This lecture is being recorded

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

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Carnegie Mellon University

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http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

- **Waiting list updates …**

- **Course admin: On Wednesday, one slide was missing from the slide deck**
  - » **See next slide**

More Administrative Stuff

- Lectures are Mo/Wed 2:30 – 4:20 EST
  - But lectures will typically be ~80 minutes, which is the typical lecture duration for a 12 unit course
- Recitations are Fr 11:50am -1:10pm EST
  - Only 70 minutes
- Course admin: Michele Passerrello – HH 1112
  - Appointments: Tracy Farbacher (CSD)
- Teaching assistant: Jingxian Wang

- Syllabus has more details on course policies

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 remote, 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, …

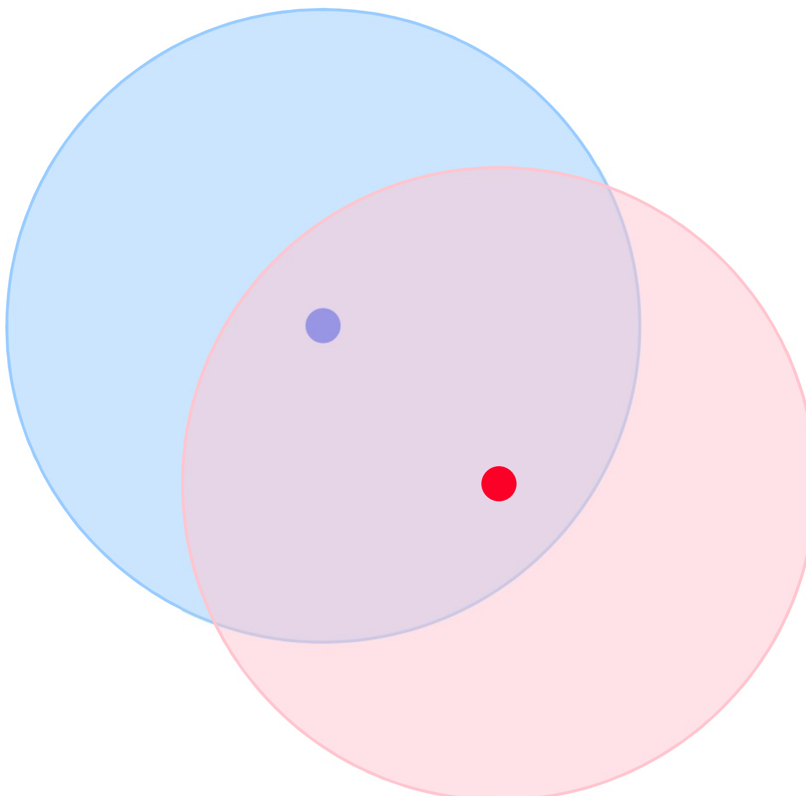
What is Hard about Wireless?

