This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 3: Physical Layer
Capacity and Signal Propagation

Peter Steenkiste

Carnegie Mellon University

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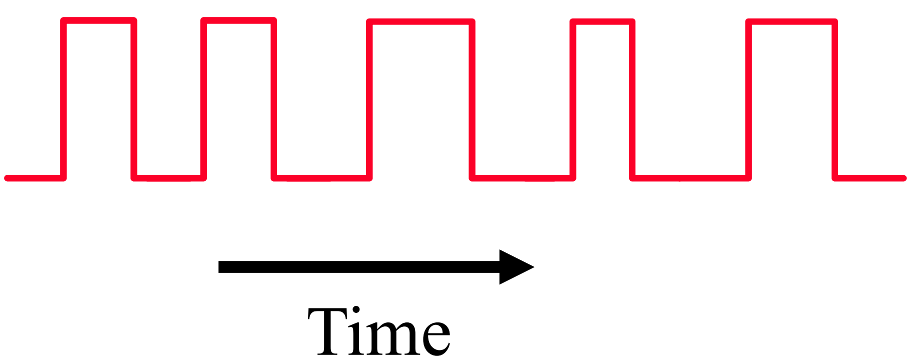
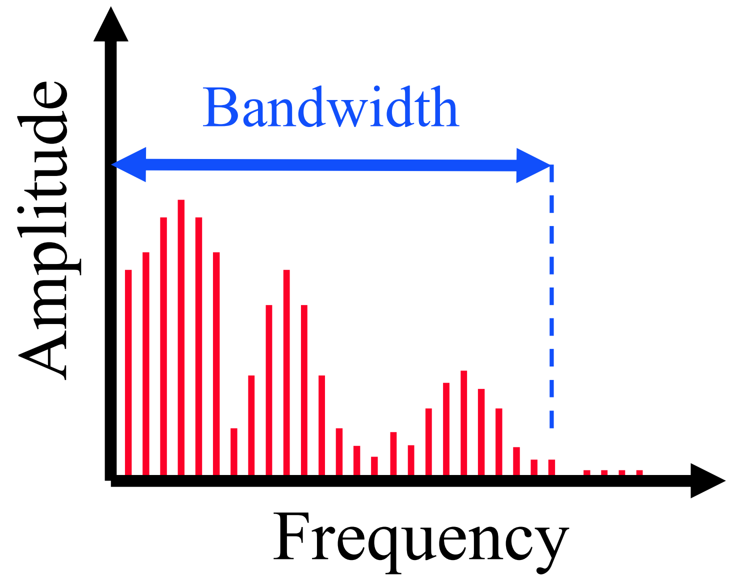
Outline

- Challenges in Wireless Networking
- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM

From Previous Lecture: The Frequency Domain

- **A (periodic) signal can be viewed as a sum of sine waves of different strengths.**
  - **Corresponds to energy at a certain frequency**
- **Every signal has an equivalent representation in the frequency domain.**
  - **What frequencies are present and what is their strength (energy)**
- **We can translate between the two formats using a fourier transform**

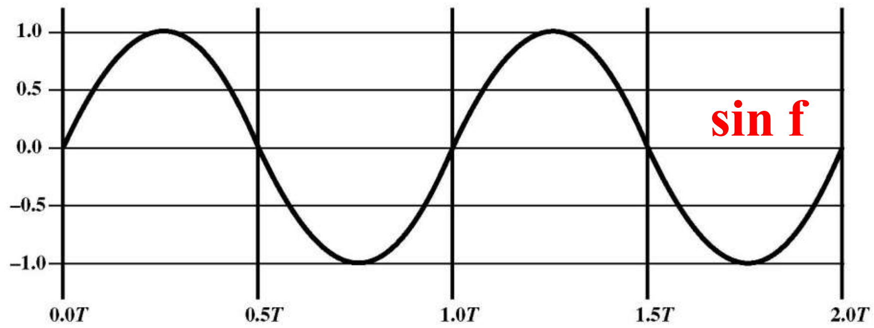




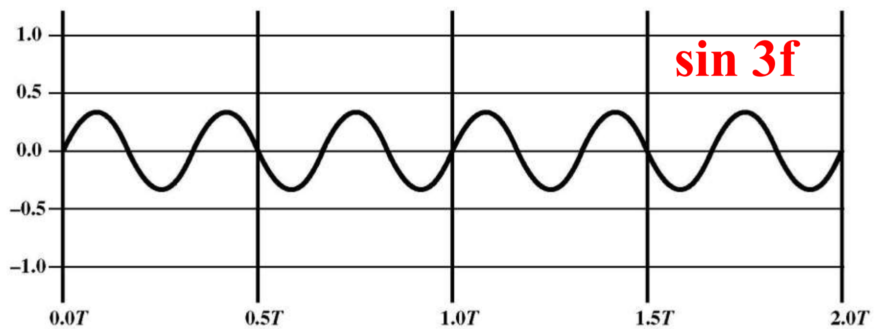
Relationship between Data Rate and Bandwidth

- The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal
- Intuition: 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
- Can we make this more precise?

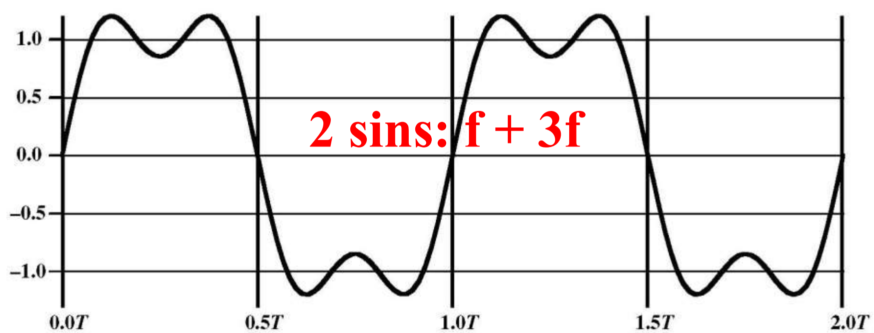
Adding Detail to the Signal:



