18-452/18-750
Wireless Networks and Applications
Lecture 3: Physical Layer
Signals, Modulation, Multiplexing

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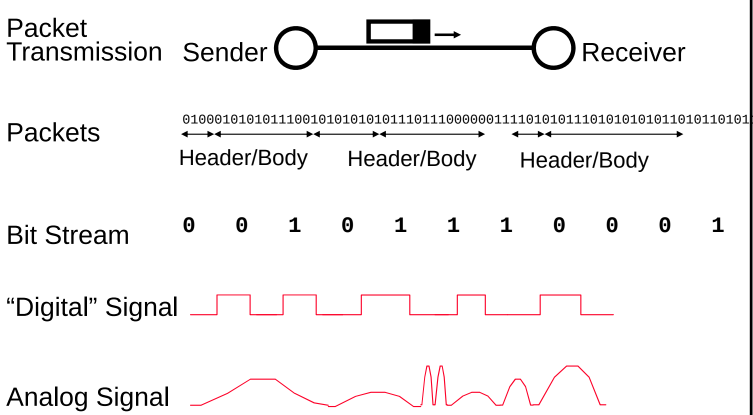
http://www.cs.cmu.edu/~prs/wirelessS17/

Outline

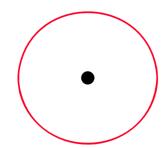
- **RF introduction**
  - » A cartoon view
  - » Communication
  - » Time versus frequency view
- **Modulation and multiplexing**
- **Channel capacity**
- **Antennas and signal propagation**
- **Modulation**
- **Diversity and coding**
- **OFDM**

From Signals to Packets



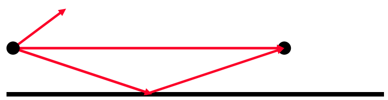
Cartoon View 1 – A Wave of Energy

- **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
- **Useful when studying attenuation**
  - » Receiving antennas catch less energy with distance
  - » Notion of cellular infrastructure



Cartoon View 2 – Rays of Energy

- Can also view it as a "ray" that propagates between two points
- Rays can be reflected etc.
  - » We can have provide 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, …



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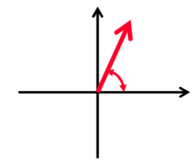
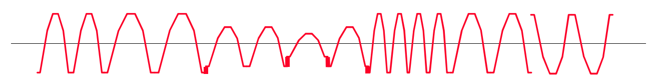
(Not so) Cartoon View 3 – Electro-magnetic Signal

- Signal that propagates and has an <u>amplitude</u> and <u>phase</u>
  - » Can be represented as a complex number
- … and that changes over time with a certain <u>frequency</u>
- Simple example is a sine wave
  - » Has an amplitude, phase, and frequency
  - » … that can change over time



Relevance to Networking?



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Sine Wave Parameters

- General sine wave
  - » $s(t) = A \sin(2\pi f t + \phi)$
- Example on next slide shows the effect of varying each of the three parameters
  - a) $A = 1$, $f = 1$ Hz, $\phi = 0$; thus $T = 1$s
  - b) Reduced peak amplitude; A=0.5
  - c) Increased frequency; $f = 2$, thus $T = ½$
  - d) Phase shift; $\phi = \pi/4$ radians (45 degrees)
- note: 2π radians = 360° = 1 period

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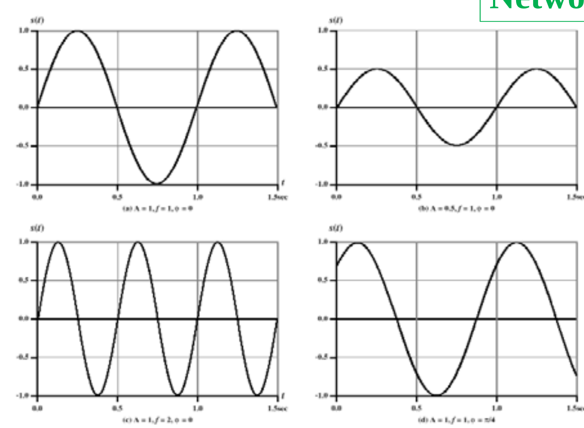
Changing Parameters of Sine Wave

Relevance to Networking?