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

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

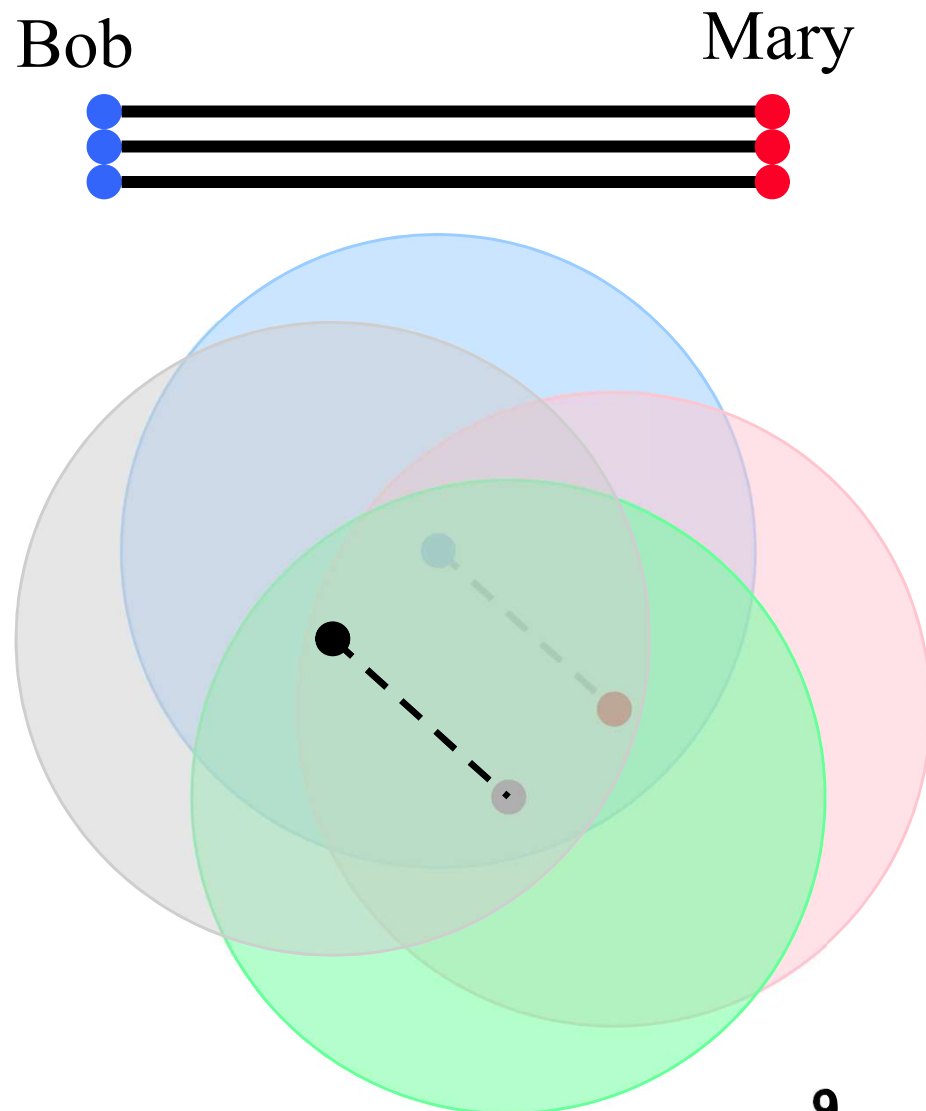


Attenuation and Errors

- 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

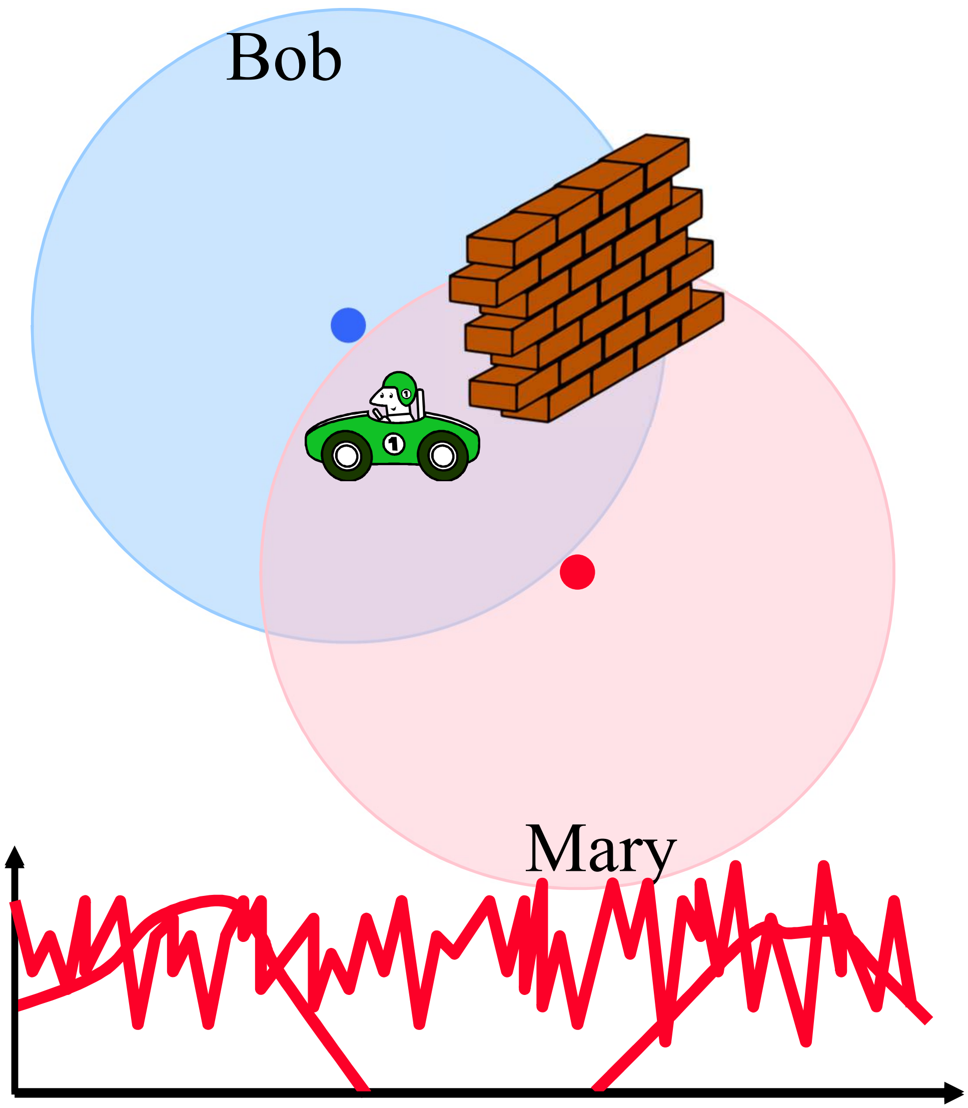
How Do We Increase Network Capacity?

- 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.



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

- 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?

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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From Signals to Packets