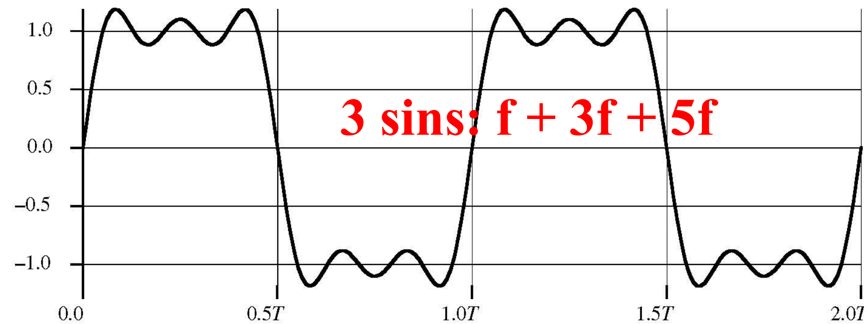
(a) sin (2 ft)



(b) (1/3) sin (2 (3f)t)

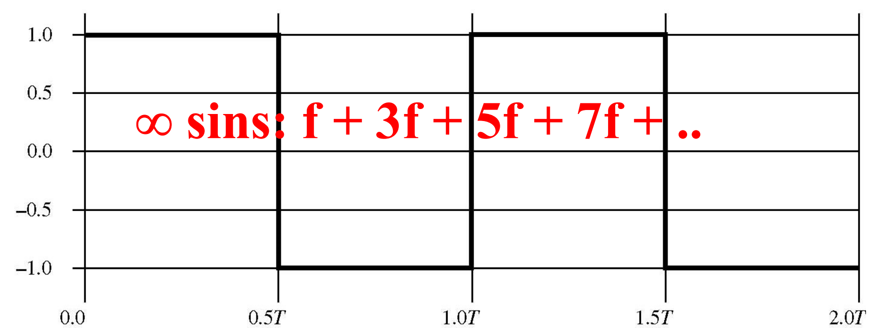


(c) (4/) [sin (2 ft) + (1/3) sin (2 (3f)t)]



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

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

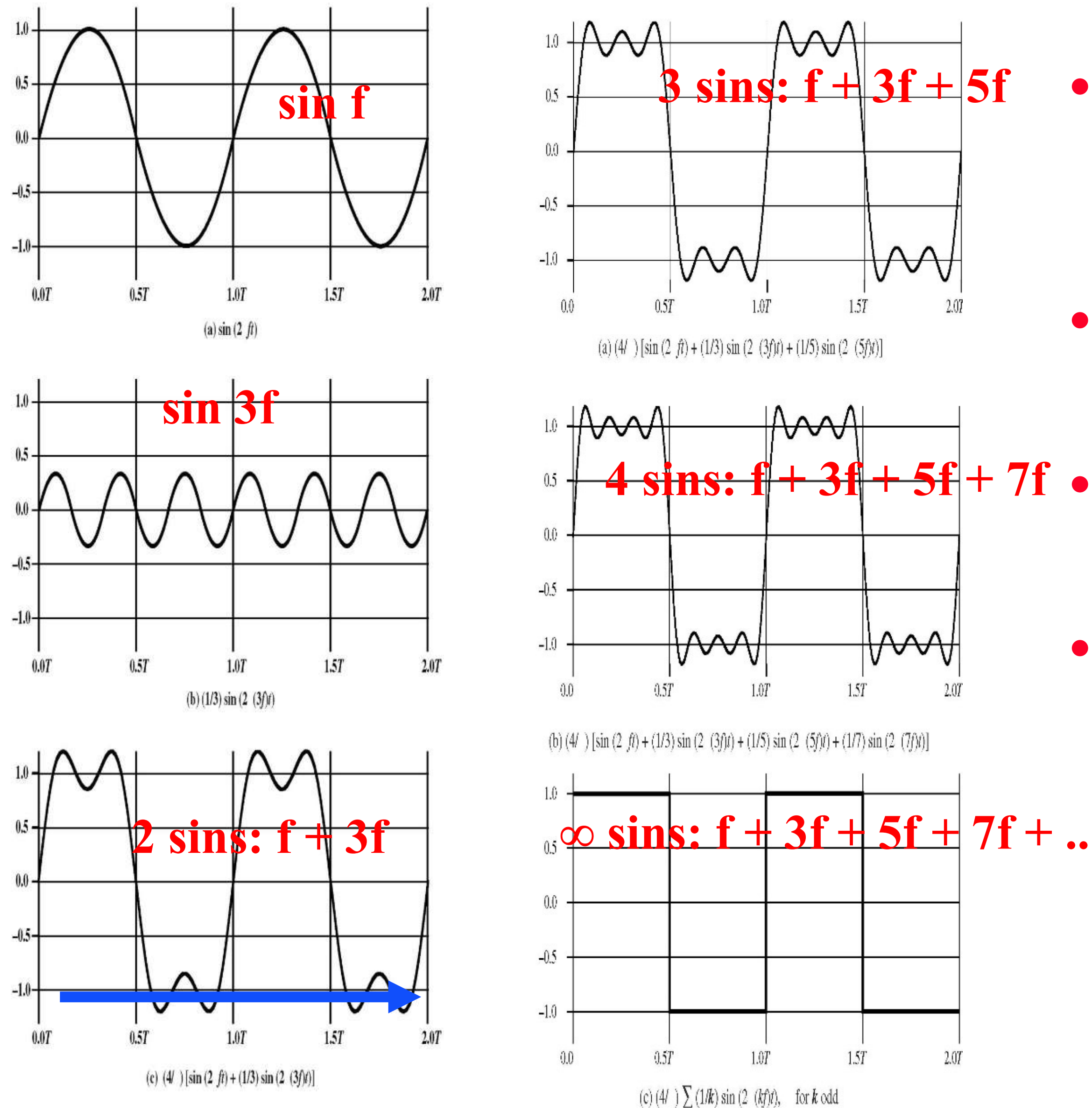


(c) (4/) ∑ (1/*k*) sin (2 (*kf*)*t*), for *k* odd

Some Intuition

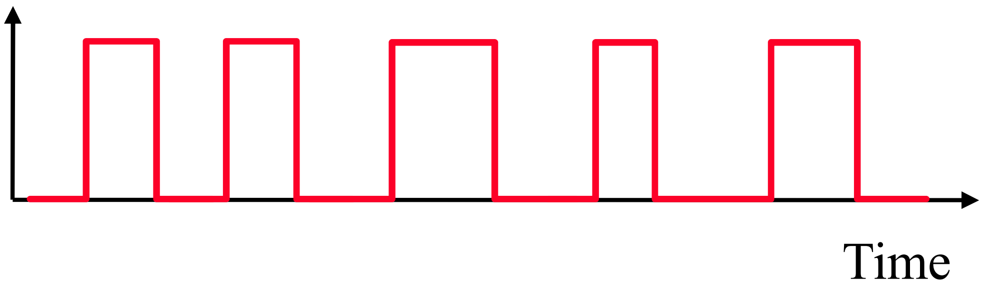
- Smooth time domain signal has narrow frequency range
  - » Sine wave → pulse at exactly one frequency
- Adding detail widens frequency range
  - » Need to add additional frequencies to represent details
  - » Very sharp edges are especially bad (many frequencies)
- The opposite is also true
  - » Pulse (very sharp edge!) in time domain has a very wide spectrum
  - » Same is true for random noise (“noise floor”)
- Implication: modulation has a big impact on how much (scarce) spectrum is used

What happens when I Double the Bandwidth?



