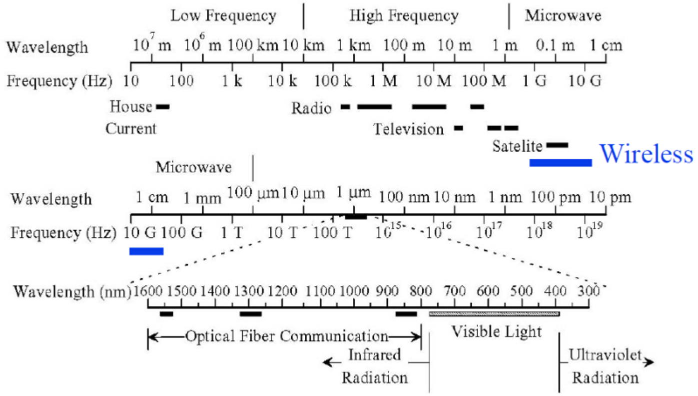
Frequency Spectrum for Wireless Communication

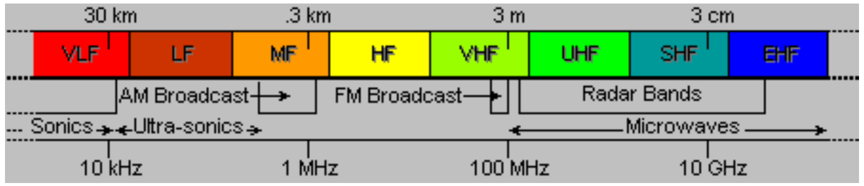


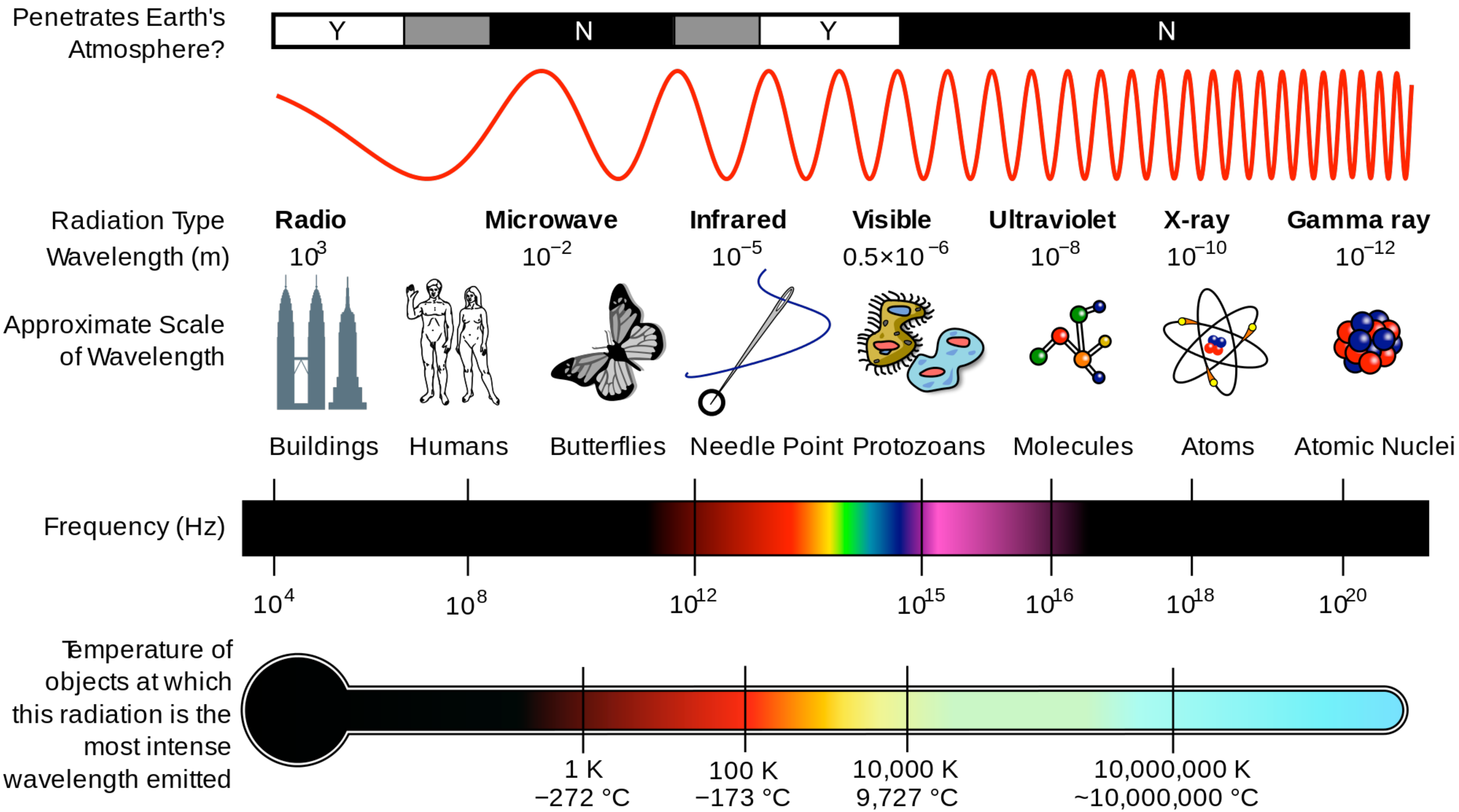
Designation	Band	Designation	Band
Direct Current (DC)	0 Hertz	Very High Frequency (VHF)	30 - 300 MHz
Very Low Frequency (VLF)	3 - 30 KHz	Ultra High Frequency (UHF)	300 - 3000 MHz
Low Frequency (LF)	30 - 300 KHz	Super High Frequency (SHF)	3 - 30 GHz
Medium Frequency (MF)	300 - 3000 KHz	Extreme High Frequency (EHF)	30 - 300 GHz
High Frequency (HF)	3 - 30 MHz	Microwave Frequencies	500 MHz - 300 GHz

Spectral region	VHF	UHF	Microwave	Infrared	Visible	Ultraviolet	X-rays	γ-rays
Common usage	NMR	EPR	rotational transitions	vibrational transitions	electronic transitions		ionisation	nuclear effects
Frequency (Hz)	5×10^{8}	3×10^{10}	3×10^{11}	3×10^{13}	6×10^{14}	1.2×10^{15}	3.0×10^{17}	1.5×10^{19}
Wavelength	0.6 m	1 cm	1 mm	10 μm	500 nm	250 nm	1 nm	20 pm
Wavenumber (cm^{-1})	0.017	1.0	10.0	1000	20,000	40,000	1.0×10^{7}	5.0×10^{8}
Single photon energy (eV)	2.07×10^{-6}	1.24×10^{-4}	1.24×10^{-3}	1.24×10^{-1}	2.5	5.0	1.24×10^{3}	6.2×10^{4}
Photon energy (kJ mol^{-1})	2.03×10^{-4}	1.20×10^{-2}	1.20×10^{-1}	12.0	239	479	1.2×10^{5}	6×10^{6}



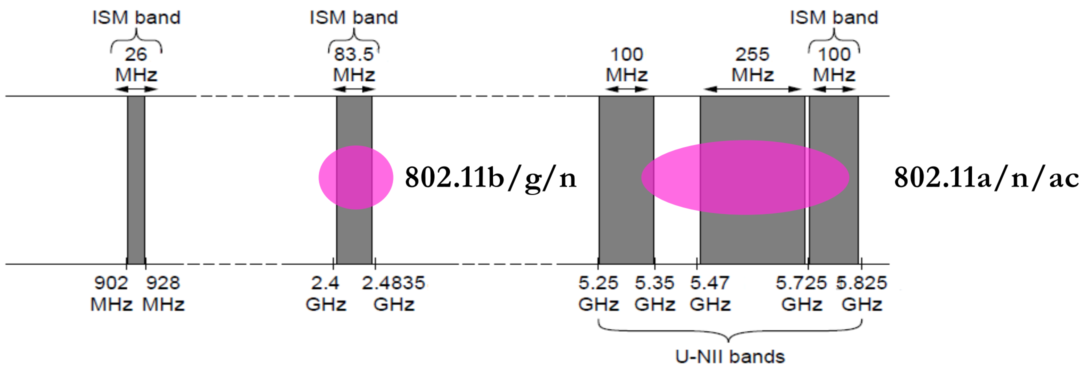


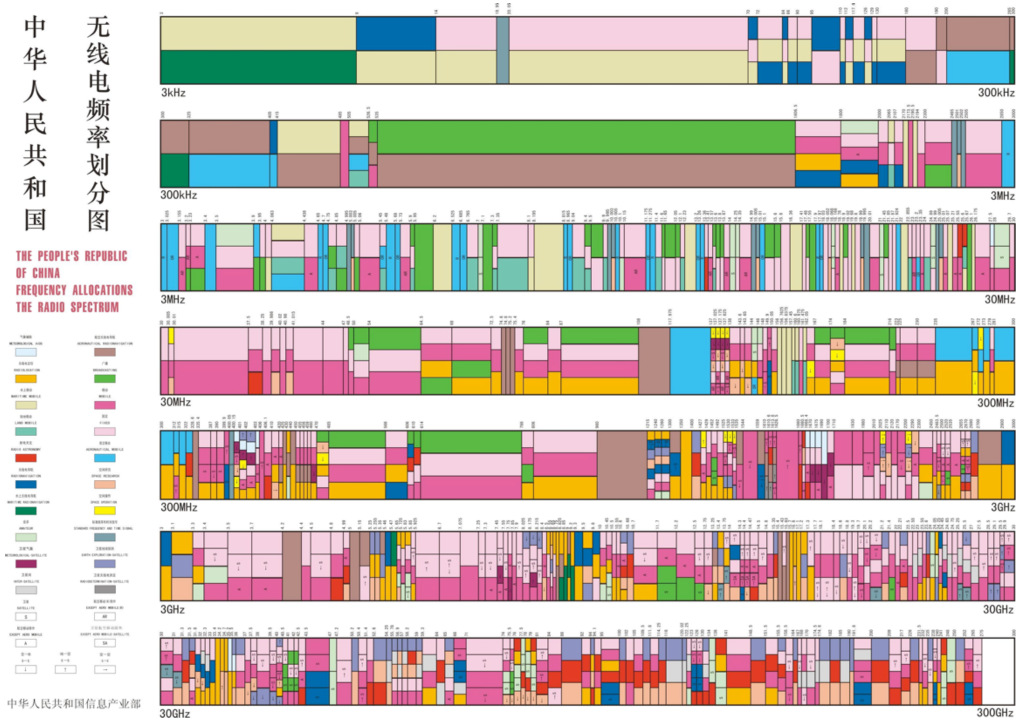


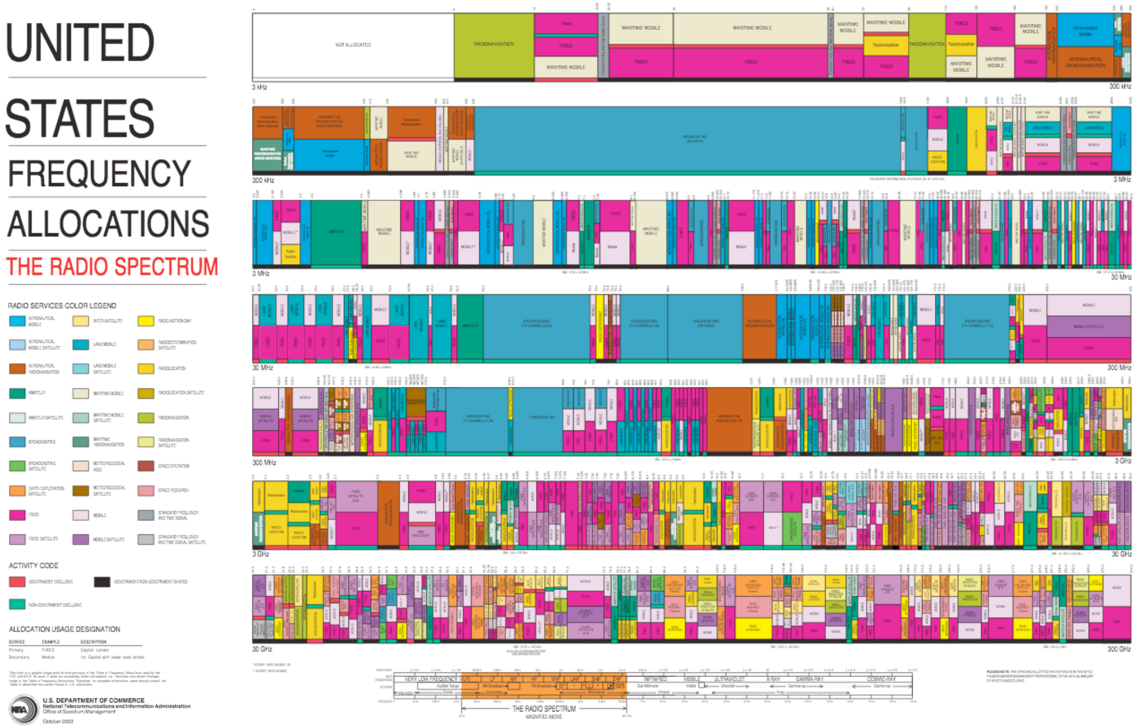

Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^{3}
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

Spectrum Regulation

- Microwave, e.g., 4G, and unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking







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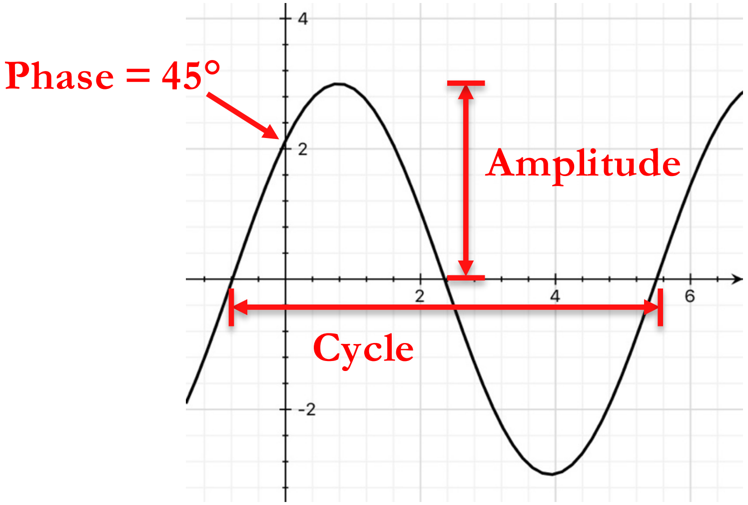
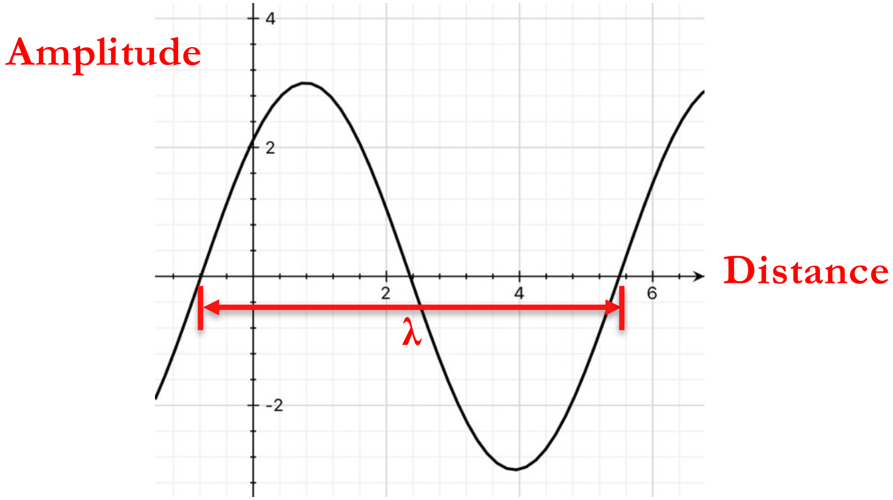
Signal fundamentals – Sine Wave

- Frequency, amplitude and phase
  - Asin(2πft+θ)
    - θ = Phase
    - Period T = 1/f
    - A = Amplitude
    - Frequency is measured in cycles/sec or Hertz
- Wavelength = λ
  - Distance occupied by one cycle
  - Distance between two points of corresponding phase in two consecutive cycles
  - Assuming signal velocity *v*
  - $\lambda = vT$, or $\lambda f = v$

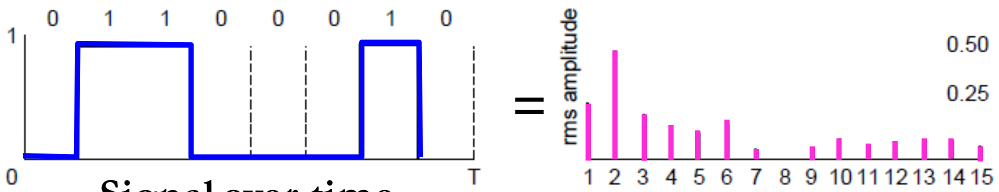




Signal fundamentals – Frequency Representation and Fourier analysis

- A signal over time can be represented by its frequency components

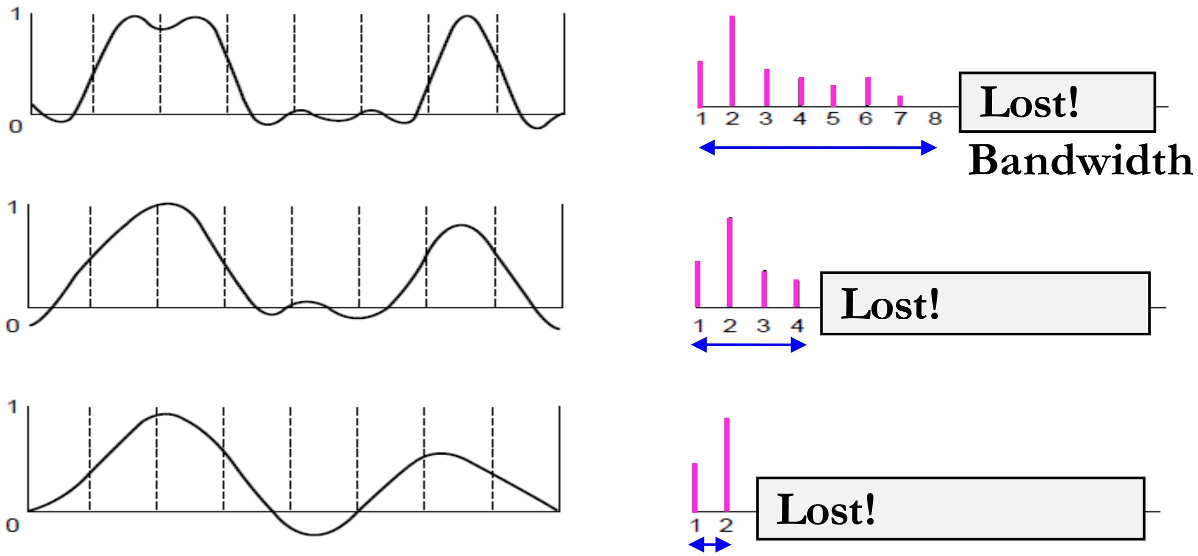
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$



