Wireless Networks

Lecture 4: More Physical Layer
Channel Capacity and Antennas

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Outline

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

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?

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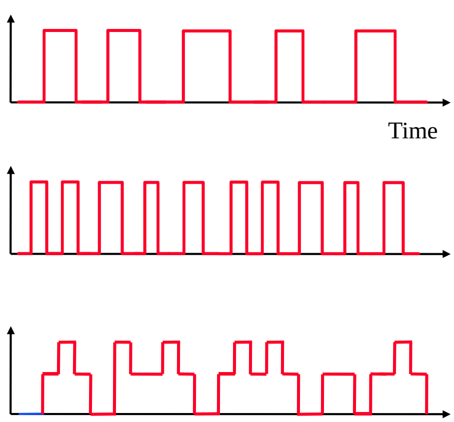
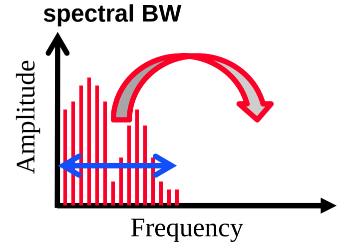
Increasing the Bit Rate



- 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



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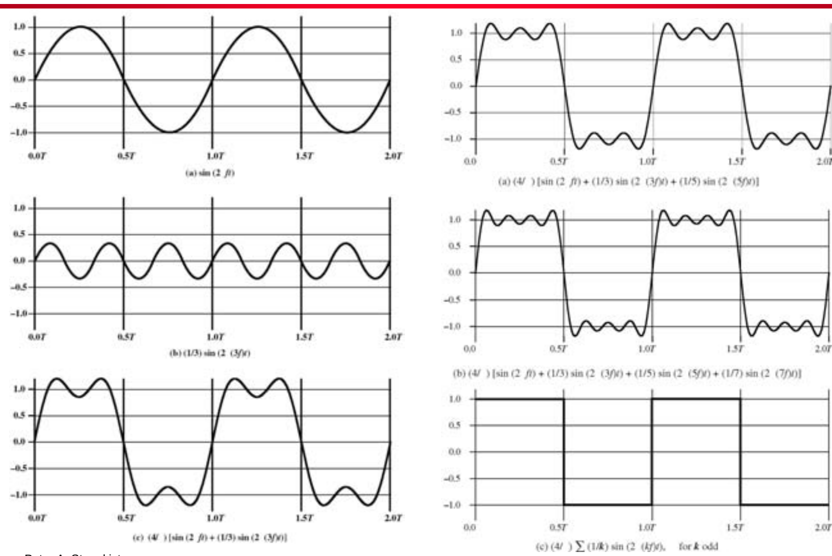
Adding Detail to the Signal



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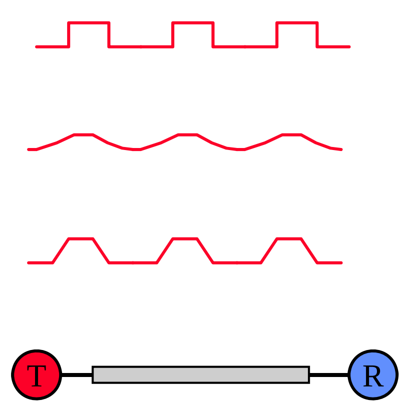
So Why Don't we Always Send a Very High Bandwidth Signal?