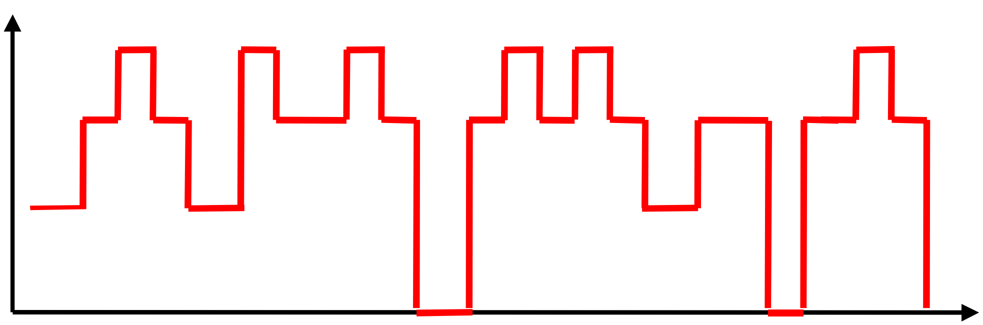
- **Shown here by scaling by two along time axis**
- **What happens to spectrum use?**
- **We have to double frequencies: f → 2f**
- **This means that we double the frequency range**

Increasing the Bit Rate

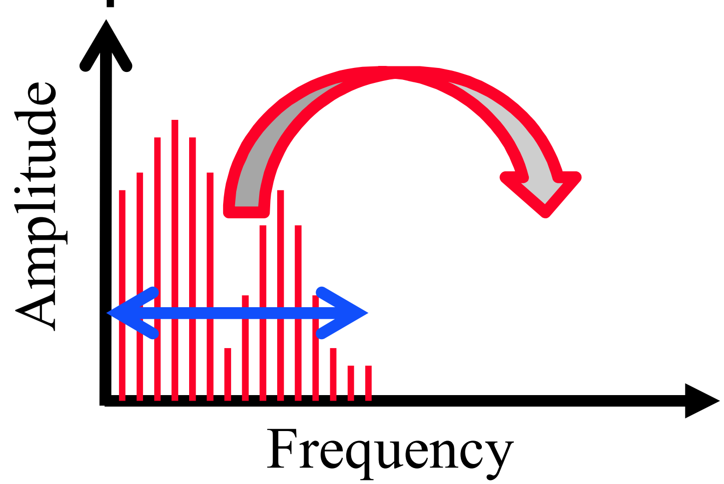


Increase frequency

Or increase bits per "symbol"

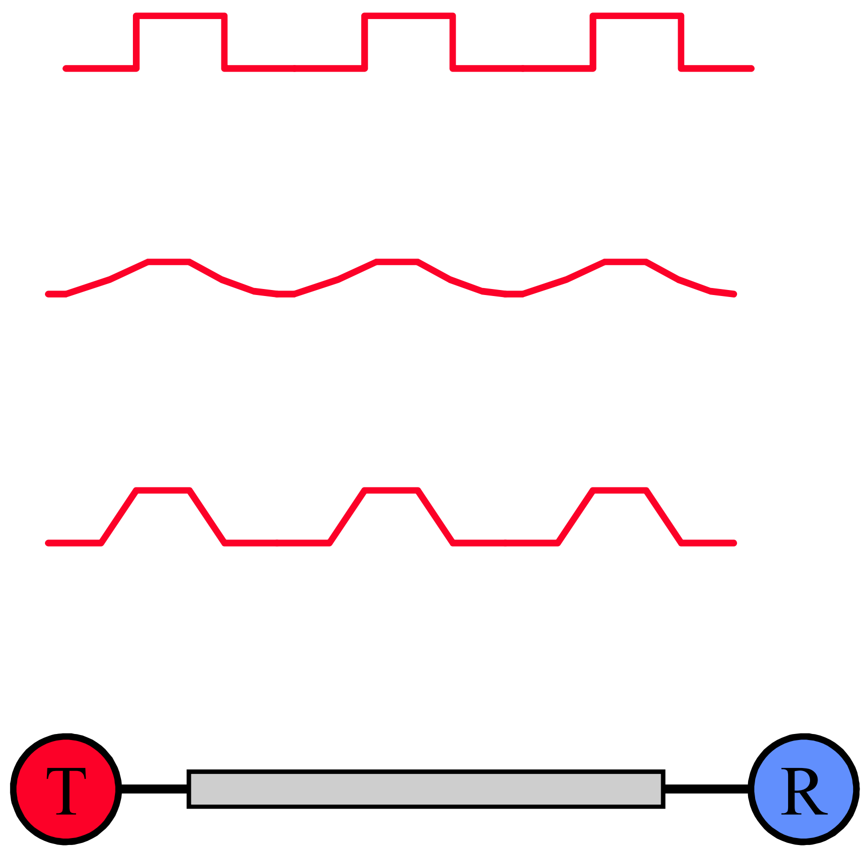


- Increases the rate at which the signal changes.
  - » Proportionally increases all signals present, and thus the spectral bandwidth
- Increase the number of bits per change in the signal
  - » Adds detail to the signal, which also increases the spectral BW



So Why Don't we Always Send a Very High Bandwidth Signal?