Signal over time

Weights of harmonic frequencies

- Less bandwidth degrades signal (less rapid transitions)



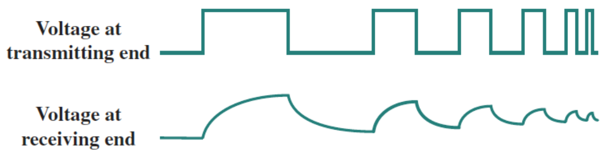
EE: Bandwidth = width of frequency band, measured in Hz

CS : Bandwidth = information carrying capacity, in bits/sec

We use Data Rate from now on for CS's bandwidth

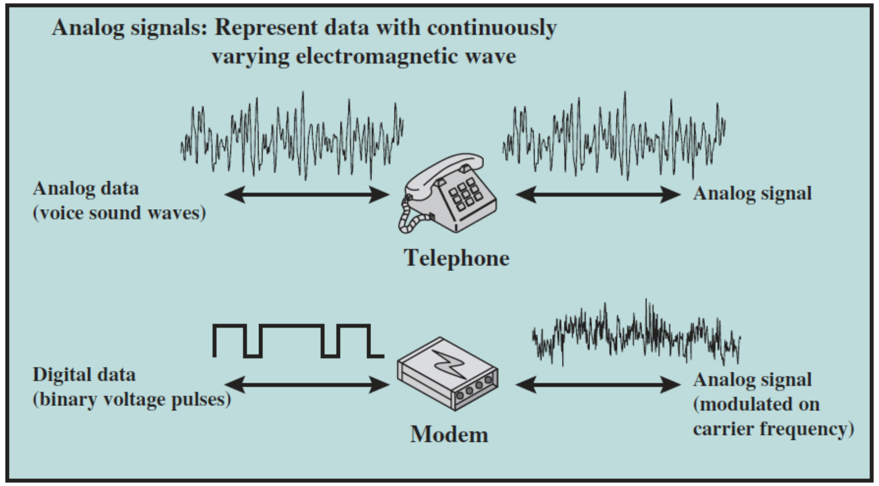
Signal fundamentals – Analog/Digital Data, Signals and Transmission

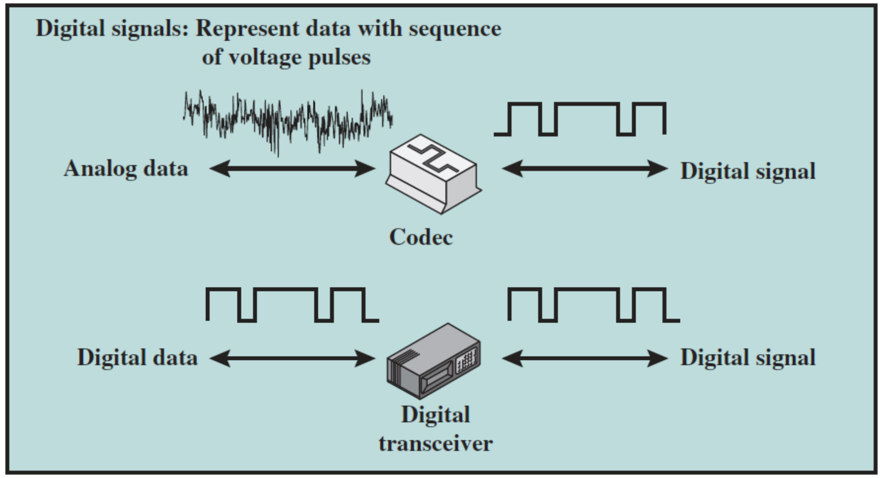
- Data: entities that convey meaning or information
  - Analog: continuous values in some interval, e.g., audio, temperature, pressure, etc
  - Digital: discrete integers, e.g., text, integers, character strings
- Signals: electric or electromagnetic representations of data
  - Analog: a continuously varying electromagnetic wave that may be propagated over a variety of media, depending on spectrum, e.g., wire, fiber optic cable, atmosphere or space
  - Digital: a sequence of voltage pulses that may be transmitted over a wire medium
    - Less susceptible to noise interference, but suffer more from attenuation



- Transmission: communication of data by the propagation and processing of signals
  - Analog: transmitting analog signals without regard to their content
    - Cascaded amplifiers boost signal's energy for longer distances but cause distortion and amplifies the noise, can't recover
  - Digital: assumes a binary content to the signal
    - Can recover from noise and distortions: regenerate signal along the path: demodulate + remodulate

Signal fundamentals – Analog/Digital Comparison





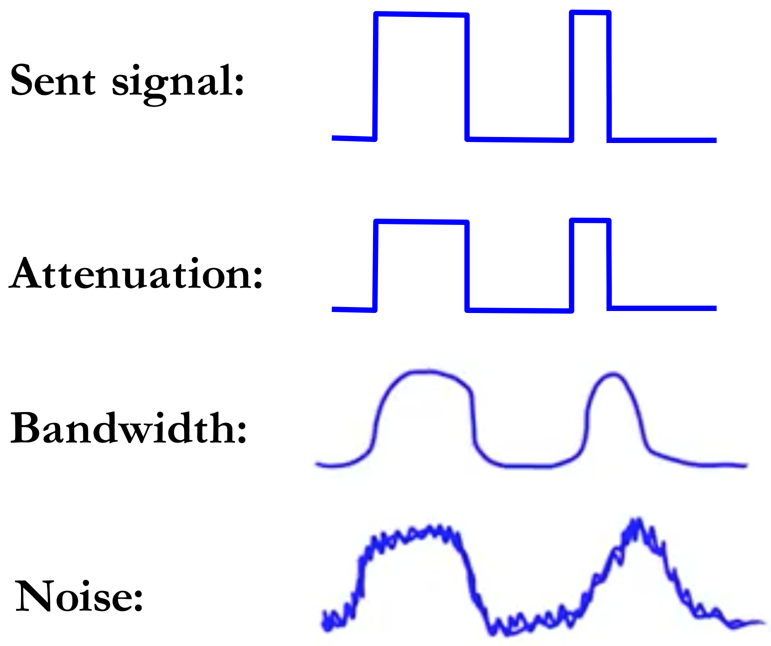
	Analog Signal	Digital Signal
Analog Data	Two alternatives: (1) signal occupies the same spectrum as the analog data; (2) analog data are encoded to occupy a different portion of spectrum.	Analog data are encoded using a codec to produce a digital bit stream.
Digital Data	Digital data are encoded using a modem to produce analog signal.	Two alternatives: (1) signal consists of two voltage levels to represent the two binary values; (2) digital data are encoded to produce a digital signal with desired properties.

(b) Treatment of Signals

	Analog Transmission	Digital Transmission
Analog Signal	Is propagated through amplifiers; same treatment whether signal is used to represent analog data or digital data.	Assumes that the analog signal represents digital data. Signal is propagated through repeaters; at each repeater, digital data are recovered from inbound signal and used to generate a new analog outbound signal.
Digital Signal	Not used	Digital signal represents a stream of 1s and 0s, which may represent digital data or may be an encoding of analog data. Signal is propagated through repeaters; at each repeater, stream of 1s and 0s is recovered from inbound signal and used to generate a new digital outbound signal.

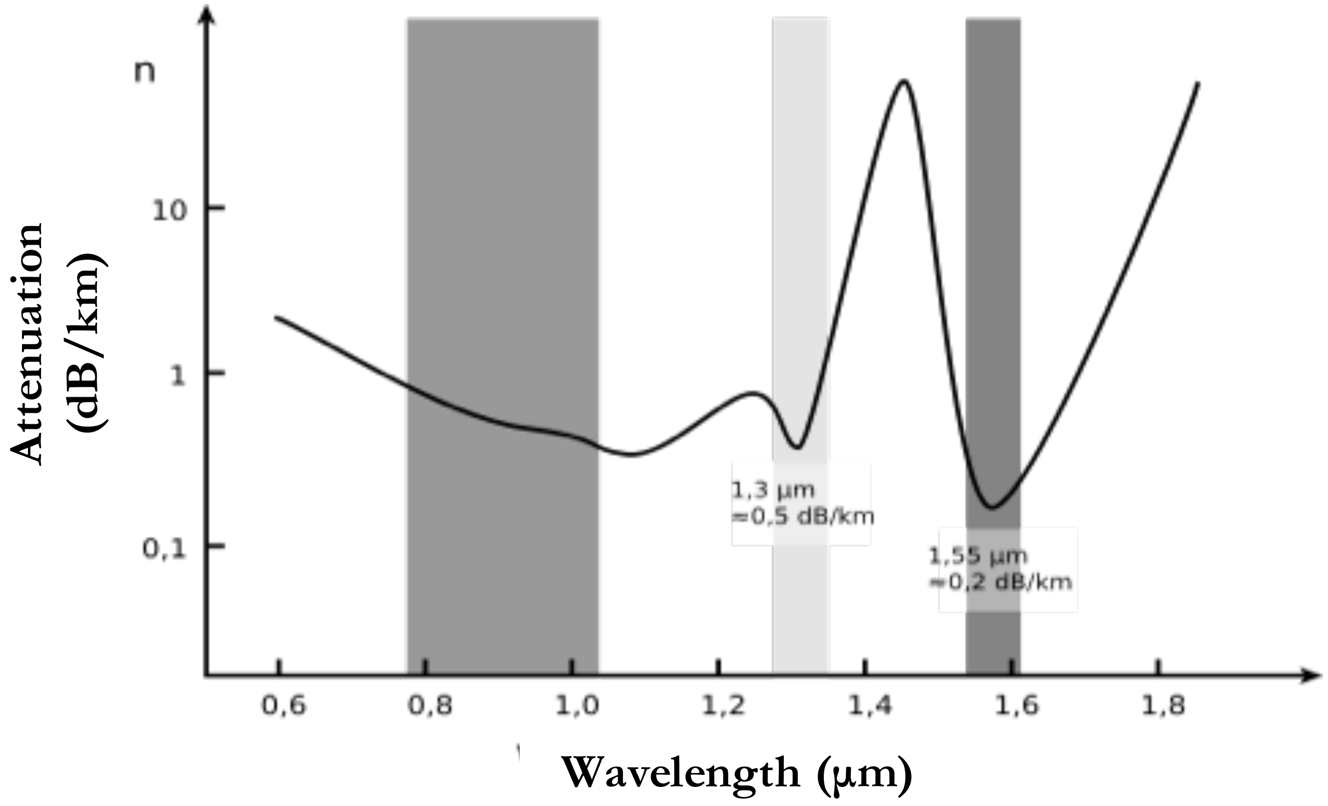
Signals over a Wire

- What happens to a signal as it passes over a wire?
  - The signal is delayed (propagates at ⅔c)
  - The signal is attenuated (goes for m to km)
  - Frequencies above a cutoff are highly attenuated
  - Noise is added to the signal (later, causes errors)



Signals over Fiber

- Light propagates with very low loss in three very wide frequency bands
  - Use a carrier to send information



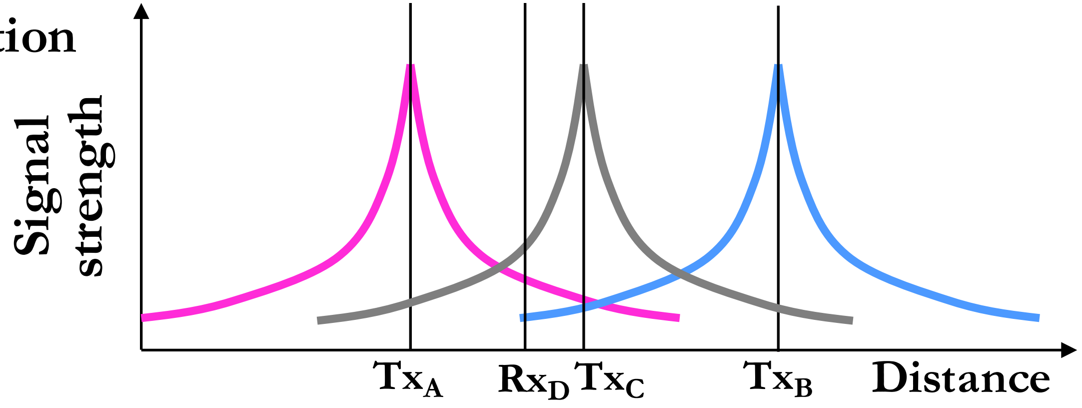
A ratio between signal powers is expressed in decibels:
decibels (db) = $10\log_{10}(P_1 / P_2)$

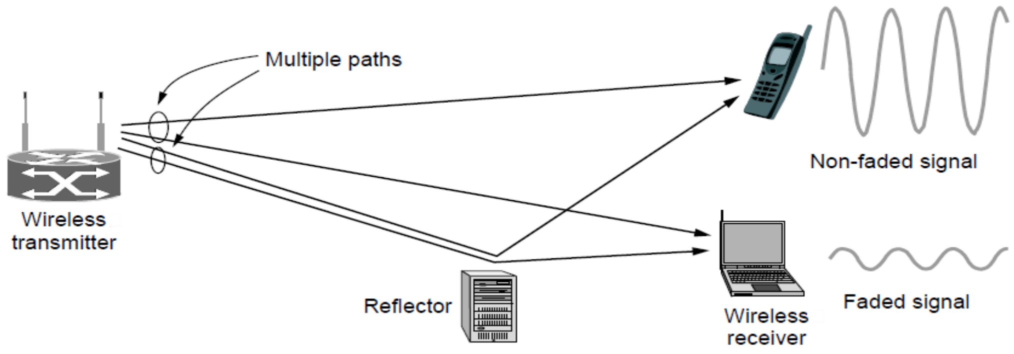
Signals over Wireless

- Signals transmitted on a carrier frequency, like fiber
- Spread out and attenuate faster than $1/d^2$
- Propagation model is complex, depends on environment
- Why use wireless
  - Supports mobile users: move around, remote control, communication
- No need to install and maintain wires
  - Reduces cost and simplifies deployment

But what is hard/different about wireless?

- Shared medium
  - Uncoordinated for concurrent user access and contention
- Unguided propagation and path loss
  - Energy is distributed in many directions in space
- Interference
  - Intra/inter technology
  - Hint: throughput does not scale as more Tx-Rx pairs
- Shadowing and multipath fading
  - Indoor complexities
  - Client/environment mobility
    - Doppler shift and temporary fading





(Limited) Goals

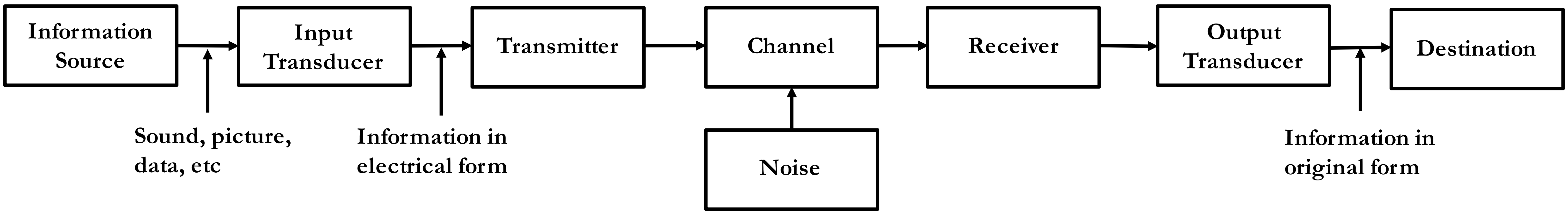
- Non-goal: turn you into electrical engineers
- But why we still care about?
  - 5G, IoT, Fog, …
- Basic understanding of how communication is done
- Understand the tradeoffs involved in speeding up the transmission

A Computer Science view of Communication Engineering!

