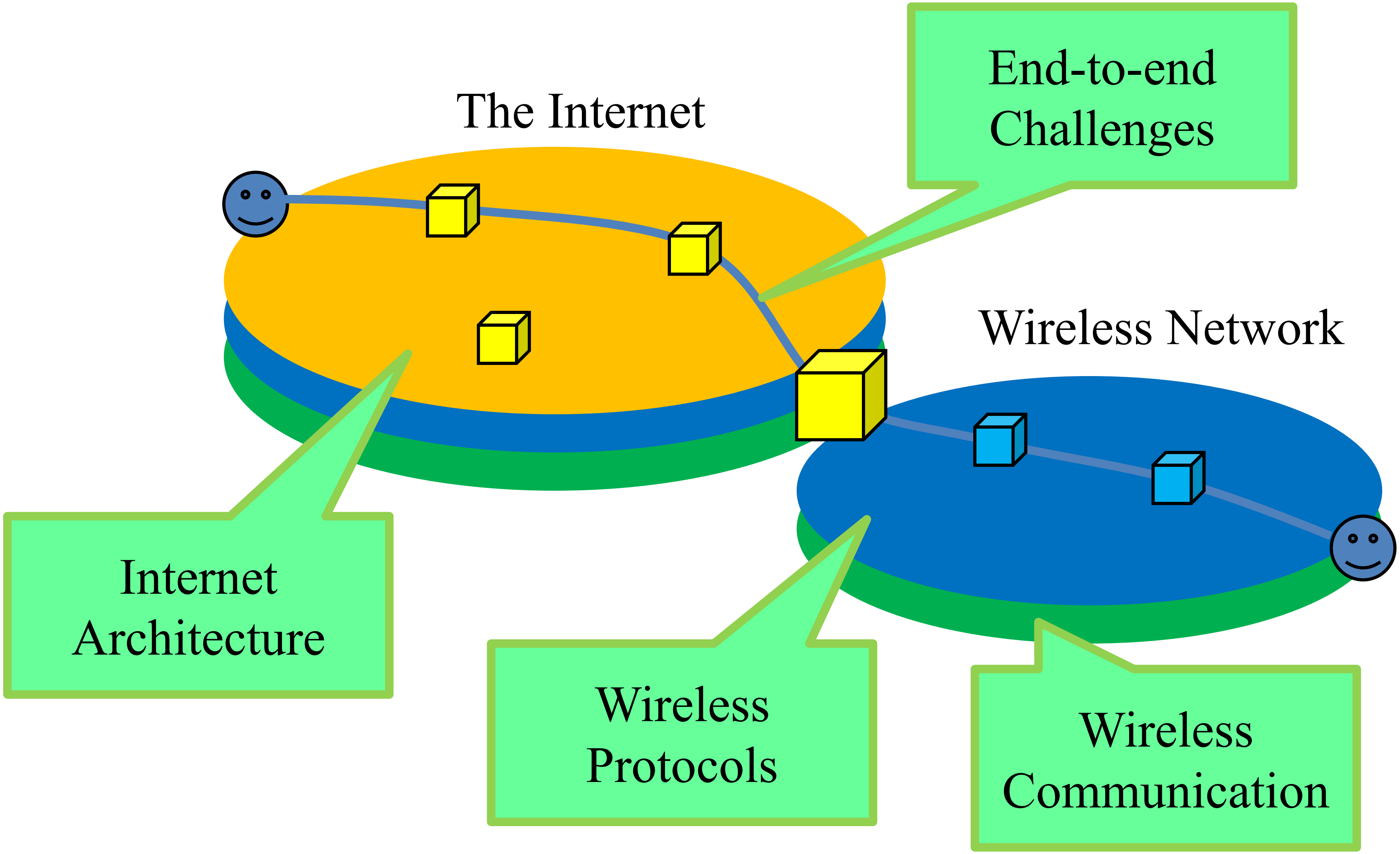
PHY I: Introduction to Radio, Multiplexing

COS 598a: Wireless Networking and Sensing Systems

Kyle Jamieson

[Adapted from P. Steenkiste; parts adapted from D. Tse]

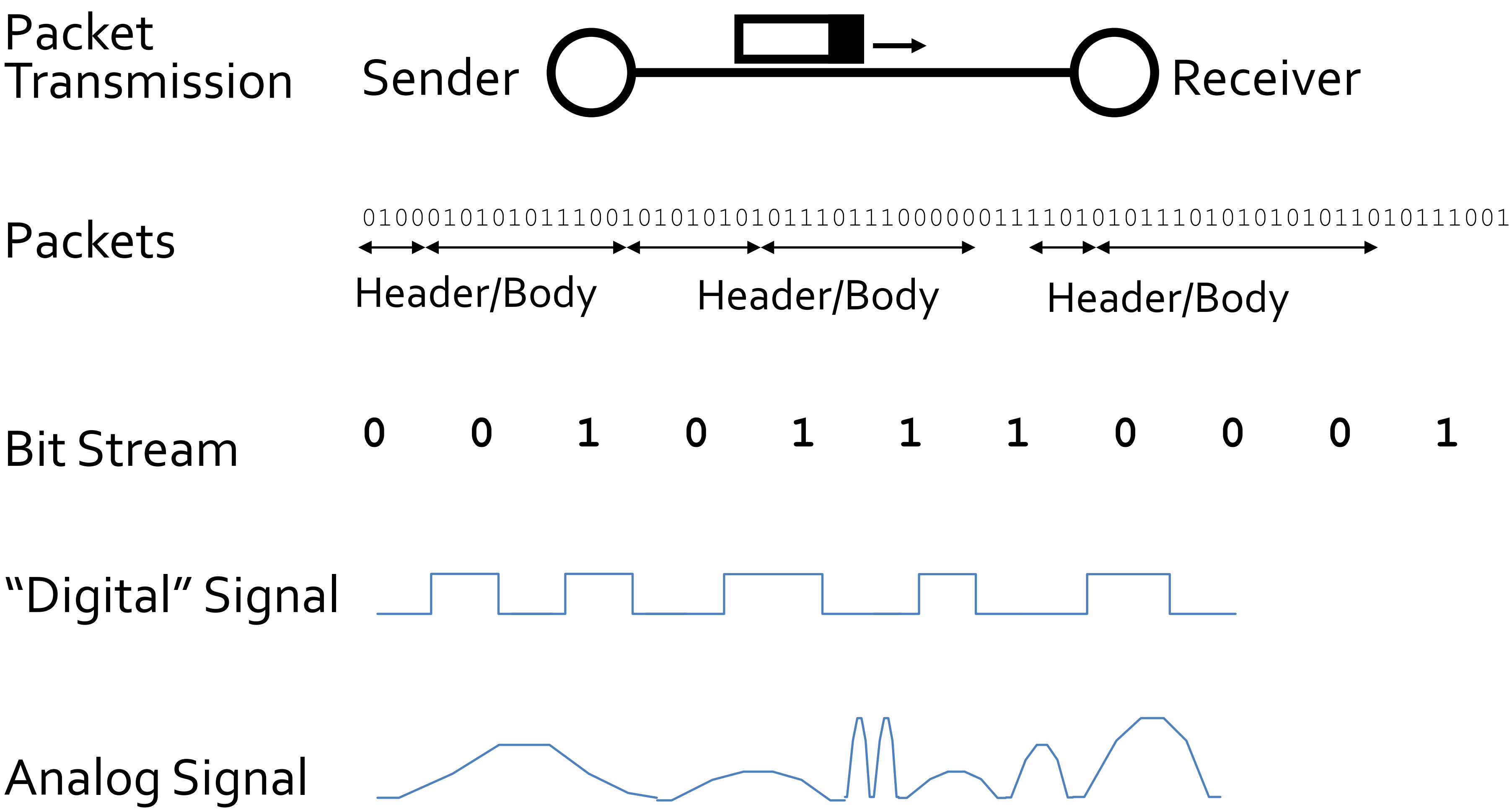
A bird's-eye view



Today

- **RF introduction**
  - Two "cartoon" views
  - Time versus frequency view
- Modulation
- Multiplexing
- Channel capacity

From Signals to Packets

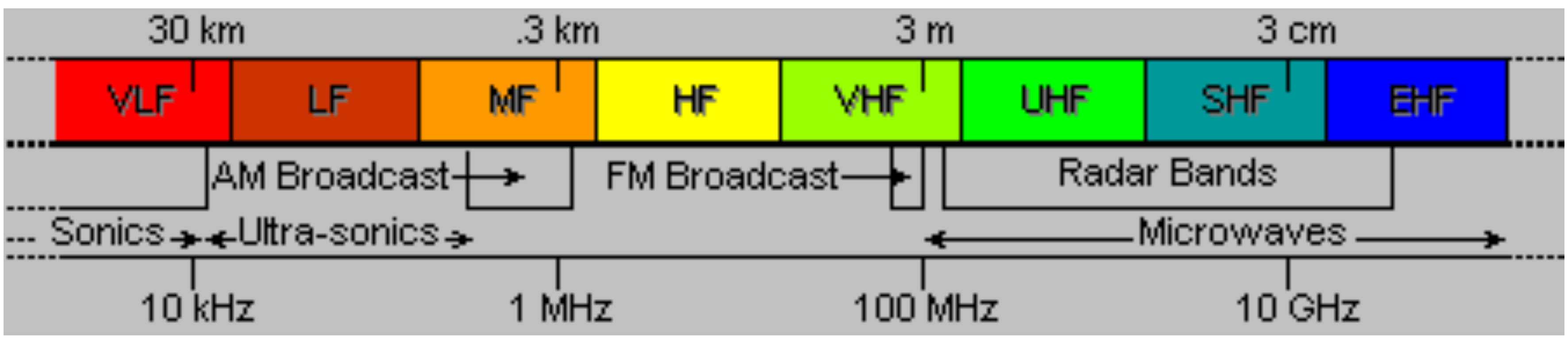


Radio Frequency (RF)