- Channels have a limit on the type of signals they can carry effectively
- Wires only transmit signals in certain frequency ranges
  - » Stronger attenuation and distortion outside of range
- Wireless radios are only allowed to use certain parts of the spectrum
  - » The radios are optimized for that frequency band
- Distortion makes it hard for receiver to extract the information
  - » A major challenge in wireless

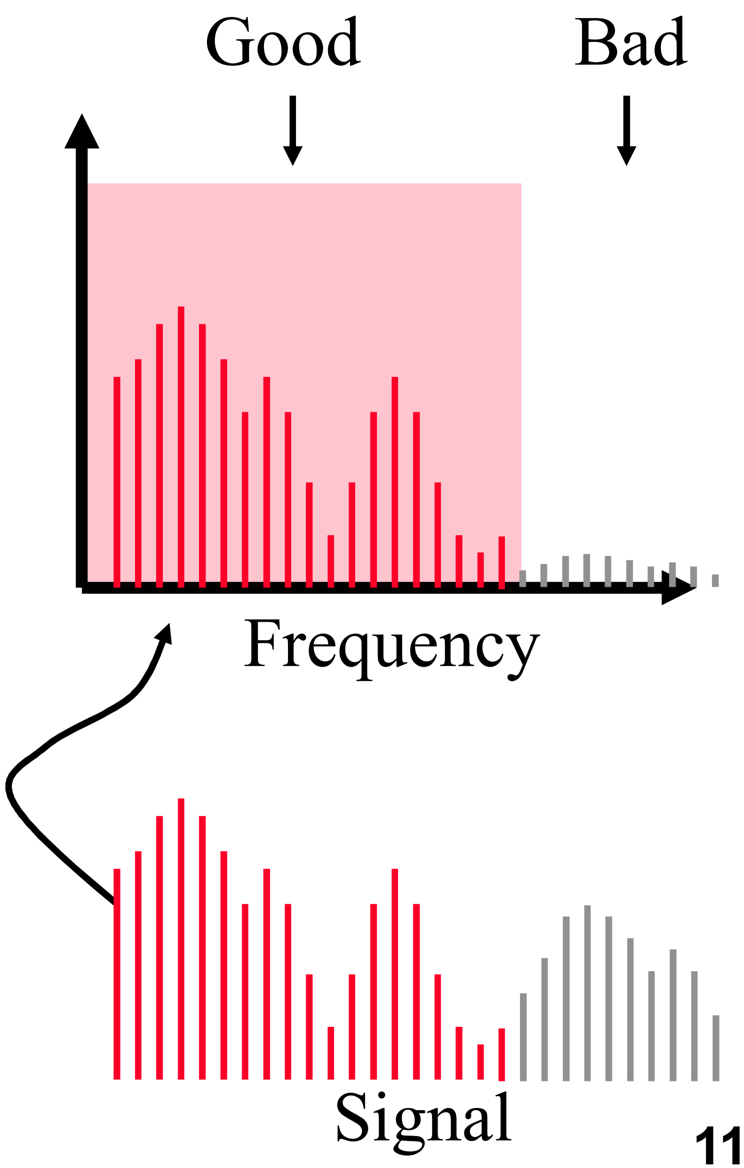


Propagation Degrades RF Signals

- 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
- 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

Transmission Channel Considerations

- **Example: grey frequencies get attenuated significantly**
- **For wired networks, channel limits are an inherent property of the wires**
  - **Different types of fiber and copper have different properties**
  - **Capacity also depends on the radio and modulation used**
  - **Improves over time, even for same wire**
- **For wireless networks, limits are often imposed by policy**
  - **Can only use certain part of the spectrum**
  - **Radio uses filters to comply**



Outline

- Challenges in Wireless Networking
- RF introduction
- Modulation and multiplexing
  - » Analog versus digital signals
  - » Forms of modulation
  - » Baseband versus carrier modulation
  - » Multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM

Channel Capacity

- Data rate - rate at which data can be communicated (bps)
  - » Channel Capacity – the maximum rate at which data can be transmitted over a given channel, under given conditions
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - » Error = transmit 1 and receive 0; transmit 0 and receive 1

The Nyquist Limit

- **A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity 2B**
  - » **E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second**
  - » **Assumes binary amplitude encoding**
- ***For M levels:*** $C = 2B \log_2 M$
  - » **M discrete signal levels**
- **More aggressive encoding can increase the actual channel bandwidth**
  - » **Example: modems**
- **Factors such as noise can reduce the capacity**

Decibels

- Decibels: ratio between signal powers

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- Is used in many contexts:
  - » The loss of a wireless channel, gain of an amplifier, …
- Note that dB is a relative value.
- Absolute value requires a reference point.
  - » Decibel-Watt – power relative to 1W
  - » Decibel-milliwatt – power relative to 1 milliwatt (dbm)
- Some example values (WiFi):
  - » Noise floor -90 dbm
  - » Received signal strength: -70 to -65 dbm
  - » Transmit power (2.4 GHz): 20 dbm

Signal-to-Noise Ratio

- 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)

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

- 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

Shannon Capacity Formula

- **Equation:** $$C = B \log_2 (1 + \mathrm{SNR})$$
- **Represents error free capacity**
  - » It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- **Result is based on many assumptions**
  - » Formula assumes white noise (thermal noise)
  - » Impulse noise is not accounted for
  - » Various types of distortion are also not accounted for
- **We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel**

Shannon Discussion

- Bandwidth B and noise N are not independent
  - » N is the noise in the signal band, so it increases with the bandwidth
- Shannon does not provide the coding that will meet the limit, but the formula is still useful
- The performance gap between Shannon and a practical system can be roughly accounted for by a gap parameter
  - » Still subject to same assumptions
  - » Gap depends on error rate, coding, modulation, etc.

$$C = B \log_2 \left(1 + \mathrm{SNR}/\Gamma\right)$$

Example of Nyquist and Shannon Formulations

- **Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB**

$$B = 4\ \text{MHz} - 3\ \text{MHz} = 1\ \text{MHz}$$

$$\text{SNR}_{\text{dB}} = 24\ \text{dB} = 10\log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- **Using Shannon's formula**

$$C = 10^6 \times \log_2(1 + 251) \approx 10^6 \times 8 = 8\text{Mbps}$$

Example of Nyquist and Shannon Formulations

- **How many signaling levels are required using Nyquist?**

$$C = 2B\log_2 M$$

$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

- **Look out for: dB versus linear values, $\log_2$ versus $\log_{10}$**

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- Antennas and signal propagation
  - How do antennas work
  - Propagation properties of RF signals
  - Modeling the channel
- Modulation
- Diversity and coding
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What is an Antenna?