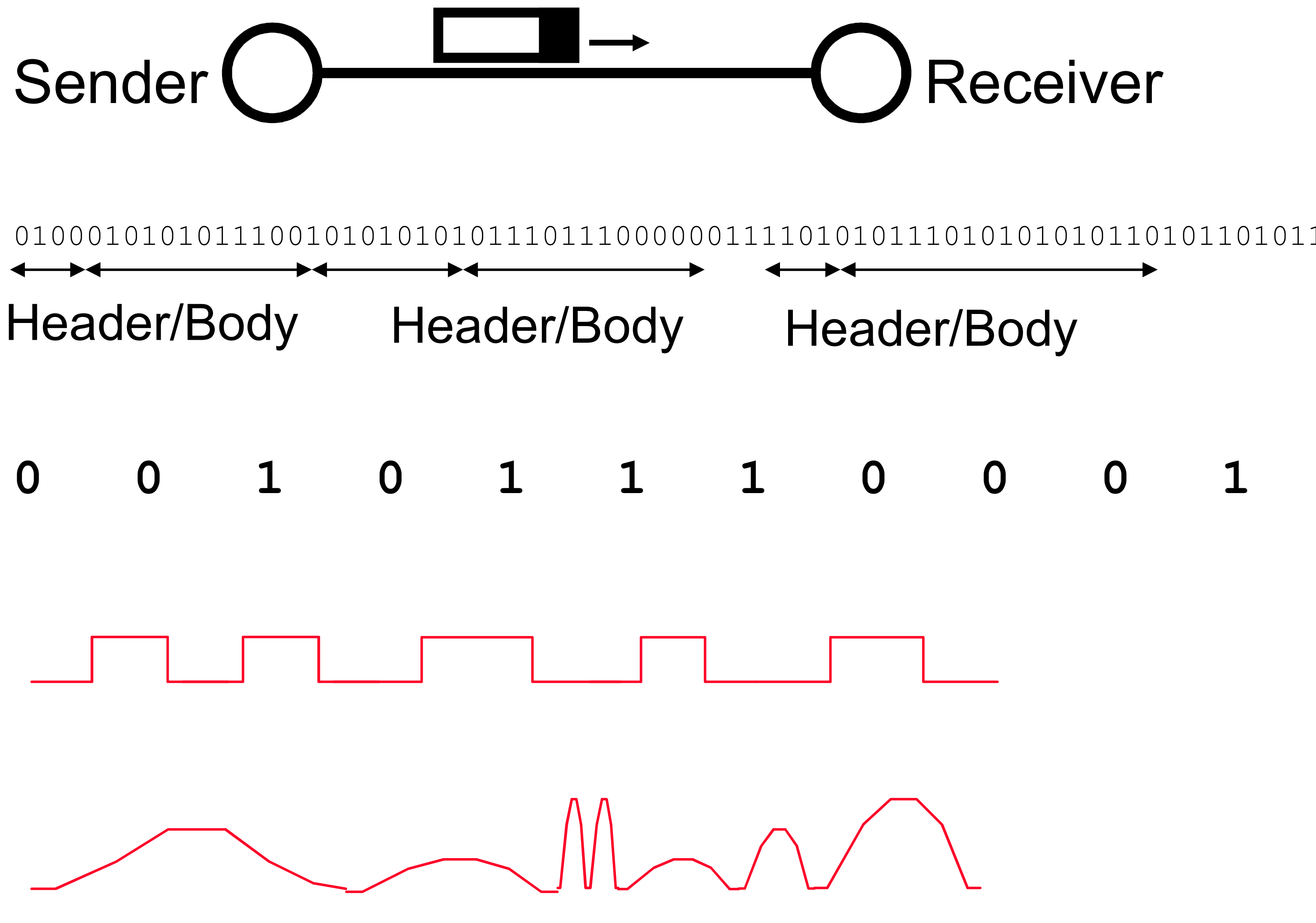
Packet Transmission

Packets

Bit Stream

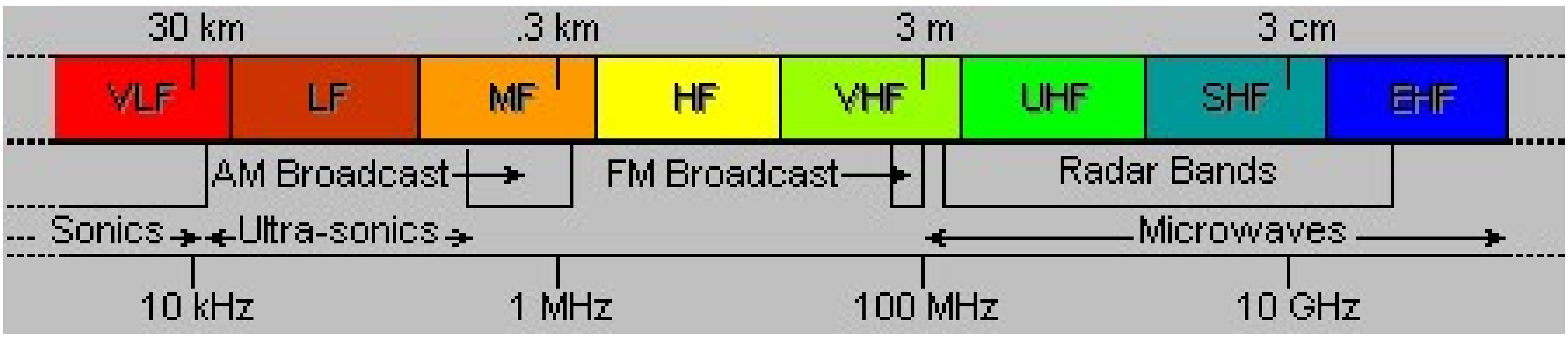
“Digital” Signal

Analog Signal



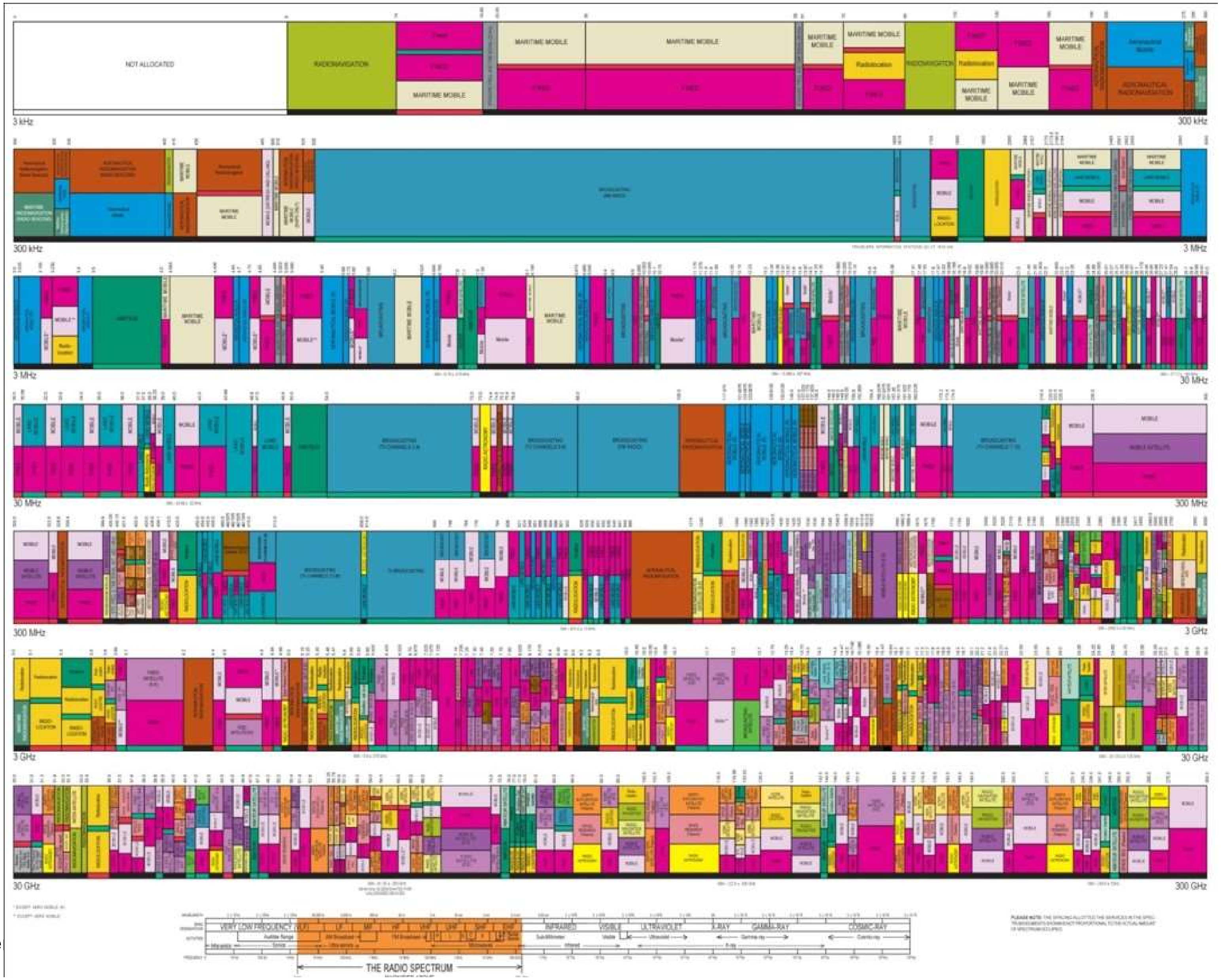
RF Introduction

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



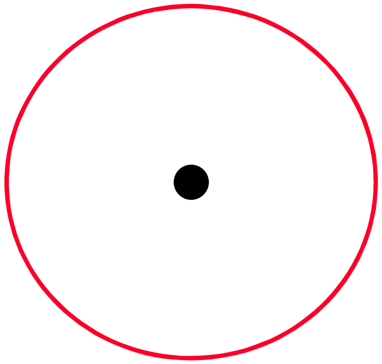
- Travels at the speed of light
- Can take both a time and a frequency view

Wireless Spectrum in the US



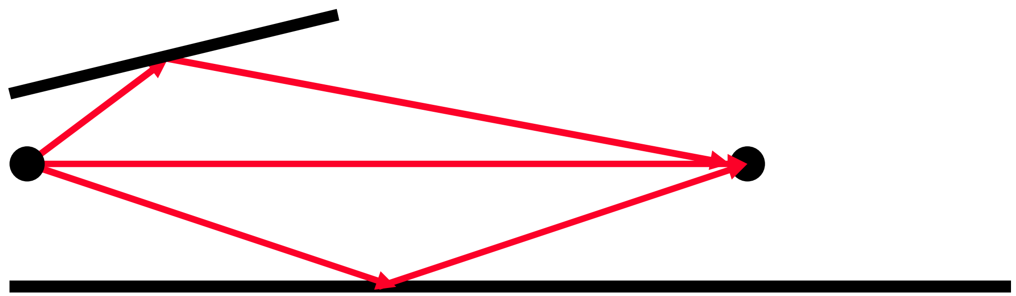
Cartoon View 1 – A Wave of Energy

- 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, 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