- Electromagnetic signal that propagates through space
  - Transmitted at some **carrier frequency** f_c
  - Travels at the **speed of light** (c)

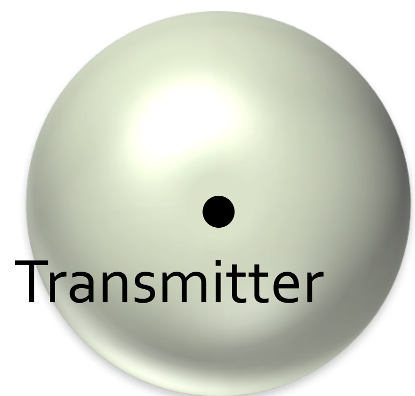
- **Wavelength** in air: $\lambda = c/f_c$

- f_c range: 3 KHz to 300+ GHz (or, λ = 100 km to 1 mm)



Cartoon View 1 – Energy Wave

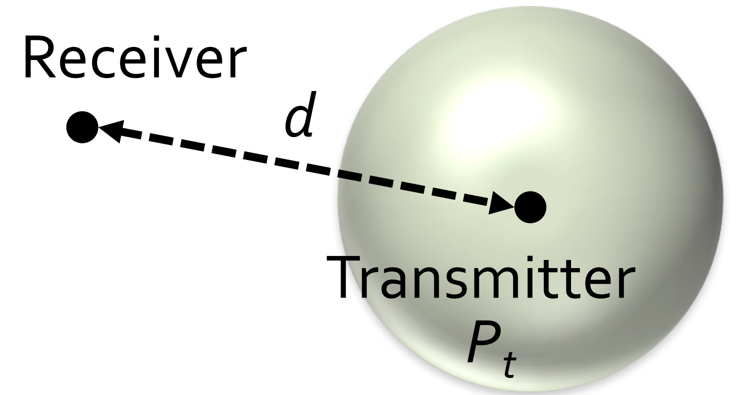
- Think of it as energy that radiates from an antenna and is picked up by another antenna
  - Helps explain properties such as attenuation
  - Density of the energy reduces over time and with distance
- **Assumption:** Propagation in **free space**



- Useful when studying attenuation
  - Receiving antennas catch less energy with distance

Friis free space propagation model

- Transmitter and receiver have unobstructed line-of-sight path

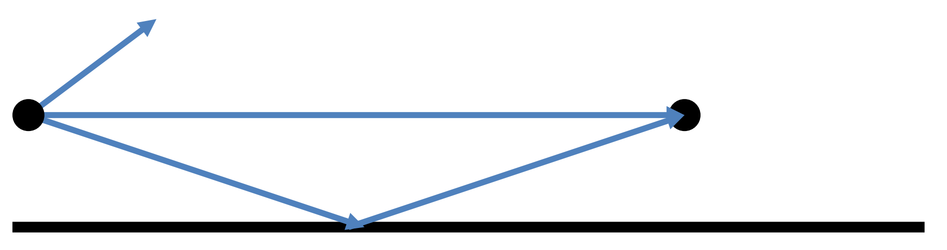


- Predicts **received signal power** P_r
- **Friis equation:** $P_r \propto \frac{P_t \lambda^2}{(4\pi d)^2}$
- Observe:
  1. Received power falls off with square of distance d^2
  2. Received power falls off with square of carrier frequency f_c^2

Cartoon View 2 – Rays of Energy

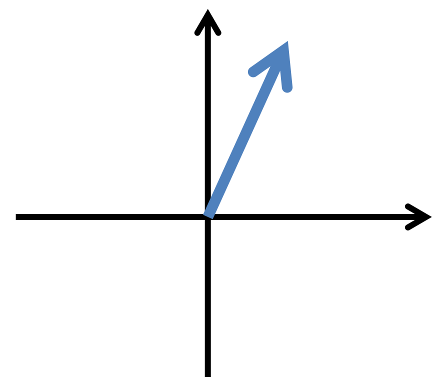
- Can also view it as a "ray" that propagates between two points
  - Rays can be reflected *et c.*
    - Can provide connectivity without line of sight
  - Called ***ray-tracing*** models

- Channel can also include multiple "rays" that take different paths
  - Helps explain properties such as multipath propagation

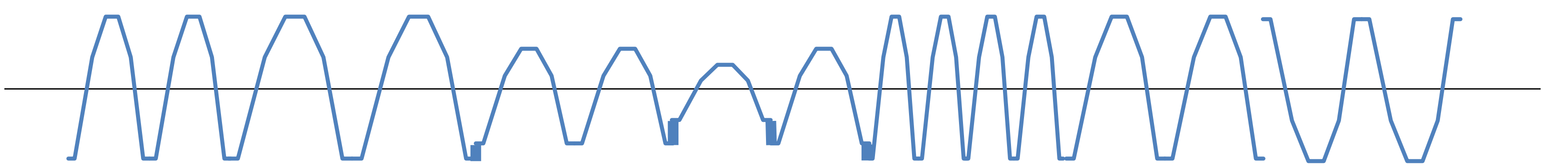


(Not so) Cartoon View 3 – Electro-magnetic Signal

- Signal that propagates and has an amplitude and phase
  - Can be represented as a complex number
- … and that changes over time
  - Loosely represented as a frequency
- Simple example is a sine wave (***sinusoidal carrier signal***)
  - Can change amplitude, phase and frequency

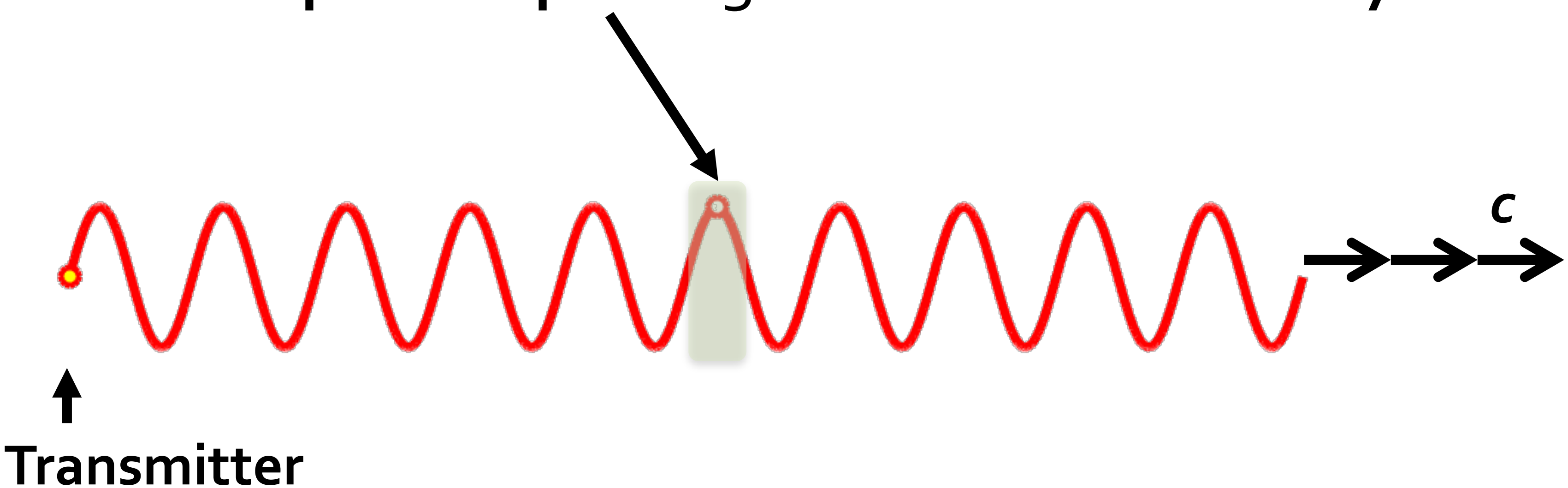


- What is the relevance to networking?