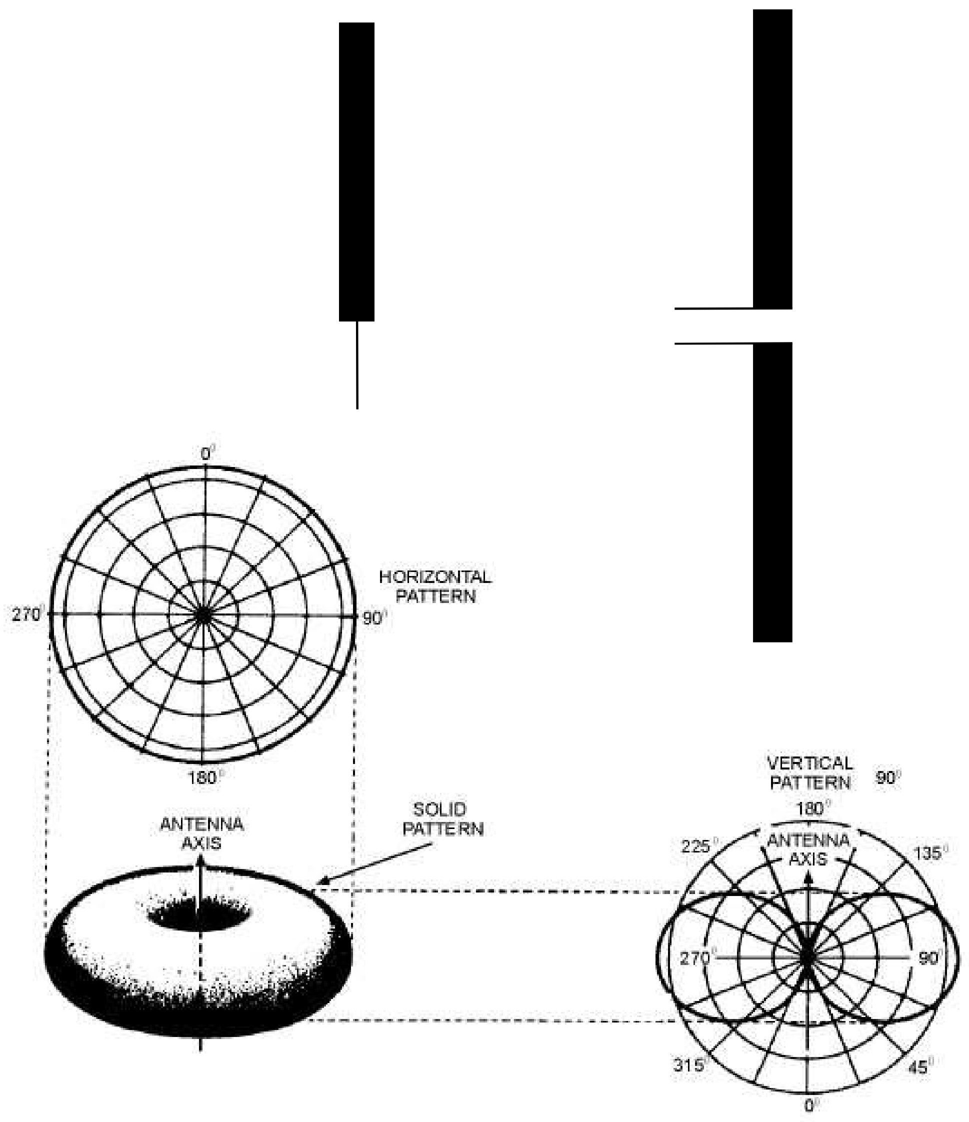
- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal "is a copy of" the electrical signal in the conductor
- Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted (i.e. decoded)
- Efficiency of the antenna depends on its size, relative to the wavelength of the signal.
  - » E.g. quarter of a wavelength

Types of Antennas

- **Abstract view: antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic.**
  - » 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 shape is a straight conductor.**
  - » Creates a “disk” pattern, e.g. dipole
- **Shaped antennas can be used to direct the energy in a certain direction.**
  - » Well-known case: a parabolic antenna
  - » Pringles boxes are cheaper

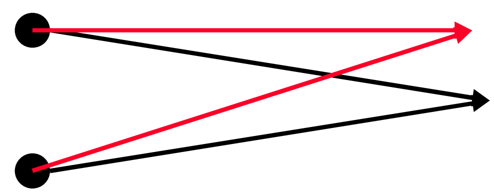
Antenna Types: Dipoles

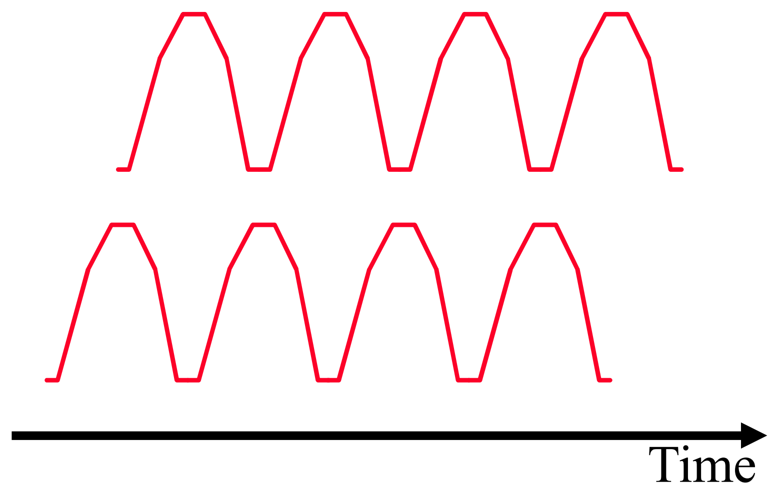
- General rule: length of the antenna should be ~half a wavelength
  - » Length depends on the carrier frequency!
  - » Wavelength at 900MHz: 1 foot
- Simplest: half-wave dipole and quarter wave vertical antennas
  - » Very simple and very common
  - » Elements are quarter wavelength of frequency that is transmitted most efficiently
  - » Donut shape radiation