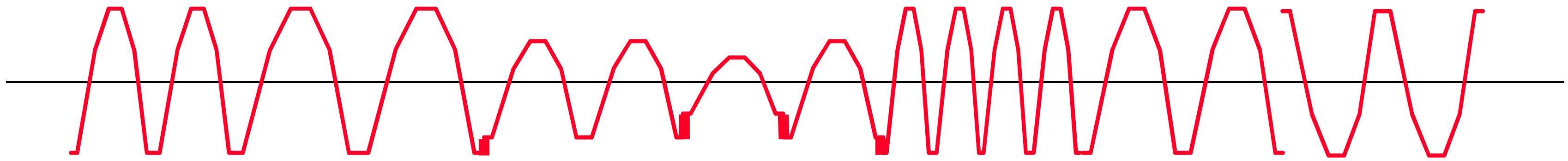
Cartoon View 2 – Rays of Energy

- **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

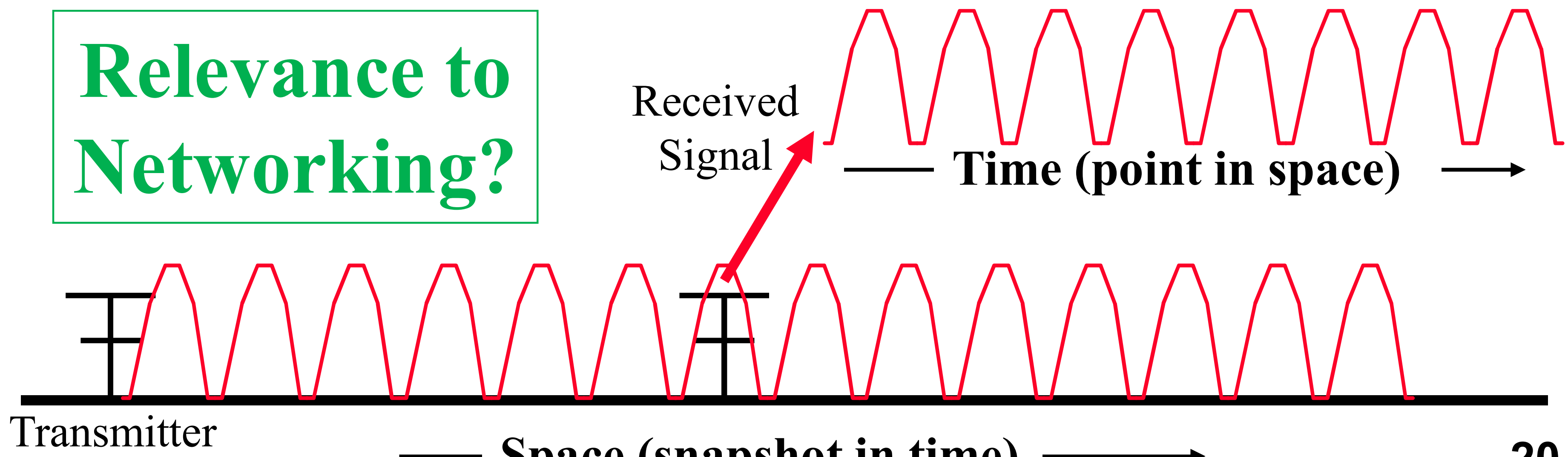
- Signal that propagates and changes over time with a certain <u>frequency</u> and has an <u>amplitude</u> and <u>phase</u>
  - » Think: sine wave
- Relevance to networking?
  - » The sender can change the properties of the EM signal over time to convey information
  - » Receivers can observe these changes and extract the information



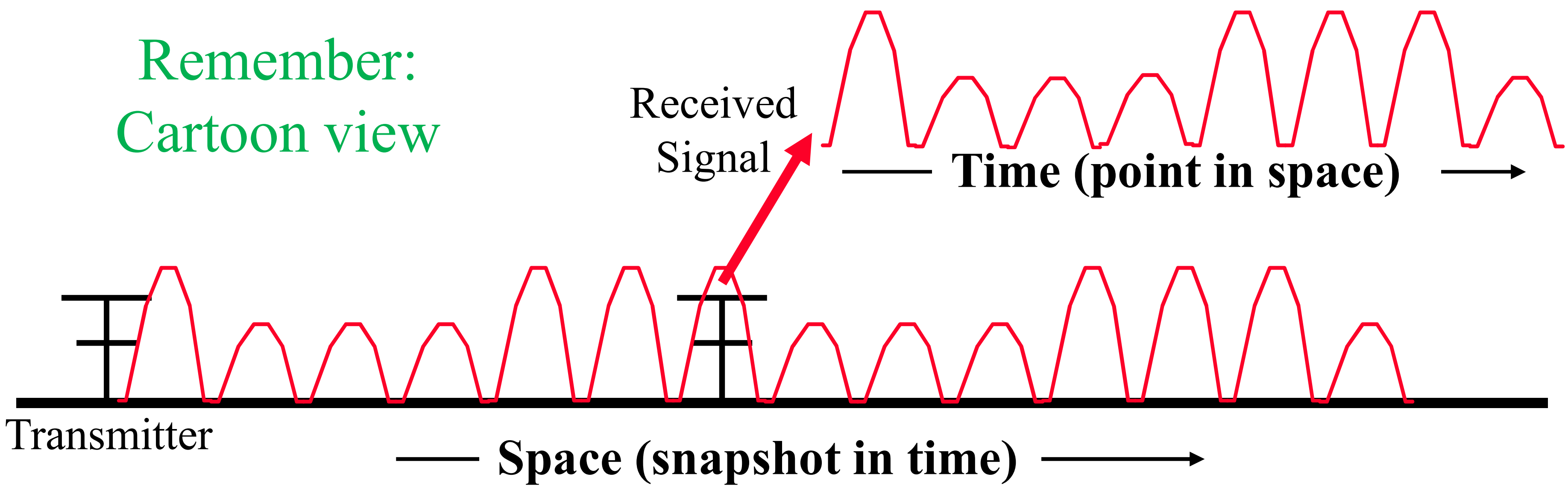
Time and Point View of Signal

- 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?