History of Wireless Communications

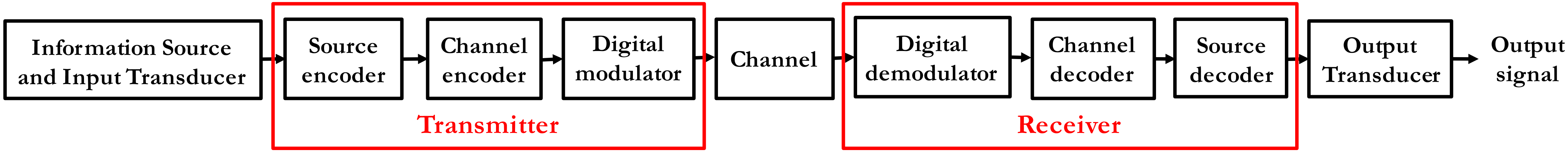
- James C. Maxwell in 1864 predicted the existence of EM radiation and formulated the basic theory (Maxwell's equations)
- Maxwell's theory was verified experimentally by Hertz in 1887
- On December 12, 1901, Guglielmo Marconi successfully received a radio signal at Signal Hill in Newfoundland, North America, which was transmitted from Cornwall, England-a distance of about 1700 miles
- Marconi is credited with the development of wireless telegraphy
- Amplitude modulation (AM) broadcast was started in 1920
- In 1933, Edwin Armstrong built and demonstrated the first frequency modulation (FM) communication system
- First television system was built in the United States by Vladimir Zworykin and demonstrated in 1929
- Commercial television broadcasting began in London in 1936 by the British Broadcasting Corporation (BBC)
- Color TV in late 1960', digital TV in 1990, high-definition TV: 720p = 1280 x 720p = 0.92 Mp; 1080p = 1920 x 1080 = 2.07Mp
- Satellite named Telstar 1 was launched in 1962 and used to relay TV signals between Europe and the United States
- Commercial satellite communication services began in 1965 with the launching of the Early Bird satellite
- First global mobile satellite communication system (Iridium) in operation in 1999
- Mobile cellular systems developed since 1980' – analog (TACS, AMP), digital (GSM, CDMA), third generation (wideband CDMA)

Data Communication System



- Information source produce required message which has to be transmitted
- Transducer converts one form of energy into another form (typically time-varying electrical signal)
- Transmitter amplifies and modulate the electrical signal in appropriate frequency range if necessary
- Channel provides a physical connection between the transmitter and receiver
- Receiver detects and demodulates the signal to reproduce the message signal in electrical form from the distorted received signal
- Destination converts an electrical message signal into its original form

Digital Communication System



- Source encoder converts the output of either an analog or a digital source into a sequence of binary digits
- Channel encoder introduces in a controlled manner some redundancy in the binary information sequence to increases the reliability of the received data and improve the fidelity of the received signal
- Digital modulator maps the binary information sequence into signal waveforms
- Digital demodulator processes the channel-corrupted transmitted waveform and reduces each waveform to a single number that represents an estimate of the transmitted data symbol (binary or M-ary)
- Channel decoder attempts to reconstruct the original information sequence from knowledge of the code used by the channel encoder and the redundancy contained in the received data
- Source decoder accepts the output sequence from the channel decoder and attempts to reconstruct the original signal from the source

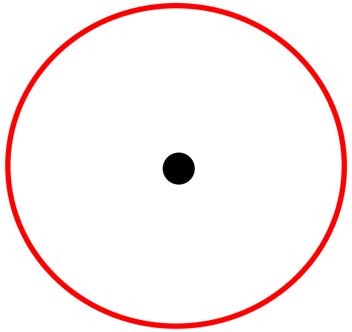
Wireless Signal Propagation

- What do we use to send and receive signal (data) in wireless media?
  - Antenna in radio channel
  - LED-Photodetector in optical channel
  - Speaker-Microphone in sound channel
- We have to consider many things about wireless channel:
  - Path Loss
  - Delay distortion
  - Interference
  - Multipath
  - Noise
  - ……

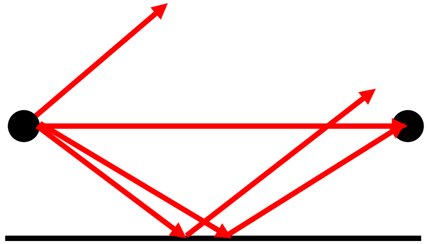
We primarily focus on radio-based wireless communication

Radio propagation basics

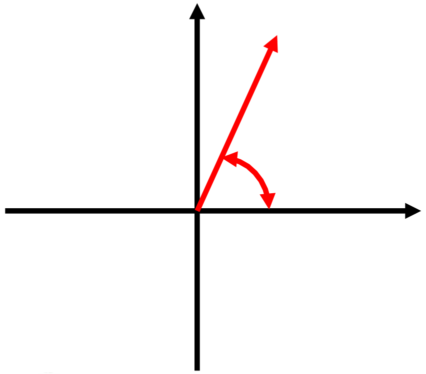
- A wave of energy
  - Think of it as energy that radiates from an antenna and is picked up by another antenna.
    - Helps explain properties such as attenuation
    - Density of the energy reduces over time and with distance
    - Receiving antennas catch less energy with distance



- Rays of energy
  - Can also view it as a “ray” that propagates between two points
  - Rays can be reflected etc. – we can have connectivity without line of sight
  - A channel can also include multiple “rays” that take different paths – “multi-path”
    - Helps explain properties such as signal distortion, fast fading, …



- Electromagnetic signal
  - Signal that propagates and has an <u>amplitude</u> and <u>phase</u> – complex number representation
  - … and that changes over time with a certain <u>frequency</u>

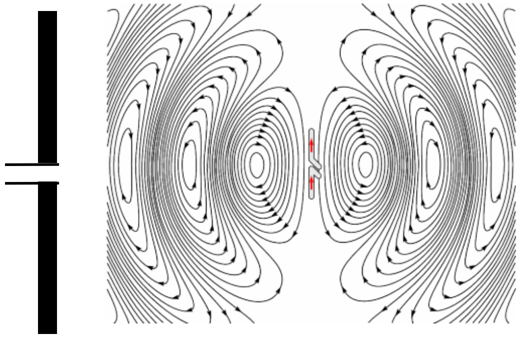


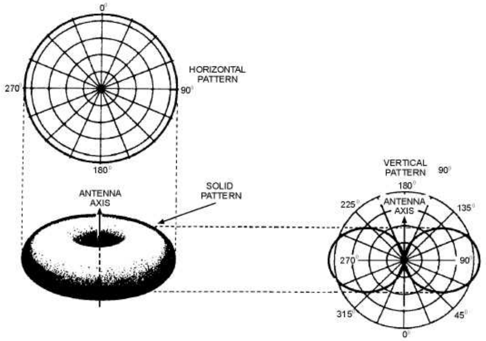
Antenna Concepts

- An electrical conductor which radiate or collect electromagnetic energy
- Transmitter converts electrical energy to electromagnetic waves.
  - Conductor that carries an electrical signal and radiates an RF signal.
  - The RF signal "is a copy of" the electrical signal in the conductor
- Receiver converts electromagnetic waves to electrical energy.
  - RF signals are "captured" by the antenna and create an electrical signal in the conductor.
- Efficiency of the antenna depends on its size, relative to the wavelength of the signal.
  - E.g. quarter of a wavelength ($\lambda/4$)
- Same antenna is used for transmission and reception.
- Antenna Gain (dBi) = Power at particular point / Power with Isotropic
  - Does not refer to obtaining more output power than input power but rather to directionality

Types of Antennas

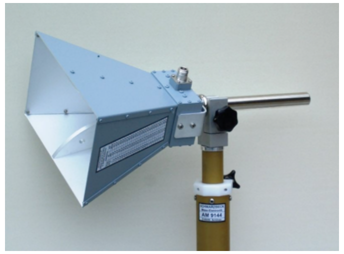
- Isotropic antenna: a point source that radiates with the same power level in all directions – sphere shape
  - Not common: shape of the conductor tends to create a specific radiation pattern
    - Note that isotropic antennas are not very efficient!
      - Unless you have a very large number of receivers
  - Common: omnidirectional antenna radiates equally well in all horizontal directions
    - Simplest shape: is a straight conductor
      - Half-wave dipole and quarter wave vertical antennas – creates a "donut" pattern of 75° in vertical plane
      - Elements are quarter wavelength of frequency that is transmitted most efficiently – max gain of 2.15 dbi
- Directional antenna: shaped to be used to direct the energy in a certain direction.
  - Examples: parabolic antenna and horn antenna
- Multi-element antennas
  - Have multiple, independently controlled conductors
  - To be further discussed in MIMO

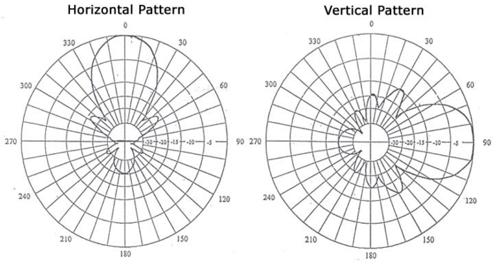

Dipole antenna



Omnidirectional radiation pattern


Parabolic antenna (70 dBi)

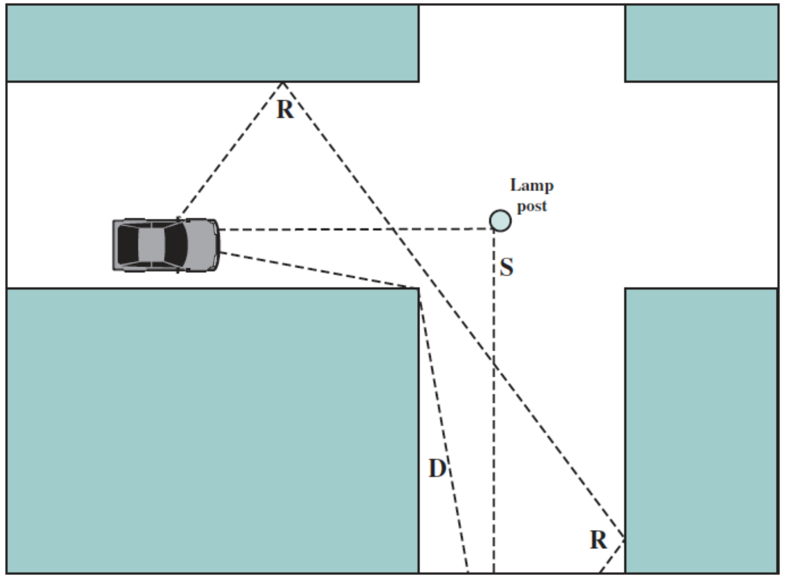

Horn antenna (30 dBi)

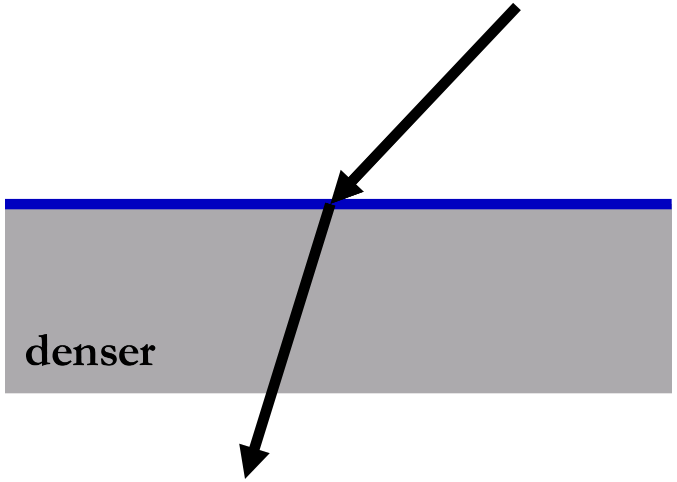


Directional radiation pattern

Impacts of Obstacles

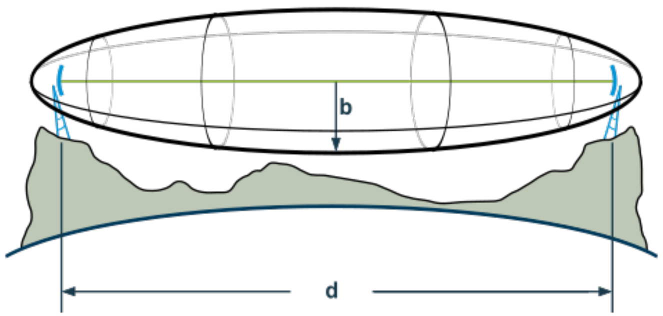
- Reflection: Surface large relative to wavelength of signal
  - May has phase shift from original
  - May cancel out original or increase it
- Diffraction: Edge of impenetrable body that is large relative to λ
  - Signal is scattered by the edge of a large object – "bends"
  - May receive signal even if no line of sight to transmitter
- Scattering: signal radiation by an obstacle that is small relative to λ
- Refraction
  - Speed of EM signals depends on the density of the material
    - Vacuum: 3×10^8 m/sec; Denser: slower
  - Density is captured by refractive index
  - Explains "bending" of signals in some environments
    - E.g. sky wave propagation: Signal "bounces" off the ionosphere back to earth – can go very long distances
    - But also local, small scale differences in the air density, temperature, etc.

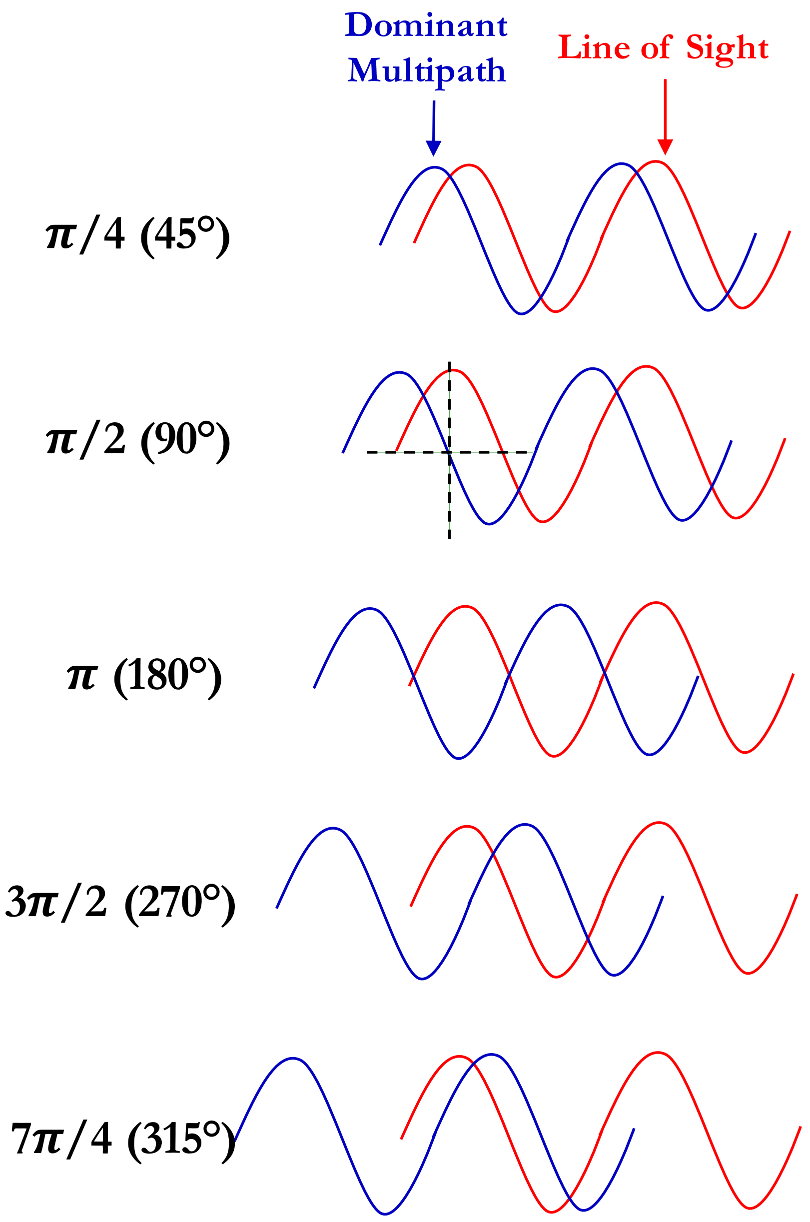




Fresnel Zones

- Sequence of ellipsoids centered around the LOS path between a transmitter and receiver
- The zones identify areas in which obstacles will have different impact on the signal propagation
  - Capture the constructive and destructive interference due to multipath caused by obstacles
- Zones create different phase differences between paths
  - First zone: $0 - \pi/2$
  - Second zone: $\pi/2 - 3\pi/2$
  - Third zone: $3\pi/2 - 5\pi/2$,
  - …
  - Odd zones create constructive interference, even zones destructive





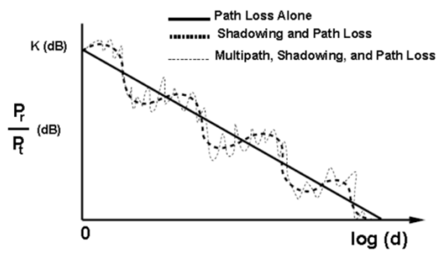
Propagation Degrades RF Signals

- Attenuation in free space: signal gets weaker as it travels over longer distances
  - Radio signal spreads out – free space loss
  - Refraction and absorption in the atmosphere
  - Delay distortion
    - For a signal with a given bandwidth, the velocity tends to be highest near the center frequency of the band
- Obstacles can weaken signal through absorption or reflection.
  - Reflection redirects part of the signal
- Multi-path effects: multiple copies of the signal interfere with each other at the receiver
  - Similar to an unplanned directional antenna
- Mobility: moving the radios or other objects changes how signal copies add up
  - Node moves ½ wavelength -> big change in signal strength

Path Loss

- Power radiates equally to spherical area $4\pi d^2$
- If the receiver collects power from area A_e:
  - $P_R = P_T G_T \frac{1}{4\pi d^2} A_e$
- Loss increases quickly with distance (d^2)
- Effective aperture for any antenna:
  - $A_e = \frac{\lambda^2}{4\pi} G_R$
  - $P_R = P_T G_T G_R \frac{\lambda^2}{(4\pi d)^2} = P_T G_T G_R \frac{c^2}{(4\pi d f)^2}$
- This is known as Frii's Law.
  - Loss depends on frequency: higher loss with higher frequency.
    - Can cause distortion of signal for wide-band signals
    - Impacts transmission range in different spectrum bands

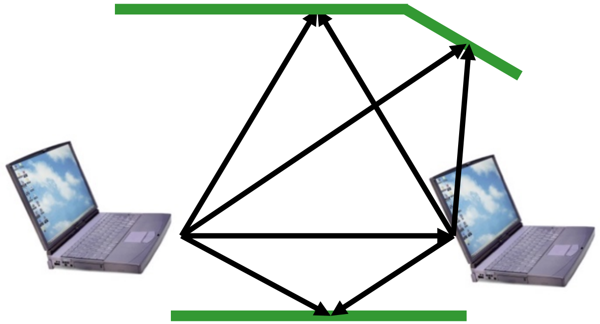
- Log Distance Path Loss Model

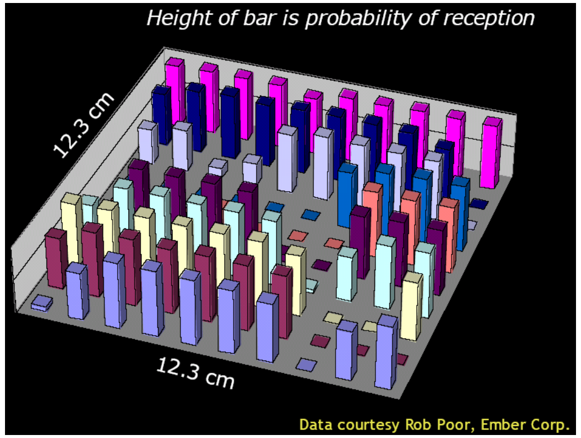


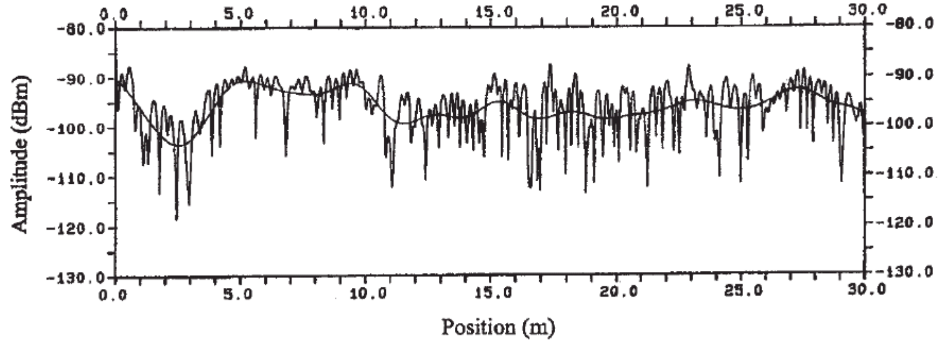
  - $L_{dB} = L_0 + 10n\log_{10}(d/d_0)$
  - L_0 is the loss at distance d_0
  - Path loss distance component n depends on environments:
    - 2 for free space, 3 for office, higher if more and thicker obstacles
- Other factors
  - Objects absorb energy was the signal passes through them
    - Degree of absorption depends strongly the material
    - Paper versus brick versus metal
  - Absorption of energy in the atmosphere.
    - Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
    - Obviously objects also absorb energy

