Wireless Networks

Lecture 3: Physical Layer
Signals, Modulation, Multiplexing

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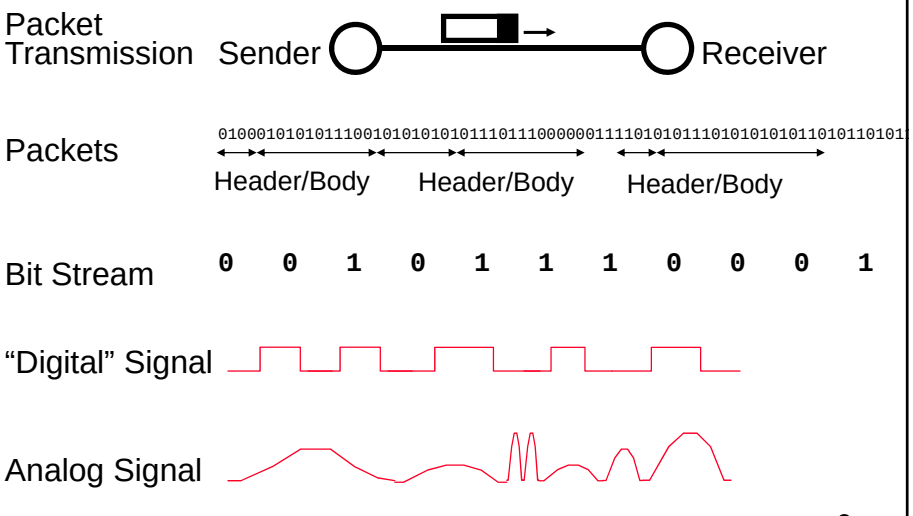
Outline

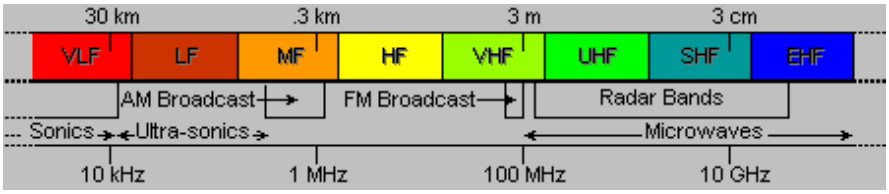
- **RF introduction**
  - » **A cartoon view**
  - » **Communication**
  - » **Time versus frequency view**
- **Modulation and multiplexing**
- **Channel capacity**
- **Antennas and signal propagation**
- **Equalization and diversity**
- **Modulation and coding**
- **Spectrum access**

From Signals to Packets



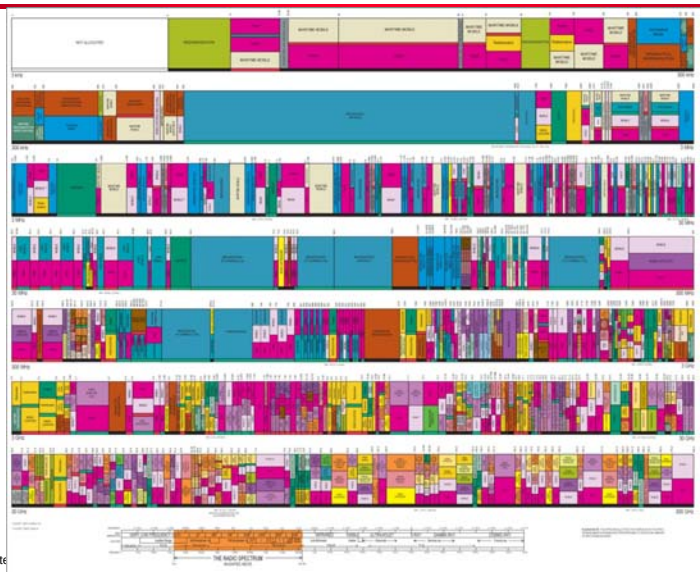
RF Introduction

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



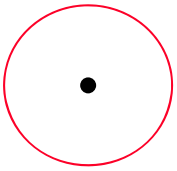
- **Travels at the speed of light**
- **Can take both a time and a frequency view**