Communication

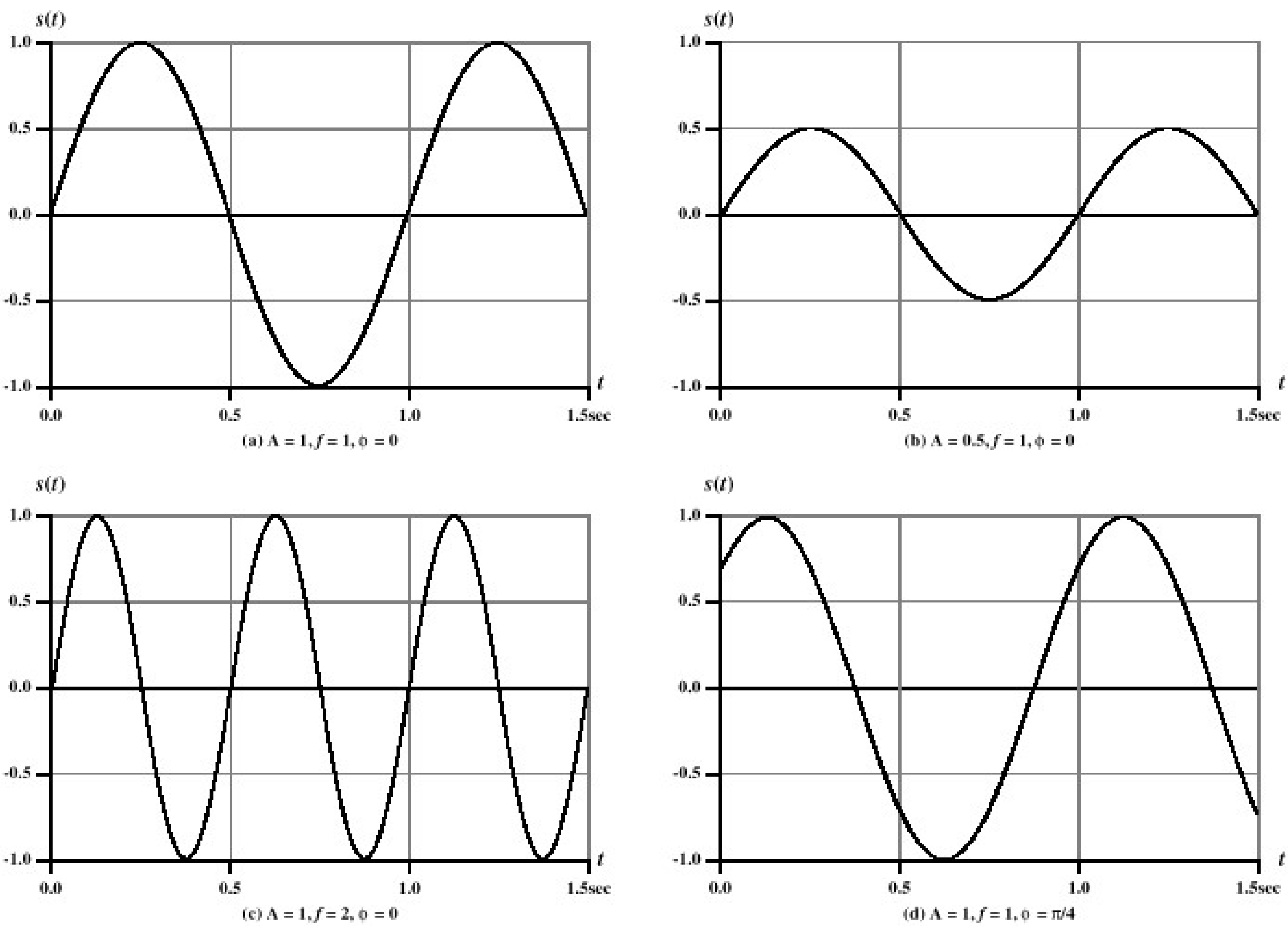


- **Sender changes signal in agree upon way and receiver interprets the changes**
  - » **"Modulation" and "demodulation"**
- **Problem: the signal gets distorted on "channel"**
  - » **Makes it harder for receiver to interpret changes**

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

Space and Time View Revisited



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

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**
  - » **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.”

Cats, Really?

- Key insight: sender "changes signal" (pull tail) and receiver "observes changes" (meows)
- Wireless network designers need to be more precise 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, cost of the radio, 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