Multipath Effect

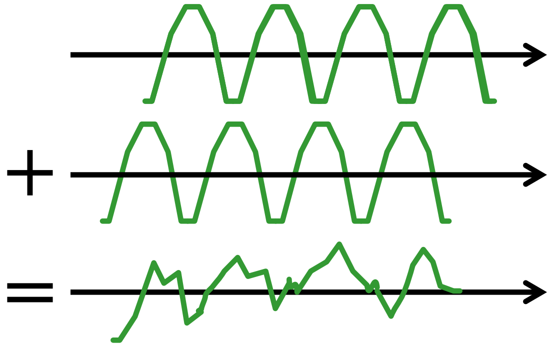
- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other
  - Depends on whether they are in our out of phase
- Changes of half a wavelength affect the outcome
  - Short wavelengths, e.g. 2.4 GHz → 12 cm, 900 MHz → ~1 ft (30cm)





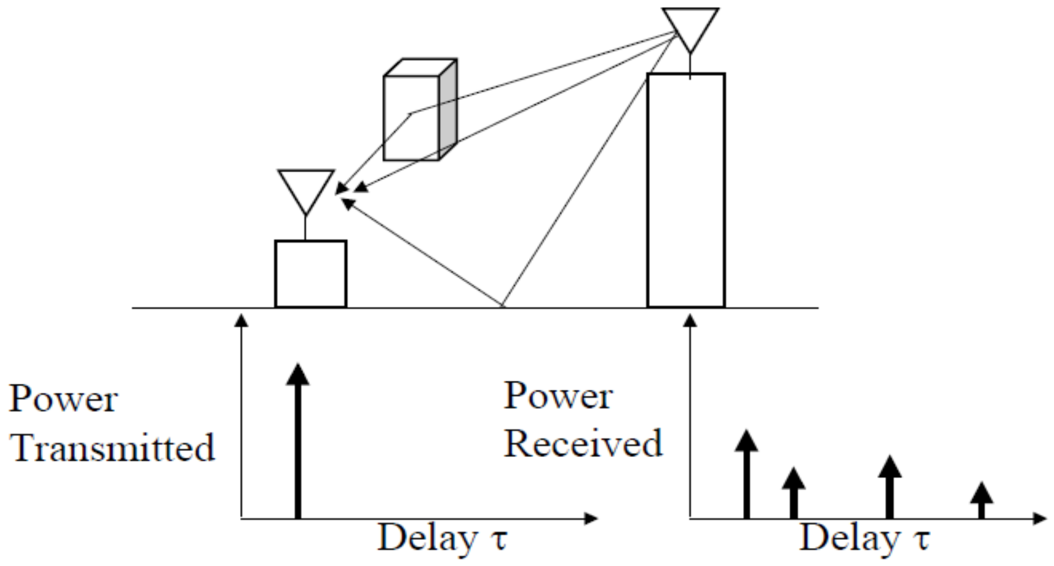


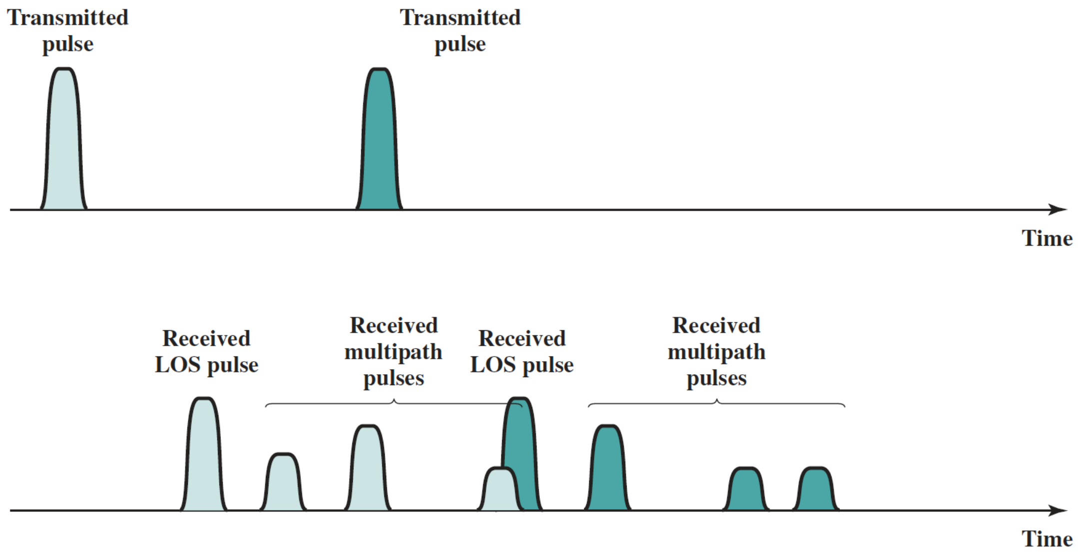
Frequency of 900 MHz or wavelength of about 33 cm



- Small adjustments in location or orientation of the wireless devices can result in big changes in signal strength – why?

Multipath Effect Cont'd



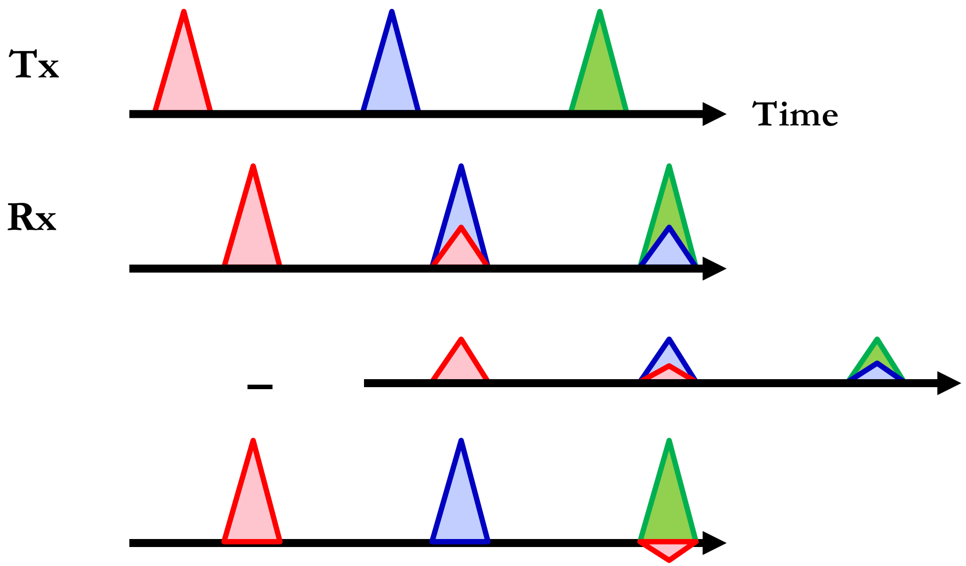


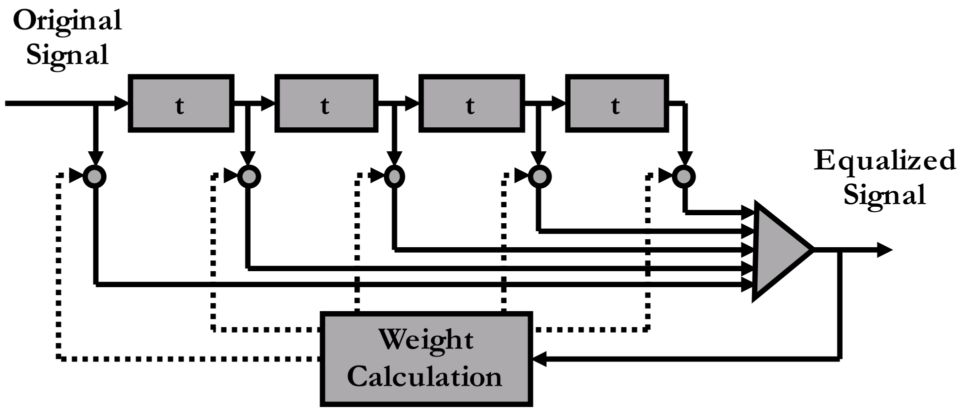
- **Multipath Power Delay Profile**
  - A single impulse results in multiple impulse at different times
  - Delay Spread = Maximum delay after which the received signal becomes negligible = τ_{max}
    - Often in nano seconds

- **One symbol interferes with subsequent symbols.**
  - Happens when the spreading of the pulse beyond its allotted time interval.
  - Larger difference in path length or higher bit rate causes higher chance of ISI

Inter-Symbol Interference

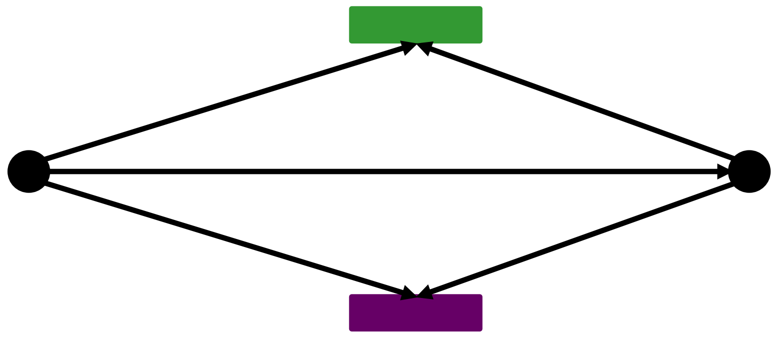
- A form of distortion of a signal in which one symbol interferes with subsequent symbols.
  - Happens when the spreading of the pulse beyond its allotted time interval.
  - Larger difference in path length causes higher chance of ISI
- Delays on the order of a symbol time result in overlap of the symbols
  - Makes it very hard for the receiver to decode
  - Corruption issue – not signal strength
- Suppose the receiver can do some processing:
  - Dynamic equalization: add/substract scaled and delayed copies of the signal
    - Weights are set dynamically based on known "training" sequence

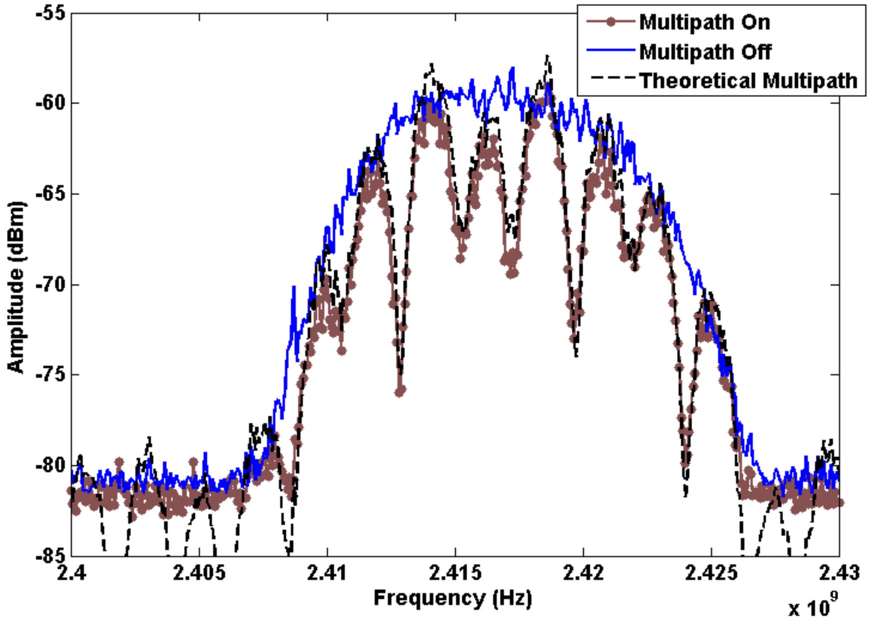




Some Intuition for Selective Fading

- Assume three paths between a transmitter and receiver
- The outcome is determined by the differences in path length
  - But expressed in wavelengths → outcome depends on frequency
- As transmitter, receivers or obstacles move, the path length differences change, i.e., there is fading
  - But changes depend on wavelength, i.e. fading is frequency selective
- Much more of a concern for wide-band channels



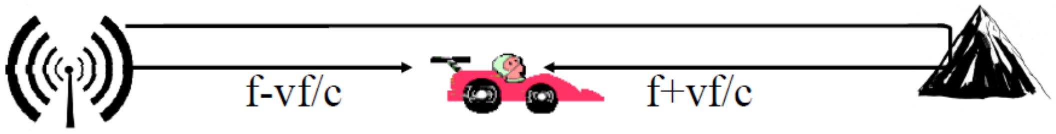


Noise

- Thermal/white Noise: caused by thermal agitation of electrons, present in all electronic devices and transmission media, and is a function of temperature
  - Noise Power Spectral Density $N_0 = k_B T$, where k_B is Boltzman's constant $= 1.38 \times 10^{-23}$ Joules/Kelvin
  - For a band of width B: Noise Power = $N_0 B = -174 + 10 log_{10}(B)$ dBm at 300K
  - Can't be eliminated, places an upper bound on communications system performance
- Receiver Noise: amplifiers and mixers add noise.
  - Noise generated before the amplifiers also gets amplified.
- Crosstalk: picking up signals from other source-destination pairs
- Impulse noise: irregular pulses of high amplitude and short duration
  - Interference from various RF transmitters, lighting, etc.
  - Should be dealt with at protocol level

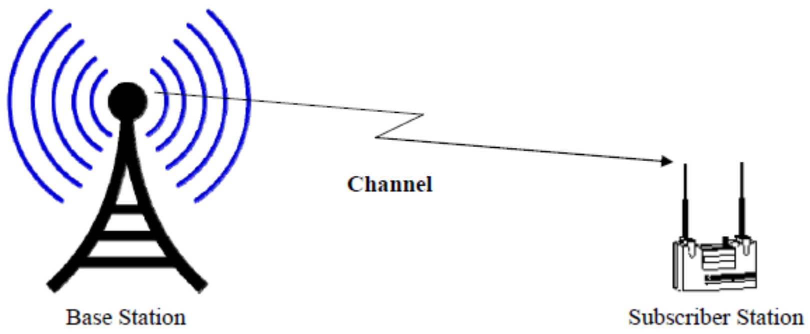
Doppler shift

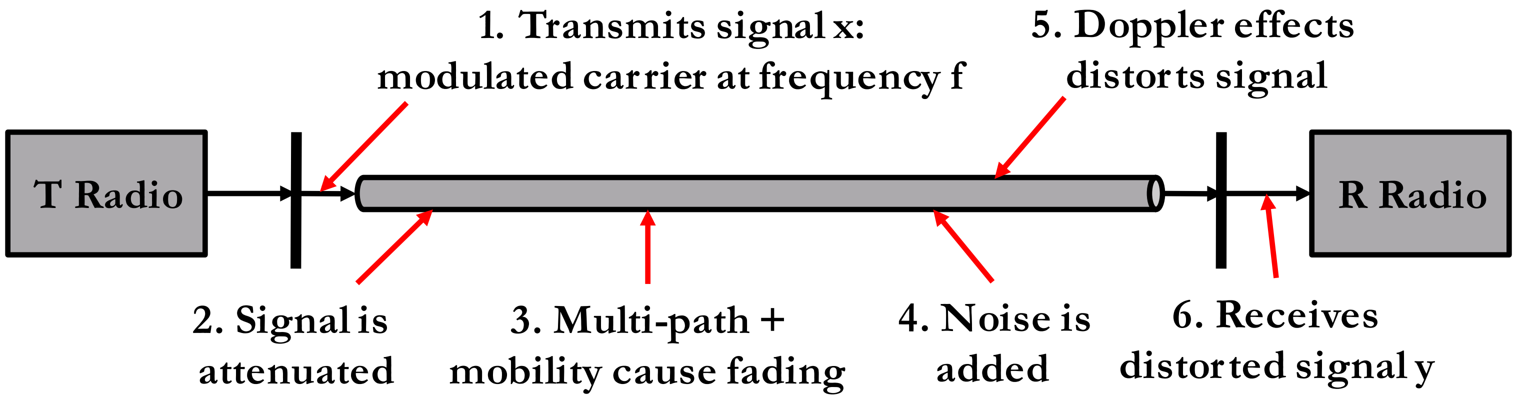
- If the transmitter or receiver or both are mobile, the frequency of received signal changes:
  - Moving towards each other → Frequency ↑
  - Moving away from each other → Frequency ↓
  - Frequency difference f_D = velocity/wavelength = vf/c
- Results in distortion of signal
  - Shift may be larger on some paths than on others
  - Shift is also frequency dependent (minor)
- Effect only an issue at higher speeds:
  - Speed of car: 10^5 m/h = 27.8 m/s
  - Shift at 2.4 GHz is 222 Hz – increases with frequency
  - Impact is that signal "spreads" in frequency domain



- Doppler Spread
  - Power Delay Profile of Channel = Power Distribution over time for an impulse signal.
  - Doppler Power Spectrum = Power Distribution over frequency for a signal transmitted at one frequency.
  - Non-zero for $(f - f_D \ to \ f + f_D)$
  - Doppler spread = f_D
  - Coherence Time = 1 / Doppler Spread
  - If transmitter, receiver, or intermediate objects move very fast, the Doppler Spread is large and coherence time is small.

Wireless Channel Model





- Power profile of the received signal can be obtained by *convolving* the power of the transmitted signal with the impulse response of the channel.
- Convolution in time = multiplication in frequency
- Signal *x*, after propagation through the channel H becomes y :
  - y(f) = H(f)x(f) + n(f) ⟶ the noise

    ↘ channel response/state, a (time-variant) complex number (matrix) that captures attenuation, multipath, … effects.
- Receiver needs a certain SNR to be able to decode the signal
  - Required SNR depends on coding and modulation schemes, i.e. the transmit rate

Comments on Data Rate and Bandwidth

- The greater the (spectral) bandwidth, the higher the information – carrying capacity of the signal
- If a signal can change faster, it can be modulated in a more detailed way and can carry more data
  - E.g. more bits or higher fidelity music
- Extreme example: a signal that only changes once a second will not be able to carry a lot of bits or convey a very interesting TV channel
- The bandwidth that can be transmitted is limited by the transmission system (tx, medium, rx)
- The greater the bandwidth, the greater the cost
- The narrower the bandwidth, the greater the distortion (errors)!

Channel Capacity

- Definition: The maximum rate at which data can be transmitted over a given channel, under given conditions
- Data rate (R) – rate at which data can be communicated (bps)
- Bandwidth (B) – 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
- Signal strength (S) and noise strength (N) – limit how many signal levels we can distinguish

Decibels and Signal-to-Noise Ratio

- A ratio between signal powers is expressed in decibels (db) = $10\log_{10}(P_1 / P_2)$
- Is used in many contexts:
  - The loss of a wireless channel
  - The gain of an amplifier
- Note that dB is a relative value.

