

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

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<http://www.cs.cmu.edu/~prs/wirelessS20/>

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Why Use Wireless?

There are no wires!

Has several significant advantages:

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

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Outline

- Goals and structure of the course
- Administrative stuff
- A bit of history
- Wireless technologies
- Building a network
 - » Designing a BIG system
 - » The OSI model
 - » Packet-based communication
 - » Challenges in Wireless Networking

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What is Hard about Wireless?

There are no wires!

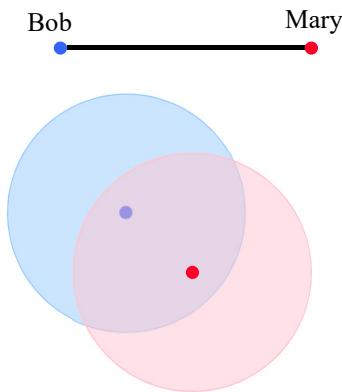
- In **wired** networks links are constant, reliable and physically isolated
 - » A 1 Gps Ethernet always has the same properties
 - » Not true for “54 Mbs” 802.11a and definitely not for “6 Gbs” 802.11ac
- In **wireless** networks links are variable, error-prone and share the ether with each other and other external, uncontrolled sources
 - » Link properties can be extremely dynamic
 - » For mobile devices they also differ across locations

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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

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Attenuation and Errors



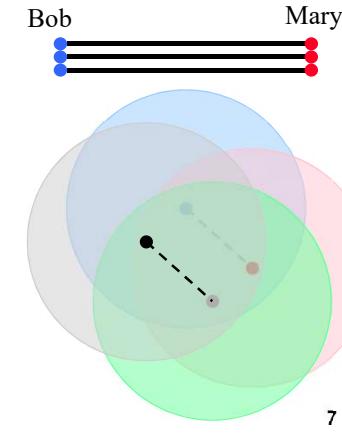
- In wired networks error rate 10^{-10} or less
 - » Wireless networks are far from that target
- Signal attenuates with distance and is affected by noise and competing signals
- Obstacles further attenuate the signal
- Probability of a successful reception depends on the “signal to interference and noise ratio” - the SINR
- More details later in the course

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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 the wireless network is fundamentally limited.

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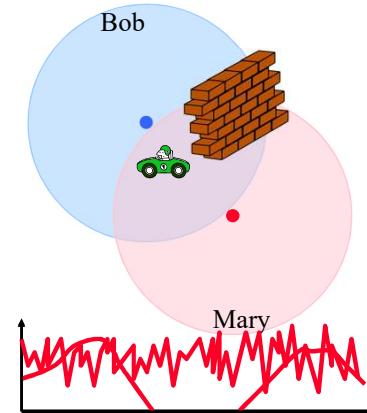
Mobility Affects the Link Throughput

- 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!

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How is Wireless Different?

Wired

- Physical link properties are fixed and specified in standards
- Designed for low error rates and throughput is fixed and known
- Datalink layer is simple and optimized for the physical layer
- Internet was designed assuming low error rates

Wireless

- Physical link properties can change rapidly in unpredictable ways
- Error rates vary a lot and throughput is very dynamic
- How do you design an efficient datalink protocol?
- How well will higher layer protocols work?

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Implications of Variability in Wireless PHY Layer

- **Wireless datalink protocols must optimize throughput across an unknown and dynamic transmission medium**
 - » Important to understand what causes the changes
- **Wireless “links” as observed by layers 3-7 will be unavoidably different from wired links**
 - » Variable bandwidth and latency
 - » Intermittent connectivity
 - » Must adapt to changes in connectivity and bandwidth
- **Understanding the physical layer is the key to making wireless work well**
 - » High level intuition is sufficient