Simple Example: Sinusoidal carrier signal

- RF signal propagates away from transmitter at light-speed (*c*)
- Take a **snapshot in time:** signal "looks" sinusoidal **in space**
- Look at **a point in space**: signal **oscillates sinusoidally in time**



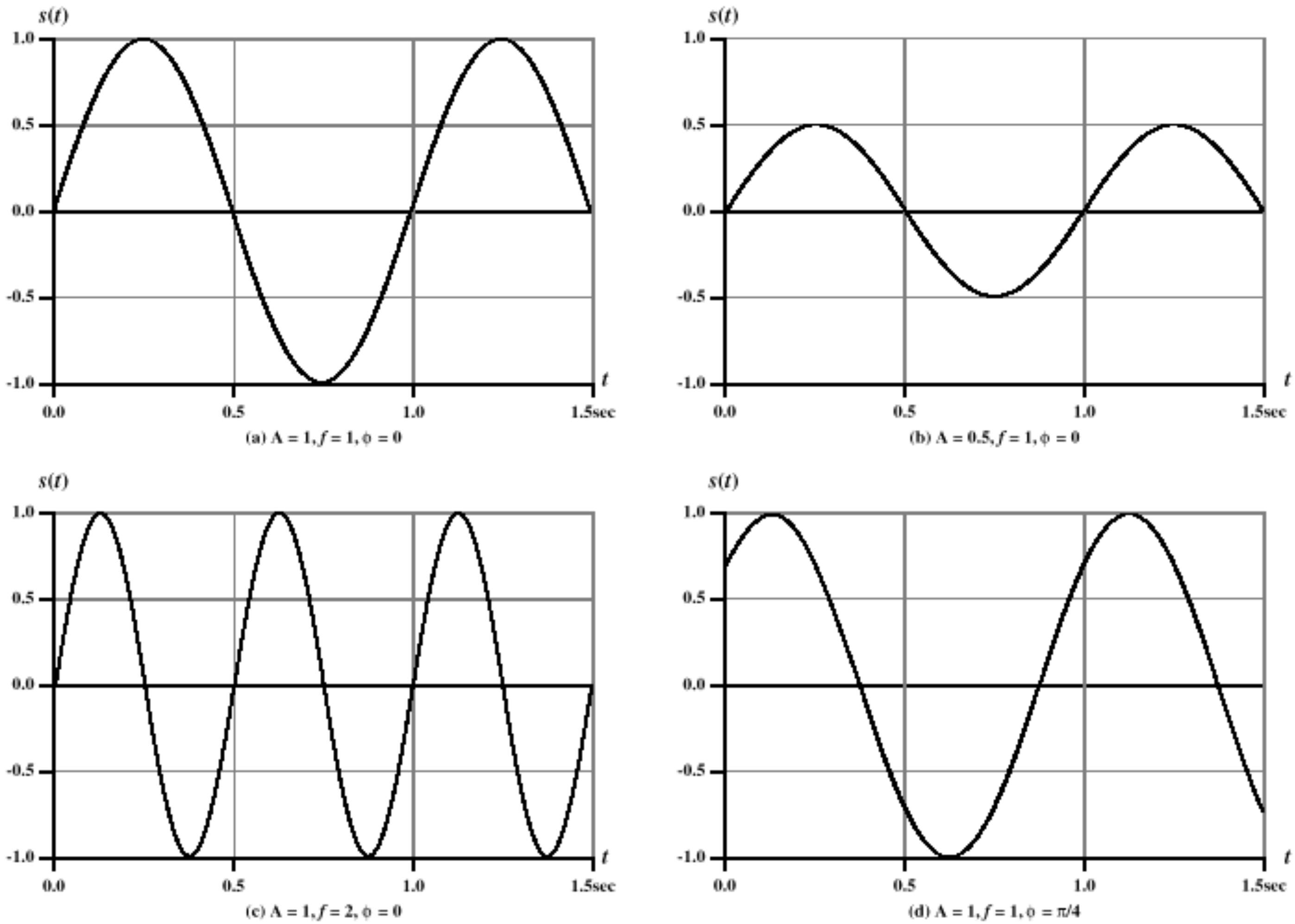
Carrier signal parameters

- 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)

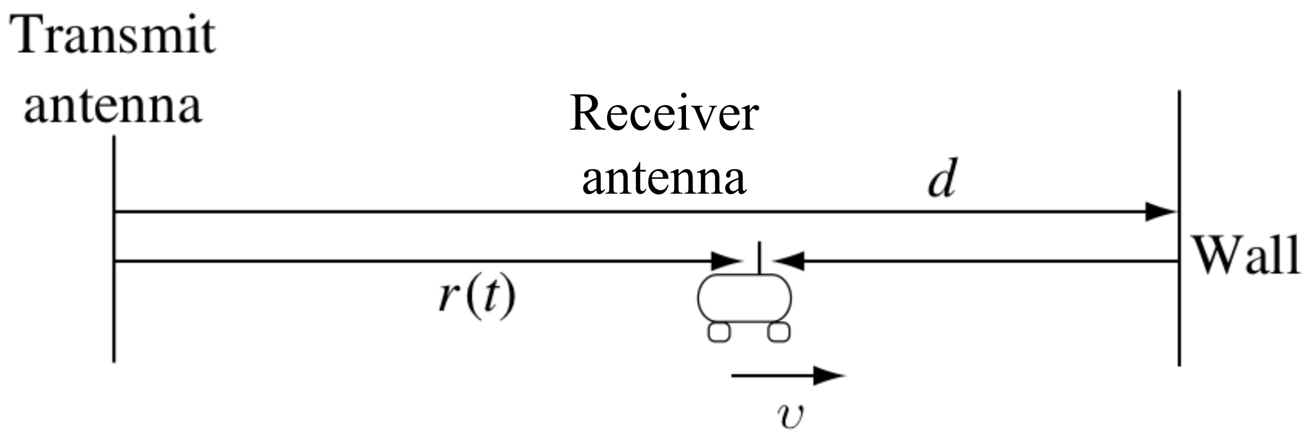
- note: 2π radians = 360 degrees = 1 period

Space and Time View Revisited



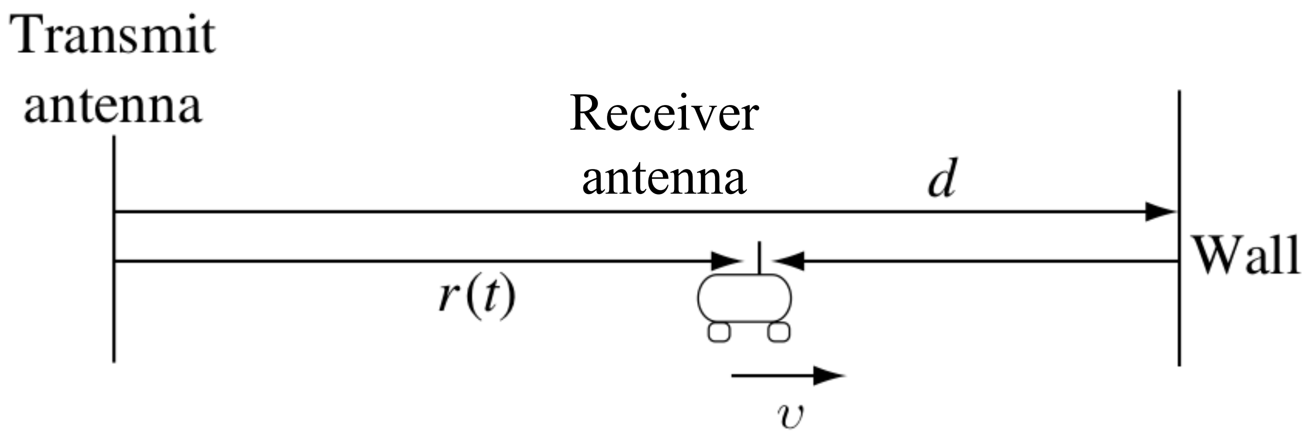
$$s(t) = A \sin(2\ ft + \phi)$$

Combining ray tracing with carrier signal



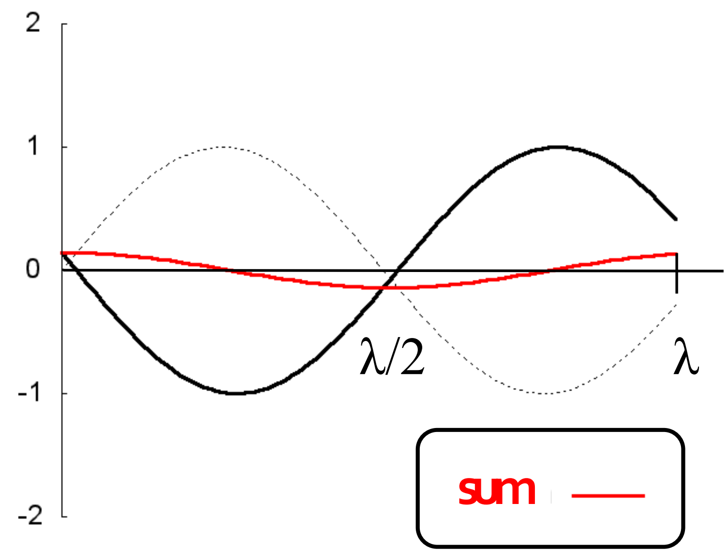
- Suppose reflecting wall, fixed transmit antenna, no other objects
- **Two arriving signals** at receiver antenna
  - Consider the **phase difference** between the two

