Outline

- RF introduction
  - A cartoon view
  - Communication
  - Time versus frequency view
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM

Signal = Sum of Sine Waves

\[ \text{Signal} = X_1 + 1.3X + 0.56X + 1.15X \]

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
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- RF introduction
- Modulation and multiplexing - review
  » Analog versus digital signals
  » Forms of modulation
  » Baseband versus carrier modulation
  » Multiplexing
- Channel capacity
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Signal Modulation

- Sender sends a “carrier” signal and changes it in a way that the receiver can recognize
  » The carrier is sine wave with fixed amplitude and frequency
- Amplitude modulation (AM): change the strength of the carrier based on information
  » High values -> stronger signal
- Frequency (FM) and phase modulation (PM): change the frequency or phase of the signal
  » Frequency or Phase shift keying
- Digital versions are also called “shift keying”
  » Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying
- Discussed in more detail in a later the course

Amplitude and Frequency Modulation

Amplitude Carrier Modulation
Analog and Digital Signal Modulation

- The signal that is used to modulate the carrier can be analog or digital
  - Analog: broadcast radio (AM/FM)
  - Digital: WiFi, LTE
- Analog: a continuously varying signal
  - Cannot recover from distortions, noise
  - Can amplify the signal but also amplifies the noise
- Digital: discreet changes in the signal that correspond to a digital signal
  - Can recover from noise and distortion:
    - Regenerate signal along the path: demodulate + remodulate

Multiplexing

- Capacity of the transmission medium usually exceeds the capacity required for a single signal
- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium
- A must for wireless – spectrum is huge!
  - Signals must differ in frequency (spectrum), time, or space

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - Divide the capacity in the frequency domain
- Time-division multiplexing (TDM)
  - Divide the capacity in the time domain
  - Fixed or variable length time slices

Multiple Users Can Share the Ether

- Different users use different carrier frequencies

Frequency
Frequency versus Time-division Multiplexing

With frequency-division multiplexing different users use different parts of the frequency spectrum.
- I.e. each user can send all the time at reduced rate
- Example: roommates
- Hardware is slightly more expensive and is less efficient use of spectrum

With time-division multiplexing different users send at different times.
- I.e. each user can sent at full speed some of the time
- Example: a time-share condo
- Drawback is that there is some transition time between slots; becomes more of an issue with longer propagation times

The two solutions can be combined.

Frequency Reuse in Space

- Frequencies can be reused in space
  - Distance must be large enough
  - Example: radio stations
- Basis for “cellular” network architecture
- Set of “base stations” connected to the wired network support set of nearby clients
  - Star topology in each circle
  - Cell phones, 802.11, …

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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

- 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

Some Intuition

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
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

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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)
  \[ (\text{SNR})_{\text{db}} = 10\log_{10} \frac{\text{signal power}}{\text{noise power}} \]
- 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.
  \[ C = B \log_2(1 + \frac{\text{SNR}}{\Gamma}) \]

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz; \( \text{SNR}_{\text{dB}} = 24 \text{ dB} \)
  - \( B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz} \)
  - \( \text{SNR}_{\text{dB}} = 24 \text{ dB} = 10 \log_{10}(\text{SNR}) \)
  - \( \text{SNR} = 251 \)
- 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?
  - \( C = 2B \log_2 M \)
  - \( 8 \times 10^6 = 2 \times (10^6) \times \log_2 M \)
  - \( 4 = \log_2 M \)
  - \( M = 16 \)
- 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