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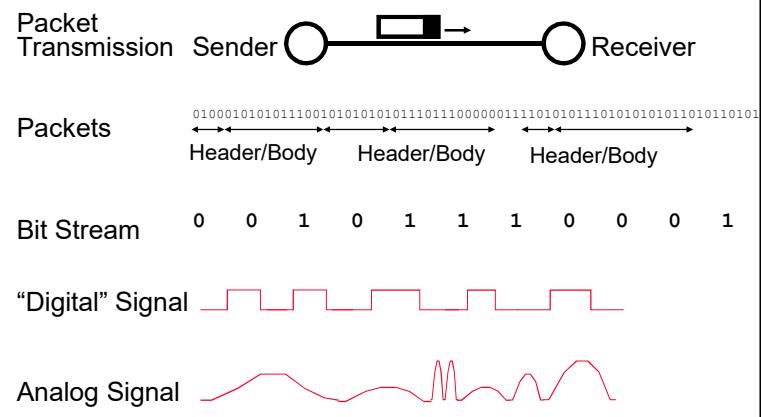
Outline

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

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From Signals to Packets



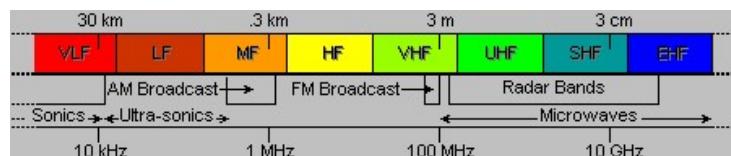
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RF Introduction

- **RF = Radio Frequency**

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

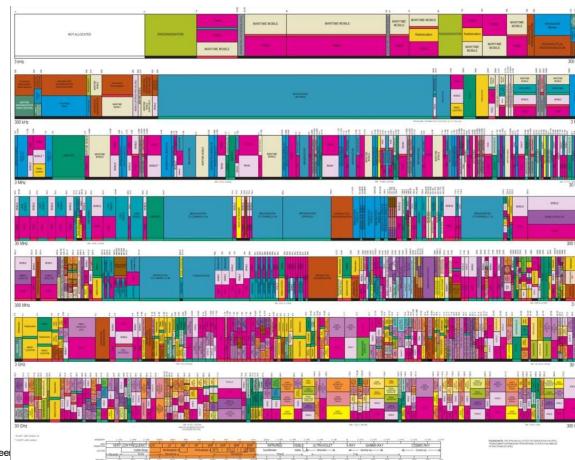


- Travels at the speed of light
- Can take both a time and a frequency view

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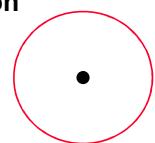
Wireless Spectrum in the US



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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

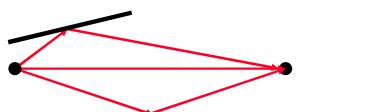


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Cartoon View 2 – Rays of Energy

- 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



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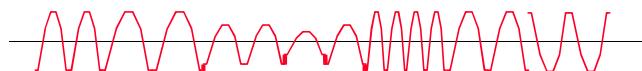
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(Not so) Cartoon View 3 – Electro-magnetic Signal

- Signal that propagates and changes over time with a certain frequency and has an amplitude and phase
 - » Think: sine wave

• Relevance to networking?

- » The sender can change the properties of the EM signal over time to convey information
- » Receivers can observe these changes and extract the information



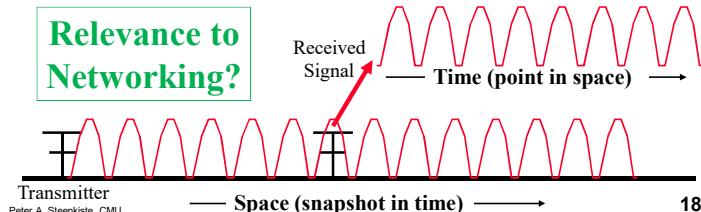
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Time and Point View of Signal

- 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

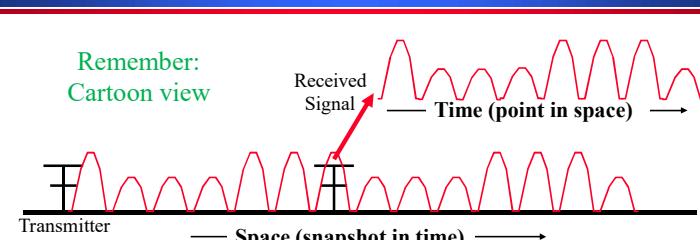
Relevance to Networking?