Combining ray tracing with carrier signal



- Phase difference between two:
$$\Delta\theta = \frac{4\pi f}{c}(d - r) + \pi$$

- As cart moves, they **add together, then cancel** each other



Time Domain View: Periodic versus Aperiodic Signals

- ***Periodic signal:*** analog or digital signal 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 Signals

- Peak amplitude (*A*): Maximum value of signal over time
- Period (*T*) - amount of time it takes for one repetition of the signal
- Frequency ($f = 1/T$): Rate (***Hertz***) at which signal repeats
- Phase (ϕ): Measure of the relative position in time within a single period of a signal

Key Property of Periodic EM Signals

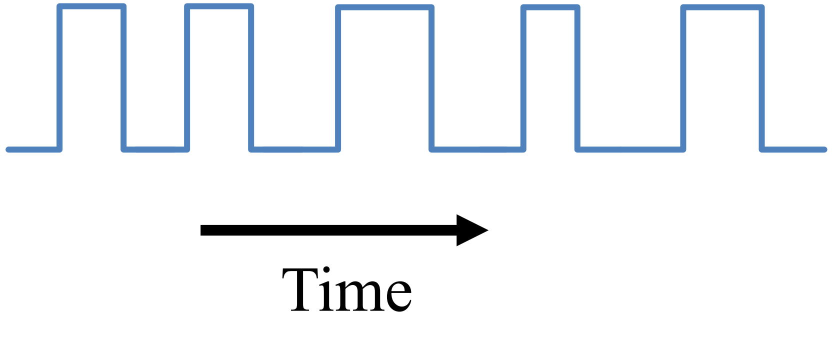
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases

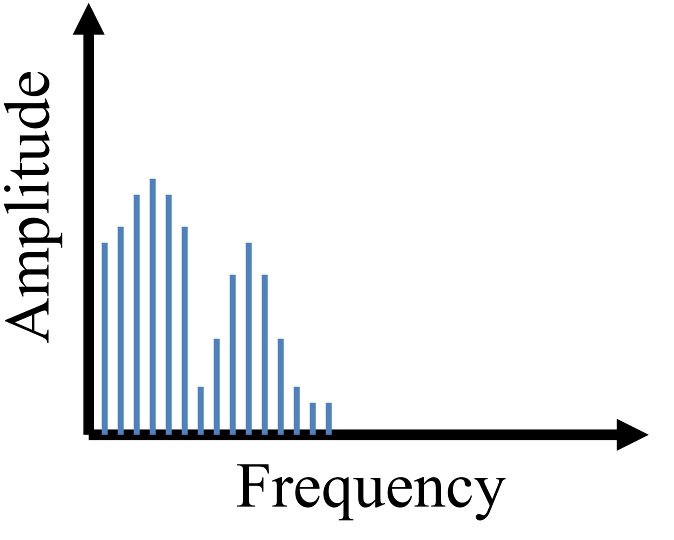
- The period of the total signal is equal to the period of the fundamental frequency
  - All other frequencies are an integer multiple of the fundamental frequency

- Strong relationship between the "shape" of the signal in the time and frequency domain
  - Discussed in more detail later

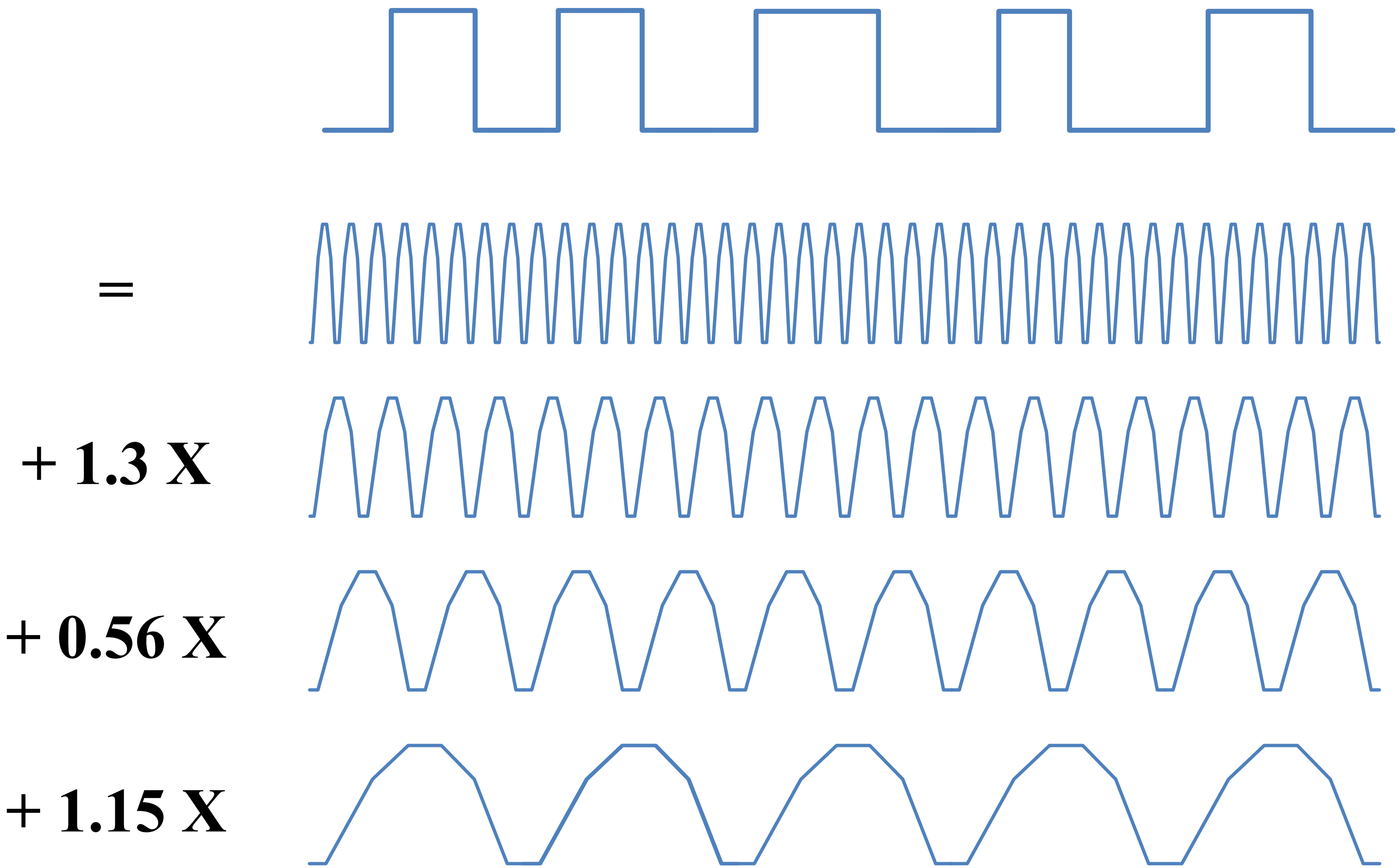
The Frequency Domain

- 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)
- Again: Similar to radio and TV signals.





Signal = Sum of Sine Waves



Frequency-Domain Concepts

- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

Today

- RF introduction

- **Modulation**
  - Analog versus digital signals
  - Forms of modulation
  - Baseband versus carrier modulation

- Multiplexing

- Channel capacity

Key Idea of Wireless Communication

- Sender transmits a radio signal, changes its properties over time
  - Changes reflect **another digital signal**, e.g., binary or multi-valued signal
    - Amplitude, phase, frequency

- Receiver learns the **digital signal** by observing how the received signal changes
  - *n.b.*, radio signal is no longer a simple sine, or even periodic

> *"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."*

Analog and digital signals

- Sender **changes carrier** in a way the receiver can recognize

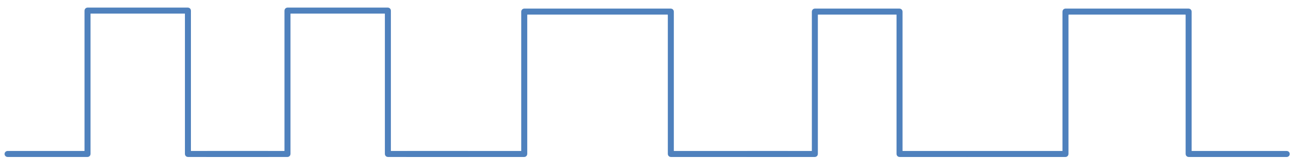
- **Analog:** A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
  - Wired: Twisted pair, coaxial cable, fiber
  - Wireless: Atmosphere or space propagation
  - Cannot recover from distortions, noise

- **Digital:** Discrete **changes** in RF signal corr. to digital signal
  - Less susceptible to noise but can suffer, e.g., attenuation
  - Can regenerate signal along the path (repeater versus amplifier)

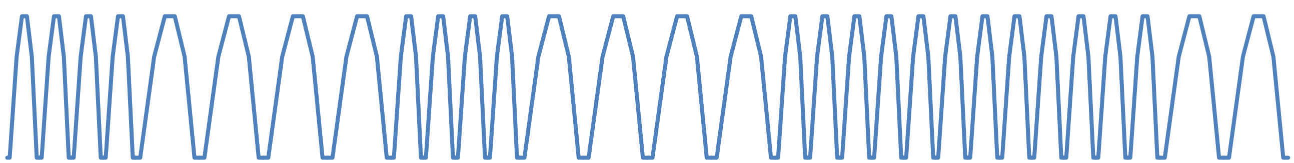
Digital Signal Modulation

- **Amplitude modulation (AM):** change the strength of the carrier signal based on information
- **Frequency (FM), Phase modulation (PM):** change the frequency or phase of the signal
- Digital versions are sometimes called "shift keying"
  - Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying
- Discussed later in more detail