Multi-element Antennas

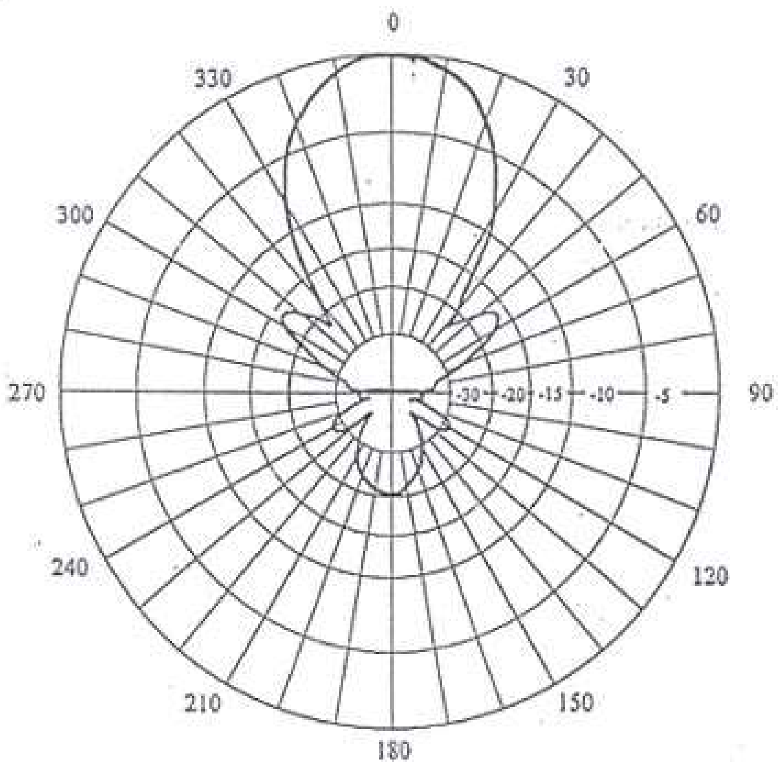
- **Multi-element antennas have multiple, independently controlled conductors.**
  - » **Signal is the sum of the individual signals transmitted (or received) by each element**
- **Can electronically direct the RF signal by sending different versions of the signal to each element.**
  - » **For example, change the phase in two-element array.**
- **Covers a lot of different types of antennas.**
  - » **Number of elements, relative position of the elements, control over the signals, …**



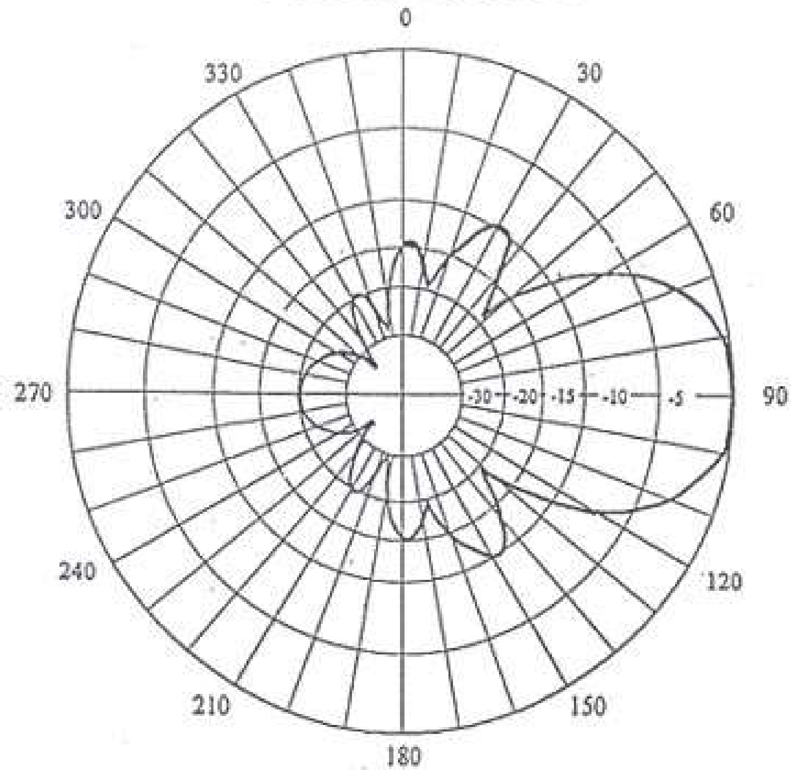


Directional Antenna Properties

Horizontal Pattern



Vertical Pattern



- **dBi: antenna gain in dB relative to an isotropic antenna with the same transmit power**
  - » **Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)**

Examples 2.4 GHz

Summary

- The maximum capacity of a channel depends on the SINR
  - » How close you get to this maximum depends on the sophistication of the radios
  - » Distortion of the signal also plays a role – next lecture
- Antennas are responsible for transmitting and receiving the EM signals
  - » The "ideal" isotropic antenna is a point source that radiates energy in a sphere
  - » Practical antennas are directional in nature, as a result of the antenna shape or the use of multi-element antennas
  - » The antenna gain is expressed in dBi

