18-452/18-750
Wireless Networks and Applications
Lecture 2: Wireless Challenges

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http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- **Waiting list update (Th afternoon)**
  - » **Class size has been increased to 30**
  - » **Waiting lists are shrinking**
- **We will post project P1 soon**
  - » **You have plenty of time for the project – no need to rush**
  - » **As part of the Monday's lecture we will have a short overview and Q&A for P1**

Outline

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

Why Use Wireless?

"No wires" has several significant advantages:

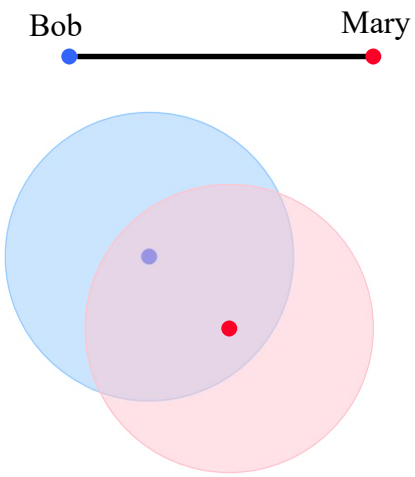
- Supports mobile users
  - » Move around office, campus, city, … - users get hooked
  - » Cordless phones, cell phones, ..
  - » Remote control devices (TV, garage door, ..)
  - » WiFi and cellular, but also: Bluetooth, RFID, LoRaWan, …
- No need to install and maintain wires
  - » Reduces cost – important in offices, hotels, …
  - » Simplifies deployment – important in homes, hotspots, …

But Wireless Links are Challenging!

- In wired networks, links are constant, reliable and physically isolated
  - » A 1 Gps Ethernet always has the same performance
  - » Reason: all link properties are standardized
  - » Also, the wire isolates the signal from other the environment
- In wireless networks links are variable, error-prone and they share the ether with each other and other external, uncontrolled sources
  - » Link properties can be extremely dynamic, e.g., mobility
  - » Other transmitters in the same frequency band
  - » Worst case: no connectivity

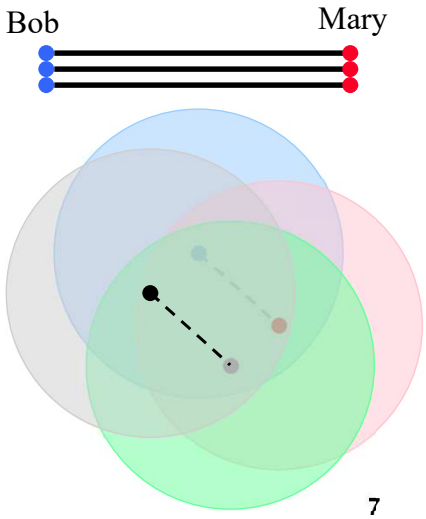
Wireless is a shared medium

- In wired communication, signals are contained in a conductor
  - » Copper or fiber
  - » Guides energy to destination
  - » Protects signal from external signals
- Wireless communication uses broadcasting over the shared ether
  - » Energy is distributed in space
  - » Signal must compete with many other signals in same frequency band



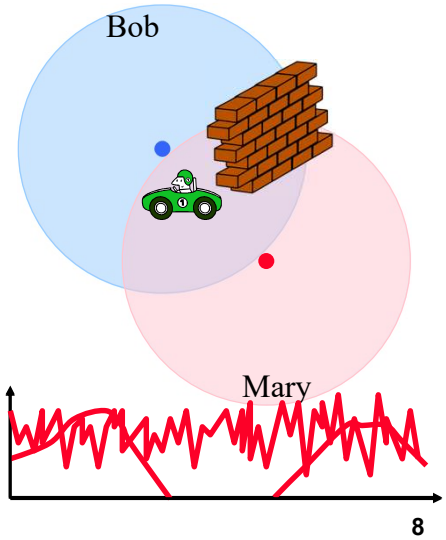
How Do We Increase Network Capacity?

- Easy to do in wired networks: simply add wires
  - » Fiber is especially attractive
- Adding wireless "links" increases interference.
  - » Frequency reuse can help … subject to spatial limitations
  - » Or use different frequencies … subject to frequency limitations
- The capacity of a wireless network is fundamentally limited.



Mobility Affects the Link Throughput

- Quality of the transmission depends on distance and obstacles blocking the "line of sight" (LOS)
  - » "Slow fading" – the signal strength changes slowly
- Reflections off obstacles combined with mobility can cause "fast fading"
  - » Very rapid changes in the signal
  - » More on this later
- Hard to predict signal!