Amplitude and Frequency Modulation



0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 1 1 0 0 0 1 1 1 0

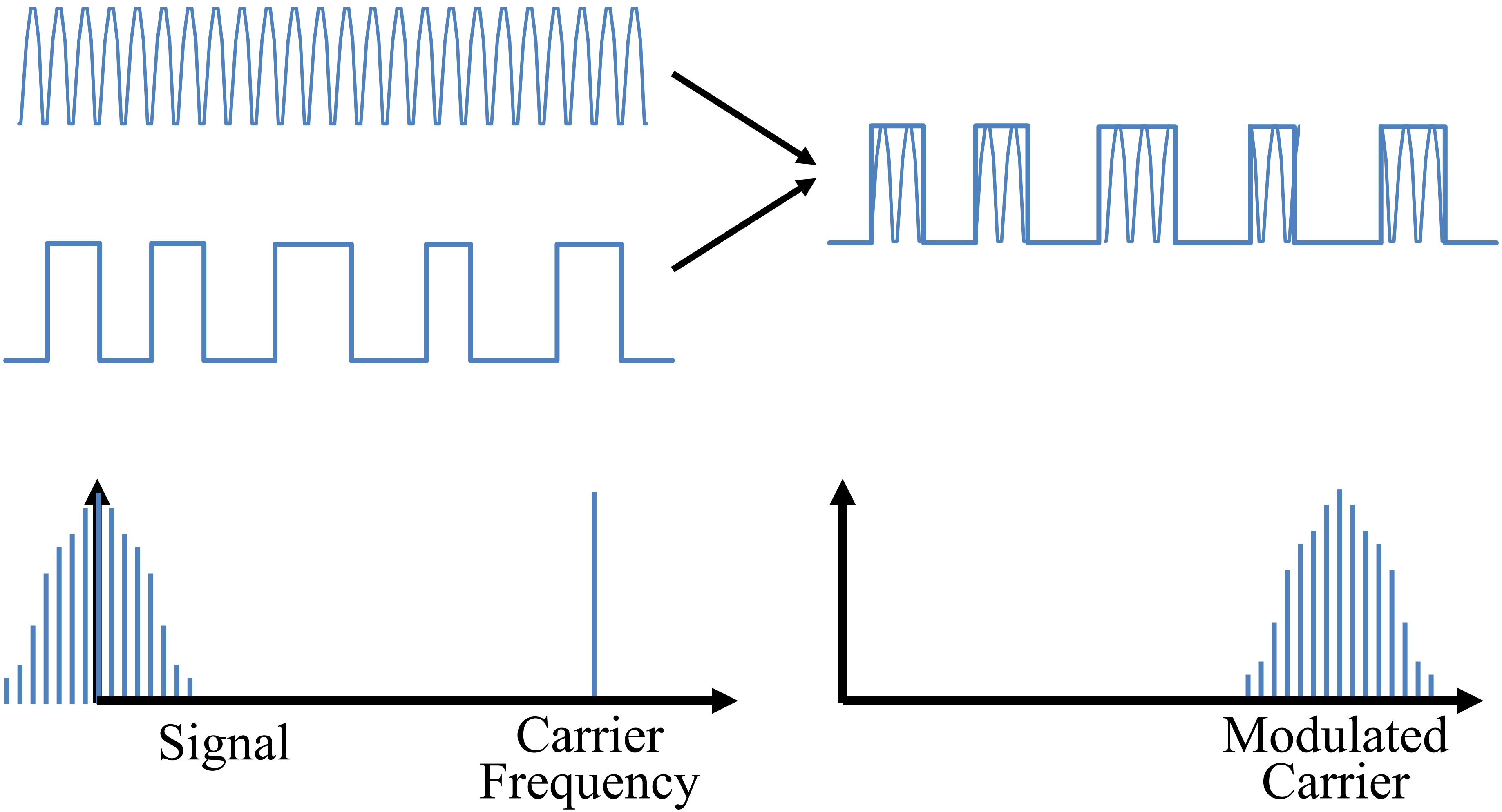


0 1 1 0 1 1 0 0 0 1

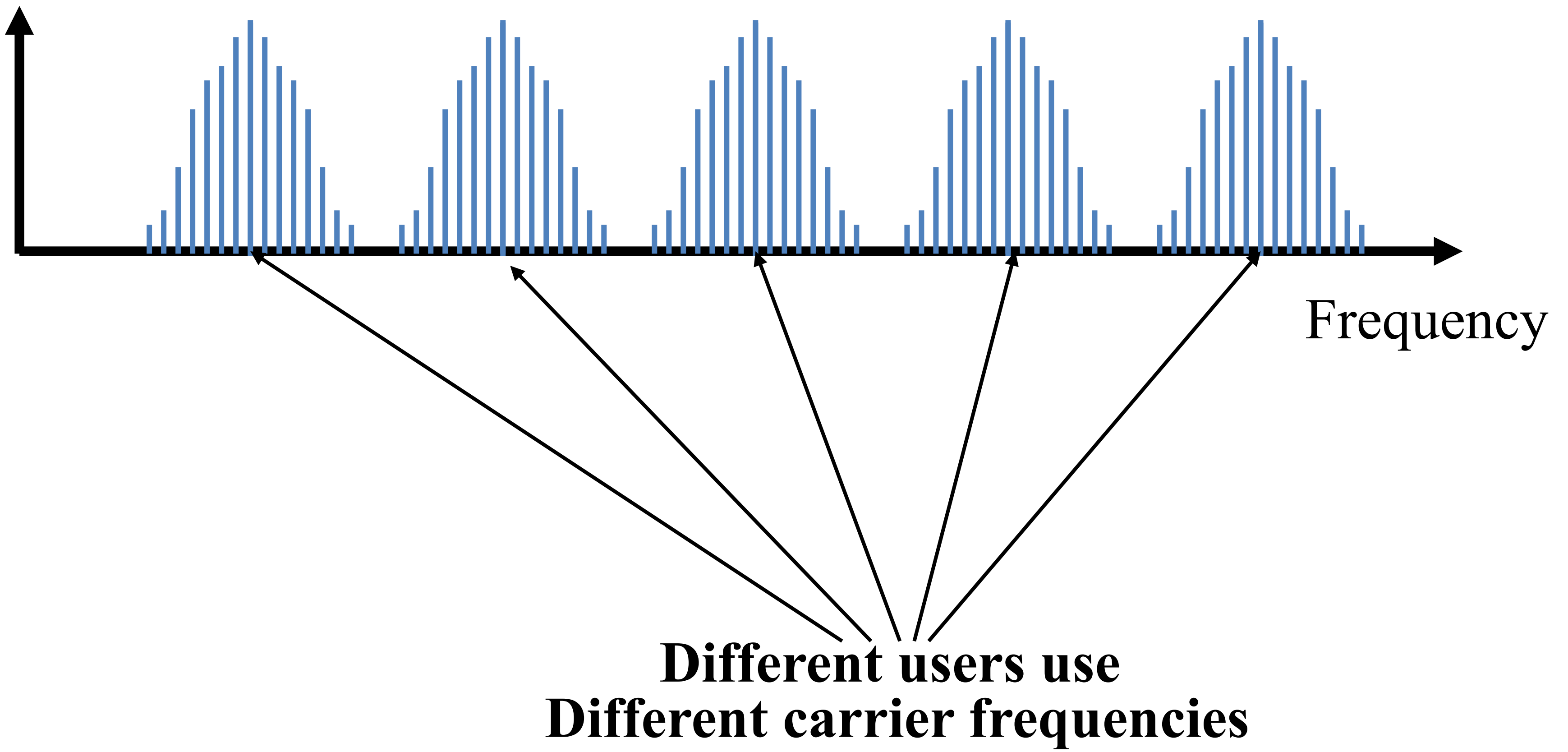
Baseband versus Carrier Modulation

- **Baseband modulation:** Send the "bare" signal
  - Use the lower part of the spectrum
- Baseband modulation has limited use
  - Everybody competes – only makes sense for point-to-point links, but unattractive for wireless
  - Use of higher frequencies requires transmission of a single high bandwidth signal
  - Some media only transmit higher frequencies, e.g. optical
- **Carrier modulation:** use the (information) signal to modulate a higher frequency (carrier) signal
  - Can be viewed as the product of the two signals
  - Corresponds to a shift in the frequency domain

