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Wireless Networks and Applications
Lecture 3: Physical Layer
Capacity and Signal Propagation

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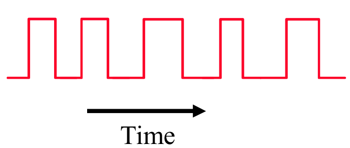
http://www.cs.cmu.edu/~prs/wirelessS20/

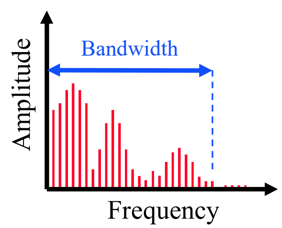
Outline

- RF introduction
- Modulation and multiplexing - review
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM

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

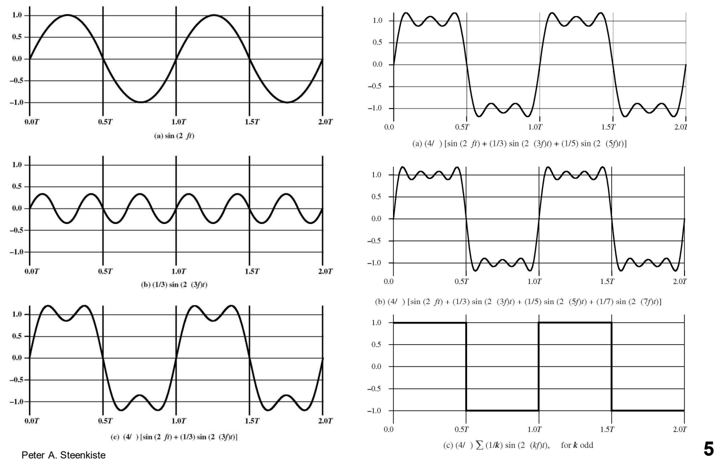




Relationship between Data Rate and Bandwidth

- 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?

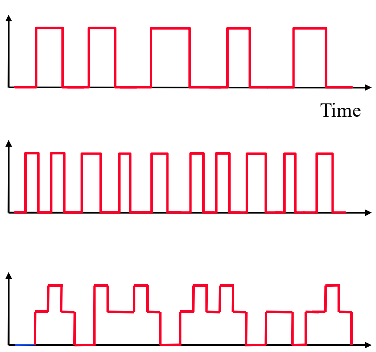
Adding Detail to the Signal



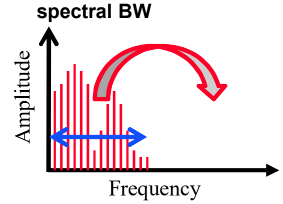
Some Intuition

- 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 in time domain has very wide spectrum
  - » Same is true for random noise (“noise floor”)
- Implication: modulation has a bid impact on how much (scarce) spectrum is used

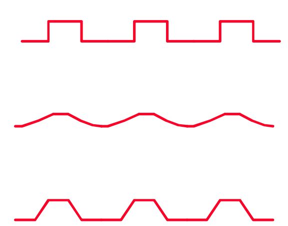
Increasing the Bit Rate



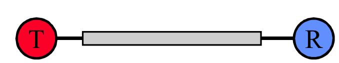
- Increases the rate at which the signal changes.
  - » Proportionally increases all signals present, and thus the spectral bandwidth
- Increase the number of bits per change in the signal
  - » Adds detail to the signal, which also increases the spectral BW



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

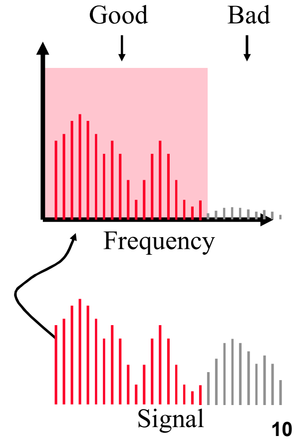


Propagation Degrades RF Signals

- 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

- RF introduction
- Modulation and multiplexing - review
  - » 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
  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 ; $\mathrm{SNR}_{\mathrm{dB}}$ = 24 dB**

$$B = 4\,\mathrm{MHz} - 3\,\mathrm{MHz} = 1\,\mathrm{MHz}$$

$$\mathrm{SNR}_{\mathrm{dB}} = 24\,\mathrm{dB} = 10\log_{10}\left(\mathrm{SNR}\right)$$

$$\mathrm{SNR} = 251$$

- **Using Shannon's formula**

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

Example of Nyquist and Shannon Formulations

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

$$C = 2B\log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

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

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- **RF introduction**
- **Modulation and multiplexing**
- **Channel capacity**
- **Antennas and signal propagation**
  - » How do antennas work
  - » Propagation properties of RF signals
  - » Modeling the channel
- **Equalization and diversity**
- **Modulation and coding**
- **Spectrum access**

What is an Antenna?