How is Wireless Different?

Wired	Wireless
• Physical link properties are fixed and specified in standards	• Physical link properties can change rapidly in unpredictable ways
• Designed for low error rates and link capacity is fixed and known	• Error rates vary a lot and capacity is very dynamic
• Datalink layer is simple and optimized for the physical layer	• How do you design an efficient datalink protocol?
• Internet was designed assuming low error rates	• How can higher layer protocols deal with this?

Understanding the physical layer is key to making wireless work well

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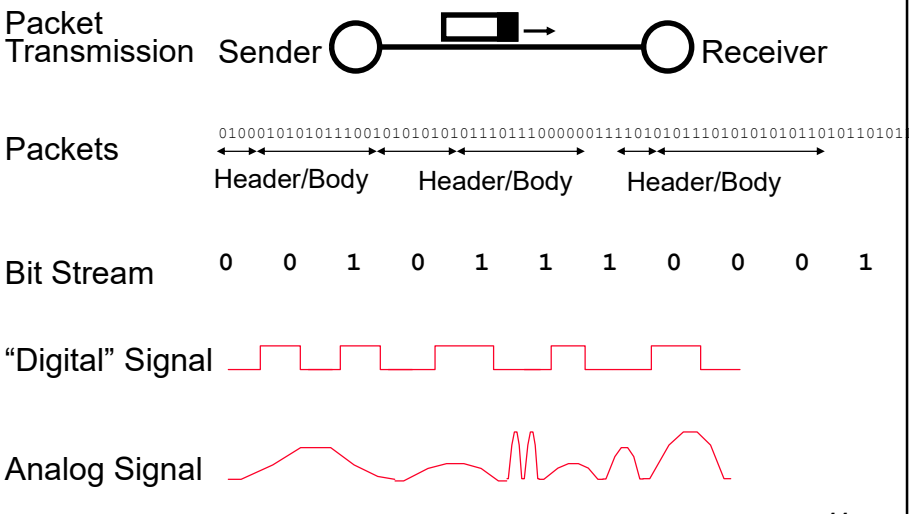
From Signals to Packets



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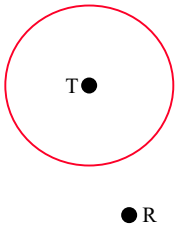
Cartoon View 1 – A Wave of Energy

- **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, distance**
  - » **Signal strength is reduced, error rates go up**
- **Relevance to networking?**
  - » **Error rates of "wireless" depend on distance**
    - – **Also depends on many properties**
  - » **Notion spatial reuse of frequencies**
    - – **Basis of cellular and WiFi infrastructures**



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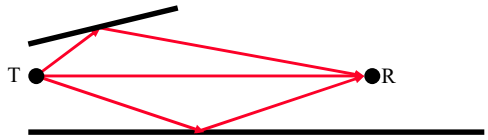
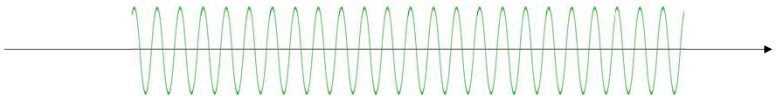
Cartoon View 2 – Rays of Energy

- Can also view it as a "ray" that propagates between two points
  - » Rays can be reflected etc.
  - » A channel can include multiple "rays" that take different paths – "multi-path" effect
- Implications for wireless networks
  - » We can have provide connectivity without line of sight!
  - » Receiver can receive multiple copies of the signal, which leads to signal distortion
  - » Combined with mobility, it also leads to fast fading



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

- Electro-magnetic signal that propagate
  - » Sigh, this is getting too complicated!
- Cartoon version: sine wave with a certain frequency, amplitude and phase that propagates from the sender to the receiver

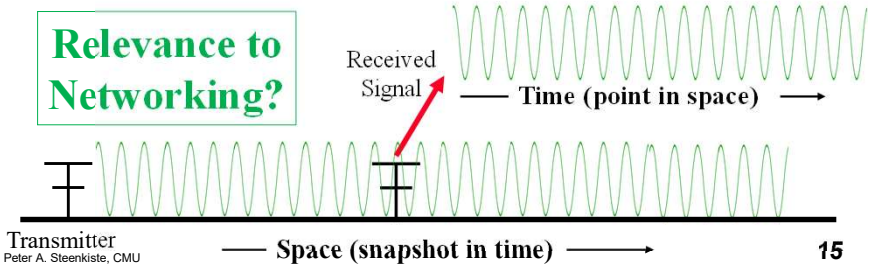


- The EM signal/sine wave is the *basis for* communication:
  - » The sender can change the properties of the EM signal over time to convey information
  - » Receivers can observe these changes and extract the information