Amplitude Carrier Modulation



Multiple Users Can Share the Ether

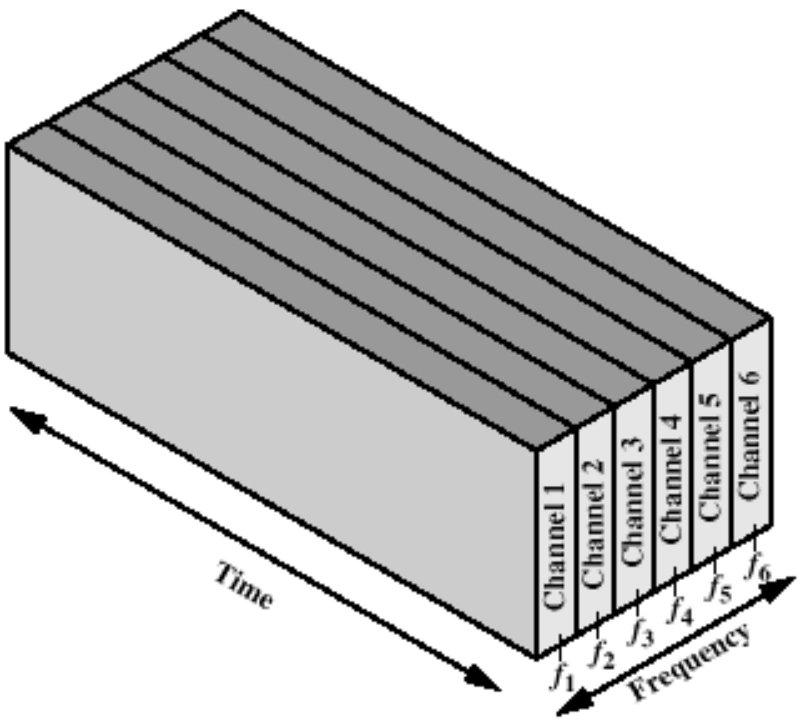


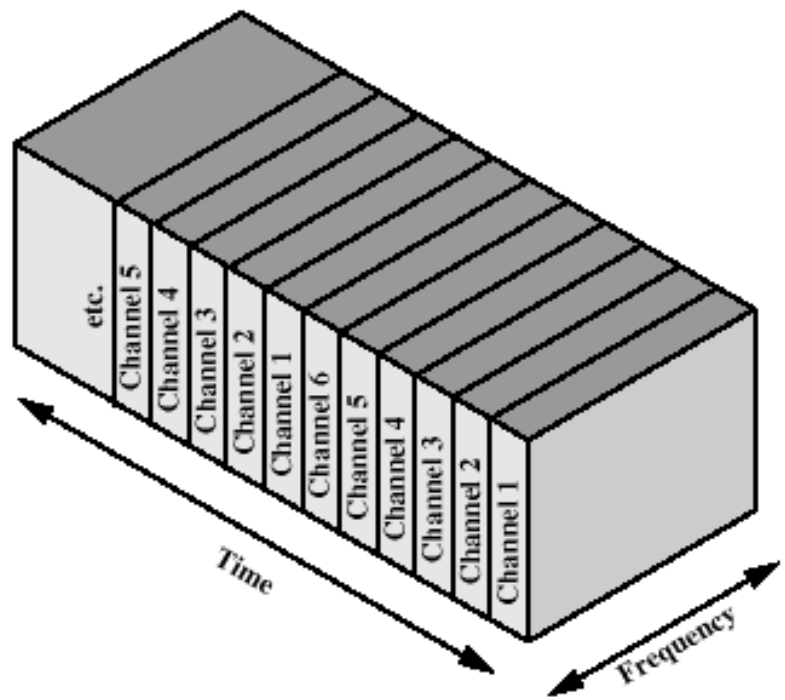
Multiplexing

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal
- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium

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

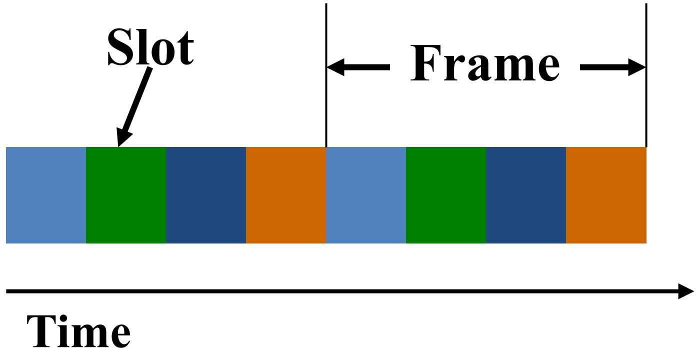




Frequency- versus time-division multiplexing

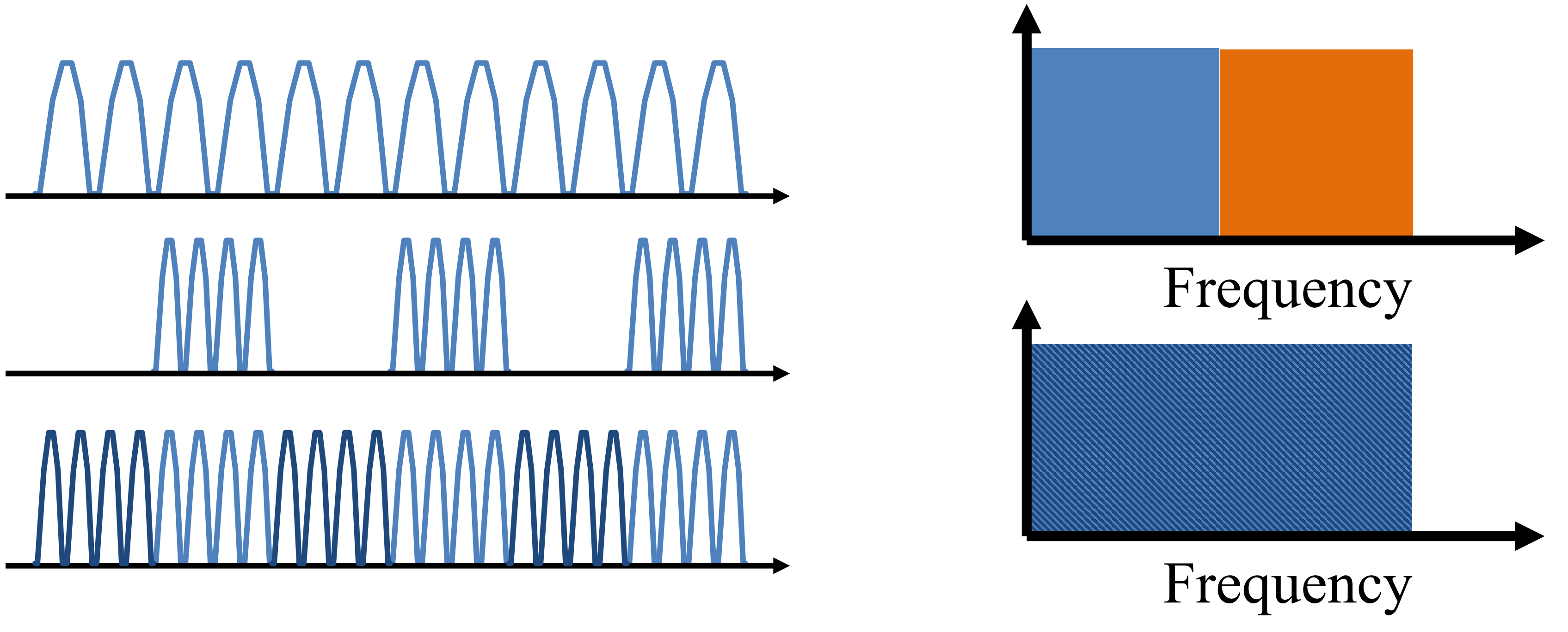
- FDM: Different users use different frequency bands
  - *i.e.* each user can send all the time at reduced rate
  - Hardware is slightly more expensive, less efficient use of spectrum

- TDM: Different users send at different times
  - *i.e.* each user can sent at full speed some of the time
  - Drawback is that there is some **transition time between slots;** becomes more of an issue with longer propagation times



Use of Spectrum

- Different users use the wire at different points in time.
- Aggregate bandwidth also requires more spectrum.