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



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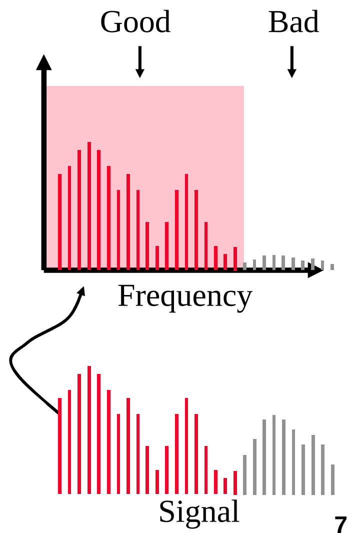
Transmission Channel Considerations

- 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



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

- A ratio between signal powers is expressed in decibels

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

- Is used in many contexts:
  - » The loss of a wireless channel
  - » The gain of an amplifier
- Note that dB is a relative value.
- Can be made absolute by picking a reference point.
  - » Decibel-Watt – power relative to 1W
  - » Decibel-milliwatt – power relative to 1 milliwatt

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)

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

- 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

Shannon Capacity Formula

- Equation: $$C = B \log_2 (1 + \text{SNR})$$
- 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 ; $\mathrm{SNR_{dB}}$ = 24 dB

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

$$\mathrm{SNR_{dB}} = 24\,\mathrm{dB} = 10\log_{10}(\mathrm{SNR})$$

$$\mathrm{SNR} = 251$$

- Using Shannon’s formula

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

Example of Nyquist and Shannon Formulations

- How many signaling levels are required?

$$C = 2B\log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

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

Outline

- 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

Typical Bad News Good News Story

What is an Antenna?

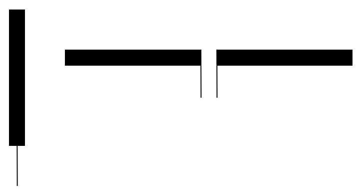
- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal “is a copy of” the electrical signal in the conductor
- Also the inverse process: RF signals are “captured” by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted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

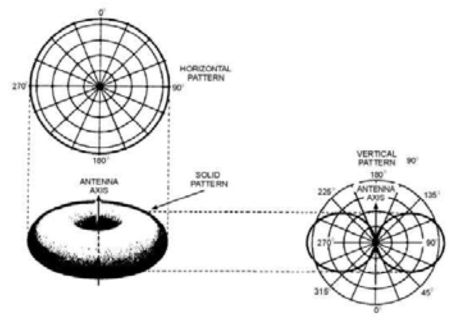
Types of Antennas

- 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

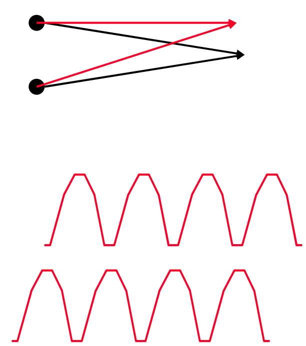
- Simplest: half-wave dipole and quarter wave vertical antennas
  - » Very simple and very common
  - » Elements are quarter wavelength of frequency that is transmitted most efficiently
  - » Donut shape
- May other designs



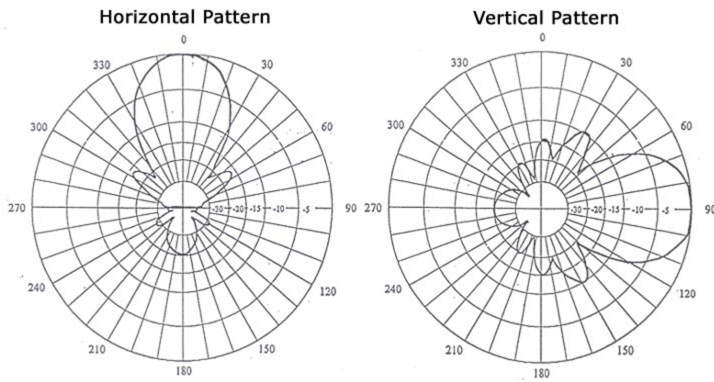


Multi-element Antennas

- 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)

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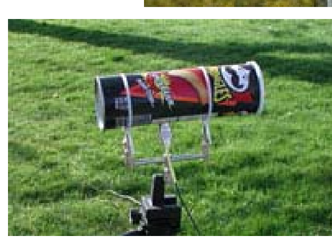
Examples 2.4 GHz



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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**