Power ratio	1000	100	10	4	2	1.26	1
dB	30	20	10	6	3	1	0

- Can be made absolute by picking a reference point.
  - Decibel-Watt – power relative to 1 W
  - Decibel-milliwatt – power relative to 1 mW

- Ratio of the power in a signal to the power contained in the noise that is present at a particular point in the transmission
  - Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\text{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

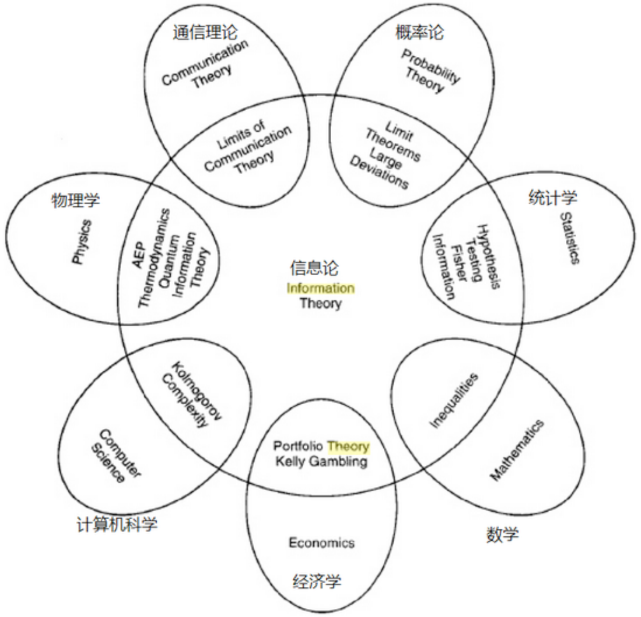
- A high SNR means a high-quality signal
- Low SNR means that it may be hard to "extract" the signal from the noise
- SNR sets upper bound on achievable data rate

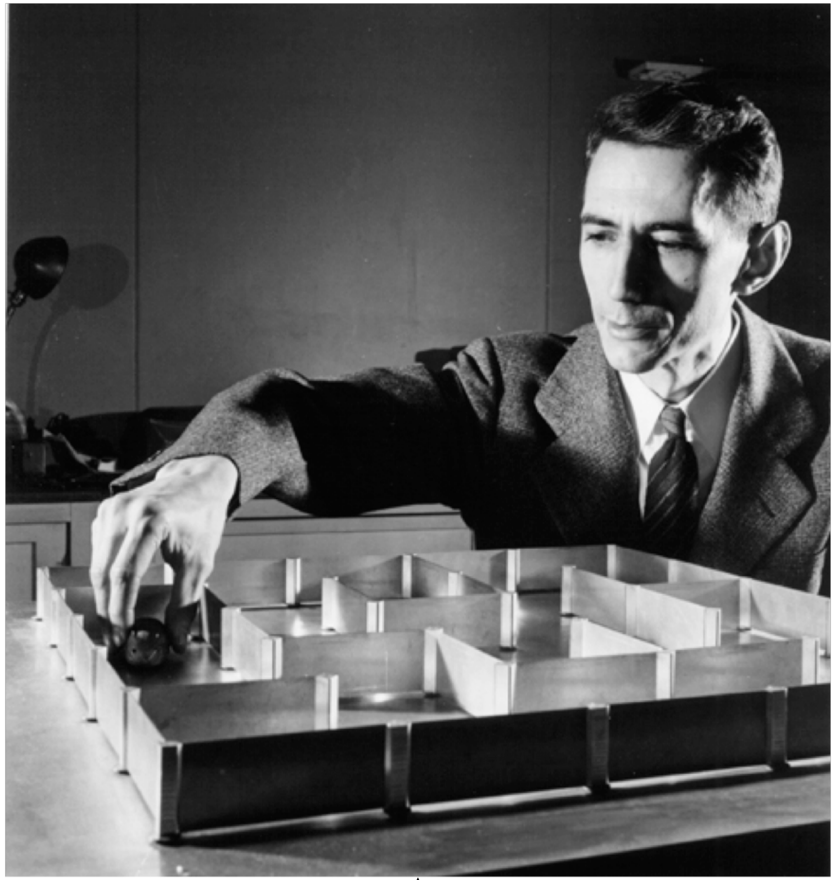
Nyquist Capacity

- A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity 2B
  - Assumes binary amplitude encoding
  - Limitation is due to the effect of intersymbol interference and noise
- For M levels: $C = 2B \log_2 M$
  - M discrete signal levels
- More aggressive encoding can increase the actual channel bandwidth (data rate)
  - Example: modems
- Factors such as noise can reduce the capacity
- Example: consider a voice channel being used, via modem, to transmit digital data. For B = 3100 Hz:
  - C = 2B = 6200 bps.
  - For M = 8, C = 18,600 bps for a bandwidth of 3100 Hz.
  - No upper limit?

Claude Shannon (1916-2001)

- Father of information theory
  - “A Mathematical Theory of Communication”, 1948
- Fundamental contributions to digital computers, security, and communications
- Search for:
  - “他被誉为码农鼻祖，智商完爆爱因斯坦，竟还是20世纪最帅科学家 …”
  - “香农的信息论究竟牛在哪里？”





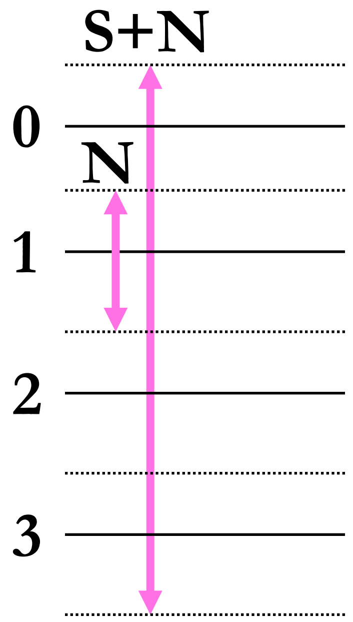
Electromechanical mouse that “solves” mazes!

Shannon Capacity

- How many levels we can distinguish depends on S/N or SNR
  - Note noise is random, hence some errors
  - Shorter bits are more likely affected by a given pattern noise
- Shannon limit is for capacity (C), the maximum information carrying rate of the channel with only white noise, not including impulse noise and various types of distortion):

$$C = B \log_2(1 + S/N) \text{ bits/sec}$$

- Represents error free capacity
  - It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- Example: Phone wire with bandwidth = 3100Hz, $(S/N)_{dB}$ = 30dB
  - $10\log_{10}(S/N) = 30 \rightarrow S/N = 10^3 = 1000$
  - Capacity = $3100\log_{10}(1+1000)$ = 30984 bps



Wired/Wireless Perspective

- Wires, and Fiber

  Engineer SNR for data rate

  - Engineer link to have requisite SNR and B
  - Can fix data rate
- Wireless

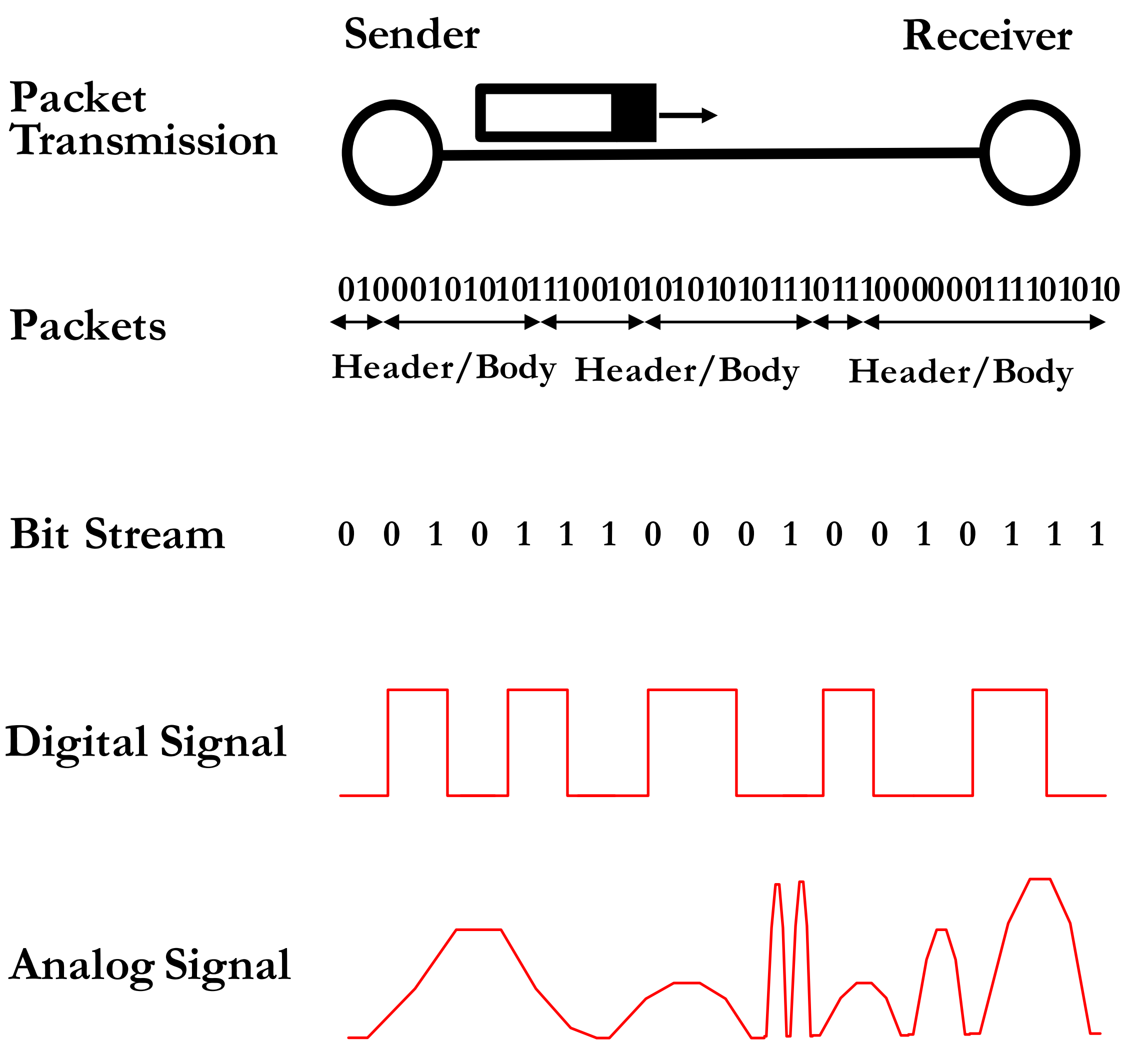
  Adapt data rate to SNR

  - Given B, but SNR varies greatly, e.g., up to 60 dB!
  - Can't design for worst case, must adapt data rate

Topics

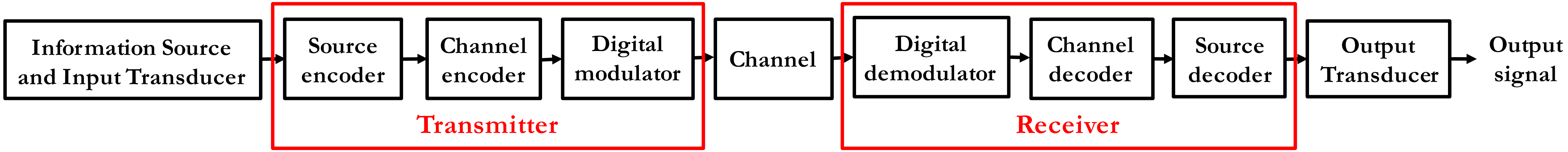
- Properties of media
  - Wires, fiber optics, wireless
- Signal propagation and wireless basics
  - Bandwidth, channel model, and multipath effect
- Coding, modulation, and multiplexing
  - Representing and communicating bits
- Advanced wireless transmission techniques
  - MIMO, OFDM, Spread spectrum, CDMA

From Signals to Packets



- Communication is based on sender transmitting the carrier signal
  - A sine wave with an amplitude, phase, frequency
  - A complex value at a certain point in space and time captures the amplitude and phase
- The sender sends an EM signal and changes its properties over time
  - Changes reflect a digital signal, e.g., binary or multi-valued signal
  - Can change amplitude, phase, frequency, or a combination
- Receiver learns the digital signal by observing how the received signal changes
  - Note that signal is no longer a simple sine wave or even a periodic signal

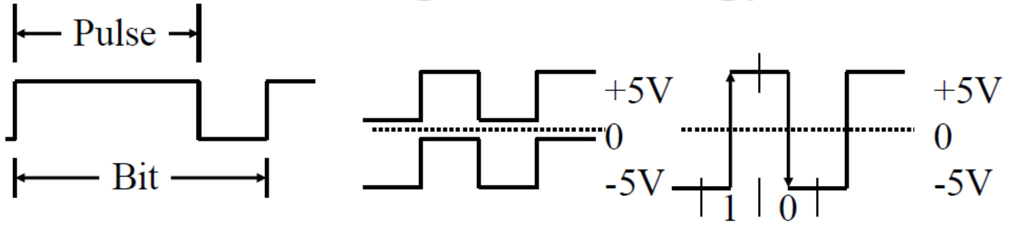
Remainder: Digital Communication System



- Source encoder converts the output of either an analog or a digital source into a sequence of binary digits
- Channel encoder introduces in a controlled manner some redundancy in the binary information sequence to increases the reliability of the received data and improve the fidelity of the received signal
- Digital modulator maps the binary information sequence into signal waveforms
- Digital demodulator processes the channel-corrupted transmitted waveform and reduces each waveform to a single number that represents an estimate of the transmitted data symbol (binary or M-ary)
- Channel decoder attempts to reconstruct the original information sequence from knowledge of the code used by the channel encoder and the redundancy contained in the received data
- Source decoder accepts the output sequence from the channel decoder and attempts to reconstruct the original signal from the source

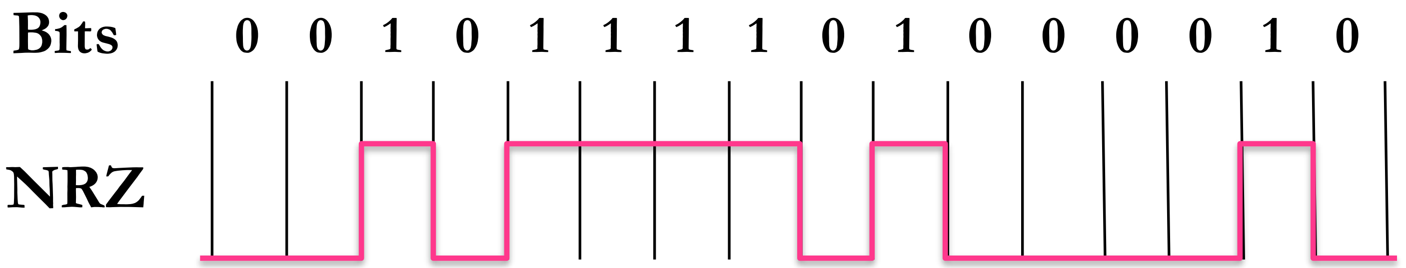
Coding for Digital Communication

- Source coding or data compression is concerned with the problem that given a source of information how should messages from this source be represented such that on average the information is conveyed *using the minimum number of bits.*
  - E.g., ASCII
- Channel or error control coding introduces extra bits into the transmitted signal to provide carefully structured redundancy, in order to detect or correct the presence of errors in the received pattern.
  - E.g., parity, CRC, Hamming codes, LDPC codes, etc
- Line or transmission coding encodes digital data into electrical pulses or waveforms for the purpose of transmission over the channel – use a specific method to express information with bits.
  - Signal element: Pulse (of constant amplitude, frequency, phase)
  - Modulation rate D (baud): 1/Duration of the smallest element
  - Data rate R (bps): $DL = D\log_2 M$
    - L = # of bits per signal element
    - M = # of different signal elements = 2^L

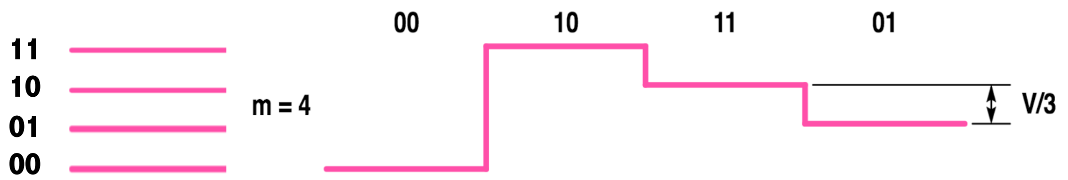


Line/Transmission Coding

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - NRZ (Non-Return to Zero): has additional rest state other than conditions for ones and zeros



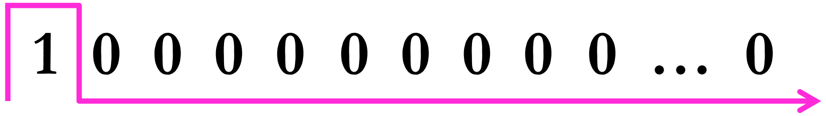
- Can use more signal levels, e.g., 4 levels is 2 bits per <u>symbol</u>



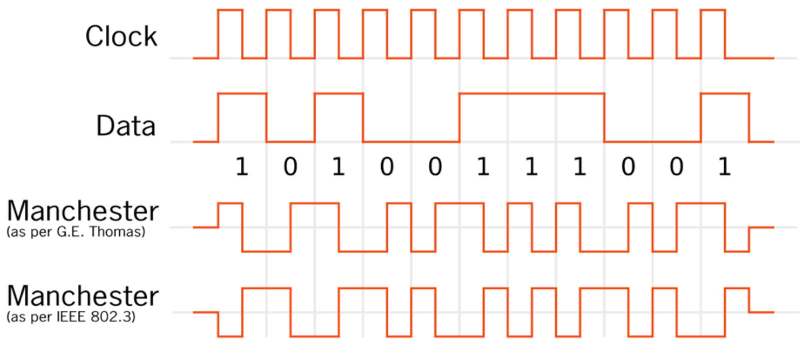
- Practical schemes are driven by engineering considerations
  - E.g., clock recovery

Clock Recovery

- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

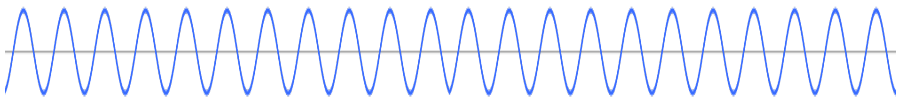


- Several possible designs
  - Manchester coding, also known as phase encoding
    - Encode data bit either low then high, or high then low, of equal time
    - Self-clocking
      - Signals can be decoded without the need for a separate clock signal or other source synchronization
    - A special case of binary phase-shift keying (BPSK)
  - 4B/5B – Map every 4 data bits into 5 code bits without long runs of zeros
    - 0000 → 11110, 0001 → 01001, … 1110 → 11100, 1111 → 11101
    - Has at most 3 zeros in a row