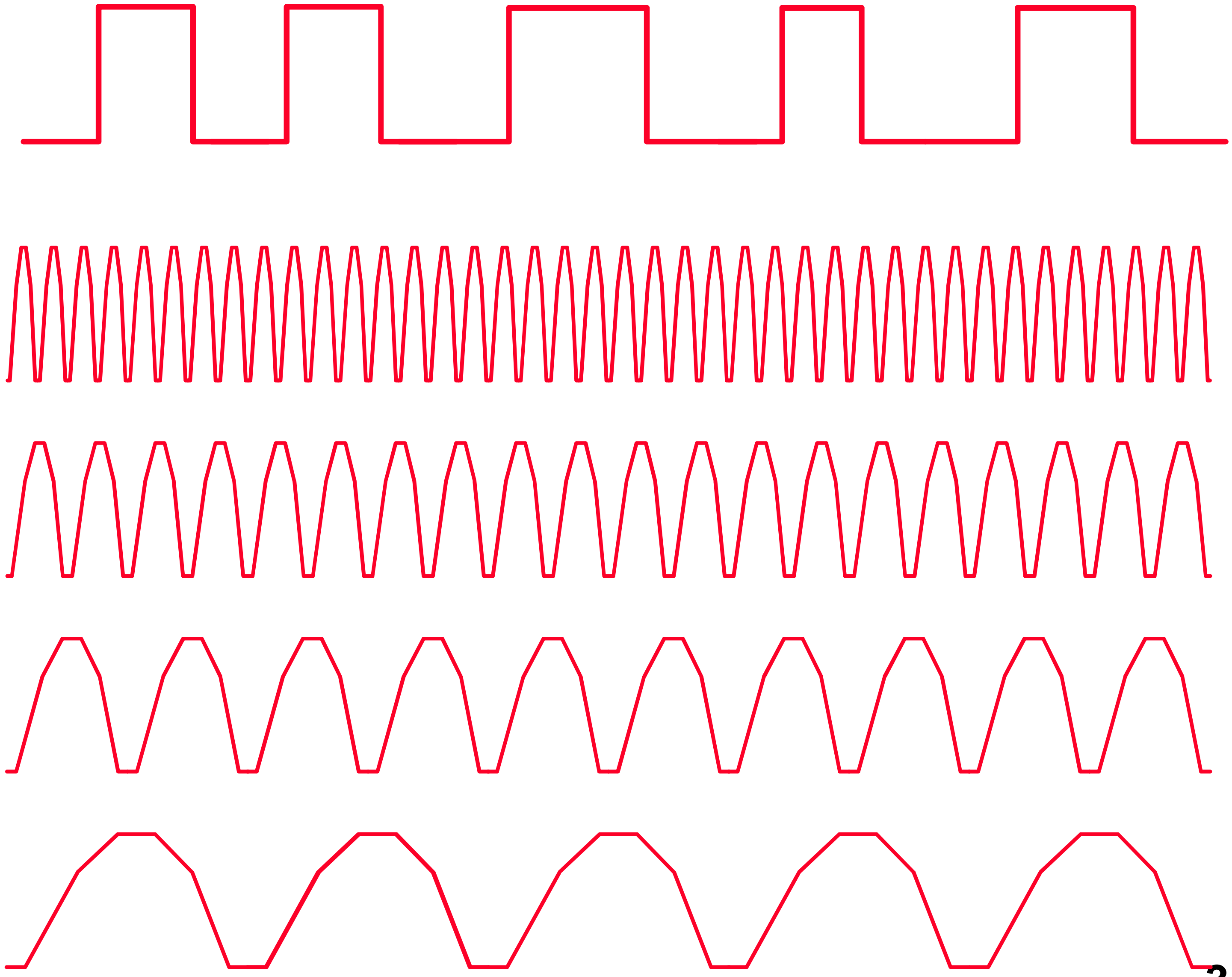
Key Parameters of (Periodic) Signal

- 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

Signal = Sum of Sine Waves



=

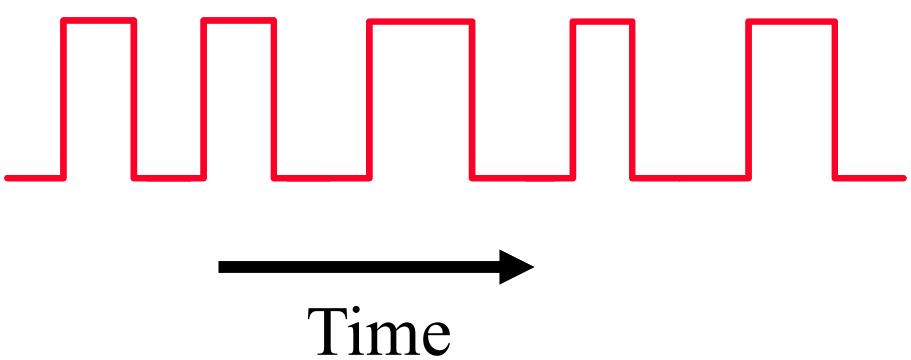
+ 1.3 X

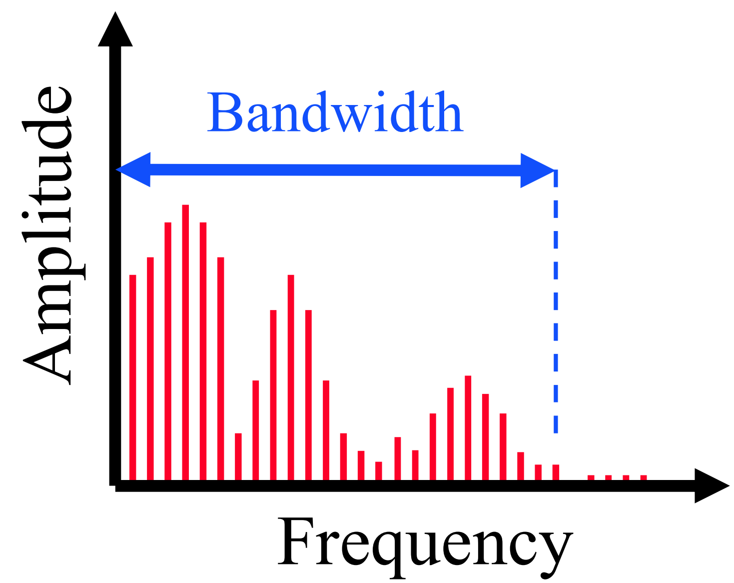
+ 0.56 X

+ 1.15 X

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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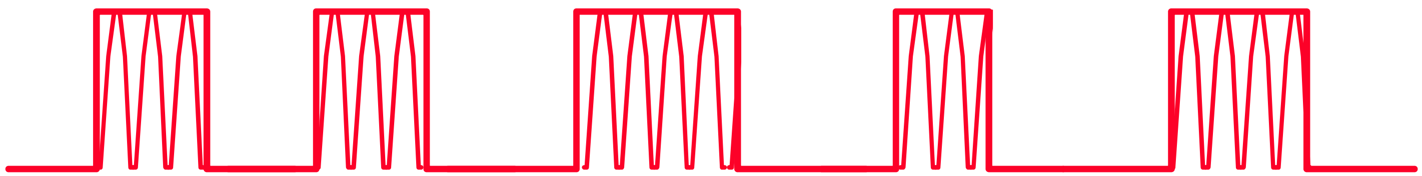
Signal Modulation

- 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 in a later the course

Amplitude and Frequency Modulation



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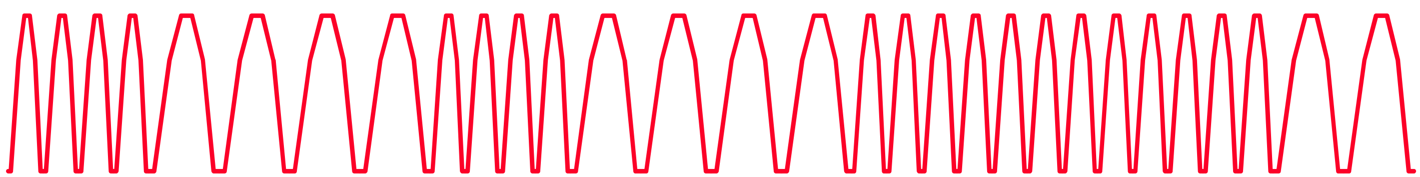
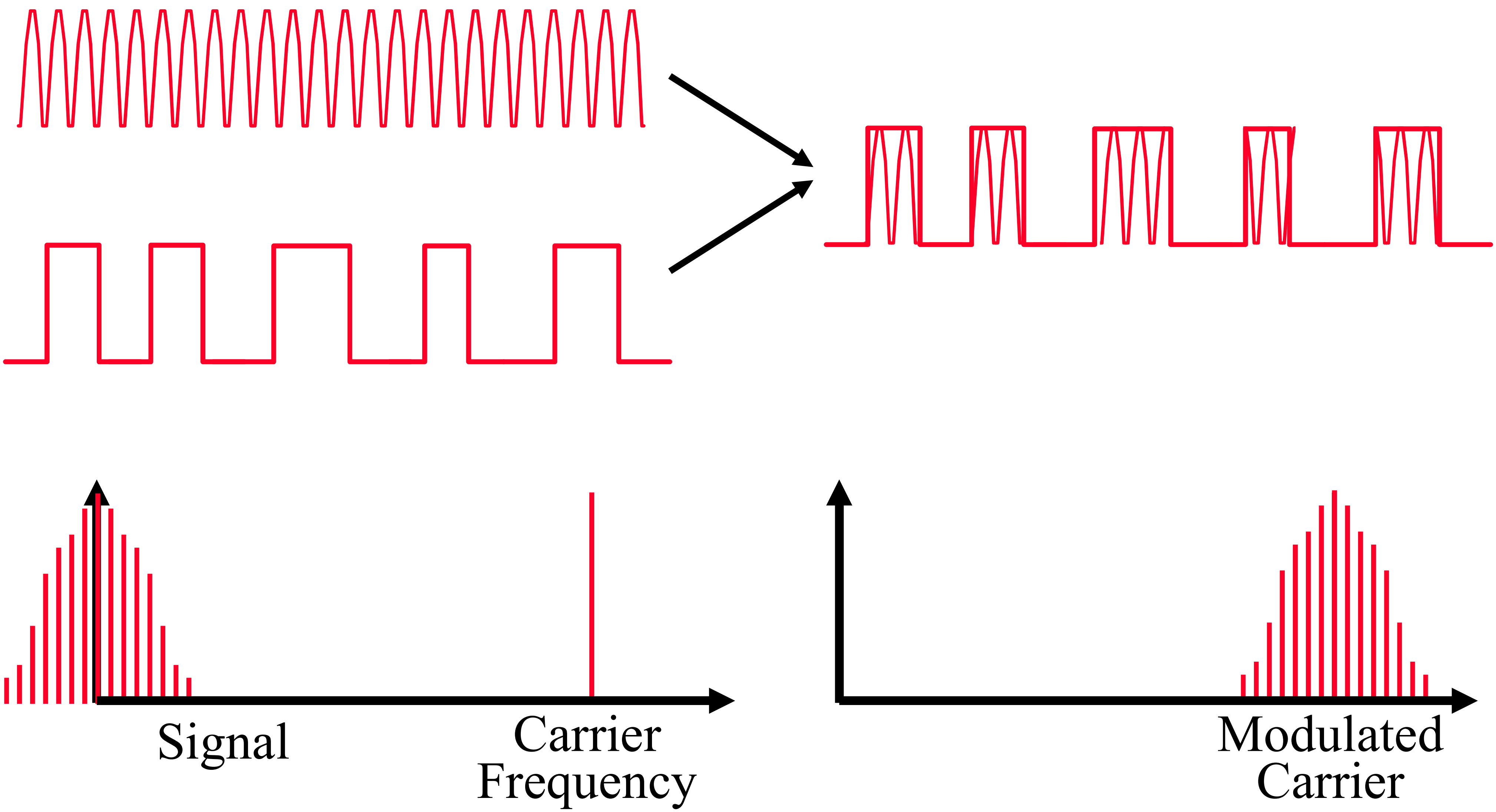