FDM Example: AMPS

- US analog cellular system in early 80s
- Each call uses an up and down link channel
  - Channels are 30 KHz
- About 12.5 + 12.5 MHz available for up and down link channels per operator
  - Supports 416 channels in each direction
  - 21 of the channels are used for data/control
  - Total capacity (across operators) is double of this

TDM Example:
Global System for Mobile communication (GSM)

- First introduced in Europe in early 90s; uses TDM and FDM

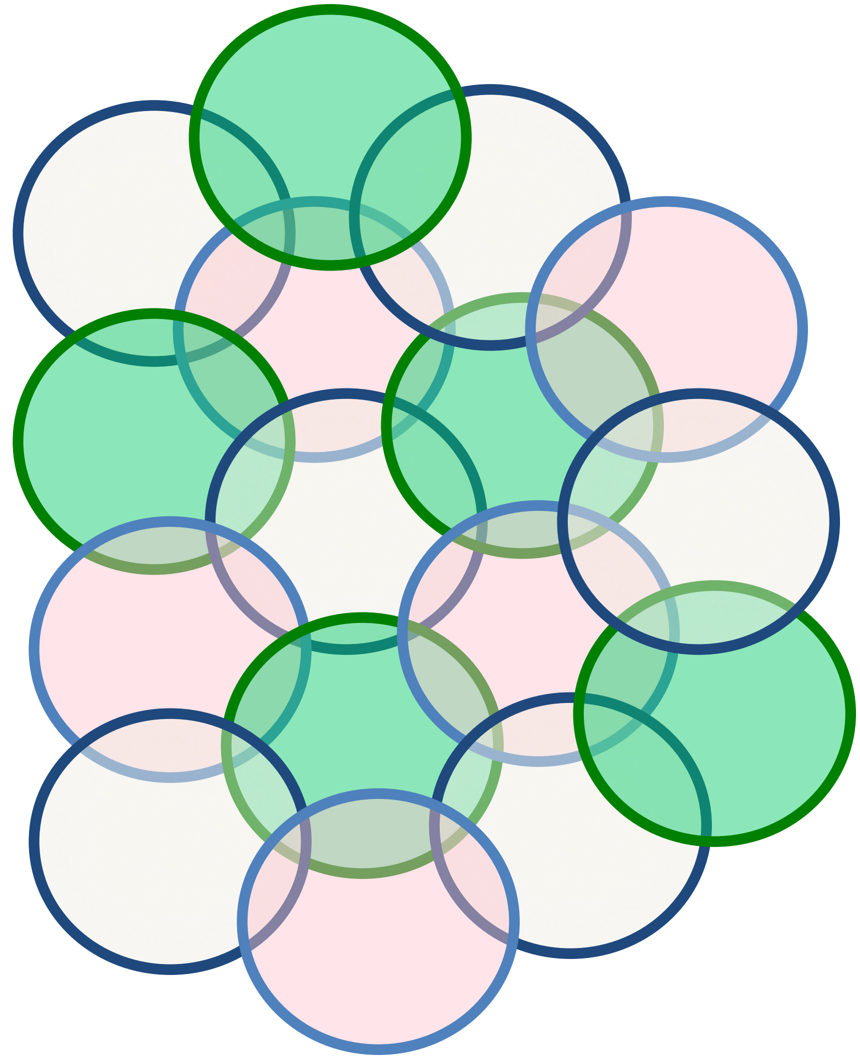
- 25 MHz each for up and down links
  - Frequency-divided into 200 KHz ***channels***
    - 125 channels in each direction
      - Each channel can carry about 270 Kbit/s

- Each channel is time-divided into eight 0.577 ms **time slots**
  - Results in 1000 channels, each with about 25 Kbit/s of useful data; can be used for voice, data, control

- *General Packet Radio Service:* Data service for GSM

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, …



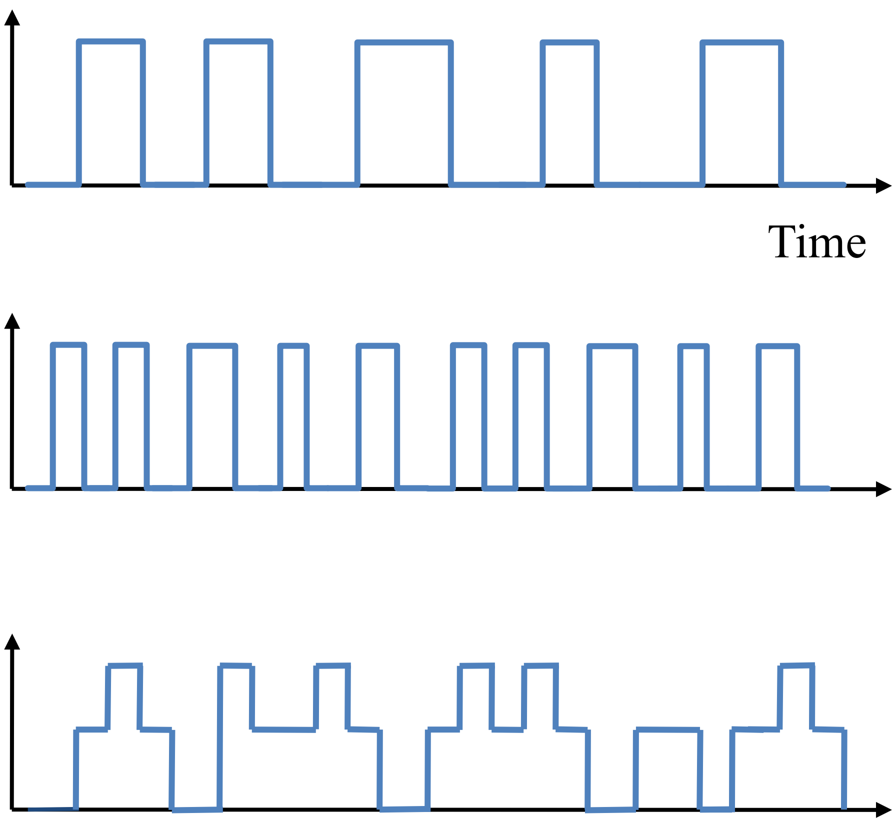
Today

- RF introduction
- Modulation
- Multiplexing
- **Channel capacity**

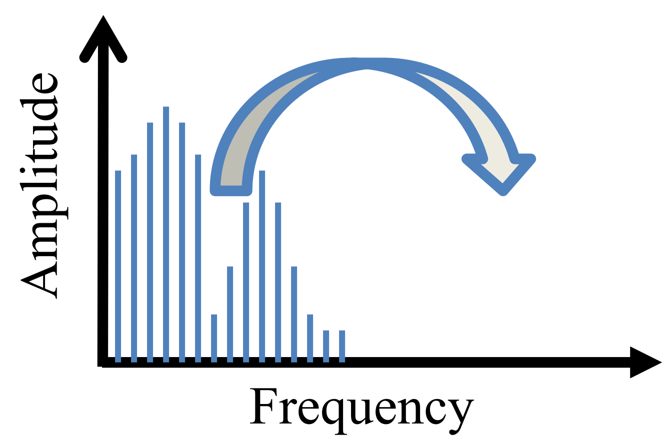
How is data rate related to bandwidth?

- 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, hence 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

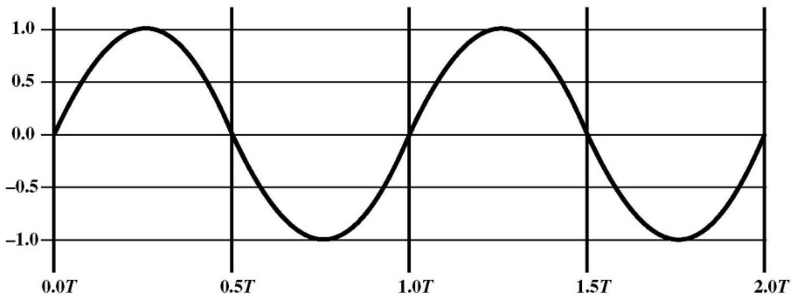
Increasing the bit rate



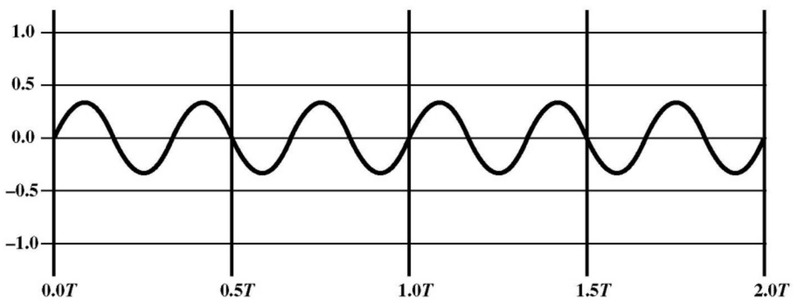
- Increases the rate at which the signal changes
  - Proportionally increases signals present, and thus the spectral BW
- Increase the number of bits per change in the signal
  - Adds detail to the signal, which also increases the spectral BW



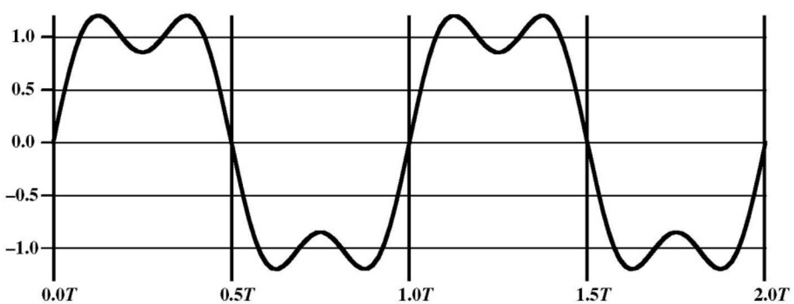
Adding Detail to the Signal



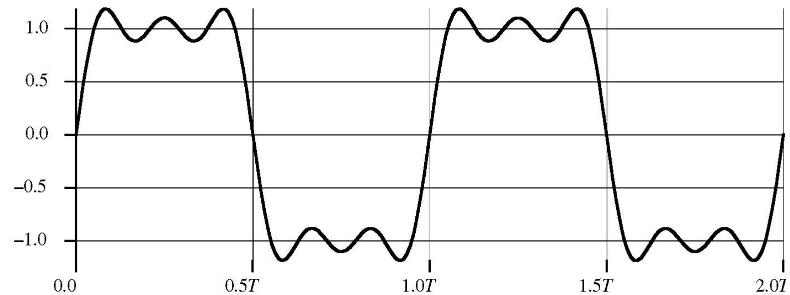
(a) sin (2 *ft*)