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Communication



- Sender changes signal in agree upon way and receiver interprets the changes
 - » “Modulation” and “demodulation”
- Problem: the signal gets distorted on “channel”
 - » Makes it harder for receiver to interpret changes

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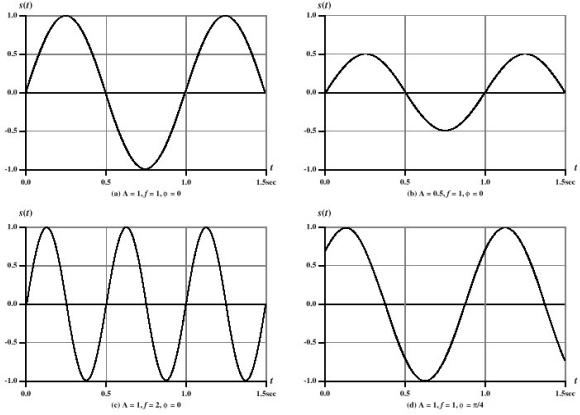
Sine Wave Parameters

- 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) $A = 1, f = 1 \text{ Hz}, \phi = 0$; thus $T = 1\text{ s}$
 - b) Reduced peak amplitude; $A=0.5$
 - c) Increased frequency; $f = 2$, thus $T = 1/2$
 - d) Phase shift; $\phi = \pi/4 \text{ radians (45 degrees)}$
- note: $2\pi \text{ radians} = 360^\circ = 1 \text{ period}$

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Space and Time View Revisited



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

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

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Challenge

- Cats, really? 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!

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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

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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

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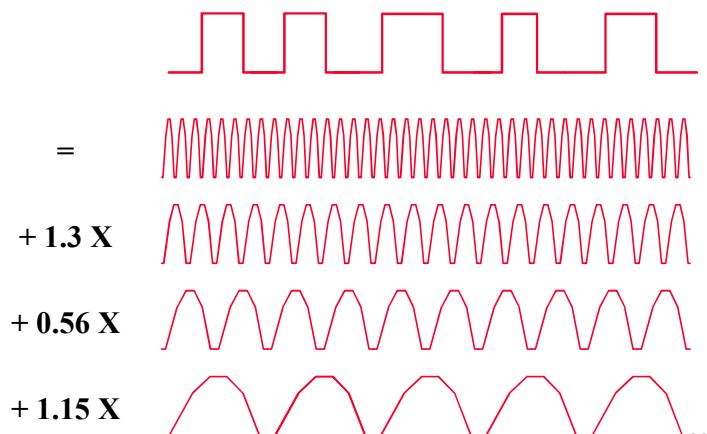
Key Property of Periodic EM Signals

- 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

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Signal = Sum of Sine Waves

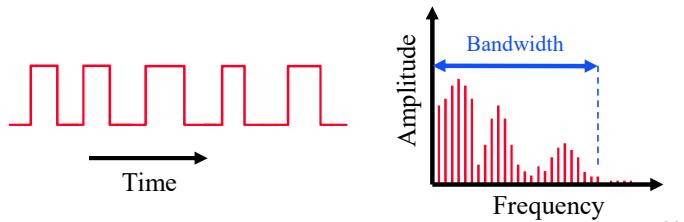


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The Frequency Domain

- 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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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

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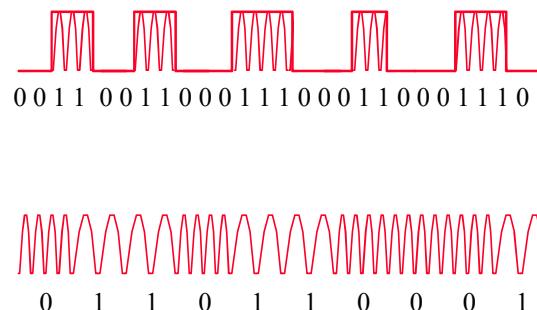
Signal Modulation