$s(t) = A \sin(2\ ft + \phi)$

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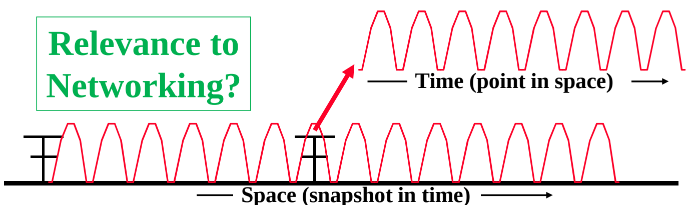
Simple Example: Sine Wave

- RF signal travels at the speed of light
- Can look at a point in space: signal will change in time according to a sine function
  - » Signal at different points are (roughly) copies of each other
- Can take a snapshot in time: signal will “look” like a sine function in space

Relevance to Networking?



Key Idea of Wireless Communication

- 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

“The wireless telegraph is not difficult to understand.
The ordinary telegraph is like a very long cat.
You pull the tail in New York, and it meows in Los Angeles.
The wireless is exactly the same, only without the cat.”

Challenge

- Cats? This is very informal!
  - » Sender “changes signal” and receiver “observes changes”
- Wireless network designers need more precise information about the performance of wireless “links”
  - » Can the receiver always decode the signal?
  - » How many Kbit, Mbit, Gbit per second?
  - » Does the physical environment, distance, mobility, weather, season, the color of my shirt, etc. matter?
- We need a more formal way of reasoning about wireless communication:

Represent the signal in the frequency domain!

Outline

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

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Time Domain View: Periodic versus Aperiodic Signals

- Periodic signal - analog or digital signal pattern that repeats over time
  - » $s(t+T) = s(t)$
    - – where T is the period of the signal
  - » Allows us to take a frequency view – important to understand wireless challenges and solutions
- Aperiodic signal - analog or digital signal pattern that doesn't repeat over time
  - » Hard to analyze
- Can "make" an aperiodic signal periodic by taking a time slice T and repeating it
  - » Often what we do implicitly

Key Parameters of (Periodic) Signal

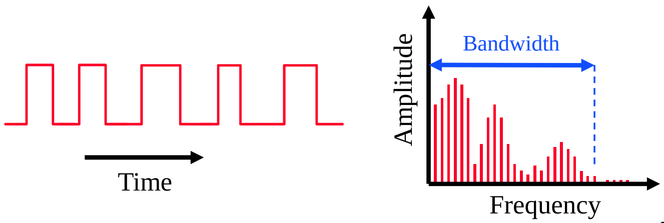
- Peak amplitude (A) - maximum value or strength of the signal over time; typically measured in volts
- Frequency (f)
  - » Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- Period (T) - amount of time it takes for one repetition of the signal
  - » $T = 1/f$
- Phase (ϕ) - measure of the relative position in time within a single period of a signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - » Or, the distance between two points of corresponding phase of two consecutive cycles

Key Property of Periodic EM Signals

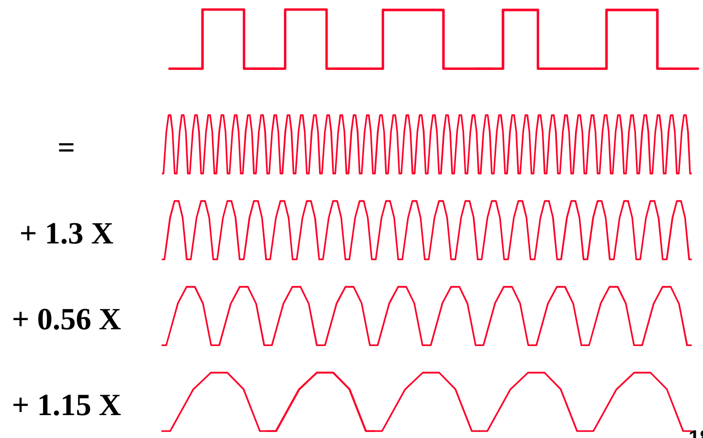
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases
- The period of the total signal is equal to the period of the fundamental frequency
  - » All other frequencies are an integer multiple of the fundamental frequency
- There is a strong relationship between the "shape" of the signal in the time and frequency domain
  - » Discussed in more detail later