Spectrum Allocation in US



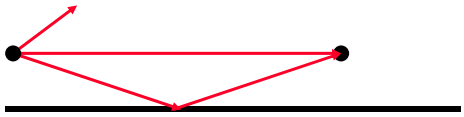
Cartoon View 1 – A Wave of Energy

- 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



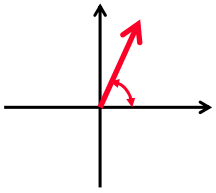
Cartoon View 2 – Rays of Energy

- 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, …

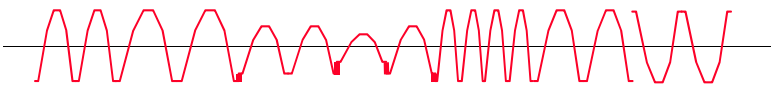


(Not so) Cartoon View 3 – Electro-magnetic Signal

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



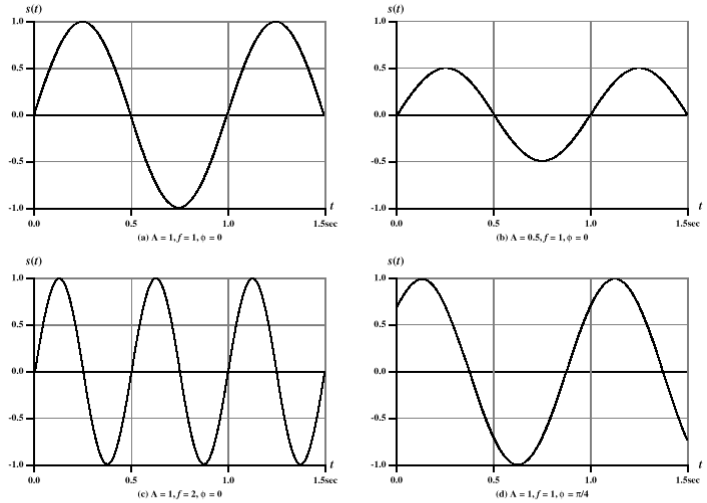
Relevance to Networking?



Sine Wave Parameters

- **General sine wave**
  - » $s(t) = A \sin(2\pi ft + \phi)$
- **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**

Space and Time View Revisited

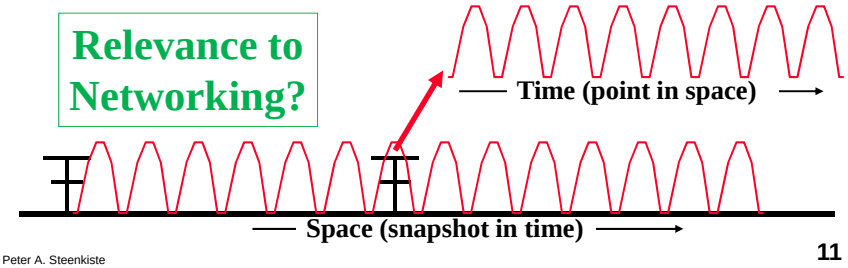


$s(t) = A \sin(2\ ft + \phi)$

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."

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  - A cartoon view
  - Communication
  - Time versus frequency view
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

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!

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

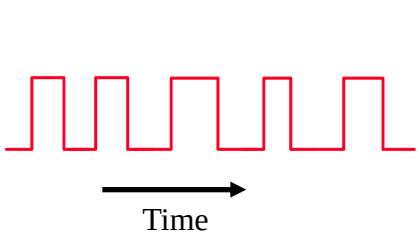
- Peak amplitude (A) - maximum value or strength of the signal over time; typically measured in volts
- Frequency (f)
  - » Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- Period (T) - amount of time it takes for one repetition of the signal
  - » $T = 1/f$
- Phase (ϕ) - measure 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