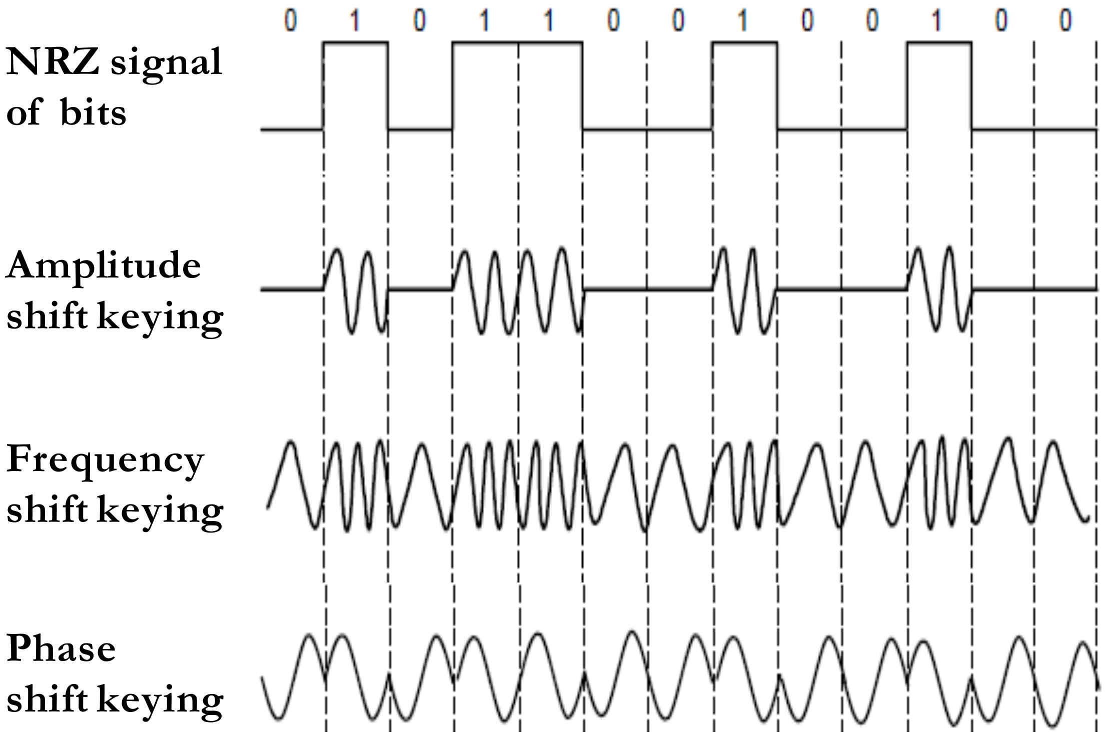


Passband/Carrier Modulation

- What we have seen so far is baseband modulation for wires, or baseband digital transmission
  - Signal is sent directly on a wire
- These signals do not propagate well on fiber/wireless
  - Need to send at higher frequencies
- Passband/Carrier modulation carries a signal by modulating a carrier
  - The process of encoding source data onto a carrier signal with frequency f_c.
  - Carrier is simply a signal oscillating at a desired frequency compatible with the transmission medium:



- We can modulate it by changing:
  - Amplitude, frequency, or phase



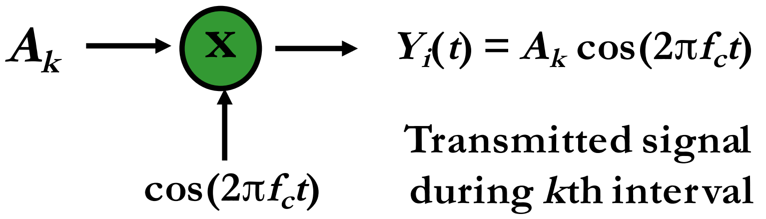
Amplitude-Shift Keying (ASK)

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

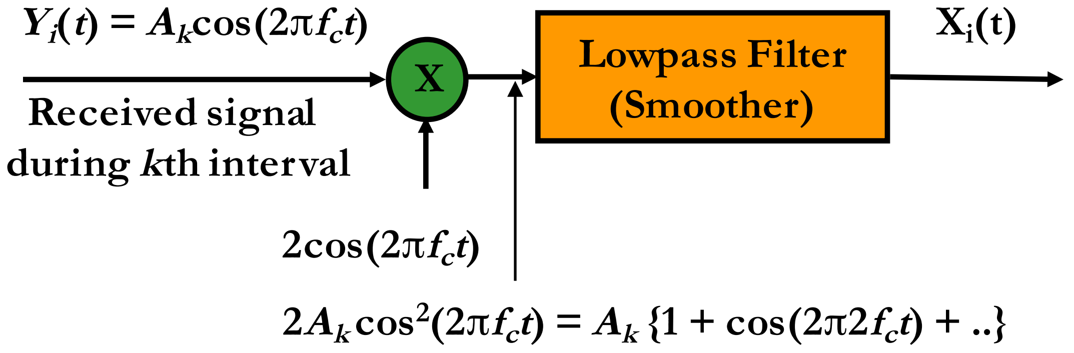
$$s(t) = \begin{cases} \cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

  - where the carrier signal is $A\cos(2\pi f_c t)$
- Inefficient because of sudden gain changes
  - Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber
- A can be a multi-bit symbol

- Modulate $\cos(2\pi f_c t)$ by multiplying by A_k for T seconds:



- Demodulate (recover A_k) by multiplying by $2\cos(2\pi f_c t)$ for T seconds and lowpass filtering (smoothing):



Frequency-Shift Keying (FSK)

- Binary Frequency-Shift Keying (BFSK)
  - Two binary digits represented by two different frequencies near the carrier frequency

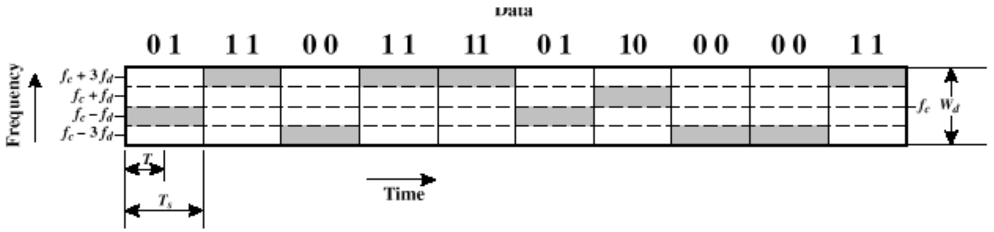
$$s(t) = \begin{cases} \cos(2\pi f_1 t) & \text{binary 1} \\ \cos(2\pi f_2 t) & \text{binary 0} \end{cases}$$

    - where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts
  - Less susceptible to error than ASK
  - Demodulator looks for power around f_1 and f_2
- How Can We Go Faster?
  - Increase the rate at which we modulate the signal
  - Modulate the signal with "symbols" that send multiple bits

- Multiple Frequency-Shift Keying (MFSK)
  - More than two frequencies are used
  - Each symbol represents L bits

$$S_i(t) = A\cos(2\pi f_i t) \quad 1 <= i <= M$$

    - $f_i = f_c + (2i - 1 - M)f_d$
    - L = number of bits per signal element
    - M = number of different signal elements = 2^L
    - f_c = the carrier frequency
    - f_d = the difference frequency
  - More bandwidth efficient but more susceptible to error
    - Symbol length is T_s=LT seconds, where T is bit period



Phase-Shift Keying (PSK)

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

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

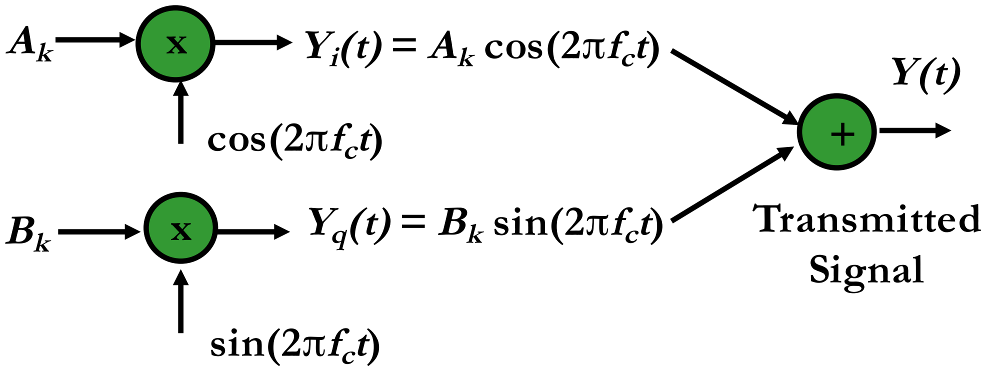
- **Differential PSK (DPSK)**
  - Phase shift with reference to previous bit
    - Binary 0 – signal of same phase as previous signal burst
    - Binary 1 – signal of opposite phase to previous signal burst

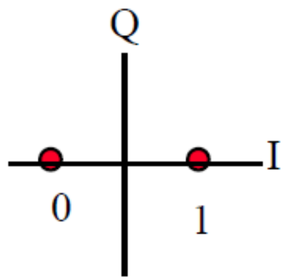
- **Quadrature PSK (QPSK)**
  - Each signal element represents more than one bit

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

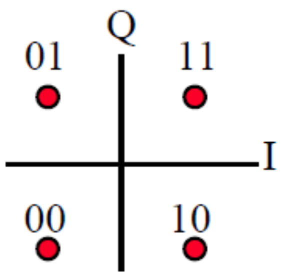
Quadrature Amplitude Modulation (QAM)

- QAM uses two-dimensional signaling
  - A_k modulates in-phase $\cos(2\pi f_c t)$
  - B_k modulates quadrature phase $\sin(2\pi f_c t)$
  - Transmit sum of inphase & quadrature phase components
- Each pair (A_k, B_k) defines a point in the plane
- Signal constellation set of signaling points
- How does distortion impact a constellation diagram?
  - Changes in amplitude, phase or frequency move the points in the diagram
  - Large shifts can create uncertainty on what symbol was transmitted
  - Larger symbols are more susceptible
  - Can adapt symbol size to channel conditions to optimize throughput

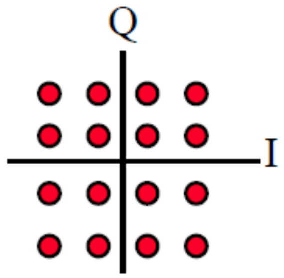




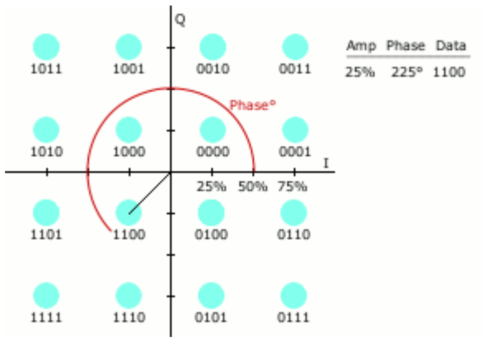
BPSK



QPSK (QAM-4)



QAM-16

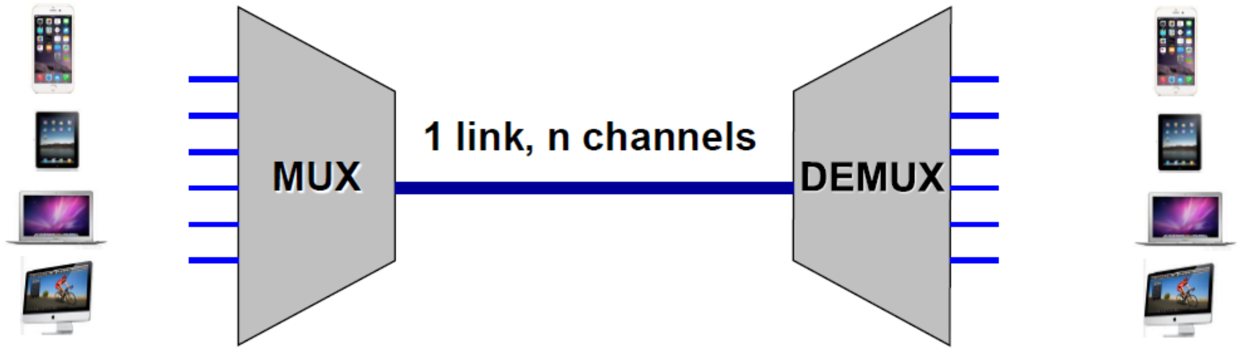


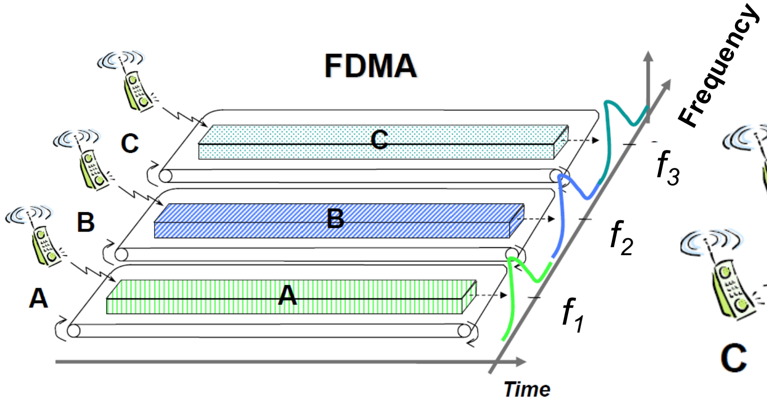
Adapting to Channel Conditions

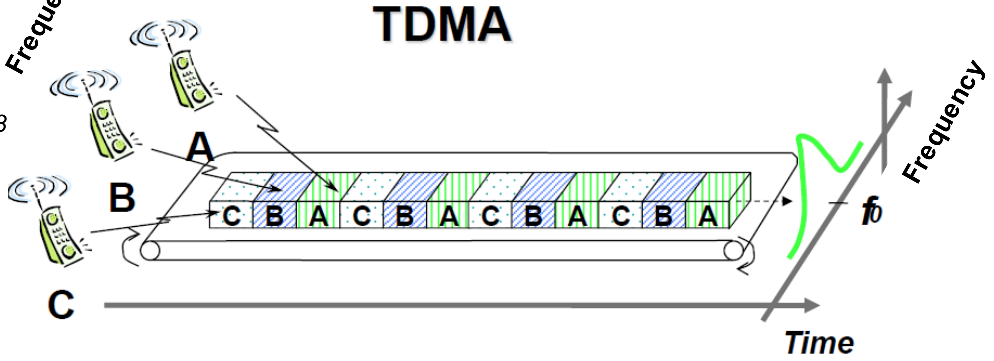
- Channel conditions can be very diverse
  - Affected by the physical environment of the channel
  - Changes over time as a result of slow and fast fading
- Fixed coding/modulation scheme will often be inefficient
  - Too conservative for good channels, i.e. lost opportunity
  - Too aggressive for bad channels, i.e. lots of packet loss
- Adjust coding/modulation based on channel conditions – "rate" adaptation
  - Controlled by the MAC protocol
  - E.g. 802.11a: BPSK – QPSK – 16 QAM – 64 QAM

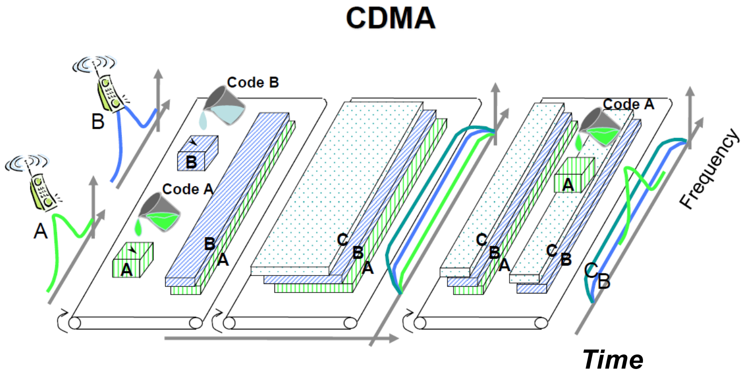
Multiple Access Methods – Scheduled Multiplexing

- Capacity of the transmission medium usually exceeds the capacity required for a single signal
- Multiplexing – carrying multiple signals on a single medium, the network word for the resource sharing
  - Individual need of bit rate is relatively low
    - More efficient use of transmission medium
- A must for wireless – spectrum is huge!
  - Signals must differ in frequency, time, or space
- MUX: n low-rate links → 1 high-rate link
- DEMUX: 1 to n, send each data to the corresponding output link



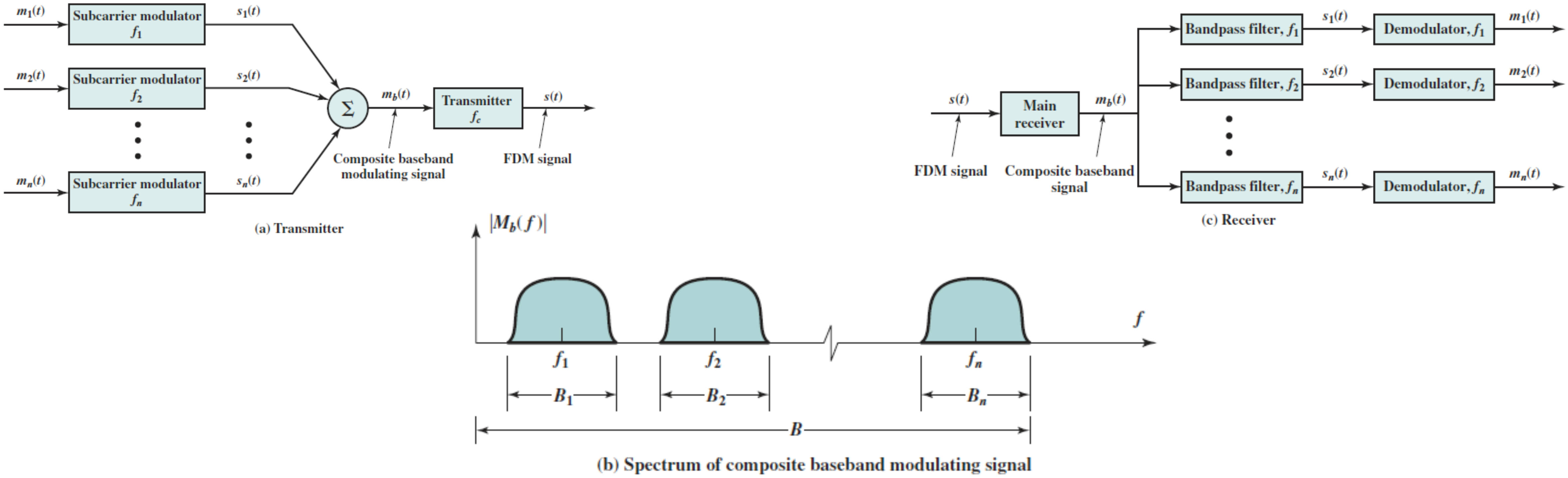






Frequency Division Multiplexing (FDM)