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



Signal = Sum of Sine Waves



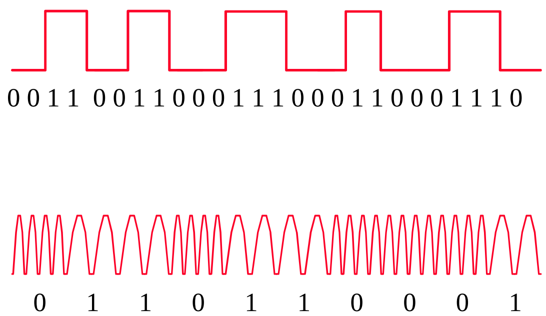
Outline

- 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

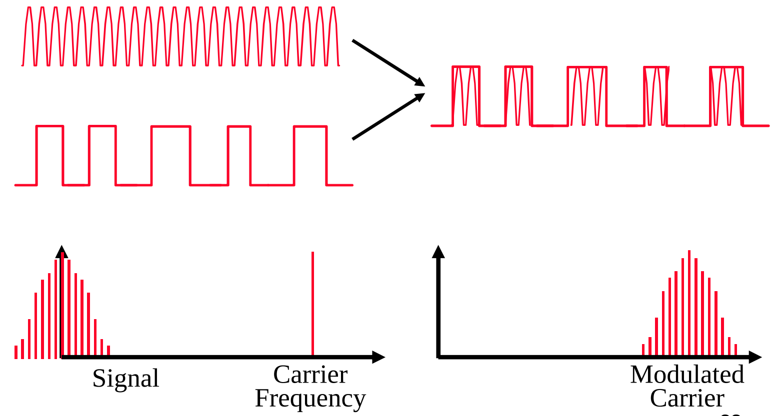
Signal Modulation

- 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 lecture

Amplitude and Frequency Modulation



Amplitude Carrier Modulation

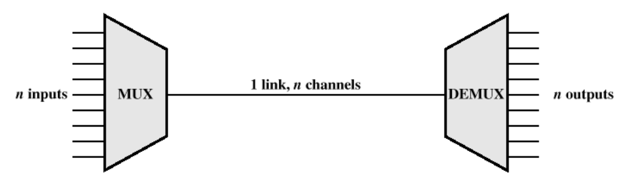


Analog and Digital Signals

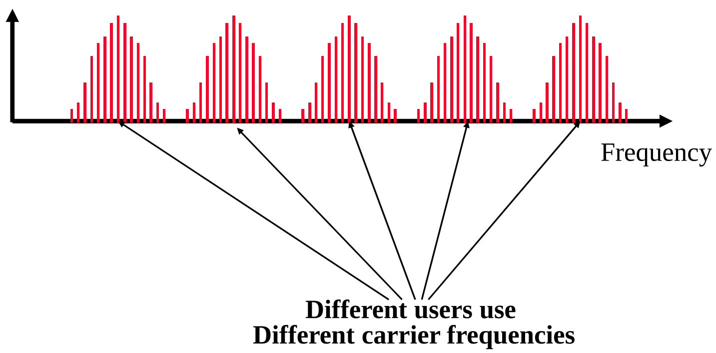
- The signal that is used to modulate the carrier can be analog or digital
  - » Wired: Twisted pair, coaxial cable, fiber
  - » Wireless: Atmosphere or space propagation
- Analog: a continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
  - » 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