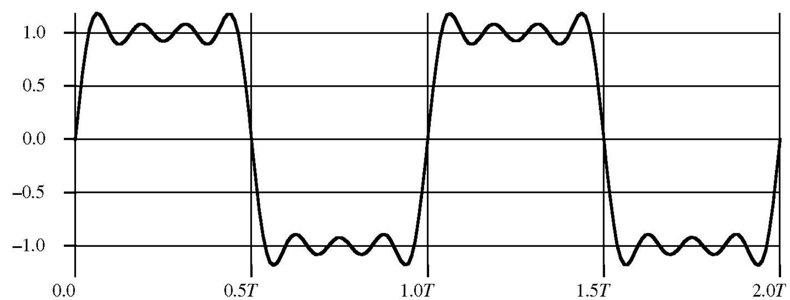
(b) (1/3) sin (2 (3*f*)*t*)



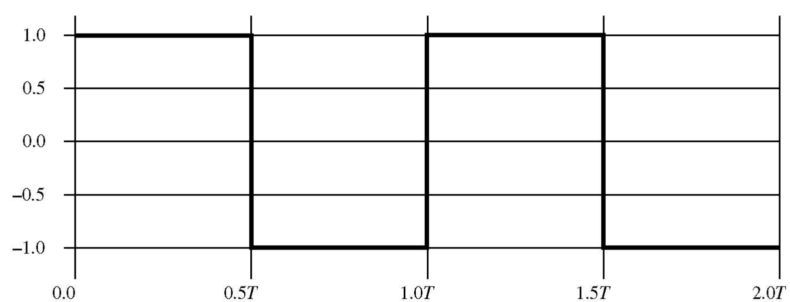
(c) (4/) [sin (2 *ft*) + (1/3) sin (2 (3*f*)*t*)]



(a) (4/) [sin (2 *ft*) + (1/3) sin (2 (3*f*)*t*) + (1/5) sin (2 (5*f*)*t*)]



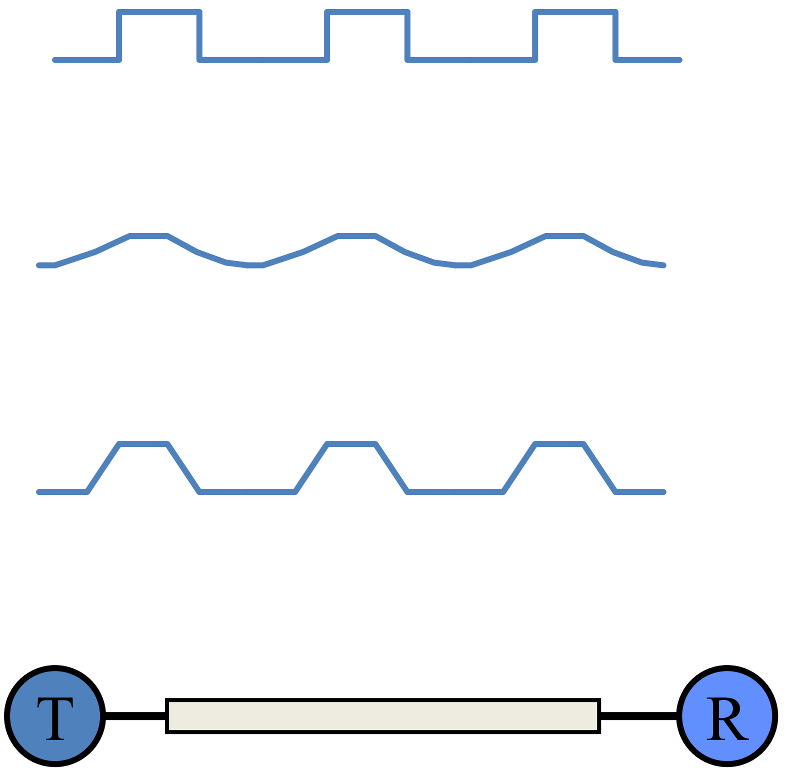
(b) (4/) [sin (2 *ft*) + (1/3) sin (2 (3*f*)*t*) + (1/5) sin (2 (5*f*)*t*) + (1/7) sin (2 (7*f*)*t*)]



(c) (4/) ∑ (1/***k***) sin (2 (*kf*)*t*),   for ***k*** odd

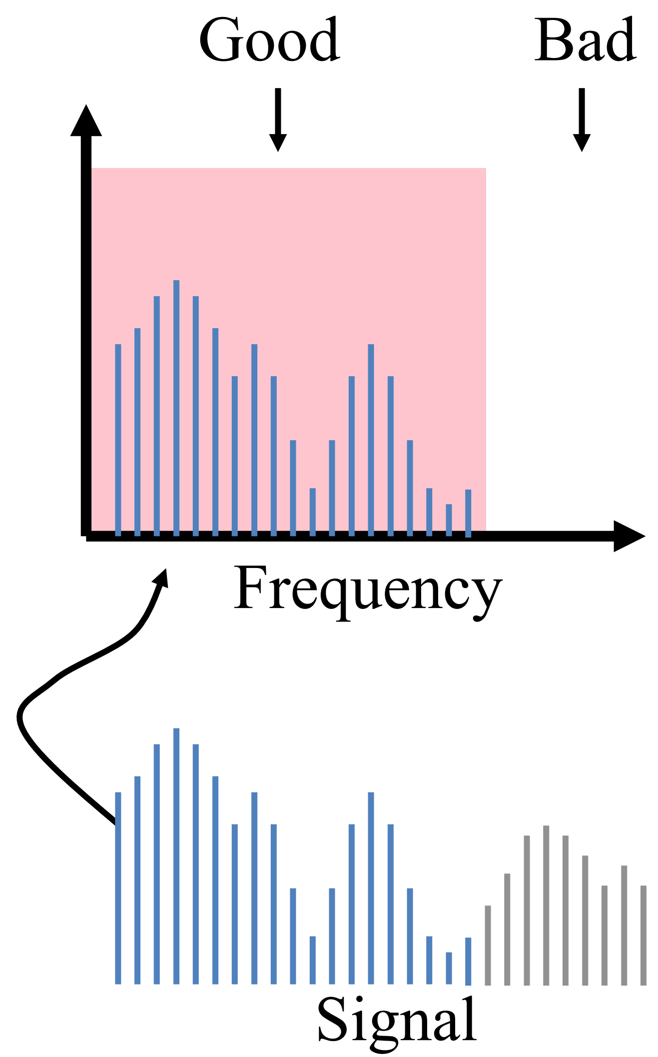
So Why Don't we Always Send a High Bandwidth Signal?

- Channels have a limit on the type of signals it can carry
- Wires only transmit signals in certain frequency range
  - Attenuation and distortion outside of range
  - Distortion makes it hard for receiver to extract the information
- Wireless radios are only allowed to use certain parts of the spectrum
  - Radios optimized for that frequency



Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the channel
  - Different types of fiber and copper have different properties
- As technology improves, these parameters change, even for the same wire
  - EE technology improvements
- For wireless networks, limits are often imposed by policy
  - Can only use certain part of the spectrum
  - Radio uses filters to comply



Channel Capacity

- **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

Decibels

- A ratio between any two numbers x_1, x_2 can be expressed in ***decibels (dB)*** as follows: $\left(\frac{x_1}{x_2}\right)_{\text{dB}} = 10\log\left(\frac{x_1}{x_2}\right)$

- Is used in many contexts:
  – The loss of a wireless channel
  – The gain of an amplifier

- Note that a quantity expressed in dB is a **relative value**
  - But can be made absolute by picking a reference point
    – Decibel-Watt – power relative to 1 W
    – 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)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal
- Low SNR means it may be hard to "extract" signal from noise
- SNR sets upper bound on achievable data rate

Shannon Capacity Formula

$$C = B\log_2\left(1+\text{SNR}\right)$$

- Represents error free capacity:
  - **It is possible to design a suitable signal code** that will achieve error-free transmission (you design the code)
  - We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel
- Result assumes additive Gaussian white noise (thermal noise)

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.

$$C = B\log_2\left(1 + \mathrm{SNR}/\Gamma\right)$$

Example of Nyquist and Shannon Formulations

- Spectrum of a channel from 3-4 MHz; $SNR_{dB} = 24$ dB

$$B = 4\ \mathrm{MHz} - 3\ \mathrm{MHz} = 1\ \mathrm{MHz}$$

$$\mathrm{SNR}_{\mathrm{dB}} = 24\ \mathrm{dB} = 10\log_{10}(\mathrm{SNR})$$

$$\mathrm{SNR} = 251$$

- Applying the Shannon capacity formula:

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

Today

- RF introduction
- Modulation
- Multiplexing
- Channel capacity

- **Next time:**
  - Antennas, the wireless channel, wireless channel prediction