Time and Point View of Signal

- Can look at a point in space: signal will change in time according to a sine function
  - » But transmitter can change phase, amplitude, frequency
- Can take a snapshot in time: signal will "look" like a sine function in space
  - » Signal at different points are (rough) copies of each other
- Receiver can observe transmitter's changes

Relevance to Networking?



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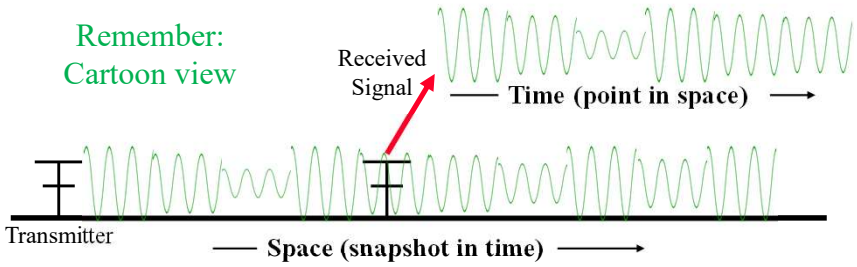
Communication

Remember: Cartoon view



- Sender changes signal in agree upon way and receiver interprets the changes
  - » "Modulation" and "demodulation"
- Problem: the signal gets distorted on "channel"
  - » This may make it harder for the receiver to interpret changes

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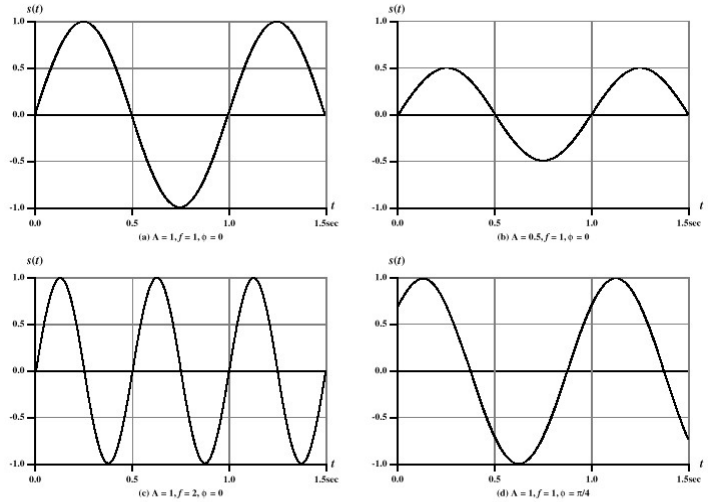
Sine Wave Parameters

- 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

Modulation: Changing the Wireless Signal



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

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, that represent information
  - Can change amplitude, phase, frequency, or a combination
  - Note that the transmitted signal is no longer a simple sine wave or even a periodic signal
- Receiver can identify the digital signal by observing how the received signal changes
  - It can then interpret the digital signal to identify the user information that was sent
  - As a result of signal distortions on the wireless signal, it may be hard to correctly extract the information

Frequency View

- The time domain view is a good basis for working with wireless signals
  - Communication is based on a sine wave – "carrier signal"
  - Transmitters continuously change the properties of the carrier signal based on the sequence of bits in the packets
  - Receivers interpret the changes in the carrier wave to identify the bit stream encoded in the signal
- But: users must share the spectrum – they must stay within their allocated frequency band
  - How can a sender guarantee that it does not interfere with communication in neighboring bands?
  - How much can you really change the wireless signal?
  - Does the amount of spectrum matter: 1MHz versus 160MHz?
  - Are all spectrum bands the same? 900 MHz, 2.4, 5, 60 GHz?