- FDM is possible when the useful bandwidth of the transmission medium exceeds the required bandwidth of signals to be transmitted
- Each user can send all the time at reduced rate

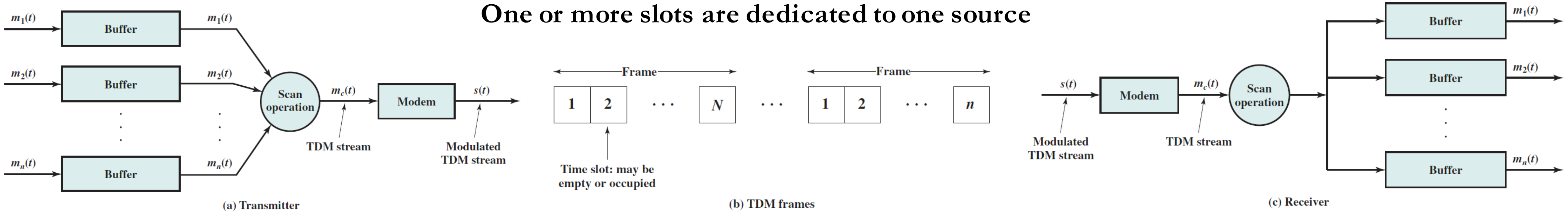


- Hardware is slightly more expensive and is less efficient use of spectrum

Synchronous Time Division Multiplexing (TDM)

- Multiple signals can be carried on a single tx path by interleaving portions of each signal in time
  - Interleaving can be at the bit level or in blocks of bytes or even larger

Each frame contains a cycle of time slots
One or more slots are dedicated to one source



- Channel: the sequence of slots dedicated to one source, from frame to frame
- Synchronous: time slots are pre-assigned to source and are fixed
  - The time slots for each source are transmitted whether or not the source has data to send
  - More efficiency: allocate more slots to faster devices per cycle
- Alternative: statistical TDM: the multiplexer scan the input buffers and send the frame only if it is filled
- Transition time between slots, become an issue with longer propagation times

Topics

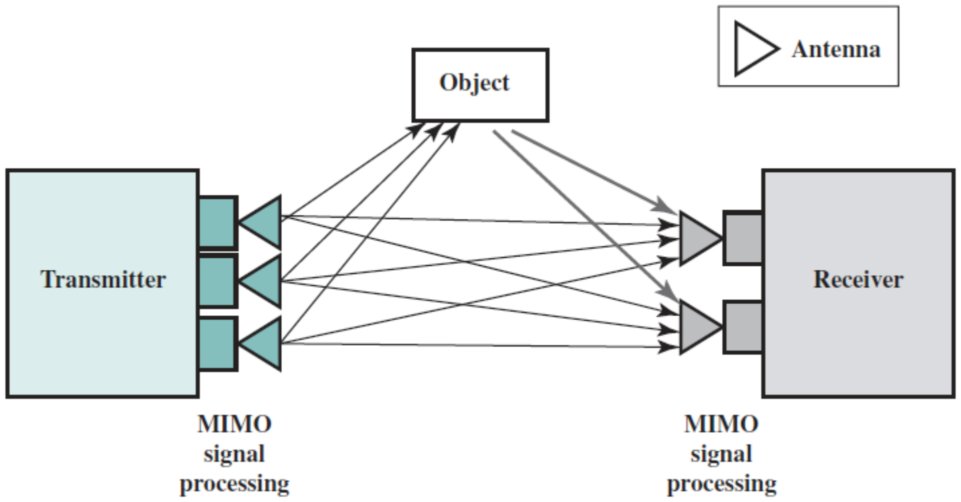
- Properties of media
  - Wires, fiber optics, wireless
- Signal propagation and wireless basics
  - Bandwidth, channel model, and multipath effect
- Coding, modulation, and multiplexing
  - Representing and communicating bits
- Advanced wireless transmission techniques
  - MIMO, OFDM, Spread spectrum, CDMA

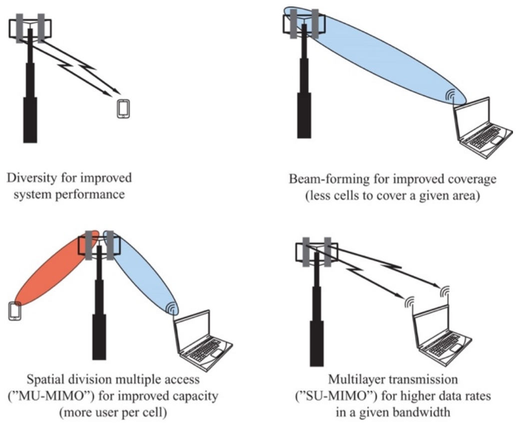
Diversity Techniques – Distribute data over multiple "channels"

- The quality of the channel depends on time, space, and frequency
- Space diversity: use multiple nearby antennas and combine signals
  - Receiver diversity
    - Maximal ratio/weight combining – phase alignment is needed to amplify each other, need help from transmitter diversity
  - Transmitter diversity
    - Ample space, power, and processing capacity (at the transmitter)
      - If the channel is known, pre-align each component and weight it before transmission so that they arrive in phase at the receiver
      - If the channel is not known, use space time block codes or learn from receiver or receiving packets based on channel reciprocity
- Time diversity: spread data out over time
  - Useful for avoiding burst errors, i.e., errors are clustered in time: if the number of errors within a code word exceeds the error-correcting code's capability, it fails to recover the original code word
- Frequency diversity: spread signal over multiple frequencies
  - Fight with frequency selective fading, e.g., spread spectrum, OFDM

Multiple-input-multiple-output (MIMO) Antenna Architecture

- N x M subchannels that can be used for simultaneous reception or transmission of multiple streams
  - Coordinate the processing at the transmitter and receiver to overcome channel impairments
    - Boost capacity, range and reliability, and reduce interference
- Fading on channels is largely independent
  - Assuming antennas are separate ½ wavelength or more
- Combines ideas from spatial and time diversity, e.g. 1 x N and N x 1
- Very effective if there is no direct line of sight
  - Subchannels become more independent
- MIMO is used in 802.11n/ac
  - See “802.11 with Multiple Antennas for Dummies” in detail.

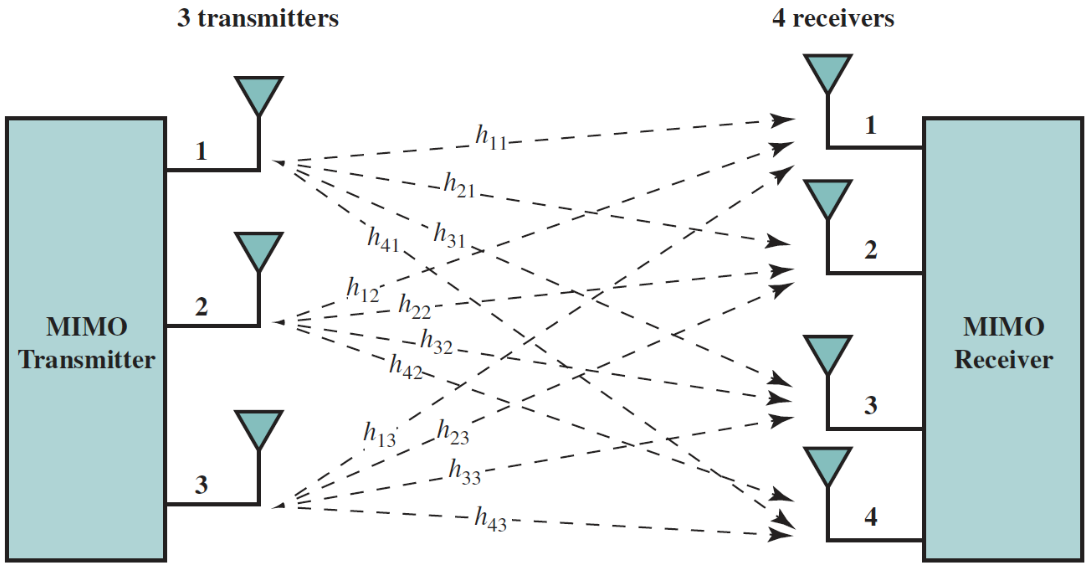




Method	Capacity
SISO	$B \log_2(1 + r)$
1xN or Nx1	$B \log_2(1 + rN)$
NxN	$B \log_2(1 + rN^2)$
Multiplexing	$NB \log_2(1 + r)$

Two types of MIMO Transmission Schemes

- Spatial diversity: same data is coded and transmitted through multiple antennas
  - Higher SNR: increases the power in the channel proportional to the number of transmitting antennas
  - More robust: diverse multipath fading offers multiple “views” of the transmitted data at the receiver



- Spatial multiplexing: a source data stream is divided among the transmitting antennas
  - Need favorable channel conditions and short link
  - Receiver do considerable signal processing
  - Channel response: y = Hc + n

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \\ h_{41} & h_{42} & h_{43} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

  - The h_{ij} are complex numbers x + jz that represent both the amplitude attenuation (x) over the channel and the path dependent phase shift (z)
  - The receiver measures the channel gains based on training fields containing known patterns in the packet preamble and can estimate the transmitted signal

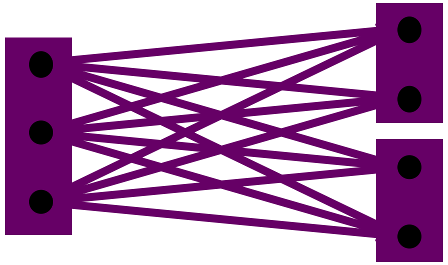
MIMO Discussion

- Need channel matrix H: use training with known signal
- So far we have ignored multi-path
  - Each channel is multiple paths with different properties
  - Becomes even messier!
- MIMO is used in 802.11n/ac
  - Can use two adjacent non-overlapping "WiFi channels"
  - Raises lots of compatibility issues
  - Potential throughputs of 100s of Mbps
- Focus is on maximizing throughput between two nodes

802.11n Overview

- 802.11n extends 802.11 for MIMO
  - Supports up to 4x4 MIMO
  - Preamble that includes high throughput training field
- Standardization was completed in Oct 2009, but, early products have long been available
  - WiFi alliance started certification based on the draft standard in mid-2007
- Supported in both the 2.4 and 5 GHz bands
  - Goal: typical indoor rates of 100-200 Mbps; max 600 Mbps
- Use either 1 or 2 non-overlapping channels
  - Uses either 20 or 40 MHz
  - 40 MHz can create interoperability problems
- Supports frame aggregation to amortize overheads over multiple frames
  - Optimized version of 802.11e

Multi-User MIMO Discussion



- Math is similar to MIMO, except for the receiver processing (P_R)
  - Receivers do not have access to the signals received by antennas on other nodes
    - Limits their ability to cancel interference and extract a useful data stream
- MU-MIMO versus MIMO is really a tradeoff between TDMA and use of space diversity
  - Sequential short packets versus parallel long packets
- Uplink: Multiple Access Channel (MAC)
  - Multiple clients transmit simultaneously to a single base station
  - Multiuser detection techniques are used to separate the signals transmitted by the users
    - Requires coordination among clients on packet transmission – hard problem because very fine-grained
- Downlink: Broadcast Channel (BC)
  - Base station transmit separate data streams to multiple independent users
  - Processing of the data symbols at the transmitter to minimize interuser interference
    - Easier to do: closer to traditional models of having each client receive a packet from the base station independently

802.11ac Multi-user MIMO

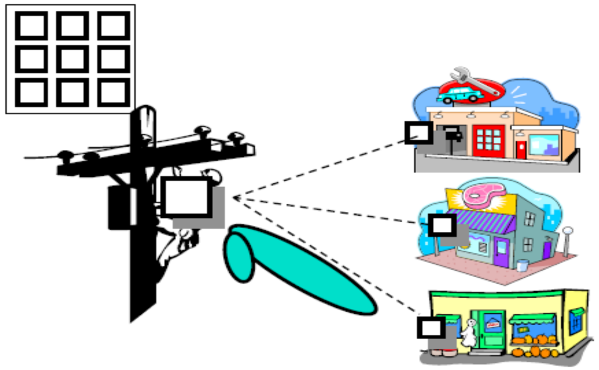
- Extends beyond 802.11n
  - MIMO: up to 8 x 8 channels (vs. 4 x 4)
  - More bandwidth: up to 160 MHz by bonding up to 8 channels (vs. 40 MHz)
  - More aggressive signal coding: up to 256 QAM (vs. 64 QAM); both use 5/6 coding rate (data vs. total bits)
  - Uses RTS-CTS for clear channel assessment
  - Multi-gigabit rates (depends on configuration)
- Support for multi-user MIMO on the downlink
  - Can support different frames to multiple clients at the same time
  - Especially useful for smaller devices, e.g., smartphones
  - Besides beam forming to target signal to device, requires also nulling to limit interference

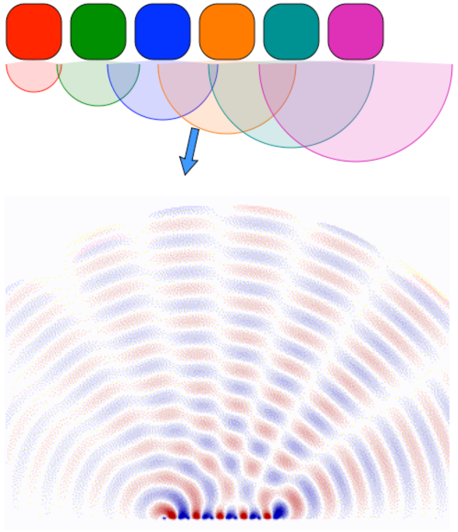
Beam forming

- Multi-element antennas have multiple, independently controlled conductors.
  - Can electronically direct the RF signal by sending different versions of the signal to each element.
- Phased Antenna Arrays:
  - Receive the same signal using multiple antennas
- By phase-shifting various received signals and then summing → Focus on a narrow directional beam
  - Digital Signal Processing (DSP) is used for signal processing → Self-aligning

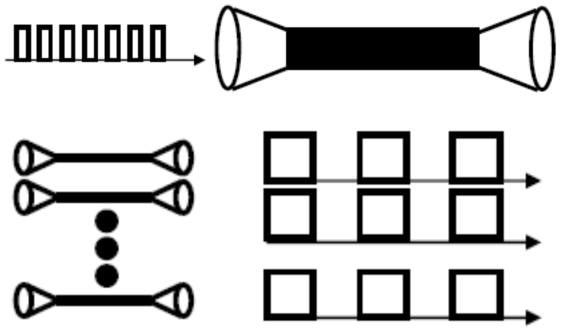

Today's WiFi


802.11ac Beamforming Technology

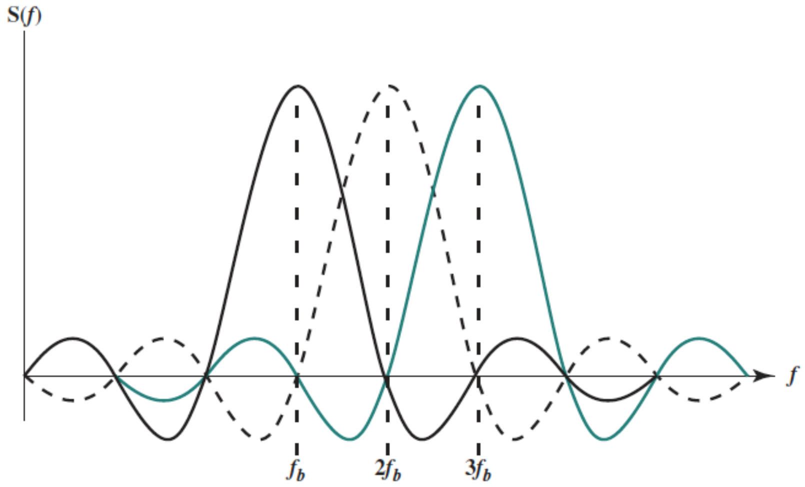


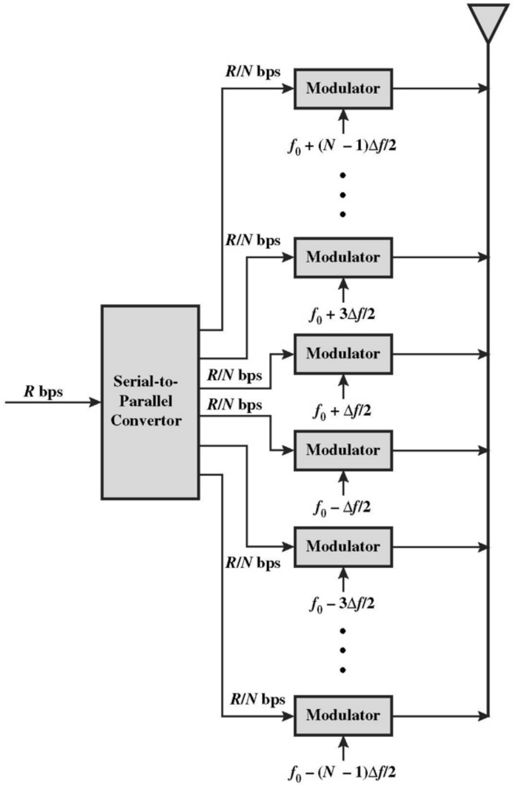


Orthogonal Frequency Division Multiplexing (OFDM)



- Distribute bits over N subcarriers that use different frequencies in the band
- Hypothesis: Ten 100-kHZ channel is better than one 1 MHz Channel, why?
  - Lower data rate reduces inter-symbol interference
    - Higher bit rate means smaller distance between bits or symbols
      - Delay spread remain the same for each symbol
    - NT_s >> root-mean-square of delay spread of the channel, where T_s is the symbol period
  - Better treatment for frequency selective fading
    - Adaptive modulation on each subcarrier
- The subcarriers are orthogonal to each other
  - Peak of one at null of others
- Cyclic prefixes are used to separate symbols
- Used in 802.11a/g/n/ac, 802.16