- 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 course

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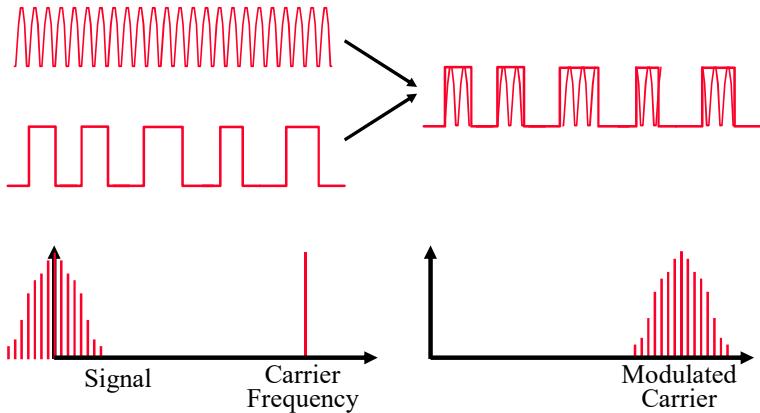
Amplitude and Frequency Modulation



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Amplitude Carrier Modulation



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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: discrete changes in the signal that correspond to a digital signal
 - » Can recover from noise and distortion:
 - » Regenerate signal along the path: demodulate + remodulate

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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

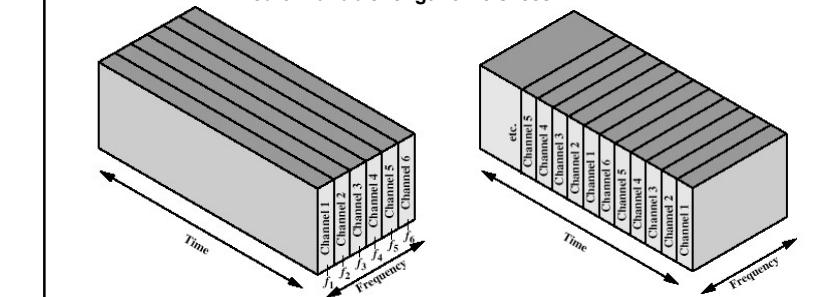


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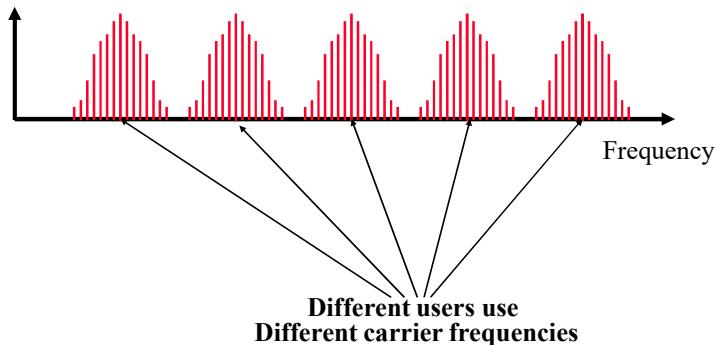
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Multiplexing Techniques

- 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



Multiple Users Can Share the Ether

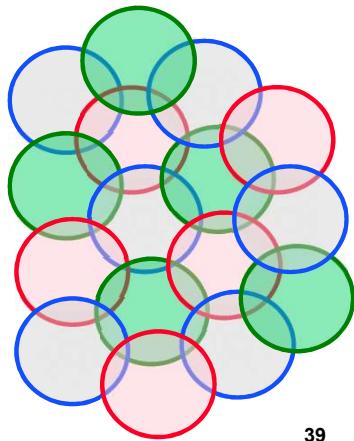


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Frequency Reuse in Space

- 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, ...

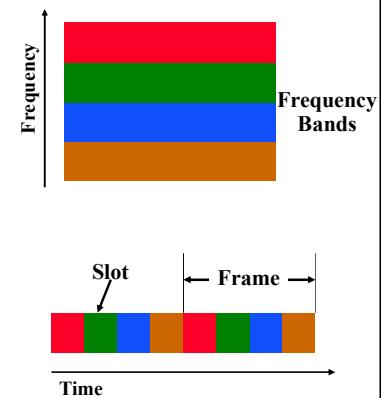


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Frequency versus Time-division Multiplexing

- 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 send 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.



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