0 1 1 0 1 1 0 0 0 1

Amplitude Carrier Modulation

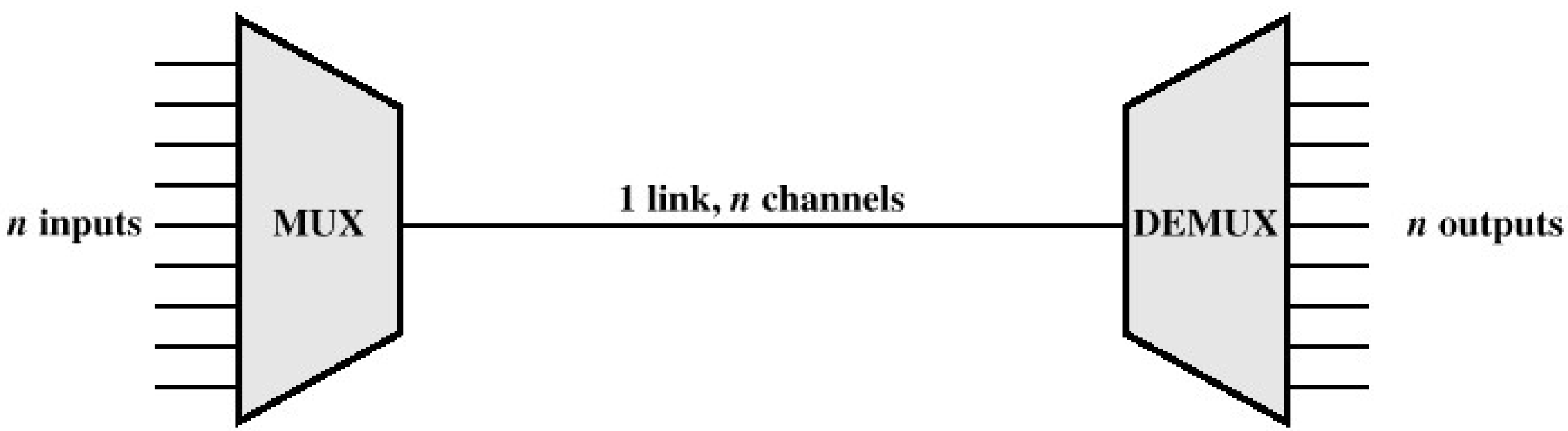


Analog and Digital Signal Modulation

- 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

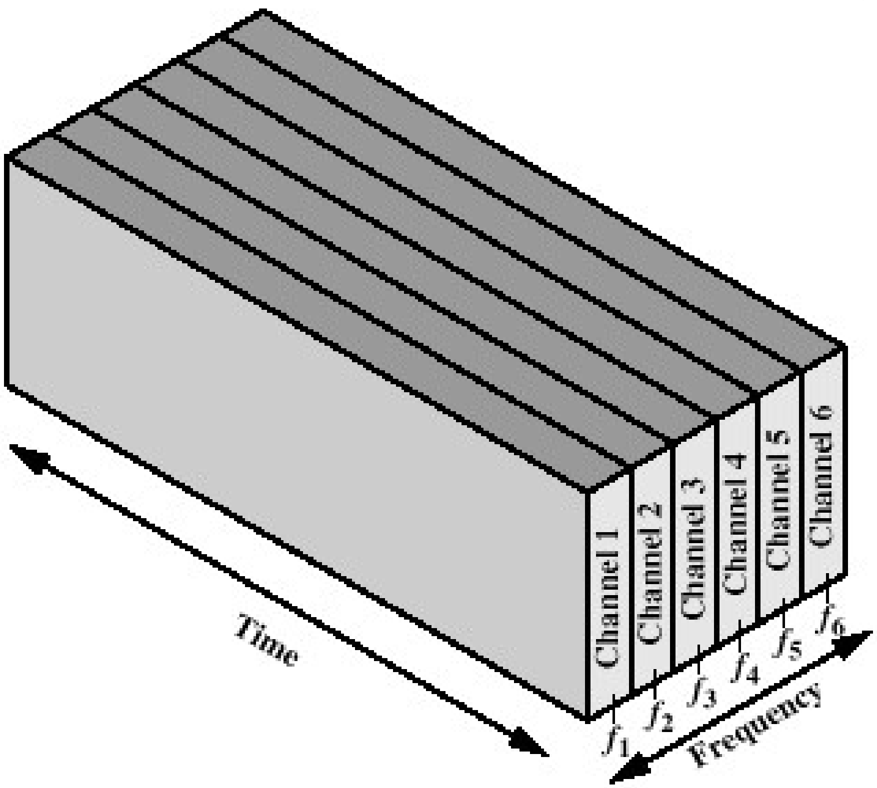
Multiplexing

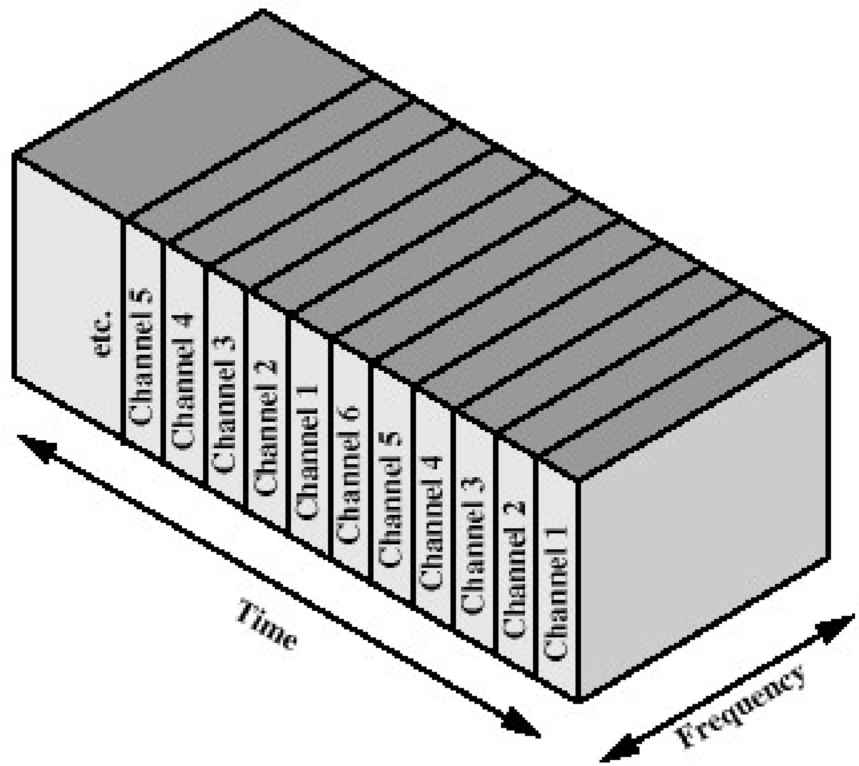
- Capacity of the transmission medium usually exceeds the capacity required for a single signal
- Multiplexing - carrying multiple signals on a single medium
  - » More efficient use of transmission medium
- A must for wireless – spectrum is huge!
  - » Signals must differ in frequency (spectrum), time,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