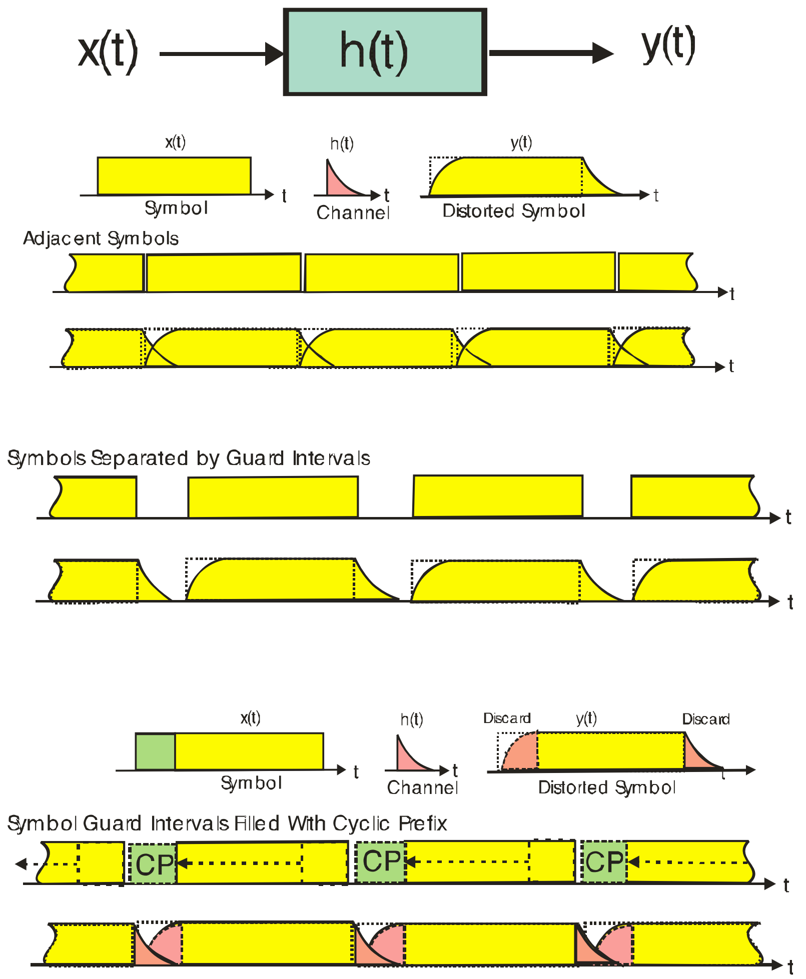
Further fighting ISI with “Cyclic Prefix”

- Sending a “cyclic prefix” before every burst of symbols
  - Can be used to absorb delayed copies of real symbols, without affecting the symbols in the next burst
  - Prefix is a copy of the tail of the symbol burst to maintain a smooth symbol
  - E.g. a cyclic prefix of 64 symbols and data bursts of 256 symbols using QPSK modulation

Intersymbol Interference (ISI) symbol smearing

Guard Interval inserted between adjacent symbols to suppress ISI

Cyclic Prefix Inserted in Guard Interval to suppress ISI



Example: 802.11a

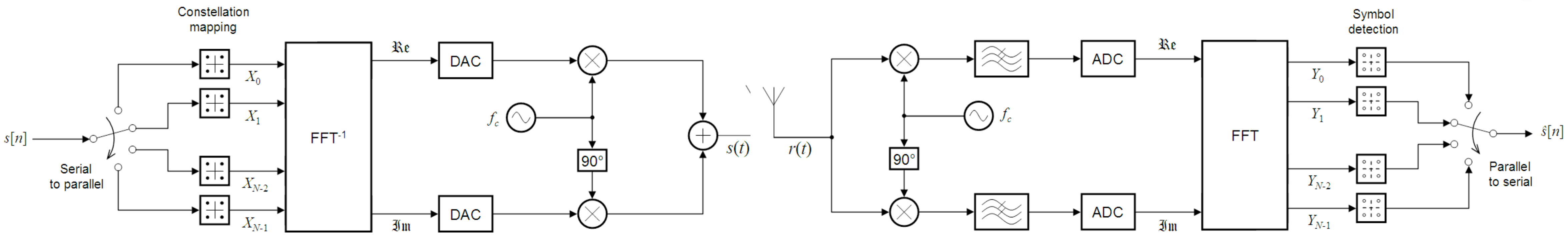
- Uses OFDM with up to 48 subcarriers
  - Used for data, pilots for control, and guard bands
- Subcarrier spacing is 0.3125 MHz
- Subcarriers are modulated using BPSK, QPSK, 16 QAM, and 64 QAM
- Uses a convolutional code at a rate of 1/2, 2/3, 3/4, or 5/6 to provide forward error correction
- Results in data rates of 6, 9, 12, 18, 24, 36, 48, and 54 MBps
- Cyclic prefix is 25% of a symbol burst (16 vs 64)

OFDM Discussion

- OFDM is very effective in fighting frequency selective fading and ISI
- Finally a free lunch?
- No – you introduce some overhead
  - Frequency: you need space between the subcarriers
  - Time: You need to insert prefixes
- You also add complexity
  - How do you create many, closely spaced subcarriers?
  - The OFDM signal is fairly flat in the frequency domain, so it is very variable in the time domain
    - High peak-to-average Power ratio (PAPR)
      - A multicarrier signal is the sum of many narrowband signals
    - Can be a problem for simple, mobile devices

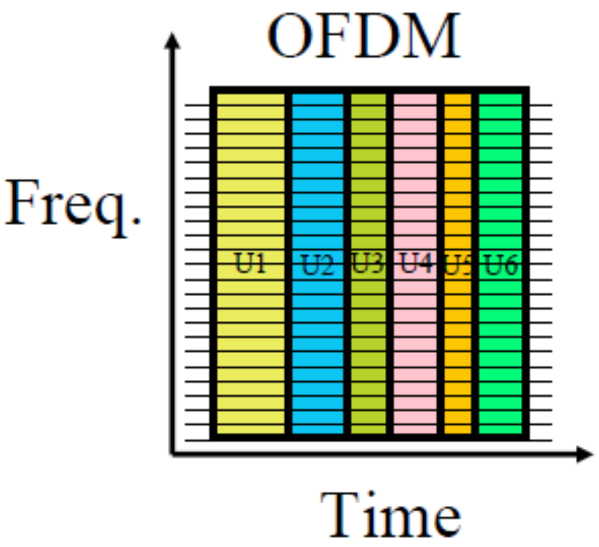
Implementing OFDM

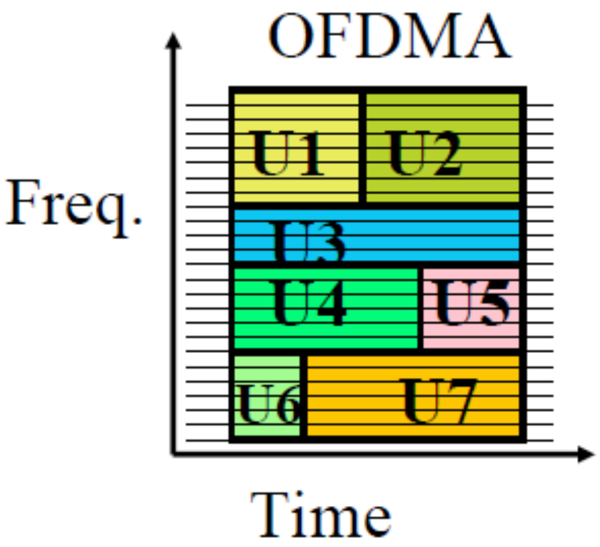
- The naïve approach is to modulate individual subcarriers and move them each to the right frequency
  - Not practical: the subcarriers are packed very densely and their spacing must be very precise
  - Also complicated: lots of signals to deal with!
- How it works: radio modulates the subcarriers and combines them in the digital domain and then converts the signal to the analog domain
  - Transmission: spread data into subcarriers, IFFT, add up all the sine wave
  - Reception: FFT, decode each subcarrier separately

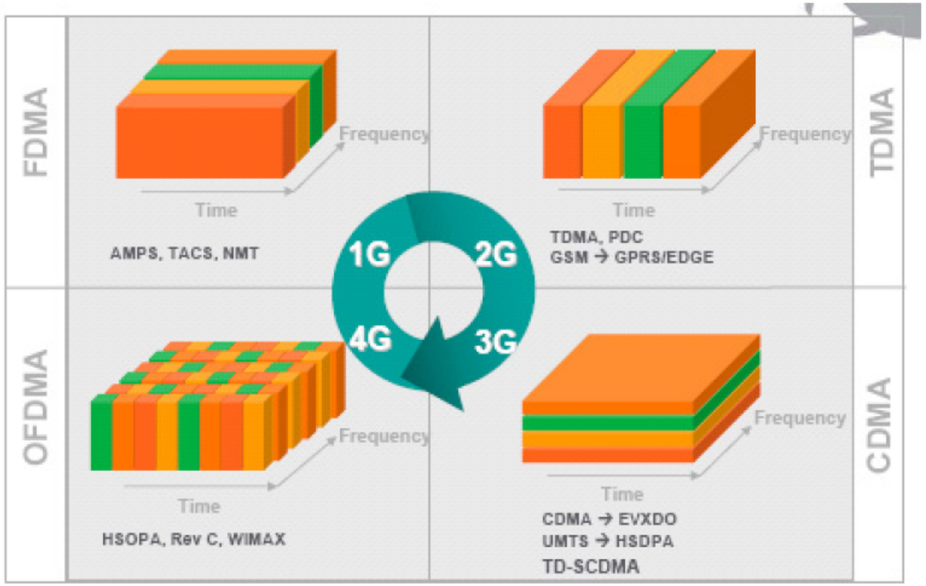


Orthogonal Frequency Division Multiple Access (OFDMA)

- Subcarriers are divided into groups – subchannels
- Each user has a set of subcarriers for a few slots
  - More flexibilities for power management
- OFDM allows time + frequency DMA → 2D Scheduling





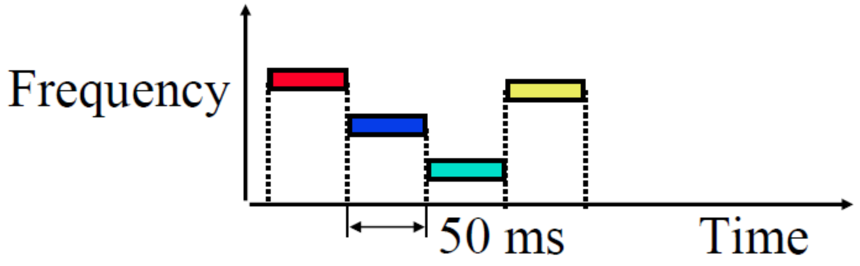


Spread Spectrum

- How about spreading transmission over a wider bandwidth?
  - Broad spectrum has better anti-interference ability and higher data rate.
  - Different sets of codes can be used at the same frequency. It makes the channel more effective.
- Good for military: jamming and interception becomes harder
- Also useful to minimize impact of a "bad" frequency in regular environments
- What can be gained from this apparent waste of spectrum?
  - Immunity from various kinds of noise and multipath distortion
  - Can be used for hiding and encrypting signals
  - Several users can independently use the same higher bandwidth with very little interference
- How to do?
  - Frequency Hopping Spread Spectrum (FHSS)
  - Direct Sequence Spread Spectrum (DSSS)

Frequency Hopping Spread Spectrum (FHSS)

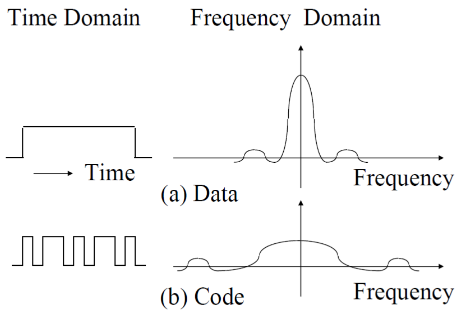
- Have the transmitter hop between a seemingly random sequence of frequencies
  - Each frequency has the bandwidth of the original signal
- Spreading code determines the hopping sequence
  - Must be shared by sender and receiver (e.g. standardized)

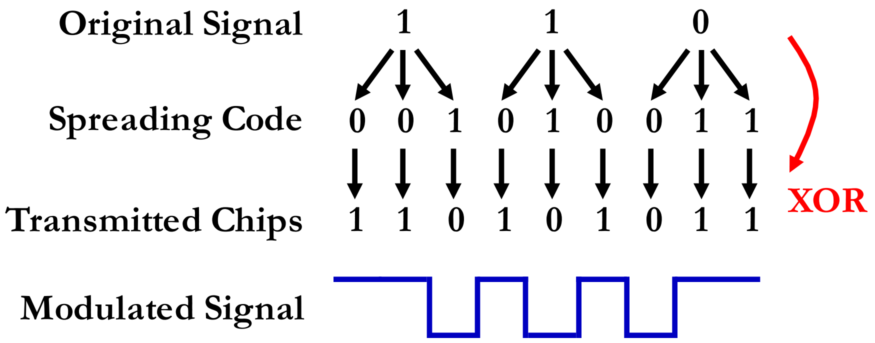


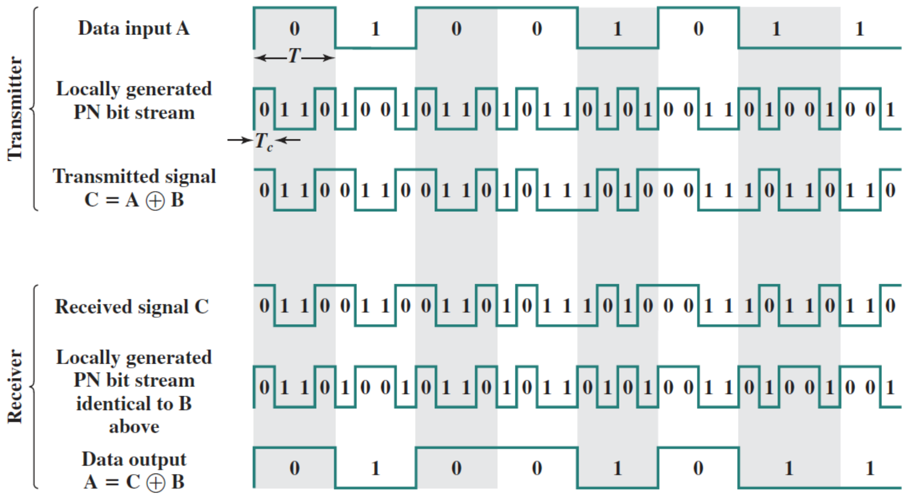
- Example: Original 802.11 Standard (FH)
  - Used frequency hopping: 96 channels of 1 MHz
    - Each channel carries only ~1% of the bandwidth
    - Uses 2 GFSK or 4 GFSK for modulation (1 or 2 Mbps)
  - The dwell time was configurable
    - FCC set an upper bound of 400 msec
    - Transmitter/receiver must be synchronized
  - Transmitter used a beacon on fixed frequency to inform the receiver of its hop sequence
- Example: Bluetooth
  - Uses frequency hopping spread spectrum in the 2.4 GHz ISM band
  - Uses 79 frequencies with a spacing of 1 MHz
    - Other countries use different numbers of frequencies
  - Frequency hopping rate is 1600 hops/s
  - Signal uses GFSK
    - Minimum deviation is 115 KHz
  - Maximum data rate is 1 MHz

Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits (chips or Pseudo Noise code) in the transmitted signal
  - A form of binary modulation with spreading sequence
  - The chips consist of pulses of a much shorter duration (larger bandwidth) than the pulse duration of the message signal
- The resulting bit stream is used for further analog modulation
- Properties
  - You need more bps and bandwidth to send the signal.
    - Number of chips per bit is called the spreading ratio/factor
  - Advantage is that the transmission is more resilient.
    - Effective against noise and multi-path
    - DSSS signal will look like noise in a narrow band
    - Can lose some chips in a word and recover easily







Code Division Multiple Access (CDMA)

- Users share spectrum, use it at the same time, but use different codes to spread their data over the freq.
  - DSSS where users use different spreading sequences
  - Use spreading sequences that are orthogonal, i.e. they have minimal overlap
  - Frequency hopping with different hop sequences
- The idea is that users will only rarely overlap and the inherent robustness of DSSS will allow users to recover if there is a conflict
  - Overlap = use the same frequency at the same time
  - Goal: the signal of other users will appear as noise

CDMA Principle

- Basic Principles of CDMA
  - D = rate of data signal
  - Break each bit into k *chips or chipping code* – user-specific fixed pattern
  - Chip data rate of new channel = kD
- If $k = 6$ and code for user A is $<c_{A1}, c_{A2}, c_{A3}, c_{A4}, c_{A5}, c_{A6}>$
  - For bit '1', A sends code $< c_{A1}, c_{A2}, c_{A3}, c_{A4}, c_{A5}, c_{A6}>$
  - For bit '0', A sends code $<-c_{A1}, -c_{A2}, -c_{A3}, -c_{A4}, -c_{A5}, -c_{A6}>$
- Receiver knows sender's code and performs electronic decode function
  - Received chip pattern: $<d_1, d_2, d_3, d_4, d_5, d_6>$
  - $S_u(d) = d_1 \times c_{u1} + d_2 \times c_{u2} + d_3 \times c_{u3} + d_4 \times c_{u4} + d_5 \times c_{u5} + d_6 \times c_{u6}$

- Example
  - User A code = <1, –1, –1, 1, –1, 1>
    - To send a 1 bit = <1, –1, –1, 1, –1, 1>
    - To send a 0 bit = <–1, 1, 1, –1, 1, –1>
  - User B code = <1, 1, –1, – 1, 1, 1>
    - To send a 1 bit = <1, 1, –1, –1, 1, 1>
  - Receiver receiving with A's code
    - User A '1' bit: 6 → 1
    - User A '0' bit: -6 → 0
    - User B '1' bit: 0 → unwanted signal ignored
- Ideally, $S_A(d_X) = S_X(d_A) = 0$ for any X not A
  - In practice, not easy to make all chips orthogonal to each other

CDMA Discussion

- CDMA does not assign a fixed bandwidth but a user's data rate depends on the traffic load
  - More users results in more "noise" and less data rate for each user, e.g. more information lost due to errors
  - How graceful the degradation is depends on how orthogonal the codes are
  - TDMA and FDMA have a fixed channel capacity
- Weaker signals may be lost in the clutter
  - This will systematically put the same node pairs at a disadvantage – not acceptable
  - The solution is to add power control, i.e. nearby nodes use a lower transmission power than remote nodes

Recommended readings

- Tutorials on Digital Communications Engineering
  - http://complextoreal.com/tutorials/
- The Scientist and Engineer's Guide to Digital Signal Processing
  - http://www.dspguide.com/
- Search for "如果看了此文你还不懂傅里叶变换，那就过来掐死我吧"