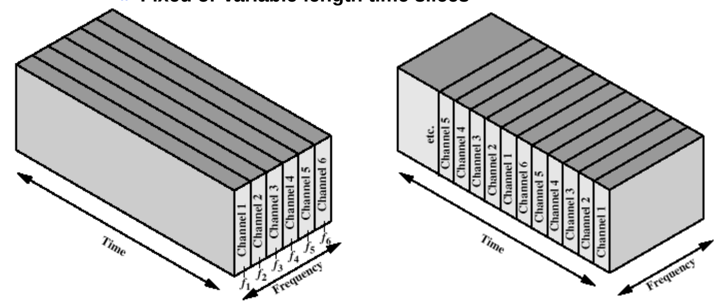


Multiple Users Can Share the Ether



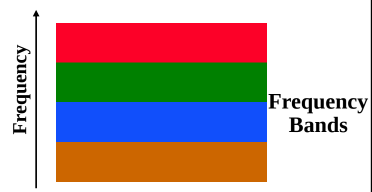
Multiplexing Techniques

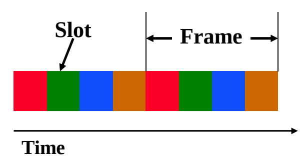
- Frequency-division multiplexing (FDM)
  - » divide the capacity in the frequency domain
- Time-division multiplexing (TDM)
  - » Divide the capacity in the time domain
  - » Fixed or variable length time slices



Frequency versus Time-division Multiplexing

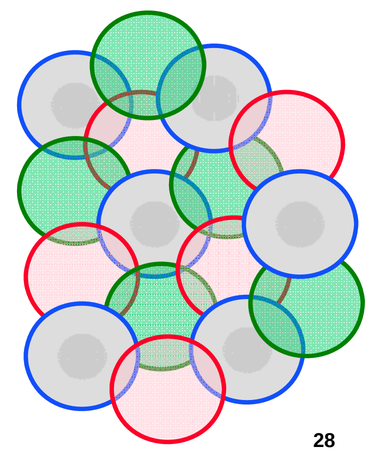
- With frequency-division multiplexing different users use different parts of the frequency spectrum.
  - » I.e. each user can send all the time at reduced rate
  - » Example: roommates
  - » Hardware is slightly more expensive and is less efficient use of spectrum
- With time-division multiplexing different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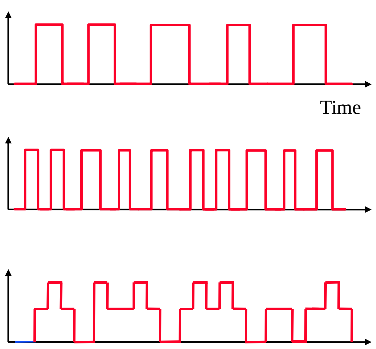
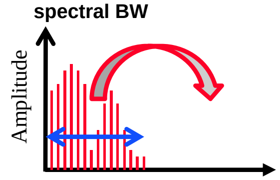
Relationship between Data Rate and Bandwidth

- 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?