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Bad News

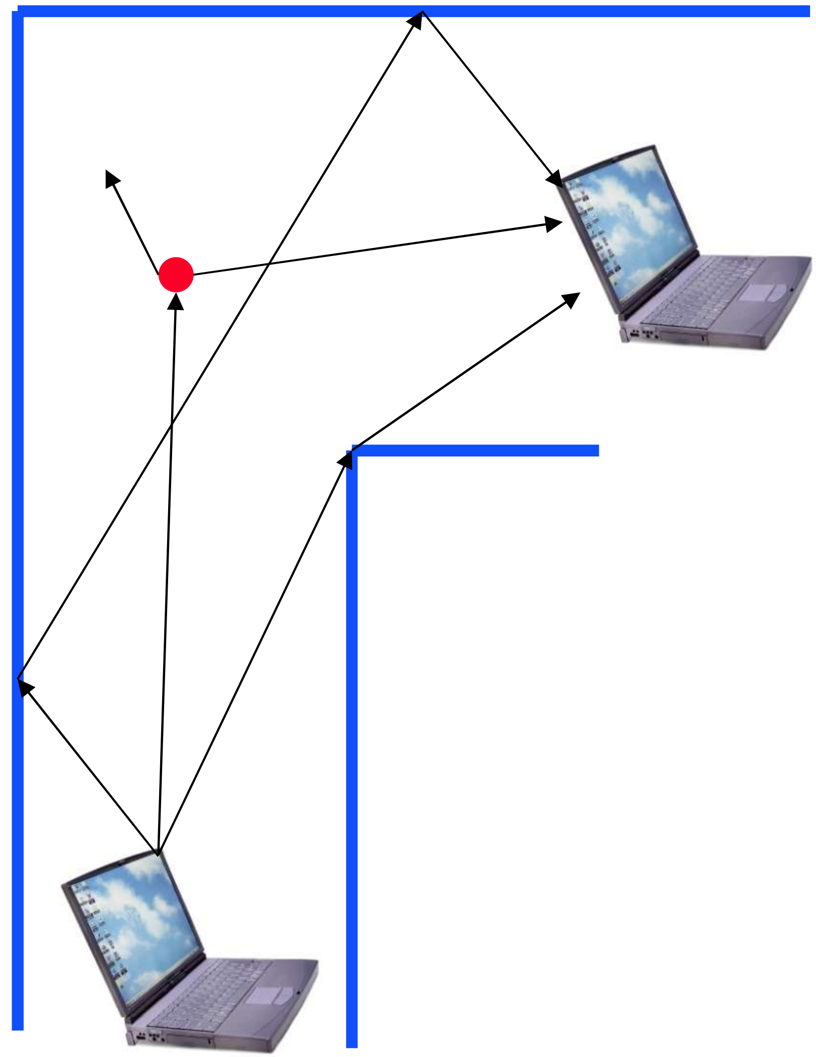
Good News Story

Propagation Modes

- Line-of-sight (LOS) propagation.
  - » Most common form of propagation
  - » Happens above ~ 30 MHz
  - » Subject to many forms of degradation (next set of slides)
- Obstacles can redirect the signal and create multiple copies that all reach the receiver
  - » Creates multi-path effects
- Refraction changes direction of the signal due to changes in density
  - » E.g., changes in air temperature, humidity, …
  - » If the change in density is gradual, the signal bends!

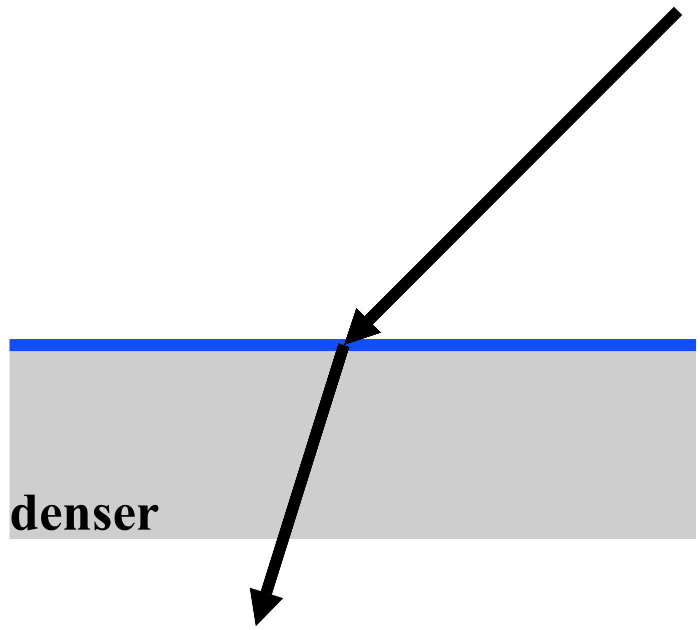
Impact of Obstacles

- Besides line of sight, signal can reach receiver in three “indirect” ways.
- Reflection: signal is reflected from a large object.
- Diffraction: signal is scattered by the edge of a large object – “bends”.
- Scattering: signal is scattered by an object that is small relative to the wavelength.



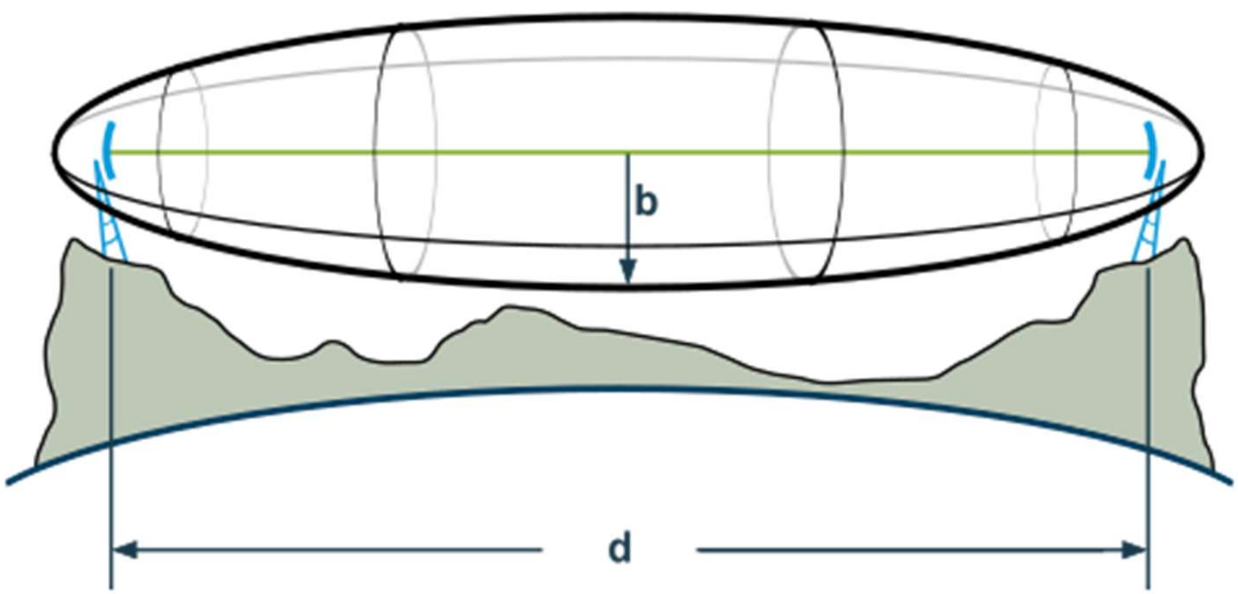
Refraction

- **Speed of EM signals depends on the density of the material**
  - » **Vacuum: 3 x 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.**