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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
  - » Harder to analyze
- Can "make" an aperiodic signal periodic by taking a time slice T and repeating it
  - » Often what we do implicitly

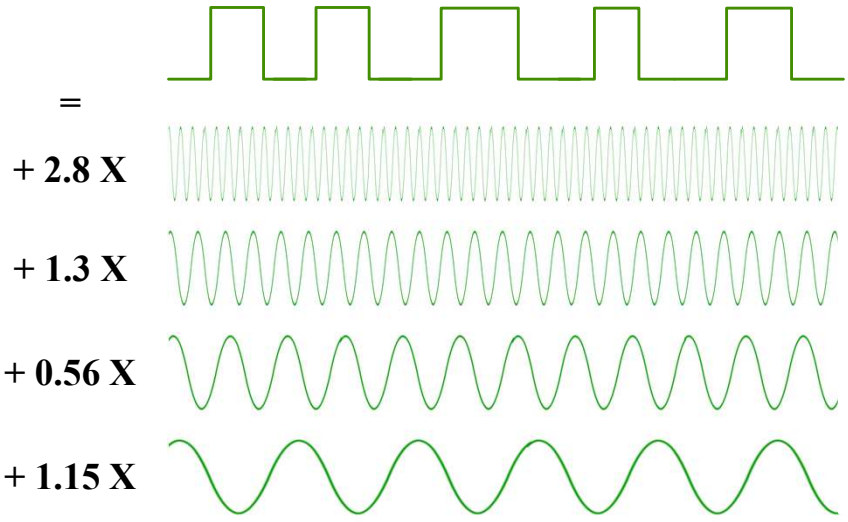
Key Parameters of (Periodic) Signal

- 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

Representation of the Signal in the Frequency Domain



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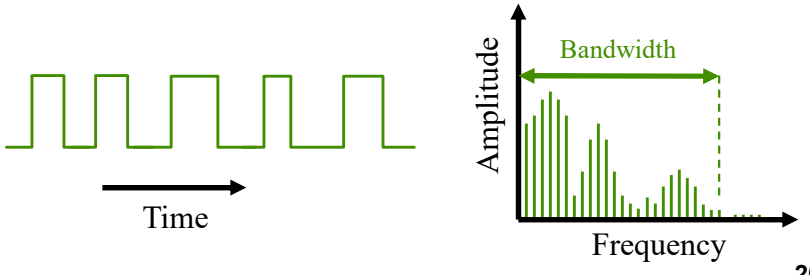
The Frequency Domain

- 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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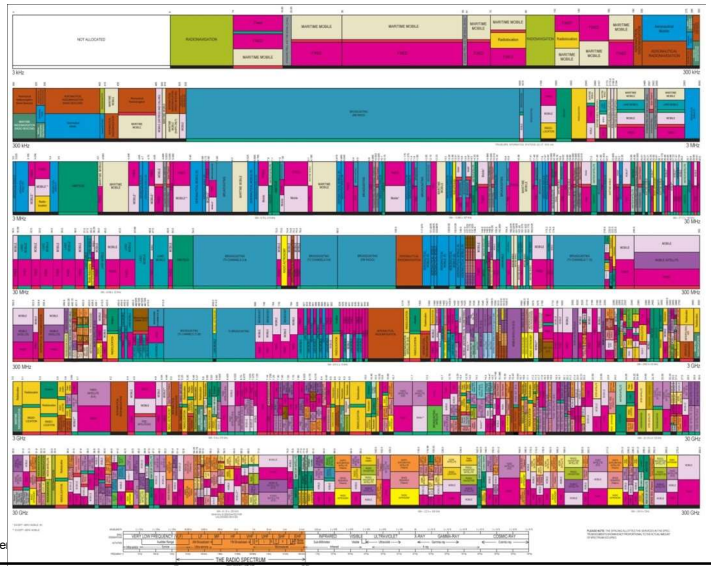
Signal Modulation

- 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 later the course

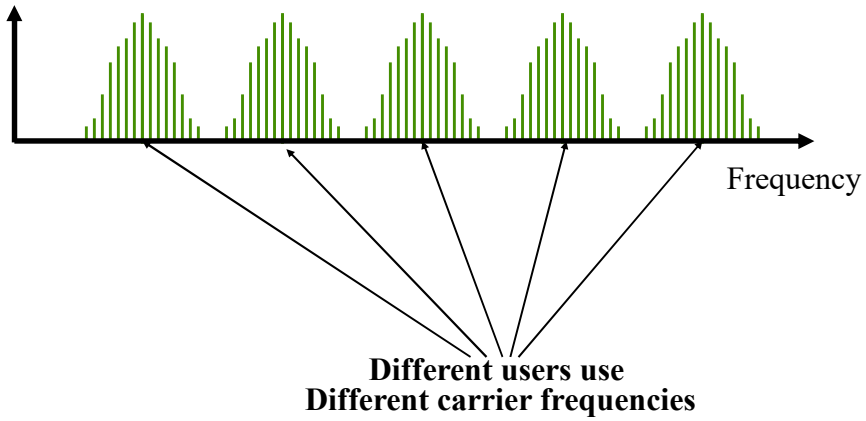
Analog and Digital Signal Modulation

- 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 since it 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