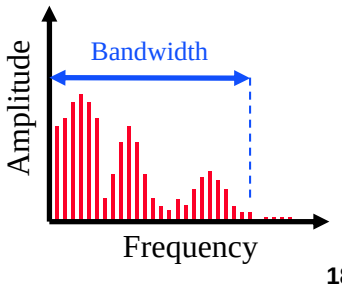
Key Property of Periodic EM Signals

- 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

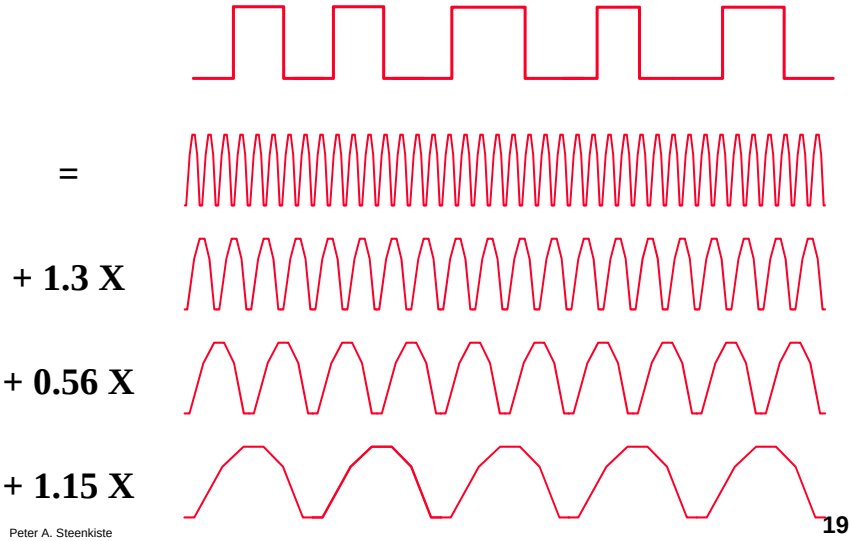
The Frequency Domain

- 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



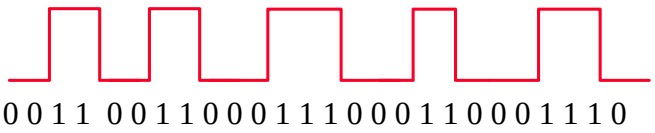
Outline

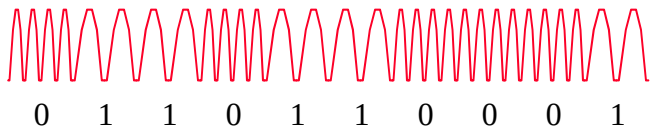
- RF introduction
- Modulation and multiplexing - review
  - Analog versus digital signals
  - Forms of modulation
  - Baseband versus carrier modulation
  - Multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

Signal Modulation

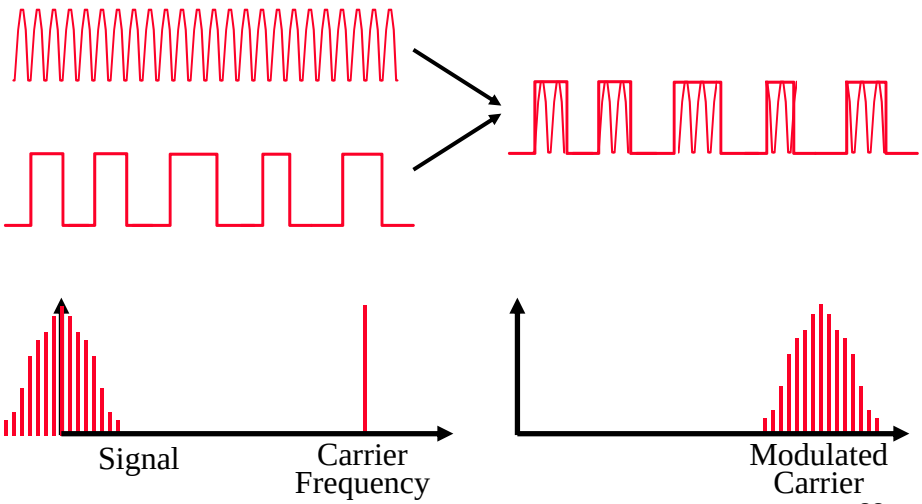
- Sender sends a “carrier” signal and changes it in a way that the receiver can recognize
  - The carrier is sine wave with fixed amplitude and frequency
- Amplitude modulation (AM): change the strength of the carrier based on information
  - High values -> stronger signal
- Frequency (FM) and phase 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