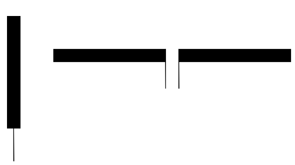
- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal "is a copy of" the electrical signal in the conductor
- Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted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

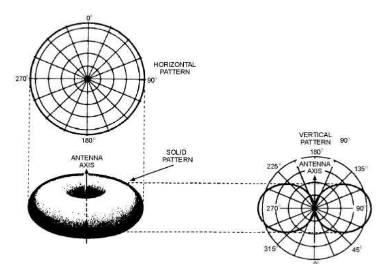
Types of Antennas

- 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

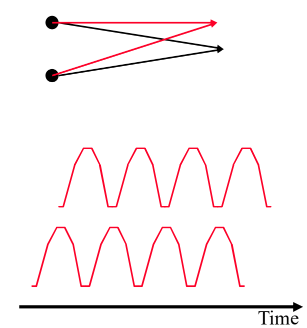
- Simplest: half-wave dipole and quarter wave vertical antennas
  - » Very simple and very common
  - » Elements are quarter wavelength of frequency that is transmitted most efficiently
  - » Donut shape
- May other designs



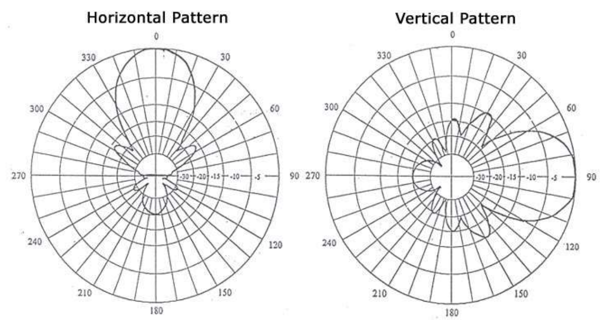


Multi-element Antennas

- 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



- dBi: antenna gain in dB relative to an isotropic antenna with the same 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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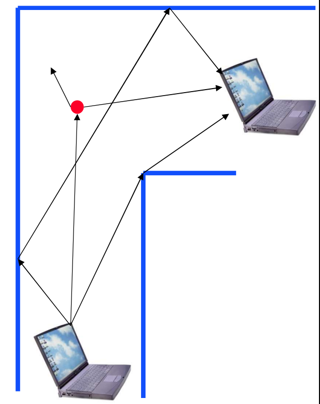
Bad News Good News Story

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!

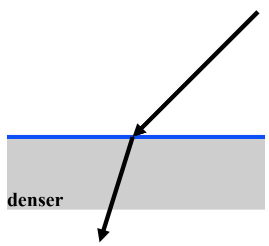
Impact of Obstacles

- 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.



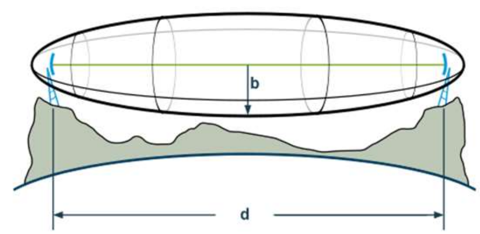
Refraction

- 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.



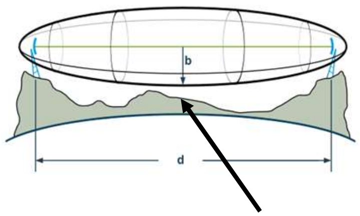
Fresnel Zones

- 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



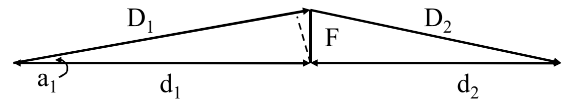
Fresnel Zones

- 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



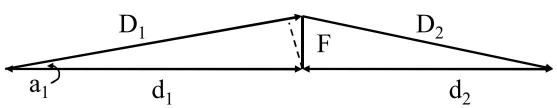
Ground
Buildings
Etc.

Sketch of Calculation: Difference in Path Length



- 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



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

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