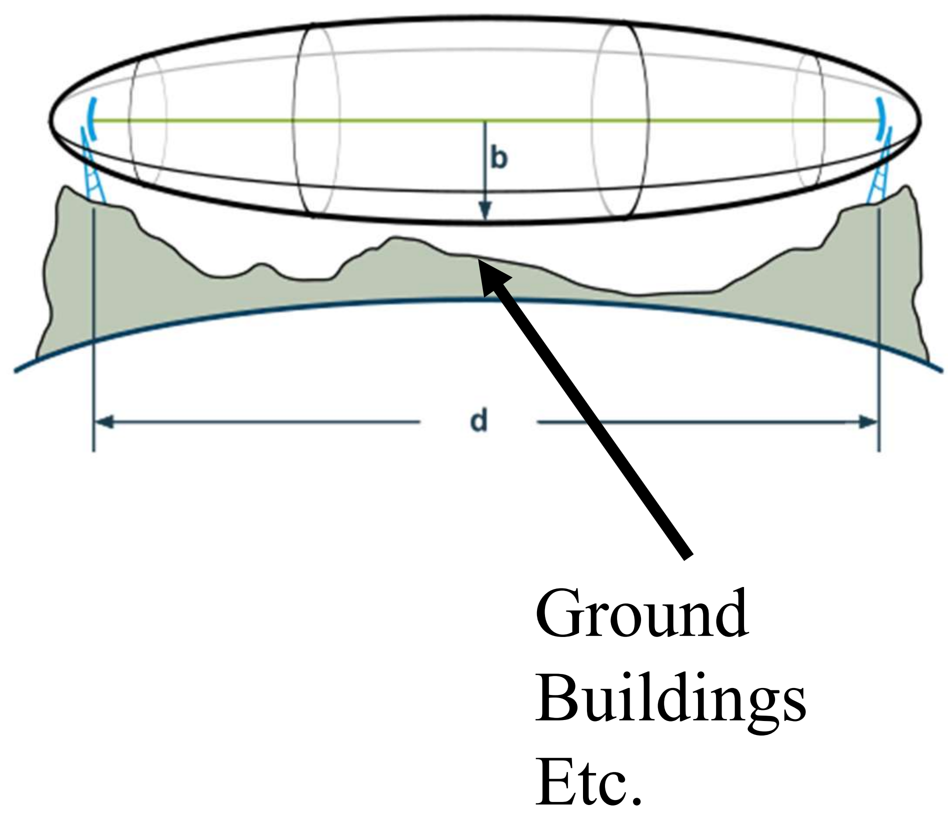
Fresnel Zones

- 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



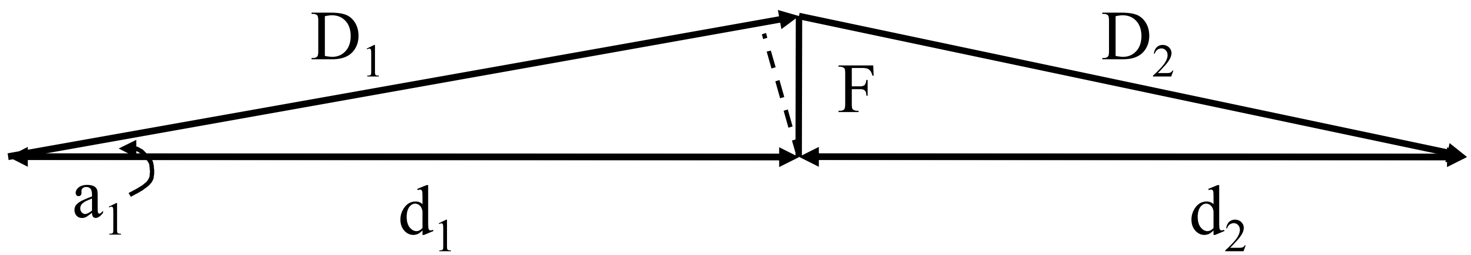
Fresnel Zones

- Zones create different phase differences between paths
  - » First zone: 0-90
  - » Second zone: 90-270
  - » Third zone: 270-450
  - » Etc.
- Odd zones create constructive interference, even zones destructive
- Also want clear path in most of the first Fresnel zone, e.g. 60%
- The radius F_n of the nth Fresnel zone depends on the distances d_1 and d_2 to the transmitter and receiver and the wavelength



Sketch of Calculation: Difference in Path Length

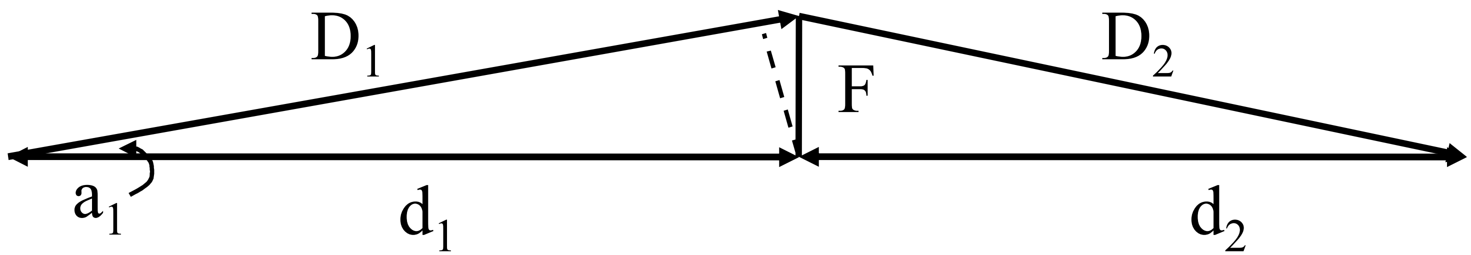
FYI only



- Goal is to calculate F
- Difference in path length (a_1 is small)
  - » $D_1 - d_1 \approx F * \sin a_1$
- But for small a_1 we also have
  - » $\sin a_1 = \tan a_1 = F / d_1$
- So $D_1 - d_1 = F^2 / d_1$

Sketch of Calculation Fresnel Radios

FYI only



- Given $D_1 - d_1 = F^2 / d_1$

So, the difference in path length is:

- $(D_1 + D_2) - (d_1 + d_1) = \lambda * n$
- Or $(D_1 - d_1) + (D_2 - d_2) = F^2 / d_1 + F^2 / d_2$
- or

$$F_n = \sqrt{\frac{n \lambda d_1 d_2}{d_1 + d_2}}$$