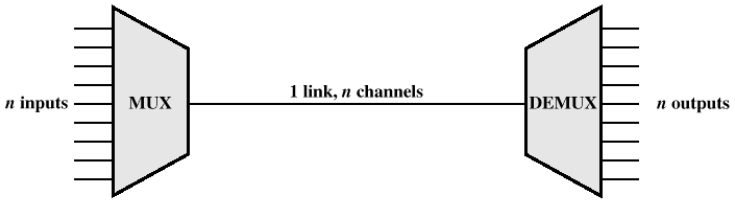


Analog and Digital Signals

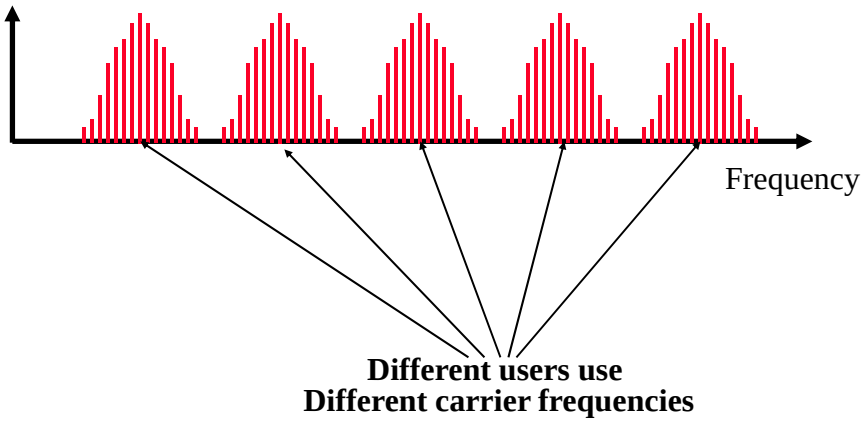
- **The signal that is used to modulate the carrier can be analog or digital**
  - » **Wired: Twisted pair, coaxial cable, fiber**
  - » **Wireless: Atmosphere or space propagation**
- **Analog: a continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency**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

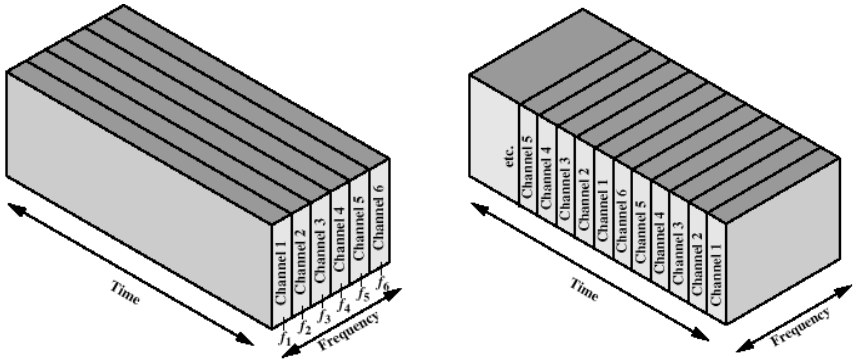


Multiple Users Can Share the Ether



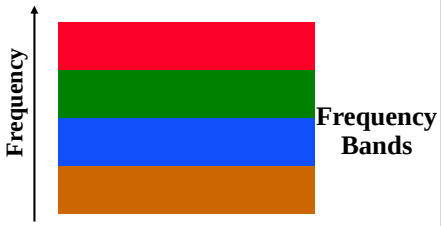
Multiplexing Techniques

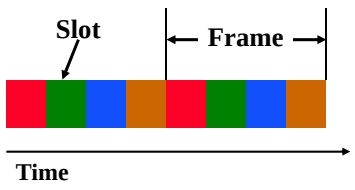
- **Frequency-division multiplexing (FDM)**
  - » divide the capacity in the frequency domain
- **Time-division multiplexing (TDM)**
  - » Divide the capacity in the time domain
  - » Fixed or variable length time slices



Frequency versus Time-division Multiplexing

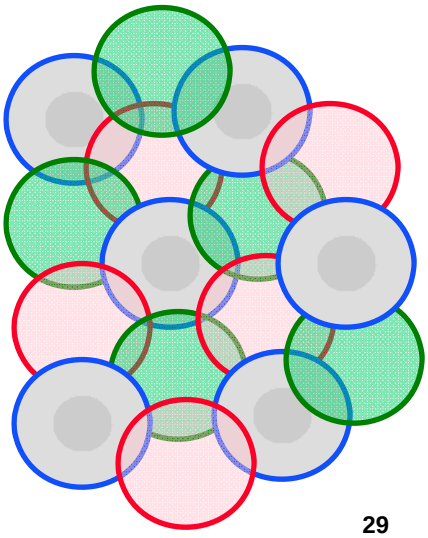
- **With frequency-division multiplexing different users use different parts of the frequency spectrum.**
  - » I.e. each user can send all the time at reduced rate
  - » Example: roommates
  - » Hardware is slightly more expensive and is less efficient use of spectrum
- **With time-division multiplexing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



Bird's Eye View