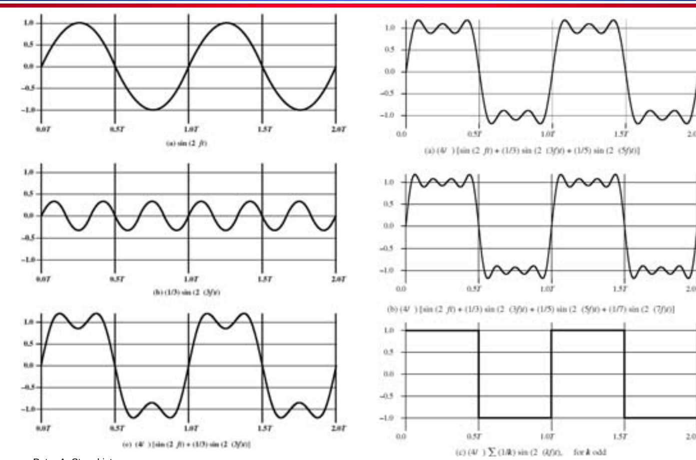
Increasing the Bit Rate



- 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

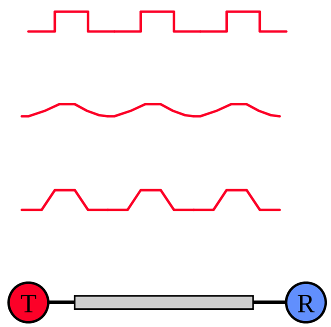


Adding Detail to the Signal



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

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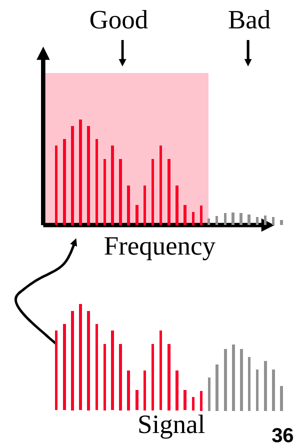
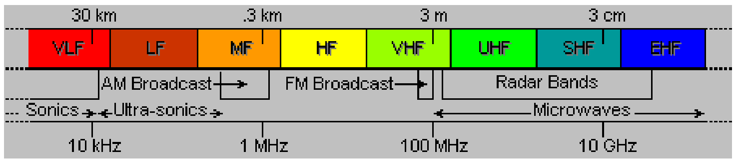
Transmission Channel Considerations

- 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



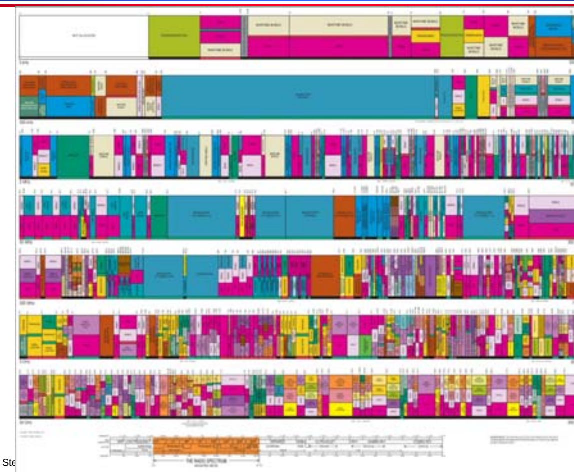
RF Introduction

- RF = Radio Frequency
  - » Electromagnetic signal that propagates through “ether”
  - » Ranges 3 KHz .. 300 GHz
  - » Or 100 km .. 0.1 cm (wavelength)



- Travels at the speed of light
- Can take both a time and a frequency view

Spectrum Allocation in US



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

  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.

$$C = B\log_2(1+\text{SNR}/\Gamma)$$

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**

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

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Example of Nyquist and Shannon Formulations

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

$$C = 2B\log_2 M$$
$$8\times10^6 = 2\times(10^6)\times\log_2 M$$
$$4 = \log_2 M$$
$$M = 16$$

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

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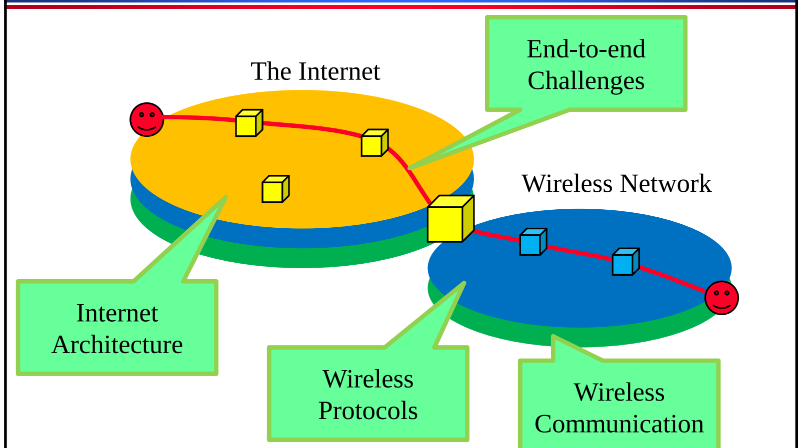
Bird's Eye View



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