Wireless Spectrum in the US



Multiple Users Can Share the Ether



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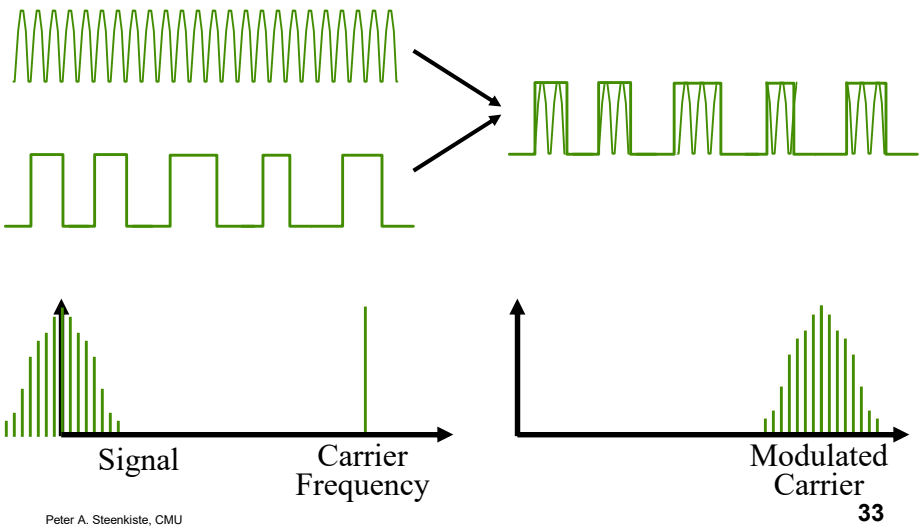
Amplitude Carrier Modulation



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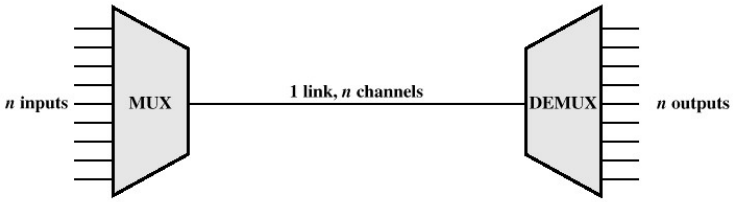
Multiplexing

- 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



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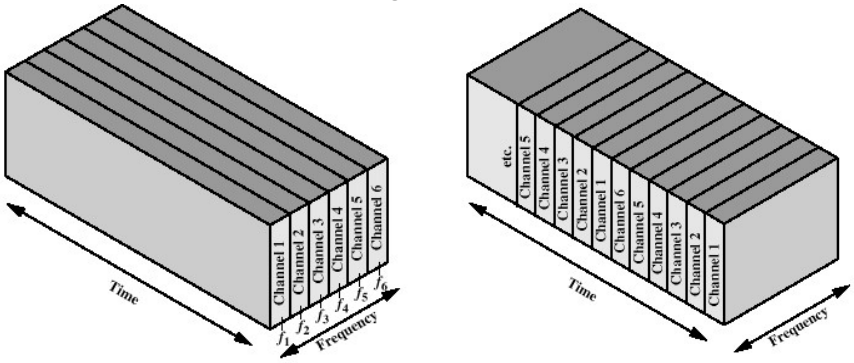
Multiplexing Techniques

- 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



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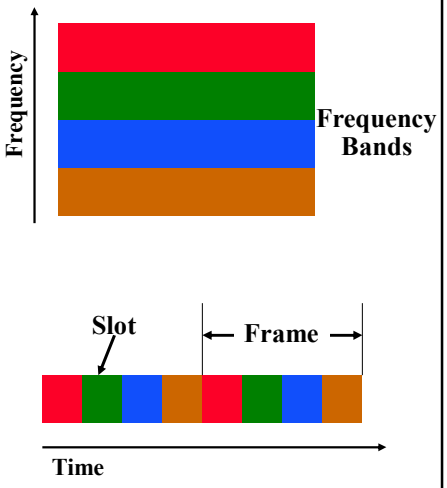
Frequency versus Time-division Multiplexing

- 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, …