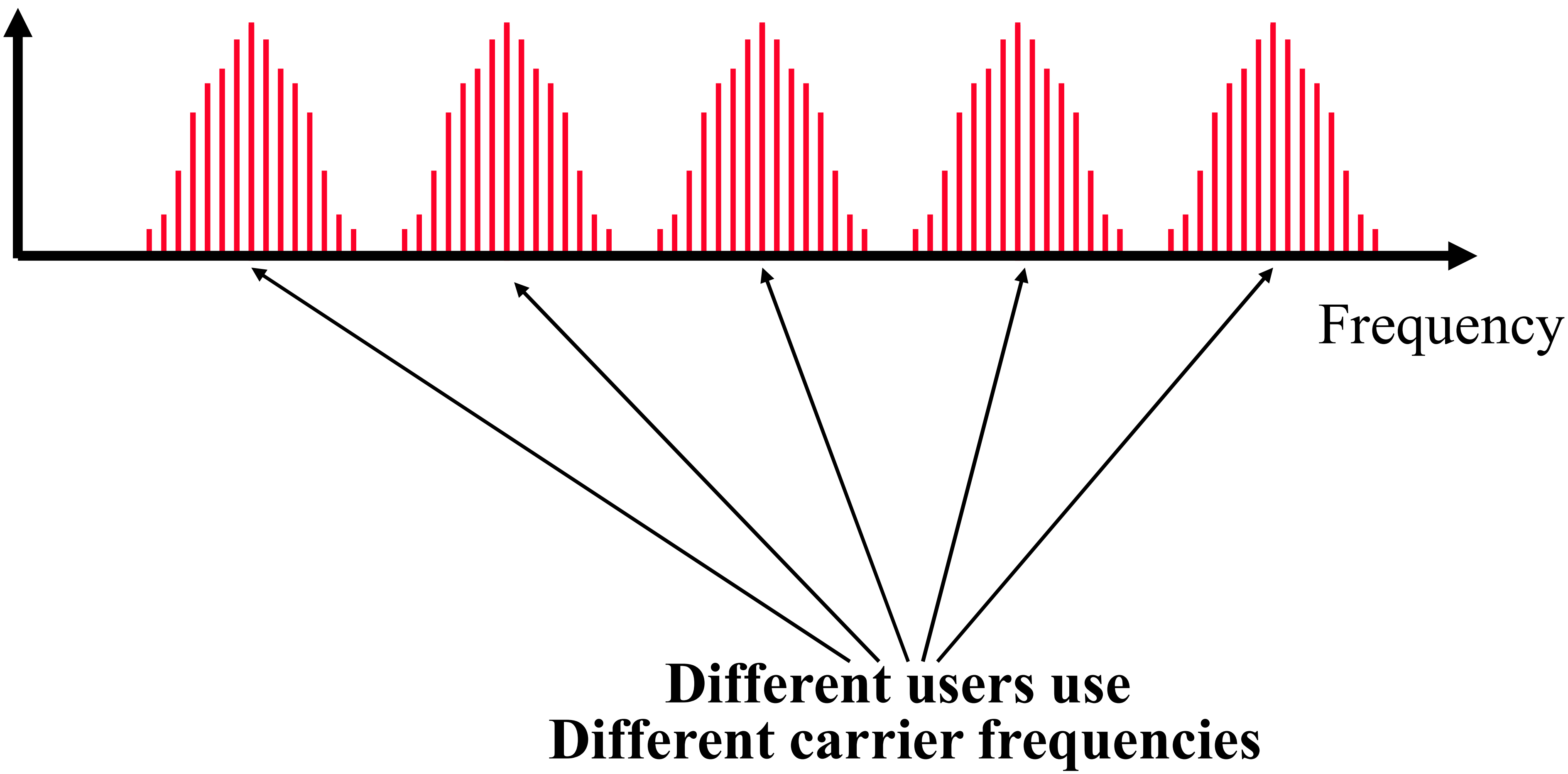
Multiplexing Techniques

- **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**



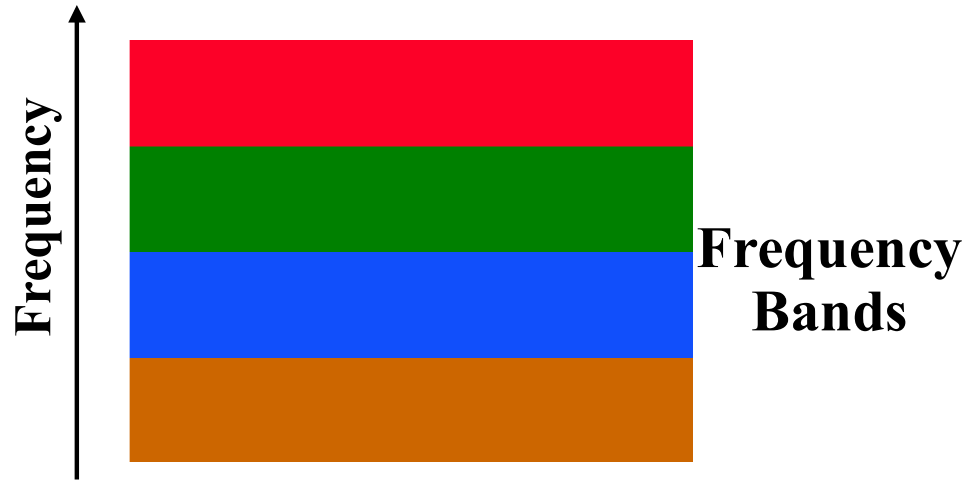


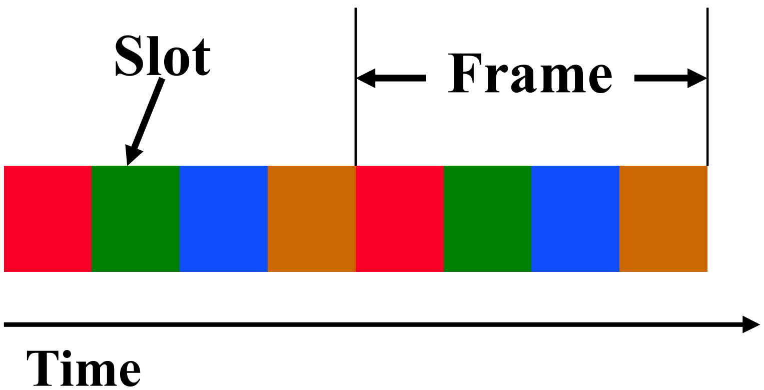
Multiple Users Can Share the Wireless Spectrum using FDM



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, …